ULTRASONIC CHARACTERISATION OF THE STRUCTURE AND PROPERTIES OF WOOD

By

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A thesis submitted to
The School of Physics and Chemistry
of the
University of Surrey
in the requirement for the
Degree of Doctor of Philosophy.

September 1999

Department of Physics
University of Surrey
To Angela, my wife.

For her encouragement without which I could not have begun, and her support without which I could not have completed this work.
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ACKNOWLEDGEMENTS

Any piece of work such as this cannot be carried out without the support, assistance and generosity of individuals in the many locations where this work was carried out.

Firstly I would like to acknowledge the great debt I owe to my supervisor Dr. R.C. Chivers, formerly of the University of Surrey. The expertise which he brought to the supervision of this work was everything I expected when choosing to work in The University of Surrey but I found his approach and personal commitment to the project to be above and beyond what one can expect from a supervisor.

I would also like to thank my co-supervisor Dr. R. A. Bacon willing support in the completion of this work and Professor E. O'Reilly, Head of Physics, for his support and interest in the work. I would also like to acknowledge my debt to the staff of the mechanical workshop (Willi and Roger) in the Physics Department of the University of Surrey who worked with great timeliness and skill on the preparation of samples and sample holders for the immersion tank work. My colleagues in the ultrasonics laboratory, Dr. M.A. Bangash and Dr. T. Esward were a font of knowledge and support for which I am grateful.

I would like to thank my employers, The Institute of Technology Tallaght, for their support in the finishing stages of this work. In particular I would like to thank Dr. T.J. Ennis who assumed the role of collaborative supervisor, Dr. T. Creedon, Head of School of Science, Dr. M. Ahern, Head of Department of Science and my colleagues in the Physics section all of whom have been very supportive.

I cannot of course forget my former colleagues in The Institute of Technology Carlow for their support in this work. The positive attitudes and genuinely supportive approach of my former colleagues were a great help during the long years over which the main body of work was carried out. I must single out some people in particular who gave significant amounts of time and technical support including Mr. R. Jordan, Mr. P. Kelly, the computing services staff, the electronics technical support staff, the mechanical workshop staff and the administrative staff. The members of the industrial liaison office, including Mr. J. McEntee were also of enormous assistance throughout the programme.
My interest in this area stems from interactions over many years with Dr. J. Evertsen of Enterprise Ireland and I would like to thank him for his advice, support and insights over those years. Mr. M. McCourt, Mr. S. Keogh and indeed all the support staff in the Forest Products Department of Enterprise Ireland were also very supportive to me over the time. I thank Mr. G. Gnaggs of the Forest Products department for his generously given expertise in the area of species identification.

I owe a special debt to Dr. V. Bucur of the I.N.R.A., Nancy Wood Quality Research Laboratory. Her generosity, enthusiasm and insights were all useful in setting me on the right road in this programme of study. I thank also Dr. G. Nepveu (Head of Department of Wood Quality Research) for allowing me to carry out some work in his department.

I must thank Dr. J. Keating of NUI Maynooth for introducing me to the field of artificial neural network analysis. I am indebted to Mr. Thomas Dunne for the generous provision of facilities which have permitted the completion of this thesis.
Summary

Wood is a versatile and strong engineering material which displays a high level of anisotropy. Modelled as an homogeneous orthotropic solid, its natural variability and unique microstructure presents a serious challenge to the application of standard non-destructive evaluation techniques for quality assessment.

In this work the characterisation of wood using ultrasonic techniques is considered. Addressing the problem is seen as requiring knowledge of three distinct areas - the structure of wood, the theoretical basis of elastic wave propagation in an orthotropic solid and ultrasonic measurement science. This forms the basis of a critical review of the literature pertaining to ultrasonic characterisation of wood.

A systematic study of ultrasound velocity and attenuation over a range of frequencies is reported in chapter 6 of this work. From this study which examines three species of wood with different microstructures a number of significant results emerge. The species are seen to display different levels of anisotropy. Velocity is seen to increase significantly with frequency, particularly for some species. Attenuation is seen to be frequency dependent. The results point to the significance of the inhomogeneity of wood. The variation of ultrasound properties from pith to bark and at different levels within the tree is also measured.

The orthotropic model is extended to include the effect of the inhomogeneity due to the annual ring structure in wood. This is modelled as a quasi-periodic structure. A novel set of measurements of acoustic inhomogeneity in the longitudinal and tangential directions, which can resolve within ring variations in wavespeeds, is presented. These measurements are used, along with data from the literature to show that the potential stop and pass bands may exist for waves travelling in the radial direction. A phase cancellation artefact and other interference effects are seen to exist for propagation in the longitudinal and tangential directions.

Finally artificial neural network analysis is used to show that ultrasonic signals may be classified by the species through which they have propagated. This method is seen as having potential for engineering applications.
1. INTRODUCTION

1.1 Wood as a Natural Material

Wood has been used by man as an engineering material since earliest times. It is a substance with which most people are familiar. Strong, light, flexible and durable, its applications range from massive structural beams to household furniture, from houses to pencils. Clearly the most efficient exploitation of this valuable resource is of economic importance.

In spite of its long history of use as an engineering material wood is a material not easily predictable in all its engineering properties. For example the classification of individual pieces of timber into standard strength or quality classes is not completely consistent. As is discussed in the next section, a wide variety of methods is used for grading timber so that the same piece of material may end up in completely different strength classes depending on the technique used (Sandoz: 1989,1993).

The reasons for the difficulty associated with fully characterising an individual piece of timber to the extent of predicting its bending or breaking strength lie in the complexity of the structure and origin of the material. Wood is inhomogeneous as a glance at the grain of any piece of timber quickly shows. It is also anisotropic, having different bending strengths depending on the orientation of the grain in the specimen under test. Ideally, the strongest planks are fashioned with a particular orientation so that they will have straight grain along their length with the same annual rings clearly visible at each end (Desch and Dinwoodie: 1996).

The biological nature of wood also gives rise to great natural variation in the physical properties of the end product. This inherent variability is in part due to growth conditions such as climate, soils, water supply, and available nutrients (Bodig and Jayne, 1982). In addition all properties of wood are to some extent heritable so that a portion of the natural variability of wood can be attributed to differences in genetic stock (Bodig and Jayne, 1982). These facts alone mean that evaluation techniques are a prerequisite for using timber as an engineering material since, unlike 'synthetic' materials, production conditions cannot be completely controlled.
In summary we may describe wood as a material which is light, strong, and easily worked. Its natural variability, however, restricts its use and leads to over-design to allow for worst case design. A great deal of effort has been expended on developing testing and evaluation techniques for wood to try to limit the influence of its natural variability. These are contained in the next section.

1.2 Assessment Of Wood Quality

A consequence of the variability of wood is that large safety margins must be employed when drawing up specifications for the use of timber elements in engineering applications. This of course means that most timber elements are over specified to allow for the worst case that might be encountered. Since it is not sensible to ignore the principle of worst case design, then the most appropriate way to reduce the ‘wastage’ of timber through over specification is to develop economic techniques to test each element for strength.

European standards on the use of wood in timber structures are given in ENV 1995-1-1, 1993. They are limit state codes meaning that requirements concerning structural reliability are linked to clearly defined states beyond which the structure no longer satisfies specified performance criteria (de Sousa, 1995). Only two types of limit state are considered: ultimate limit state and serviceability limit states (Larsen, 1995). Ultimate limit states are those associated with collapse or other forms of structural failure and include: loss of equilibrium; failure through excessive deformations; transformation of the structure into a mechanism; rupture; loss of stability. Serviceability limit states include: deformations affecting the appearance or the effective use of the structure; vibrations causing discomfort or damaging the structure; damage likely to have an adverse effect on the durability of the structure. Key issues raised by these standards is assessment of the likely deformation and rupture performance of wood members in structures as well as assessment of damage. It should be noted that the safety coefficients arrived at in the limit state codes are based on the statistical distribution of responses of particular properties to actions (Larsen, 1995).

A great deal of effort has gone into developing assessment techniques which measure the strength properties of wood. In general the strength is the property by which a
piece of timber is judged. The term strength can cover a range of ideas from compressive strength to tensile strength and bending strength. Indeed the strength for a particular piece of timber should ideally be quoted with its particular application in mind. However in practice timber is sold in strength grades or classes.

The most widely accepted techniques for measuring wood strength properties are physical destructive testing techniques such as measurement of the Modulus of Rupture (MOR), the Modulus of Elasticity (MOE) and the compressive strength (Desch and Dinwoodie, 1997; Sinclair and Farshad, 1987). These measurements are generally carried out on large test rigs using standard procedures. For MOR and MOE a four point bend test procedure is employed. The MOE is determined from the slope of the stress-strain curve as the structural member is stressed at a constant rate. The MOR is defined as the ultimate breaking strength of the structural member. A similar stress-strain measurement is carried out for the compressive strength determination with the member this time subjected to a compressive stress. The time consuming and, in the case of MOR testing, destructive, nature of these techniques makes them unsuitable for strength classifying each piece of timber intended for engineering use.

In practice most timber is graded using either a visual grading process or a machine stress grading process. The minimum European standards for visual grading have been laid down in EN518 “Structural timber- Grading - Requirements for visual strength grading standards”. Visual grading depends on the skill of a human grader. The pieces of timber are assessed for knot size and location, slope of grain and number of annual rings per unit length before being assigned a strength class. Other factors are taken into account such as distortion of a member, fungal and insect damage.

The advantages and disadvantages of visual strength grading are (Glos, 1995)

- it is simple, easily understood and does not require great technical skill,
- it does not require expensive equipment,
- it is labour intensive and rather inefficient in that wood structure and density which influence strength are not sufficiently taken into consideration,
- it lacks objectivity.
Indeed it has been shown that the same timber elements are regularly placed in different strength classes by different experienced operators using this technique (Sandoz, 1989). Computer vision based grading systems also exist but here too their application is problematic. Firstly not all features are easy to distinguish using machine vision and secondly the complexity of the data acquisition and computing required makes the system expensive. Thirdly vision systems do not measure density or other elastic properties directly. (Glos, 1995).

Requirements for machine grading can be found in EN519 “Structural timber- Grading - Requirements for machine strength graded timber and grading machines”. Machine stress grading depends on a machine which applies a constant stress to pieces of timber which are fed through the machine. The deflection of the timber in response to the applied stress is measured by the machine and a grade assigned to the timber. This may be a simple process of ‘go/ no go’ for a particular grade or involve more complex processing. While overcoming many of the objections about objectivity, machine stress grading is generally limited to timber of maximum thickness 80mm. Some problems are reported with machine stress grading, particularly the issue of whether measurement of localised deflection gives a true indication of the strength of the structural member (Lam et al., 1993; Perstoper, 1996).

Basic wood density is widely accepted as the single most important signifier of clear wood quality (Desch and Dinwoodie, 1997; Bodig and Jayne, 1982; Bazenov, 1961). Desch and Dinwoodie, 1997, report in their classic text that the mean density is the best single criterion of strength. However the importance of density is of course modified by other parameters such as the arrangement of cells and the particular structure of cell walls.

A range of secondary methods has been developed which measure wood properties in a non-destructive fashion, and relate these measurements to destructive test methods. For example, ultrasonic grading (Sandoz, 1989), and resonant frequency testing (Haines, 1979) and microwave based (Martin et al., 1987) techniques have all been used.

Ultrasonic stress grading of timber has been developed for specific situations but has not yet gained widespread acceptance (Ross et al., 1996; Sandoz, 1989; 1993).
Resonance testing is a useful laboratory technique but is simply not a practical technology on an industrial scale (Sinclair and Farshad, 1987).

Other testing techniques used to assess wood quality include X-ray densitometry (Evertsen, 1986). This method measures the variation of such parameters as density (both across the trunk and within a ring), ring width, and percentage earlywood which are seen as having a major influence on wood quality (Pearson, 1955, Harvald and Olesen, 1987; Evertsen, 1986). While these techniques are useful indicators of wood quality they infer the likely strength properties from the density of the wood rather than by physically disturbing the sample.

However X-ray densitometry can be useful in identifying certain types of potential problem. For example some pieces of wood might display a high mean density, but be prone to shear failure where abrupt changes in density occur at the summer wood / spring wood boundary (Desch and Dinwoodie, 1997).

X-ray densitometry is also used to assess the extent of juvenile or adult wood in samples. Juvenile wood is laid down near the pith of a tree. It tends to be more variable in density and strength than adult wood and so is considered to be of a lesser quality than adult wood (Olesen, 1977). Adult wood displays fairly uniform density and tends to display less faults such as bowing and splitting when converted to structural lumber (Bodig and Jayne, 1982; Desch and Dinwoodie, 1997).

Thus it can be seen that present techniques for wood quality assessment are relatively crude. They are probably wasteful in that, for safety, they err on the conservative side. Of the techniques mentioned above ultrasonic or material wave propagation methods would appear to have greatest potential to provide a systems of fast, economic and intelligent assessment of timber quality. They are essentially mechanical waves, and their propagation is dependent upon the elastic properties of the material through which they are propagating. It may be hoped that this dependence will provide a direct link to the strength parameters that are of interest to the main users of wood. In a sense they are complementary to the use of density as a parameter for grading but may have more sensitivity and flexibility of application.
1.3 The Scope of This Work.

The overall thrust of this work is thus to provide some basis for developing an improved understanding of the elastic properties of wood. While the experimental work tends to be carried out on carefully prepared specimens in the laboratory sight has not been lost of the potential future need to extend the application of techniques into the timber yard or even the forest.

The pursuit of scientific rigour in this area of the interaction of ultrasonic waves with wood is beset by a number of complexities, many of which are uncontrollable. The complex structure and origin of wood has already been mentioned in section 1.1. In chapter 2 a brief description is given of those elements of its structure which are considered particularly relevant for the measurements which represent the basis of this work. Broad classifications such as 'hardwood' and 'softwood' are often adopted for convenience, but it is generally true that the microstructural organisation of wood is characteristic of the species of tree from which the wood is taken. Even within a species there will be significant variations from tree to tree due to, for example, genetic and environmental factors, neither of which can be completely controlled- or even identified - at present. Furthermore the microstructure varies within a single tree. Thus it is not sufficient simply to state that measurements were made on a sample of Spruce, for example. It would also be necessary to at least identify the age of the tree and the position within the tree from which the sample was taken.

Of equal importance is the identification of the orientation of the sample in the tree. It is clear from Chapter 2 that the structural composition of trees is markedly different along the three major axes of the tree. Assuming idealised geometry and homogeneity in the wood material, it is thus possible, as a first approximation to model wood as an orthotropic solid. The theoretical basis of elastic wave propagation in such materials forms the bulk of Chapter 3. It is shown that 9 elastic constants are needed to fully characterise the material and that the waves that propagate along the principal axes are pure modes (whether compressional or shear).

The assumptions of this model are clearly violated by the curvature of the tree and the (radial) pattern of annual growth rings which is commonly found. The former is of particular importance in relation to the choice of specimen dimensions for the
experimental work. The dimensions are limited by ultrasonic considerations (see below) but also by the material that is available, by the potential for variation with position within a tree, and by the need to have clear wood, that is wood free from defects such as knots splits and rot. Such defects clearly complicate the understanding of wood as an engineering material still further. However the structural interaction of such gross defects with the base material will not be considered in this work which concentrates in gaining an improved understanding of clear wood. The imposition of finite dimensions on the specimen introduces the need to consider waves in unbounded solids, which is discussed briefly in Chapter 3.

The annual ring structure mentioned above may be modelled as a quasi-periodic material. The analysis at the end of chapter 3 shows that such materials may, depending on the dimensions and properties of the elements, exhibit pass and stop bands. The relevant formulae are developed for subsequent application to measurements.

In view of the obvious potential attractions of ultrasonic techniques for testing wood identified in section 1.2, it is not surprising to find that there's a considerable body of apparently relevant literature. Much of this has been summarised by Bucur (1995). The problems of ultrasonic measurements on anisotropic, inhomogeneous solids such as wood are not trivial. In nearly all experiments compromises have to be made. Thus, in order to assess the relevant literature which is reviewed in Chapter 5, a summary of the key elements of the relevant ultrasonic measurement techniques is presented in Chapter 4. Of particular importance are the choice of specimen size, of frequency, of signal analysis procedures, of coupling methods, and transducer size.

The review of the literature in Chapter 5 starts with the direct approaches to linking ultrasonic methods with engineering properties such as strength. The fact that only one example appears to exist of an ultrasonic technique being taken into standard procedures (Sandoz, 1989) is probably a reflection of a general oversimplification in failing to recognise the complexity of the material and the many variables potentially involved. The section dealing with laboratory measurements show a similar trend. Often relevant parameters are omitted from experimental descriptions. Where they are given they often cast doubt on the validity of the results reported. It is interesting to note that while authors tend to concentrate their attention on species of timber of particular economic importance, the present author has failed to find a single example
of the experiments of one author being repeated by another. In a field replete with so many potential variables such an approach would appear to be a pre-requisite for scientific progress.

A particular void in the literature appears to be a systematic set of ultrasonic (longitudinal and shear) velocity and attenuation measurements made on the same set of samples at a number of different frequencies and at a number of angles to the principal axes of the wood. The first such study is reported in Chapter 6 for measurements on Horse chestnut, Maple and Norway spruce, at 5 frequencies between 100kHz and 1.5MHz, and at incremental angles of 15°. These data sets permit the full set of elastic constants to be determined for each of the samples. The difficulty of making measurements off the principal axes due to the lack of pure mode propagation is clearly apparent. The species chosen for measurement were selected on the basis of their being typical of three classes of microstructure identified in Chapter 2.

At this stage of the work two options were open. The first was to generate a database of similar measurements on a wide range of species and to investigate inter and intra species variations. The other - which was adopted- was to attend to some of the other major questions raised by the complexity of wood as a material. This was attempted in three ways.

In the first place the potential systematic variation of acoustic properties as the tree grows was investigated by taking measurements of ultrasonic velocity along a core from the bark to the pith of Sitka spruce trees (Chapter 7). It is known that density varies systematically. The velocity measurements reveal a different variation and are interpreted in terms of microstructural and ultrastructural variations within the tree.

The second complementary approach was to use a high precision scanning measurement system to investigate the variation of ultrasonic wavespeeds and density within the annual ring structure (Chapter 8). Measurements were made on samples of Larch, Pine and Spruce with density variations being determined by X-ray densitometry. These measurements are interpreted in Chapter 9 for waves travelling in the radial direction in terms of the pass-band analysis for periodic structures which was developed at the end of Chapter 2.
Finally it became obvious that conventional methods of measuring ultrasonic velocity and attenuation can be seriously compromised in a complex material such as wood so that a pure wave pulse input can often emerge with a complicated form due to energy divergence and mode conversion. Rather than attempt to pick out a single characteristic pulse or threshold from which to calculate for velocity or attenuation, it was felt that the whole of the signal might contain useful information. In order to investigate this further a neural network approach to wood characterisation was implemented (Chapter 10). As a first stage, discrimination between 4 species with different microstructures (Oak, Maple, Alder and Pine) was attempted. The success of this approach opens up a number of new avenues for further work. The contributions of this thesis are summarised in Chapter 11 together with a number of suggestions for further work.
2. THE STRUCTURE OF WOOD.

Almost all woody plants are composed of three main structures: roots, stems and leaves. Trees are separated from other woody plants by their characteristic stem, more commonly known as the trunk of the tree. The trunk has several functions. It supports the crown of the tree which contains the energy converting leaves and reproductive elements of the tree. The trunk also carries upwards the water and minerals necessary for photosynthesis. Finally the trunk is also used for storage of both food and waste.

The trunk of the tree is, of course, the source of wood. It is the pattern of growth of this complex natural material, which produces both its anisotropy and inhomogeneity. When considering its elastic properties wood is generally modelled as an orthorhombic solid (Lee, 1958; Musgrave, 1970), having three mutually perpendicular axes of symmetry, (the longitudinal, L, radial, R, and tangential, T, axes, Figure 2.1) giving rise to nine independent elastic constants (Section 3.1).

Bodig and Jayne (1982) have reported that the Young’s Moduli for wood can be related over a wide number of species using the ratios:

\[ E_L : E_R : E_T \approx 20 : 1.6 : 1 \]  

This gives an idea of the extreme elastic anisotropy displayed by wood. It should be noted that these ratios depend on many factors such as species, moisture content, temperature to name but a few. Bodig and Jayne also report that these ratios are not
absolute but show a dependence on $E_L$. Indeed the measurements reported in Chapter 5 of this work show just how various species can vary in anisotropy. Various workers have described models to explain this behaviour. For example wood has been modelled as being constructed from air-filled polygonal tubes, axially loaded with some lateral restraint (Lee, 1958). This simple model explains the fact that the longitudinal Young’s modulus in wood $E_L$ is generally much larger than the radial or tangential moduli ($E_R$ and $E_T$). Such tubes would be more resistant to compression than bending. The tubes referred to by Lee can be related to the tracheids and fibres whose origin is discussed in section 2.2.

The macroscopic anisotropy of wood has its origins in its complex cellular structure. Indeed anisotropy can be observed at several levels of material organisation in wood. In the discussion that follows much has been taken from *Mechanics of Wood and Wood Composites* by Bodig and Jayne (1982), *Timber Structure, Properties, Conversion and Use* by Desch and Dinwoodie (1996) and *Wood as a Building Material* by Hoffmayer in *Timber Engineering* (Blass et al. editors, 1995).

Wood is laid down by a ring of cells known as the cambium at the edge of the stem of the tree. At this point these cambial initial cells divide into xylem cells on the inside and phloem cells on the outside. The phloem cells form the basis for the bark of the tree. The xylem cells are the main structural element of the material that becomes wood. To understand the physical nature of wood it is necessary to give an outline description of the structure of the cells which form it as well as the properties observed when these cells combine.

### 2.1 Wood Cell Composition, Types And Formation.

The chemical composition of woody substance is approximately 50% carbon, 6% hydrogen and 44% oxygen. This is formed into various types of cellulose and lignin. The cellulose molecules have the ability to form linear polymer chains, much longer than they are wide. In cell walls these cellulose molecules are generally located in discrete bundles called elementary fibrils. These elementary fibrils are often aggregated into larger bundles by hydrogen bonding into microfibrils, which have been observed by
a number of investigators to have cross-sectional dimensions of the order of 3.5x10 nm (Bodig and Jayne, 1982). Microfibrils, and their angle to the main axis of the cell, are considered to play a key role in determining the strength of properties of cells. Hence microfibril angle and its relation to wood grain angle is seen as an important contributor to wood strength along different axes.

The fibre cell wall has a layered structure which is illustrated in figure 2.2 (Parham and Gray, 1984). Between the individual cells there is a layer, the middle lamella (ML) which glues the cells together to form the tissue (Hoffmayer, 1995). The middle lamella is rich in lignin and pectic substances and is virtually free of cellulose. In the primary wall (P) the cellulose microfibrils are arranged in a random, irregular network. In normal wood tissue, the secondary wall consists of three fairly distinct layers S1, S2 and S3. The outermost layer S1 is very thin (0.1 to 0.2μm) and exhibits an average microfibril angle of about 50-70° to the axis of the tree. The bulk of the secondary wall is made up of the S2 layer, which is typically several micrometers thick. The microfibrils are usually oriented to the fibre axis at a relatively small angle (5-20°). Within the very thin S3 layer the microfibrils are arranged with a gentle slope but not in a strict order.
Figure 2.2 Schematic of the general wall architecture of normal wood fibres. 
L, cell lumen; ML, middle lamella; P, primary wall; and S₁, S₂ and S₃, layers of the secondary wall (Parham and Gray, 1984).

The dominant S₂ layer of almost axially oriented bundles of microfibrils very effectively takes up tension forces. In compression the bundles of microfibrils are turned into long slender columns which are then prevented from buckling by the inner and outer reinforcing layers of S₁ and S₃ microfibrils having more gentle slopes (Hoffmayer, 1995). The structure of the cell wall is sometimes termed the ultrastructure of the material. The nature and thickness of the cell wall layers depend on the cell type and position.

Most commercially important woody plants are classified into two groups:
(a) conifers, also called evergreens or softwoods, and
(b) deciduous, also called broadleaves or hardwoods.

Softwood and hardwood is the most commonly used terminology, although several softwood species are somewhat harder than many of the so-called hardwoods. A
simple model of a softwood block and a hardwood block showing the main planes of anisotropy is given in figure 3.

Figure 2.3 Models of a softwood block and a hardwood block  
(Fengel and Wegener, 1984)

Softwoods are composed mainly of long threadlike tracheids (figure 2.4(a)) and shorter less slender parenchyma cells. In hardwoods the threadlike cells are called fibres and they are accompanied by larger diameter vessels and short parenchyma cells. Tracheids provide mechanical support and fluid transport mechanisms for softwoods. In hardwoods fibres provide mechanical support and vessels are the main fluid transport mechanism (Figure 2.4(b)). Parenchyma cells are primarily used for food storage.
Figure 2.4(a). Softwood Cellular Structure
(Foulger, 1969)

Key: 1 = Cross section  2 = Radial section  3 = Tangential Section
     4 = Growth ring     5 = Earlywood      6 = Latewood
     7, 8 = Wood Rays    9, 10 = Resin ducts 11, 12 = Pits.
Table 2.1 below taken from Bodig and Jayne (1982) gives an indication of typical dimensions of each cell type observed. The ratio of length of cell to diameter is typically in the range 50 to 100.
### Table 2.1: Typical volume and dimensions of various types of wood cells (*Bodig and Jayne, 1982*).

<table>
<thead>
<tr>
<th></th>
<th>Softwood</th>
<th>Hardwood</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tracheid</td>
<td>Parenchyma</td>
</tr>
<tr>
<td>Volume %</td>
<td>85-95</td>
<td>5-12</td>
</tr>
<tr>
<td>Length, <em>l</em> (mm)</td>
<td>2.5-7.0</td>
<td></td>
</tr>
<tr>
<td>Tangent, <em>t</em> (µm)</td>
<td>25-80</td>
<td></td>
</tr>
<tr>
<td>Av. Radius, <em>r</em> (µm)</td>
<td>17-60</td>
<td></td>
</tr>
<tr>
<td>Cell wall thickness (µm)</td>
<td>2-7</td>
<td></td>
</tr>
</tbody>
</table>

Wood cells have a very particular arrangement. The greatest volume of the stem or trunk of a tree is occupied by tracheids or fibres with their longitudinal axes more or less parallel to the central axis of the tree. Vessels run parallel to fibres, along the longitudinal axis of the tree. Also observed are ray cells (figures 2.3, 2.4(a)) which are cells oriented along the radial direction of the trunk, which run from the centre to the bark of the tree, normal to the longitudinal direction. Figures 2.3, 2.4a and 2.4b and the table given above refer to a generalised model of softwood and hardwood. In practice each individual species has its own characteristic microstructure (Davidson and Freas, 1987). Consequently each species of wood has its own range of variation of elastic constants (Lee, 1958; Musgrave, 1970; Haines, 1979).

### 2.2 Growth Ring Formation And Its Influence On Stiffness.

The wood of trees grown in temperate climates displays the effects of seasonal variations in climate. This leads to the formation of an important level of organisation in wood which is the layered arrangements of cells called growth rings. Wood grown in temperate climates, particularly softwood, typically produces one growth ring each year. The wood formed early in the growing season is less dense with large cell cavities. This wood is called earlywood or springwood (See Fig. 2.3). Earlywood is associated with the conduction of water and fluids (*Bodig and Jayne, 1982*). Later in
the growth season, as winter approaches, denser latewood is laid down. Late wood is generally characterised by small diameter cells with thick cell walls. Owing to the increased amount of cell wall substance latewood has a dominant effect on the mechanical properties of wood (Bodig and Jayne, 1982). During the winter season little or no wood is laid down. This variation in growth pattern during the year results in a density variation between earlywood and latewood which can be seen visually as annual rings (Bodig and Jayne, 1983; Olesen, 1977).

In softwoods a sharp density step is usually observed at the point between the end of the late or summer wood of one growth cycle and the beginning of the early or spring wood of the next growth cycle. Hardwoods can be classified into ring porous and diffuse porous hardwoods. Ring porous hardwoods have larger vessels in the early part of the ring whereas diffuse porous hardwoods have a more or less even distribution of large vessels throughout the ring. Figure 2.5 shows a cross section of a typical softwood annual ring, a typical ring porous annual ring and a typical diffuse porous annual ring.
Figure 2.5(a). Cross Section of typical softwood annual ring.
(Species: Eastern Hemlock, Bodig and Jayne, 1982).

Figure 2.5(b) Cross Section of typical ring porous annual ring
(Species: Sweet Chestnut, Desch and Dinwoodie, 7th edition, 1996).

Figure 2.5(c) Cross Section of typical diffuse porous annual ring.
(Species: Maple, Desch and Dinwoodie, 6th edition, 1982).
As can be seen from figure 2.5, softwoods generally display a marked difference in density between the earlywood part of the annual ring and the latewood part of the annual ring. The differences in density in hardwoods are generally not as marked as in softwoods.

When compressing wood along the radial direction one is compressing dense material in series with less dense material. On the other hand when compressing along the tangential axis one is compressing dense material in parallel with less dense material (Bodig and Jayne, 1982; Kahle and Woodhouse, 1994). This might lead one to conclude that the tangential direction is stiffer than the radial direction. However this is not the case in practice as is clear from Relation 2.1 above.

The analysis in the preceding paragraph neglects the influence of ray cells, which are long, slender cells oriented in the radial direction in the tree. These cells provide extra stiffening in the radial direction by virtue of their own stiffness (Bodig and Jayne, 1982). Kahle and Woodhouse, 1994, propose that ray cells cause the cell walls in the adjacent material to align with the ray cells thereby causing an additional stiffening effect. This alignment of cell walls in the radial direction might also be attributed to their origin in the ring of cambial initial cells at the outer part of the woody stem from which woody xylem cells originate.

In contrast there are no cells which have a tangential alignment. Indeed alignment of cell walls along the tangential direction tends to be much less than along the radial direction (Kahle and Woodhouse, 1994). Also while wood may be approximated as an orthorhombic solid it should be noted that in the tangential direction curvature is always present to a greater or lesser extent.

Superimposed on the density variations due to annual density variations within the rings is an overall density variation from pith to bark of the tree (Olesen, 1977; Harvald and Olesen, 1987). This overall density variation is due many factors such as variations in growth ring width, cell wall thickness and composition. The pattern of density variation from pith to bark can be shown to depend on the particular species (Olesen, 1977; Harvald and Olesen, 1987).
Berndt and Johnson (1995) compiled a table giving length scales of wood structures. It is given here as an aid when considering interactions between ultrasound and structures in wood.

<table>
<thead>
<tr>
<th>Length Scale</th>
<th>Characteristic Feature</th>
<th>Material Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>10mm-1m</td>
<td>Lumber dimensions, knots and distances between knots.</td>
<td>Homogeneous, anisotropic continuum</td>
</tr>
<tr>
<td>1mm-10mm</td>
<td>Growth rings and their growth zones.</td>
<td>Layered composite with homogeneous, anisotropic layers</td>
</tr>
<tr>
<td>20µm-1mm</td>
<td>Cells, rays, resin canals</td>
<td>Cellular solid with homogeneous cell walls</td>
</tr>
<tr>
<td>1µm-20µm</td>
<td>Cell walls, pits.</td>
<td>Fibre reinforced laminate</td>
</tr>
<tr>
<td>1nm-1µm</td>
<td>Cellulose fibres, lignin-hemicellulose matrix</td>
<td>Fibres with internal structure; matrix, amorphous or structured.</td>
</tr>
</tbody>
</table>

Table 2.2 Length Scales of Wood Structures.

(*Berndt and Johnson, 1995*)
3. THEORY

The complex nature and origin of the structure of wood has already been described in chapter 2. The current chapter deals with the main elements of the theoretical background to the interaction of material waves with wood. Of necessity the models used to describe the passage of material waves through wood are based on assumptions which are a gross simplification of the actual situation. The approach adopted here is to consider first the interaction of material wave with an elastic isotropic solid, then to consider the effect of introducing inhomogeneity into the model.

In the first section a model of linear elasticity in an anisotropic solid with orthorhombic symmetry is described. The passage of material waves through such a solid, with the simplification that the medium is homogeneous is then examined. Such models have been developed and described in a number of classic tests such as Green (1973) and Musgrave (1970). The work set out here largely follows the models presented by the above mentioned authors. This treatment permits nine independent elastic constants to be determined from a combination of acoustic wavespeeds and density.

In section 3.3 the influence of inhomogeneity on the propagation of acoustic waves in the radial direction in wood is then considered. A wave propagating along the radial axis will experience successive layers of low and high density material as presented by the annual rings. These periodic density variations are accompanied by periodic velocity variations as measured in chapter 8. This propagation along the radial direction is examined as an example of propagation through a layered material. Propagation through layered materials has been treated well by Brillouin (1946) and Brekhovskikh (1960). The model presented here largely follows Gazanhes and Sageloli (1994) with the development as presented by Bedford and Drumheller (1994).

The concluding section of this chapter deals with the theoretical background to ultrasonic attenuation and scattering measurements. While the acoustic wavespeeds and density can be shown to be a priori linked to elastic constants, it is difficult to find a comparable basis for linking attenuation and scattering measurements to the physical
properties of a material. Nevertheless attenuation and scattering measurements have been shown to be useful parameters for the characterisation of a wide range of materials (Chivers, 1991; Szilard, 1982). The application of attenuation measurements to various materials and the techniques used to measure attenuation are discussed in chapter 3, with particular reference to those techniques which might be applied to wood.

3.1 Linear Elasticity

In this section the linear elastic model of an orthorhombic material is developed. First the concept of strain and the components of strain are defined. Next stress is defined. Then stress and strain are related for an anisotropic material via elastic constants. Finally the case of orthorhombic symmetry is considered.

3.1.1 Theoretical Basis For Linear Elasticity

The study of the mechanical properties of materials is concerned with the deformation of the material when an external force is applied. Three types of elastic behaviour may be displayed by materials under load: elastic, anelastic and plastic. Elastic behaviour describes the behaviour of materials which deform instantaneously on application of a load and which return to their original shape immediately on removal of the load. The deformation response of the material to an applied load can be linear or non-linear. Anelastic behaviour is used to describe those materials which deform over time on application of a load and which then recover their original shape over time on removal of the load. Plastic behaviour describes materials which deform upon application of a load but which do not recover their original shape upon removal of the load. In this work we concern ourselves primarily with linear elastic behaviour.

In confining ourselves to linear behaviour we need to be aware of those situations where non-linear behaviour may make a significant contribution to wave propagation. Green, 1973, has pointed out three cases where non-linear effects have a significant influence on material waves. In the first case the magnitude of physical disturbance
caused by passing high amplitude acoustic waves through a material may become large enough to cause finite strains in the material. Secondly material waves passing through a stressed material may experience non-linear effects. Thirdly defects in the material may give rise to localised regions of finite strain where non-linear behaviour can again be observed.

For the experimental work reported in this thesis the material (ultrasonic) waves used are considered to be of sufficiently small amplitude that only small strains are imposed on the samples by the wave propagation so that non-linear behaviour can generally be neglected. In testing the samples a small coupling pressure is used to attach the ultrasound probes to the samples. This coupling pressure can be shown to be negligible in comparison with the stresses needed to cause non-linear effects to become significant. Finally care has been taken to select samples free from defects as far as possible, thus minimising the possibility of encountering localised strain fields. As a result linear elastic effects may be safely taken to dominate the propagation of material waves in the experiments reported in this work.

3.1.2 Definition Of Strain

The co-ordinates of a point of material in an undeformed body can be defined using a vector \( \vec{X} \) as

\[
\vec{X} = x_1 \vec{i}_1 + x_2 \vec{i}_2 + x_3 \vec{i}_3 = \sum_{k=1}^{3} x_k \vec{i}_k = x_k \vec{i}_k \tag{3.1}
\]

with respect to the origin in an orthogonal system where \( \vec{i}_1, \vec{i}_2 \) and \( \vec{i}_3 \) are unit vectors in the orthogonal system and \( x_1, x_2 \) and \( x_3 \) are the components of \( \vec{X} \).

Let us consider the effect of a deformation of the material. The same point of material defined by \( \vec{X} \) will be displaced to a new position \( \vec{X}' \) in the material after a deformation. The displacement is a vector defined by

\[
\vec{u} = \vec{X}' - \vec{X}, \tag{3.2}
\]
having components \( u_k \). The Lagrangian strain tensor which provides a measure of the deformation with respect to the undeformed material co-ordinates is defined by

\[
\varepsilon_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_k}{\partial x_i} \frac{\partial u_k}{\partial x_j} \right].
\]  \( 3.3 \)

The assumption of linear elasticity and small strain means that since

\[
\frac{\partial u_i}{\partial x_j} \text{ and } \frac{\partial u_j}{\partial x_i} \ll 1,
\]  \( 3.4 \)

for infinitesimal deformations, then the quadratic term

\[
\left[ \frac{\partial u_k}{\partial x_i} \frac{\partial u_k}{\partial x_j} \right],
\]  \( 3.5 \)

is much smaller than the linear terms and can be neglected. Thus the small strain tensor can be defined by:

\[
\varepsilon_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right],
\]  \( 3.6 \)

It is clear from the definition of the small strain tensor that it is a symmetric tensor. i.e.:

\[
\varepsilon_{ij} = \varepsilon_{ji}.
\]  \( 3.7 \)

### 3.1.3 Physical Description Of Components Of Strain

The various components of the strain tensor can be related to physical strains. The components \( \varepsilon_{11}, \varepsilon_{22} \) and \( \varepsilon_{33} \) are longitudinal strains representing the fractional change of length of the body along the respective co-ordinate axis. For example if \( I_0 \) is the unstrained length along axis \( x_1 \) and \( I_1 \) is the strained length along axis \( x_1 \), then
The remaining strain components are the shear strains which, for small strains can be interpreted as a measure of the change in angle between two originally orthogonal axes in the undeformed medium. Consider figure 3.1 below:

\[ \varepsilon_{11} = \frac{(l_1 - l_0)}{l_0}. \]  

\[ 3.8 \]

From this diagram the strain may be taken to be (for small strains)

\[ \varepsilon_{12} = \frac{\Delta x_1}{x_2} = \tan \Theta \approx \Theta. \]  

\[ 3.9 \]

3.1.4 The Stress Tensor

The stress tensor \( \sigma_{ij} \) provides a measure of the applied forces on a body. Stress is classically defined as force per unit area. In the context of the stress tensor \( \sigma_{ij} \) represents a force on the \( i^{th} \) face in the \( j^{th} \) direction, divided by the cross-sectional area of the \( i^{th} \) face.
As in the case of strains, the components $\sigma_{11}$, $\sigma_{22}$ and $\sigma_{33}$ are the normal stress components, while the remainder are shear stress components. A diagram of the main components of the stress tensor is shown in figure 3.2 below.

![Diagram of stress tensor](image)

**Figure 3.2** Diagram of the nine components of the stress tensor.

### 3.1.5 The Relationship Between Stress And Strain.

For linear elasticity the relationship between stress and strain is simply assumed to be given by Hooke’s law:

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl},$$  \hspace{1cm} 3.10

where $C_{ijkl}$ is the fourth order linear elastic stiffness tensor having $3^4 = 81$ elements. Symmetry considerations permit the reduction of the number of independent elements. The symmetry of the stress and strain tensors implies that there are six independent choices for the pairs of suffices $ij$ and $kl$. Hence $C_{ijkl}$ can have at most 36 independent elements since
\[ c_{ijkl} = c_{klij} = c_{ijlk} = c_{ijlk} \]  \hspace{1cm} 3.11

A further reduction in the number of independent elements in the elastic stiffness tensor results from a consideration of the change in energy of a small volume subjected to a homogeneous strain. For small deformations work must be done to create a state of strain from an unstrained state. Thus if \( \Phi(0) \) is the internal energy of the unstrained material then for small deformations we expect:

\[
\Phi = \Phi(0) + \left[ \frac{\partial \Phi}{\partial \varepsilon_{ij}} \right]_0 \varepsilon_{ij} + \frac{1}{2} \left[ \frac{\partial^2 \Phi}{\partial \varepsilon_{ij} \partial \varepsilon_{kl}} \right]_0 \varepsilon_{ij} \varepsilon_{kl} \ldots \]  \hspace{1cm} 3.12

Assuming that \( \Phi(0) \) corresponds with a relative minimum, the first derivative

\[
\frac{\partial \Phi}{\partial \varepsilon_{ij}} \bigg|_0 = 0, \]  \hspace{1cm} 3.13

and, neglecting higher orders terms, the energy of deformation is given by

\[
\Phi - \Phi(0) = \Delta \Phi = \frac{1}{2} \left[ \frac{\partial^2 \Phi}{\partial \varepsilon_{ij} \partial \varepsilon_{kl}} \right]_0 \varepsilon_{ij} \varepsilon_{kl} \ldots \]  \hspace{1cm} 3.14

Since work must be done to strain the material then \( \Delta \Phi \) must always be positive. This requires that:

\[
\left[ \frac{\partial^2 \Phi}{\partial \varepsilon_{ij} \partial \varepsilon_{kl}} \right]_0 = \left[ \frac{\partial^2 \Phi}{\partial \varepsilon_{kl} \partial \varepsilon_{ij}} \right]_0; \]  \hspace{1cm} 3.15

which, by associating the work done with the deformation can give

\[ c_{ijkl} = c_{klij} \]  \hspace{1cm} 3.16

Thus the constants defined in 3.11 above can be reduced to give a maximum number of 21 independent constants.
The requirement for positive strain energy allows inversion of 3.11 to

\[ \varepsilon_{ij} = s_{ijkl} \sigma_{kl}, \]

where the \( s_{ijkl} \) have the same symmetry properties as the \( c_{ijkl} \). The quantities \( c_{ijkl} \) are known as the elastic stiffnesses. The quantities \( s_{ijkl} \) are known as the elastic compliances.

Using the Voigt notation, for each pair of indices of stress, strain and elastic moduli the following substitutions can be made.

\[ \begin{align*}
11 & \rightarrow 1 \\
22 & \rightarrow 2 \\
33 & \rightarrow 3 \\
23, 32 & \rightarrow 4 \\
31, 13 & \rightarrow 5 \\
12, 21 & \rightarrow 6.
\end{align*} \]

This notation allows Hooke’s law to be presented as

\[ \sigma_A = C_{AB} \varepsilon_B, \]

where capital subscripts are summed from one to six and provided that

\[ \varepsilon_B = \varepsilon^T = [\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, 2\varepsilon_{23}, 2\varepsilon_{12}, 2\varepsilon_{13}] \]

In matrix form the elastic stiffness moduli are now given by:

\[ C_{AB} = \begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\
C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\
C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\
C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\
C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\
C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66}
\end{bmatrix}. \]

A further reduction in the number of independent elastic constants requires consideration of the symmetry of the material under investigation. In general the greater the degree of symmetry exhibited by the material, the fewer the independent elastic constants that are needed to describe it.
3.1.6 Elastic Constants For Orthorhombic Symmetry

In this section the twenty-one elastic constants presented in 3.21 above are reduced using the symmetry properties of an orthorhombic material. In an orthorhombic material there are three perpendicular planes of elastic symmetry. Thus if the coordinate axes are chosen such that they are normals to these planes, then the independent elastic moduli can be determined by applying two fold rotations about each of these axes on the strain energy function. The strain energy function is initially given by:

\[
\Delta \Phi = \frac{1}{2} \left( C_{11} \varepsilon_1^2 + C_{22} \varepsilon_2^2 + C_{33} \varepsilon_3^2 + C_{44} \varepsilon_4^2 + C_{55} \varepsilon_5^2 + C_{66} \varepsilon_6^2 \right) \\
+ C_{12} \varepsilon_1 \varepsilon_2 + C_{13} \varepsilon_1 \varepsilon_3 + C_{14} \varepsilon_1 \varepsilon_4 + C_{15} \varepsilon_1 \varepsilon_5 + C_{16} \varepsilon_1 \varepsilon_6 \\
+ C_{23} \varepsilon_2 \varepsilon_3 + C_{24} \varepsilon_2 \varepsilon_4 + C_{25} \varepsilon_2 \varepsilon_5 + C_{26} \varepsilon_2 \varepsilon_6 + C_{34} \varepsilon_3 \varepsilon_4 \\
+ C_{35} \varepsilon_3 \varepsilon_5 + C_{36} \varepsilon_3 \varepsilon_6 + C_{45} \varepsilon_4 \varepsilon_5 + C_{46} \varepsilon_4 \varepsilon_6 + C_{56} \varepsilon_5 \varepsilon_6
\]

Consider the effect of a 180° rotation about the \(x_2\) axis.

The transformation matrix is:

\[
[a_{ij}] = \begin{bmatrix}
-1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{bmatrix}
\]

The effect of this rotation on the strains is given by

\[
\varepsilon'_y = a_{im} a_{jn} \varepsilon_{mn}
\]

This gives the following relations between the rotated and original strains

\[
\varepsilon_1' = \varepsilon_1 \\
\varepsilon_2' = \varepsilon_2 \\
\varepsilon_3' = \varepsilon_3 \\
\varepsilon_4' = -\varepsilon_4 \\
\varepsilon_5' = \varepsilon_5 \\
\varepsilon_6' = -\varepsilon_6
\]
Now the strain energy function for the rotated state can be written:

\[
\Delta \Phi' = \frac{1}{2} \left( C_{11} E_1^2 + C_{22} E_2^2 + C_{33} E_3^2 + C_{44} E_4^2 + C_{55} E_5^2 + C_{66} E_6^2 \right) \\
+ C_{12} E_1 E_2 + C_{13} E_1 E_3 - C_{14} E_1 E_4 + C_{15} E_1 E_5 - C_{16} E_1 E_6 \\
+ C_{23} E_2 E_3 - C_{24} E_2 E_4 + C_{25} E_2 E_5 - C_{26} E_2 E_6 - C_{34} E_3 E_4 \\
+ C_{35} E_3 E_5 - C_{36} E_3 E_6 - C_{45} E_4 E_5 + C_{46} E_4 E_6 - C_{56} E_5 E_6
\]

Equating the rotated energy function to the original strain energy function yields

\[
C_{14} = -C_{14} \\
C_{16} = -C_{16} \\
C_{24} = -C_{24} \\
C_{26} = -C_{26} \\
C_{34} = -C_{34} \\
C_{36} = -C_{36} \\
C_{45} = -C_{45} \\
C_{56} = -C_{56}
\]

This is true only if

\[
C_{14} = C_{16} = C_{24} = C_{26} = C_{34} = C_{36} = C_{45} = C_{56} = 0 .
\]

The matrix of elastic stiffness moduli is then given by

\[
[C_{4R}] = \begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & C_{15} & 0 \\
C_{12} & C_{22} & C_{23} & 0 & C_{25} & 0 \\
C_{13} & C_{23} & C_{33} & 0 & C_{35} & 0 \\
0 & 0 & 0 & C_{44} & 0 & C_{46} \\
C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & 0 \\
0 & 0 & 0 & C_{46} & 0 & C_{66} 
\end{bmatrix}
\]

with the strain energy function now given by:

\[
\Delta \Phi = \frac{1}{2} \left( C_{11} E_1^2 + C_{22} E_2^2 + C_{33} E_3^2 + C_{44} E_4^2 + C_{55} E_5^2 + C_{66} E_6^2 \right) \\
+ C_{12} E_1 E_2 + C_{13} E_1 E_3 + C_{15} E_1 E_5 + C_{23} E_2 E_3 + C_{25} E_2 E_5 \\
+ C_{35} E_3 E_5 + C_{46} E_4 E_6
\]
The effect of a 180° rotation about the $x_1$ axis can now be considered. In this case the transformation matrix is given by

$$[a_{0}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}.$$  \hspace{1cm} (3.31)

Following a similar analysis to that given above we find the elastic stiffness matrix is reduced to:

$$[C_{4t}] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}.$$ \hspace{1cm} (3.32)

Application of the rotation about the $x_3$ symmetry axis can be shown to have no further effect on the elastic stiffness tensor. Thus this is the final form of the elastic stiffness tensor for an orthorhombic material such as wood and it can be seen that only 9 elastic constants are needed to define an orthorhombic material.

### 3.2 The Propagation of Material Waves in Materials of Orthorhombic Symmetry.

The elastic stiffness moduli of a material can be determined by measuring the density and the relevant ultrasonic wave velocities in the material. In this section of the thesis the theoretical background to this technique as developed and reviewed by Musgrave, (1970) and Green (1973) is presented.

A number of assumptions are made in the following derivation of the wave equations which describe the propagation of material or ultrasonic waves in anisotropic materials. The propagation medium, in this case wood, is generally taken to be unbounded, homogeneous and continuous. The waves propagating are taken to be plane waves.

Consider the effect of a force acting in the $x_1$ direction on a typical volume element as shown in figure 3.3 below.
Figure 3.3 Elementary volume element showing stresses along $x_1$ direction.

The net unbalanced force along $x_1$ is given by

$$
\begin{align*}
\left[ \sigma_{11} + \frac{\partial \sigma_{11}}{\partial x_1} \delta x_1 \right] & \delta x_2 \delta x_3 + \\
\left[ \sigma_{21} + \frac{\partial \sigma_{21}}{\partial x_2} \delta x_2 \right] & \delta x_1 \delta x_3 + \\
\left[ \sigma_{31} + \frac{\partial \sigma_{31}}{\partial x_3} \delta x_3 \right] & \delta x_1 \delta x_2
\end{align*}
$$

Simplifying gives

$$
\left( \frac{\partial \sigma_{11}}{\partial x_1} + \frac{\partial \sigma_{21}}{\partial x_2} + \frac{\partial \sigma_{31}}{\partial x_3} \right) \delta x_1 \delta x_2 \delta x_3
$$

which by Newton's second law of motion, neglecting body forces, we set equal to

$$
\rho \left( \delta x_1 + \delta x_2 + \delta x_3 \right) \frac{\partial^2 u_1}{\partial t^2}
$$
where $\rho$ is the mass density and $u_1$ is the displacement in the $x_1$ direction.

Similar equations are valid for the $x_2$ and $x_3$ directions. Now:

$$\frac{\partial \sigma_{11}}{\partial x_1} + \frac{\partial \sigma_{21}}{\partial x_2} + \frac{\partial \sigma_{31}}{\partial x_3} = \rho \frac{\partial^2 u_1}{\partial t^2} , \quad 3.35$$

We proceed in a similar fashion for the $x_2$ and $x_3$ directions

$$\frac{\partial \sigma_{12}}{\partial x_1} + \frac{\partial \sigma_{22}}{\partial x_2} + \frac{\partial \sigma_{32}}{\partial x_3} = \rho \frac{\partial^2 u_2}{\partial t^2} \quad 3.36$$

and

$$\frac{\partial \sigma_{13}}{\partial x_1} + \frac{\partial \sigma_{23}}{\partial x_2} + \frac{\partial \sigma_{33}}{\partial x_3} = \rho \frac{\partial^2 u_3}{\partial t^2} \quad 3.37$$

The three equations of motion can be written more compactly in vector notation as:

$$\begin{pmatrix} \frac{\partial \sigma_{ji}}{\partial x_j} \end{pmatrix} = \rho \frac{\partial^2 u_i}{\partial t^2} . \quad 3.38$$

This may be presented in terms of density and displacement, using Hooke’s law (3.10) to write stress in terms of strain:

$$\sigma_{ij} = c_{ijkl} \left[ \frac{1}{2} \left( \frac{\partial u_k}{\partial x_l} + \frac{\partial u_l}{\partial x_k} \right) \right] . \quad 3.39$$

Using the symmetry of elastic coefficients this can be simplified to

$$\sigma_{ij} = \frac{1}{2} c_{ijkl} \left( \frac{\partial u_k}{\partial x_l} \right) + \frac{1}{2} c_{ijkl} \left( \frac{\partial u_j}{\partial x_i} \right) . \quad 3.40$$

Hence
which, when substituted into 3.38 above yields the final form of the equation of motion for linear elastic wave propagation in an anisotropic medium:

\[ \rho \frac{\partial^2 u_i}{\partial t^2} = c_{ijkl} \left( \frac{\partial^2 u_j}{\partial x_i \partial x_j} \right) \]  

This is the wave equation which has a plane wave solution of the form

\[ u(\vec{x} \cdot t) = A_0 \alpha_i e^{j(\omega t - k_m x_n)} , \]  

where \( A_0 \) is the amplitude of the wave, \( \alpha_i \) are the direction cosines of the particle displacement vector, \( \vec{u} \), \( t \) is the time, \( \omega \) is the angular frequency and \( k_m \) are the components of the wave vector. The wave vector components \( (k_m) \) are related to the direction cosines of the wave normal \( (l_m) \) and the wavelength \( (\lambda) \) by the expression

\[ k_m = \left( \frac{2\pi}{\lambda} \right) l_m = kl_m \]  

where \( k \) is the wave number. The solution for displacement can now be substituted into the equation for wave motion. This gives

\[ c_{ijkl} k^2 l_i l_j \alpha_k = \rho \omega^2 \alpha_i , \]  

which can be simplified to

\[ (c_{ijkl} l_i l_j - \rho v^2 \delta_{ik}) \alpha_k = 0 , \]  

where \( v \) is the phase velocity of the elastic wave and is given by

\[ v = \frac{\omega}{k} . \]  

For nontrivial solutions we need
\[
\begin{vmatrix}
\epsilon_{ijkl} l_i l_j - \rho \nu^2 \delta_{ik}
\end{vmatrix} = 0.
\]

That is, the determinant of the matrix of coefficients must equal zero. This is a characteristic equation which when expanded forms a cubic expression in terms of \(\rho \nu^2\). The physical significance of the three solutions for \(\rho \nu^2\) is that for any arbitrary direction in an anisotropic medium, three plane waves may be propagated. The velocities of these waves depend on the density, the elastic constants and the direction cosines of the wave normals.

The particle displacement vector direction cosines can be determined for each of the three waves propagating along a given direction. This is accomplished by solving for the eigenvectors for each eigenvalue (\(\rho \nu^2\)) using the relation

\[
\rho \nu^2 \alpha_i = \epsilon_{ijkl} l_j \alpha_k ,
\]

and also using

\[
\alpha_i \alpha_i = 1.
\]

These direction cosines determine the mode of the wave. If they are the same as the wave normal direction cosines, i.e.

\[
\alpha_i = l_i ,
\]

then the particle displacement of the elastic wave is in the same direction as the direction of propagation of the wave. This is known as a pure mode longitudinal or compressional wave. If the particle displacement is perpendicular to the direction of propagation of the wave, i.e.

\[
\alpha_i l_i = 0
\]

then the wave is called a pure mode shear (transverse) wave.

In general it should be noted that the wave need not be pure mode (Green, 1973). It may be either quasi-longitudinal or quasi-transverse depending on which type of wave motion is more dominant. These 'quasi' or 'non-pure' mode waves display energy flux
deviation, whereby the wave normal and the energy flux vector are not aligned. Of the three waves propagating along a particular direction one is longitudinal or quasi-longitudinal while the other two are transverse or quasi-transverse.

The analysis presented above provides a means to determine the elastic stiffnesses of an orthorhombic material such as wood. Several cautions have to be given regarding the applicability of these results to wood. Firstly wood is clearly a heterogeneous material. This clearly violates one of the initial assumptions: that of homogeneity. However it is generally assumed that if the wavelength of the elastic waves is much larger than the size of the inhomogeneities then the material may be considered to be macroscopically homogeneous and the wave equations are applicable. There are several layers of inhomogeneity in wood as described in Chapter 2. These range from the cellulose molecules of which the basic wood material is constructed, to the annual rings which give wood its grain pattern. The influence of inhomogeneity on the propagation of ultrasound in wood is considered in Chapter 9. For the moment it can be said that depending on the wavelength of the waves propagated wood may, in the first instance, considered to be homogeneous.

The wave equations arrived at depend on the validity of the generalised Hooke’s law when applied to wood. While wood can display viscoelastic behaviour under certain conditions little viscoelastic behaviour would generally be expected from the small strains involved in the ultrasound propagation in this work.

3.2.1 Slowness Representations of Waves Propagating in Orthorhombic Media.

The plane wave solution (3.43) to the wave equation (3.42) can be written in terms of the slowness vector, \( s_m = \frac{k_m}{\omega} = \frac{l_m}{v} \), where \( l_m \) is the wave normal and \( v \) is the velocity. The result is:

\[
u_i(x_k, t) = A_0 \alpha_i e^{i\omega(t - s_m x_m)} \tag{3.53}\]
which when substituted into the wave equation (3.42) yields the conditions:

\[(c_{ijkm} s_m s_j - \rho \delta_{ik}) \alpha_k = 0.\]  

(3.54)

In general the solution to (3.54) will be three mutually orthogonal displacement vectors. We require non-zero solutions for \( \alpha_k \) and hence the characteristic equation is:

\[S = |c_{ijkm} s_m s_j - \rho \delta_{ik}| = 0.\]  

(3.55)

This surface defined by \( S = 0 \) represents the slowness surface and the following algebraic argument will demonstrate the relationship between this surface and the energy flux vector, \( F_i \).

Considering first equation (3.55), and letting \( S_{ik} = c_{ijkm} s_m s_j - \rho \delta_{ik} \), then the normal to the slowness surface has direction cosines given by \( \frac{\partial S}{\partial s_j} \).

Defining \( C_{ik} \) to be the cofactor corresponding to element \( S_{ik} \), then the direction cosines can be written in the form

\[\frac{\partial S}{\partial s_j} = \frac{\partial S_{ik}}{\partial s_j} C_{ik}\]  

(3.56)

We notice that from (3.54) that \( S_{ik} \alpha_k = 0 \) and also since \( S_{ik} \) is symmetric

\[S_{ki} \alpha_k = 0\]

but \( \det(S_{ik}) = S_{i1}C_{i1} = S_{i2}C_{i2} = S_{i3}C_{i3} = 0 \), hence \( S_{ik}C_{jk} = S_{ki}C_{jk} = 0 \)

so \( C_{ij} \) must vary as \( \alpha_j \) and by symmetry \( C_{ij} \) must vary as \( \alpha_i \) which restricts the form of \( C_{ij} \) to be:
\[ C_{ik} = f \alpha_i \alpha_k \quad \text{where } f \text{ is a constant.} \quad (3.57) \]

Putting this back into (3.56) we find the general form for the normal vector to the slowness surface is:

\[
\frac{\partial S}{\partial s_j} = \frac{\partial S_{ik}}{\partial s_j} f \alpha_i \alpha_k = f c_{iklm} s_m \alpha_i \alpha_k
\]

where \( f \) is a constant.

Now moving our attention to the energy flux vector, which will be derived from the total energy \( E \).

The total energy \( E \) in a wavefront is obtained by integrating the sum of the kinetic and potential energies over the volume of the wavefront, as follows:

\[
E = \int V \left( \frac{\rho}{2} \frac{\partial u_j}{\partial t} \frac{\partial u_j}{\partial t} + c_{ijkm} \frac{\partial^2 u_i}{\partial x_j \partial x_m} u_{k,m} + \frac{1}{2} c_{iklm} u_{i,j} \frac{\partial^2 u_k}{\partial t \partial x_m} \right) dV
\]

(3.59)

Differentiating with respect to time gives the rate of change of energy to be:

\[
\frac{\partial E}{\partial t} = \int V \left( \frac{\partial u_j}{\partial t} \frac{\partial^2 u_j}{\partial t^2} + \frac{1}{2} c_{ijkm} \frac{\partial^2 u_i}{\partial x_j} u_{k,m} + \frac{1}{2} c_{iklm} u_{i,j} \frac{\partial^2 u_k}{\partial t \partial x_m} \right) dV
\]

\[
= \int V \left( \frac{\partial u_j}{\partial t} \frac{\partial^2 u_j}{\partial t^2} + c_{ijkm} \frac{\partial^2 u_i}{\partial t \partial x_j} u_{k,m} \right) dV, \quad \text{by symmetry}
\]
\[
\begin{align*}
\int_V \left( \rho \frac{\partial u_i}{\partial t} \frac{\partial^2 u_i}{\partial t^2} + \frac{\partial}{\partial x_j} \left( c_{ijkm} \frac{\partial u_i}{\partial t} u_{k,mj} \right) - c_{ijkm} \frac{\partial u_i}{\partial t} u_{k,mj} \right) \, dV \\
\int_V \left( \frac{\partial u_i}{\partial t} \left( \rho \frac{\partial^2 u_i}{\partial t^2} c_{ijkm} u_{k,mj} \right) + \frac{\partial}{\partial x_j} \left( c_{ijkm} \frac{\partial u_i}{\partial t} u_{k,mj} \right) \right) \, dV
\end{align*}
\]

The first bracketed term inside this integral is zero by the wave equation (3.42) and applying the divergence theorem to the second term we reduce the integral to:

\[
\frac{\partial E}{\partial t} = \int_{\Sigma} \left( c_{ijkm} \frac{\partial u_i}{\partial t} u_{k,mj} \right) \, d\Sigma \tag{3.60}
\]

where the integral is over the surface \( \Sigma \) of the wavefront.

However, the energy flux flowing out from any surface \( \Sigma \) is given by an integral of the form:

\[
-\int_{\Sigma} F_j l_j \, d\Sigma
\]

where \( F_j \) is the energy flux vector. Comparing this to (3.60) above we find that in this case

\[
F_j = -c_{ijkm} \frac{\partial u_i}{\partial t} u_{k,m} \tag{3.61}
\]

Now we can substitute the wave solution (3.53) into this equation for \( F_j \), but first to ensure that we only consider real displacements \( u_j \) and real energy flux \( F_j \) we rewrite (3.61) taking the real parts of the right hand side only i.e.
where $\bar{u}_i$ denotes the complex conjugate.

Inserting the expression for the wave for $u_j$ from (3.53) into (3.62) results in:

$$F_j = -\frac{1}{4} c_{ijkm} \left( \frac{\partial u_i}{\partial t} + \frac{\partial \bar{u}_i}{\partial t} \right) \left( u_{k,m} + \bar{u}_{k,m} \right)$$ (3.62)

Comparing this to the vector normal to the slowness surface given in (3.58) it is clear that the two vectors are in the same direction.

Hence we have demonstrated that the path traced by the energy flux is identical in direction to the normal to the slowness curve.

In general when an elastic wave is generated in an aeolotropic medium, for a given wave normal, there will be three mutually orthogonal displacement vectors, each of which will have an energy flux which may deviate from the wave normal. The directions of these energy flux vectors can be found from the corresponding normals to the slowness surfaces. For this reason measurements of ultrasonic wave propagation made at different angles through a specimen are often shown as slowness curves. This convention is followed in displaying the relevant results in Chapter 6.
3.3.2 Determination Of The Elastic Constants Of An Orthorhombic Medium

From Acoustic Wavespeeds

The solution for displacement in the equation of motion (3.42) may be more conveniently written if a matrix \([\mathbf{\lambda}_{ik}]\) is defined:

\[
\mathbf{\lambda}_{ik} = c_{ijkl} l_i l_j .
\]

Now equation 3.48 becomes

\[
\mathbf{\lambda}_{ik} - \rho v^2 \delta_{ik} = 0 .
\]

The expressions for the velocities of material or ultrasonic waves may now be derived. The \(\lambda_{ij}\) matrix components are given by

\[
\begin{align*}
\lambda_{11} &= c_{11} l_1^2 + c_{66} l_2^2 + c_{55} l_3^2 \\
\lambda_{22} &= c_{66} l_1^2 + c_{22} l_2^2 + c_{44} l_3^2 \\
\lambda_{33} &= c_{55} l_1^2 + c_{44} l_2^2 + c_{33} l_3^2 \\
\lambda_{12} &= \lambda_{21} = (c_{12} + c_{66}) l_1 l_2 \\
\lambda_{13} &= \lambda_{31} = (c_{55} + c_{13}) l_1 l_3 \\
\lambda_{23} &= \lambda_{32} = (c_{44} + c_{23}) l_2 l_3 .
\end{align*}
\]

For propagation along the x_1 or longitudinal axis these equations reduce to

\[
\begin{align*}
\lambda_{11} &= c_{11} \\
\lambda_{22} &= c_{66} \\
\lambda_{33} &= c_{55} .
\end{align*}
\]

and all other components are zero. When these values are substituted into equation 3.53 the wave solutions can be found to be
with the first wave being a pure mode longitudinal wave. The second wave is a pure mode shear wave with particle displacements along the $x_2$ or radial axis. The third wave is a pure mode shear wave with particle displacements along the $x_3$ or tangential axis. For propagation along $x_2$ the components of $\lambda_{ij}$ reduce to

$$\lambda_{11} = c_{66}$$

$$\lambda_{22} = c_{22}$$

$$\lambda_{33} = c_{44}$$

and all other $\lambda_{ij} = 0$. When substituted these yield the solutions:

$$v_1 = \left( \frac{c_{66}}{\rho} \right)^{\frac{1}{2}}$$

$$v_2 = \left( \frac{c_{22}}{\rho} \right)^{\frac{1}{2}}$$

$$v_3 = \left( \frac{c_{44}}{\rho} \right)^{\frac{1}{2}}$$
In this case the first and third waves are pure shear waves polarised along the $x_1$ (longitudinal) and $x_3$ (tangential) axes respectively. The second wave is a pure mode compressional wave.

For propagation along the $x_3$ or tangential axis the components of $\lambda_{ij}$ reduce to

$$\lambda_{11} = c_{55}$$
$$\lambda_{22} = c_{44}$$
$$\lambda_{33} = c_{33}$$

with all other $\lambda_{ij}$ components equal to zero. These yield the solutions for the three modes of propagation as:

$$\nu_1 = \left( \frac{c_{55}}{\rho} \right)^{\frac{1}{2}}$$
$$\nu_2 = \left( \frac{c_{44}}{\rho} \right)^{\frac{1}{2}}$$
$$\nu_3 = \left( \frac{c_{33}}{\rho} \right)^{\frac{1}{2}}$$

In this case the first and second waves are pure mode shear waves. The first wave is polarised along the $x_1$ (longitudinal) axis. The second wave is polarised along the $x_2$ or radial axis. The third wave is a pure compressional wave. It is interesting to note that propagation along the axes gives pure propagation modes, which is of value in relation to making measurements (see Chapter 4).

The off-diagonal terms of the stiffness matrix ($c_{12}$, $c_{13}$ and $c_{23}$) can only be accessed by measuring waves propagating off the main axes of symmetry in wood. We consider for example waves propagating in the longitudinal-radial plane ($x_1x_2$ plane) at 45 degrees
from each axis with \( l_3 = 0 \). The direction cosines of the wave normal are given by \( l_1 = l_2 = 1/\sqrt{2} \), and \( l_3 = 0 \). Thus the \( \lambda_{ij} \) matrix components are

\[
\lambda_{11} = \frac{1}{2}(c_{11} + c_{66})
\]

\[
\lambda_{22} = \frac{1}{2}(c_{66} + c_{22})
\]

\[
\lambda_{33} = \frac{1}{2}(c_{55} + c_{44})
\]

\[
\lambda_{12} = \lambda_{21} = \frac{1}{2}(c_{12} + c_{66})
\]

and all other \( \lambda_{ij} = 0 \). The solutions for the waves propagating along this direction can then be determined to be

\[
\rho v_1^2 = \frac{1}{4} \left[ c_{11} + 2c_{66} + c_{22} + \sqrt{(c_{11} - c_{22})^2 + 4(c_{12} + c_{66})^2} \right]
\]

\[
\rho v_2^2 = \frac{1}{2}(c_{44} + c_{55})
\]

\[
\rho v_3^2 = \frac{1}{4} \left[ c_{11} + 2c_{66} + c_{22} - \sqrt{(c_{11} - c_{22})^2 + 4(c_{12} + c_{66})^2} \right]
\]

The first wave is a quasi-longitudinal wave. The second wave is a pure mode shear wave. The third wave is a quasi-shear wave.

The next off-axis direction considered is the Longitudinal-Tangential plane ( \( x_1, x_3 \) plane) 45 degrees from either axis where the direction cosines for the wave normal are given by \( l_1 = l_3 = 1/\sqrt{2} \), and \( l_2 = 0 \). Thus the \( \lambda_{ij} \) matrix components are
\[ \lambda_{11} = \frac{1}{2}(c_{11} + c_{55}) \]

\[ \lambda_{22} = \frac{1}{2}(c_{66} + c_{44}) \]

\[ \lambda_{33} = \frac{1}{2}(c_{55} + c_{33}) \]

\[ \lambda_{13} = \lambda_{31} = \frac{1}{2}(c_{13} + c_{55}) \]

and all other \( \lambda_{ij} = 0 \). The solutions for the waves propagating along this direction can then be determined to be:

\[ \rho v_1^2 = \frac{1}{4} \left[ c_{11} + 2c_{55} + c_{33} + \sqrt{(c_{11} - c_{33})^2 + 4(c_{13} + c_{55})^2} \right] \]

\[ \rho v_2^2 = \frac{1}{2}(c_{44} + c_{66}) \]

\[ \rho v_3^2 = \frac{1}{4} \left[ c_{11} + 2c_{55} + c_{33} - \sqrt{(c_{11} - c_{33})^2 + 4(c_{13} + c_{55})^2} \right] . \]

The first wave is a quasi-longitudinal wave. The second wave is a pure mode shear wave. The third wave is a quasi-shear wave.

The final off-axis direction considered is the Radial-Tangential plane (x_2, x_3 plane) 45 degrees from either axis where direction cosines for the wave normal are given by \( l_2 = l_3 = 1/\sqrt{2} \), and \( l_1 = 0 \). The solutions for the waves propagating along this direction are
The first wave is a quasi-longitudinal wave. The second wave is a pure mode shear wave. The third wave is a quasi-shear wave. These equations allow the determination of all of the linear elastic moduli for an orthorhombic material. Table 3.1 gives equations for pure mode linear elastic wave propagation. Table 3.2 gives equations for off-axis propagation at 45°. It is possible also to derive expressions for other propagation angles by following a similar analysis and using appropriate values of the direction cosines.

It should be noted that, for bulk waves propagating in an isotropic medium the relation between longitudinal wave velocity and the Young's modulus, \( E \), the density, \( \rho \), and the Poisson's ratio, \( \nu \), is given by

\[
C_L = \sqrt{\frac{E}{\rho(1+\nu)(1-2\nu)}}
\]
<table>
<thead>
<tr>
<th>Propagation Direction Cosines</th>
<th>Particle Displacement Direction Cosines</th>
<th>Wave Mode</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_1=1$</td>
<td>$\alpha_1=1$ $\alpha_2=0$ $\alpha_3=0$</td>
<td>PL</td>
<td>$C_{11}$</td>
</tr>
<tr>
<td>Longitudinal</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>$\alpha_1=0$ $\alpha_2=1$ $\alpha_3=0$</td>
<td>PT</td>
<td>$C_{66}$</td>
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<td>$\alpha_1=0$ $\alpha_2=0$ $\alpha_3=1$</td>
<td>PT</td>
<td>$C_{55}$</td>
</tr>
<tr>
<td>$l_1=0$</td>
<td>$\alpha_1=1$ $\alpha_2=0$ $\alpha_3=0$</td>
<td>PT</td>
<td>$C_{66}$</td>
</tr>
<tr>
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<td>$\alpha_1=0$ $\alpha_2=1$ $\alpha_3=0$</td>
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<td>$C_{22}$</td>
</tr>
<tr>
<td>Radial</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>$\alpha_1=0$ $\alpha_2=0$ $\alpha_3=1$</td>
<td>PT</td>
<td>$C_{44}$</td>
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<td>$\alpha_1=1$ $\alpha_2=0$ $\alpha_3=0$</td>
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<td>$C_{55}$</td>
</tr>
<tr>
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<td>PT</td>
<td>$C_{44}$</td>
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<td>$l_3=1$</td>
<td>$\alpha_1=0$ $\alpha_2=0$ $\alpha_3=1$</td>
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<td>$C_{33}$</td>
</tr>
<tr>
<td>Tangential</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\rho v^2 =$

Table 3.1 Equations for on-axis elastic wave propagation in an orthorhombic material
<table>
<thead>
<tr>
<th>Propagation Direction Cosines</th>
<th>Wave Mode</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>l</em>₁=1/√2 Longitudinal</td>
<td>QL</td>
<td>[ \frac{1}{4} \left[ c_{11} + 2c_{55} + c_{33} + \sqrt{(c_{11} - c_{33})^2 + 4(c_{13} + c_{55})^2} \right] ]</td>
</tr>
<tr>
<td><em>l</em>₁=0</td>
<td>PT</td>
<td>[ \frac{1}{2} (c_{44} + c_{66}) ]</td>
</tr>
<tr>
<td><em>l</em>₂=1/√2 Tangential</td>
<td>QT</td>
<td>[ \frac{1}{4} \left[ c_{11} + 2c_{55} + c_{33} - \sqrt{(c_{11} - c_{33})^2 + 4(c_{13} + c_{55})^2} \right] ]</td>
</tr>
<tr>
<td><em>l</em>₁=0</td>
<td>QL</td>
<td>[ \frac{1}{4} \left[ c_{22} + 2c_{44} + c_{33} + \sqrt{(c_{22} - c_{33})^2 + 4(c_{23} + c_{44})^2} \right] ]</td>
</tr>
<tr>
<td><em>l</em>₂=1/√2 Radial</td>
<td>PS</td>
<td>[ \frac{1}{2} (c_{55} + c_{66}) ]</td>
</tr>
<tr>
<td><em>l</em>₃=1/√2 Tangential</td>
<td>QT</td>
<td>[ \frac{1}{4} \left[ c_{22} + 2c_{44} + c_{33} - \sqrt{(c_{22} - c_{33})^2 + 4(c_{23} + c_{44})^2} \right] ]</td>
</tr>
<tr>
<td><em>l</em>₁=1/√2 Longitudinal</td>
<td>QL</td>
<td>[ \frac{1}{4} \left[ c_{11} + 2c_{66} + c_{22} + \sqrt{(c_{11} - c_{22})^2 + 4(c_{12} + c_{66})^2} \right] ]</td>
</tr>
<tr>
<td><em>l</em>₂=1/√2 Radial</td>
<td>PT</td>
<td>[ \frac{1}{2} (c_{44} + c_{55}) ]</td>
</tr>
<tr>
<td><em>l</em>₃=1 Tangential</td>
<td>QT</td>
<td>[ \frac{1}{4} \left[ c_{11} + 2c_{66} + c_{22} - \sqrt{(c_{11} - c_{22})^2 + 4(c_{12} + c_{66})^2} \right] ]</td>
</tr>
</tbody>
</table>

Table 3.2 Equations for off-axis wave propagation in orthorhombic materials
3.2.2 Non-bulk Wave Propagation

The analysis in the previous sections is restricted to bulk wave propagation. The assumption is that such waves are travelling in a semi-infinite medium. If one considers the influence of boundaries then two main types of phenomena can be distinguished that are relevant to the present work.

In general an acoustic wave impinging obliquely on the flat surface of a solid material will cause a wave to be generated which propagates along the surface of the solid and penetrates only a short distance in the material. This wave is called a 'surface wave' (Musgrave, 1970). It is additional to the refracted longitudinal and shear waves that are generated and which propagate through the body of the material.

Bulk waves propagating in a material suffer reflection and mode conversion when they impinge on a boundary. If the opposite boundaries of the specimen are separated by a distance comparable to a wavelength the reflections from the two surfaces will interfere and combine to produce guided waves in different modes which have specific propagation characteristics. These will be called 'plate waves' to distinguish them from bulk waves. A brief discussion of these waves is relevant to the choice of samples dimensions for ultrasonic propagation measurements (see Chapter 4).

3.2.2.1 Surface Wave Propagation

The propagation of surface waves at the interface between anisotropic solids is a highly complex subject the full treatment of which is beyond the scope of this work. However it is of relevance to consider the conditions under which surface waves arise. Furthermore, surface waves have been employed by some of the workers reported in Chapter 4 of this work. Thus a brief sketch of some of the main features of surface waves is included at this point.

Musgrave (1970) treats the origin and nature of surface waves in anisotropic media in some depth. He reports that in studying reflection-refraction it becomes apparent that waves with complex slowness are necessary to satisfy the boundary conditions in certain circumstances. These wave were first considered by Rayleigh (1885), who showed that waves of compound complex displacement, varying in amplitude
exponentially with depth, can propagate parallel to a plane surface of an isotropic medium and leave it free of stress.

In his treatment Musgrave (1970) considered the effect of a plane wave incident on a plane wave boundary between two media. He showed that there are three possible waves with appropriate slowness vectors in each medium. Musgrave describes the possible generation (depending, inter alia, on incident angle, wave type and polarisation) of surface, shear and longitudinal waves when a plane wave is incident on a surface. This generation of other modes of propagation at an interface is known as ‘mode conversion’.

Rayleigh observed that a wave could propagate on a free flat surface of an isotropic solid with particle motion restricted to the surface. The phase velocity of the wave, $V_{\text{Surface}}$, could be related to the bulk longitudinal wave velocity, $V_{\text{Longitudinal}}$ and the bulk shear wave velocity $V_{\text{Shear}}$ through the relationship

$$\left( \frac{V_{\text{Surface}}}{V_{\text{Shear}}} \right)^6 - 8 \left( \frac{V_{\text{Surface}}}{V_{\text{Shear}}} \right)^4 + 8 \left[ 3 - 2 \left( \frac{V_{\text{Shear}}}{V_{\text{Longitudinal}}} \right)^2 \right] \left( \frac{V_{\text{Surface}}}{V_{\text{Shear}}} \right)^2 - 16 \left[ 1 - \left( \frac{V_{\text{Shear}}}{V_{\text{Longitudinal}}} \right)^2 \right] = 0$$

3.78

Curtis (1982) reports that of the six possible velocities only one real value exists for materials, such as wood, in which Poisson’s ratio lies in the range $0 < \nu < 0.5$:

$$V_{\text{Surface}} = V_{\text{Shear}} \frac{(0.87 + 1.13\nu)}{(1 + \nu)}$$

3.79

This gives a ratio of $V_{\text{Surface}}/V_{\text{Shear}}$ of less than 0.96 for Poisson’s ratios of less than 0.5. Thus the surface wave is slower than the bulk shear wave for an isotropic solid. Musgrave, (1970) and Curtis (1982) report that the wave motion is found to be compounded from a longitudinal wave motion with particle motion, $u_x$, in the plane of the surface and a shear wave with particle motion, $u_z$, normal to the plane of the surface and the direction of propagation, $x$.

$$u_z = C \left[ e^{kx} - A V^2 B^2 e^{kx} \right] \cos k(x - V_{\text{Surface}} t)$$

3.80
\[ u_z = C A \left[ e^{ktz} - A^{1/2} B^{1/2} e^{ktz} \right] \sin k(x - V_{\text{surface}} t) \]

where \( A = \left[ 1 - \left( V_{\text{surface}} / V_{\text{longitudinal}} \right)^2 \right]^{1/2}, \ B = \left[ 1 - \left( V_{\text{surface}} / V_{\text{shear}} \right)^2 \right]^{1/2}, \ k = 2\pi f / V_{\text{surface}} = 2\pi / \lambda, \ C \) is a constant, \( f \) is the frequency, and \( \lambda \) is the wavelength of the surface wave.

The form of these equations shows that the amplitude of each component wave decreases exponentially with depth.

Curtis (1982) reports that if the surface wave is launched on one surface of a plate, the thickness of which is greater than one wavelength, then it will propagate with a velocity and particle motion unmodified by the presence of the lower surface of the plate. If the plate thickness is reduced the velocity will change as the particle motion interacts with the second free surface and its velocity will change to that of a form of plate wave.

### 3.2.2.2 Plate Wave Propagation.

Surface waves propagate at the boundary of a semi-infinite medium. If the medium is not semi-infinite, that is to say if more boundaries come into contact with a wave propagating on a surface, for example, then plate and rod waves may arise. Coming into contact with another boundary is generally considered to occur where the distances between the boundaries are comparable with the wavelength.

In a plate or rod the mode and velocity of propagation may depend on the ratio of the wavelength to the lateral dimension as well as the inertia and elasticity of the medium (Szilard, 1982). Plate waves can be symmetrical or asymmetrical (Figure 3.4). Two transcendental equations can be derived for the phase velocity of plate waves, \( V_{\text{plate}} \). In the symmetrical mode:

\[
\frac{\tanh At / 2}{\tanh Bt / 2} = \frac{4k^2 AB}{(k^2 + B^2)^2}
\]

where \( A = \left[ 1 - \left( V_{\text{plate}} / V_{\text{longitudinal}} \right)^2 \right]^{1/2}, B = \left[ 1 - \left( V_{\text{plate}} / V_{\text{shear}} \right)^2 \right]^{1/2}, \ k = 2\pi f / V_{\text{plate}}, f \) is the frequency, \( V_{\text{longitudinal}} \) is the velocity of longitudinal waves and \( V_{\text{shear}} \) is the velocity of shear waves.
In a plate one considers the effect of a second boundary when determining the possible modes of propagation and their corresponding velocities. In a rod one considers a structure with boundaries in all three axes whose separation is of the same order of magnitude as the wavelength of the wave under consideration. Rod waves can propagate in the form of bulges which, if $0.1\lambda \geq d$, the diameter of the rod, the velocity is independent of the Poisson’s ratio:

$$V_{\text{rod}} = \sqrt{\frac{E}{\rho}}$$ \hspace{1cm} 3.83

### 3.3 Propagation of Material Waves in Layered Media

The assumption of an homogeneous medium made when deriving the equations of motion for material waves in wood does not hold in all cases. In particular it depends on the wavelength of the propagating elastic waves being at least an order of magnitude greater than any underlying inhomogeneities. One of the largest inhomogeneities observed in clear wood is the annual ring, the origin of which is discussed in Chapter 2. Annual rings present a periodic density variation to waves travelling in the radial direction in a piece of wood, and thus a periodic variation in wavespeeds.

A set of relations describing wave propagation in layered media has been developed by several workers. Brillouin (1946) reported work on crystal lattices. Brekhovskikh (1960) studied the transmission of acoustic waves across a medium composed of n elastic layers.

### 3.3.1 Compressional Waves in Layered Media

In this section we consider waves in a medium consisting of alternating plane layers of two elastic materials, a and b. Two adjacent layers form what is known as a unit cell of
the material. Consider a plane compressional wave propagating in the $x_1$ direction perpendicular to the interfaces between the layers. Let the subscript $\xi$ indicate either a or b.

The displacement within each layer of a unit cell is governed by the one dimensional wave equation

$$\frac{\partial^2 u_\xi}{\partial x^2} = \nu_\xi \frac{\partial^2 u_\xi}{\partial x_1^2}.$$  \hspace{1cm} 3.84

where $\nu$ is the wave velocity.

The solution within each layer can then be expressed as a sum of forward and backward propagating waves.

$$u_\xi = A_\xi e^{i(k_\xi x_1 - \omega t)} + B_\xi e^{-i(-k_\xi x_1 - \omega t)},$$  \hspace{1cm} 3.85

where the wave number $k_\xi$ is

$$k_\xi = \frac{\omega}{\alpha_\xi}. $$  \hspace{1cm} 3.86

In terms of the displacement, the normal stress within each layer is $\sigma_{11}$

$$\sigma_{\xi\xi} = \rho_\xi \alpha_\xi^2 \frac{\partial^2 u_\xi}{\partial x_1^2} = \frac{z_\xi}{\rho_\xi} \frac{\partial^2 u_\xi}{\partial x_1^2},$$  \hspace{1cm} 3.87

where the acoustic impedance is

$$z_\xi = \rho_\xi \alpha_\xi.$$  \hspace{1cm} 3.88

Note that no summation convention is used for 3.87. Let $x_1=0$ be the interface between the layers of the unit cell as detailed in figure 3.4.
Physical constraints require that the displacements and the normal stresses in the two materials must be equal at the interface giving

\[ u_a(0, t) = u_b(0, t) , \quad 3.89 \]

\[ \sigma_a(0, t) = \sigma_b(0, t) , \quad 3.90 \]

The solutions of the wave equation given in 3.85 above contain four constants \( A_a, B_b, A_b, B_b \). We can represent equations 3.85 and 3.87 above in the form

\[ u_\xi = U_\xi(x_1)e^{i(k \cdot x_1 \cdot \omega t)} , \quad 3.91 \]

\[ \sigma_\xi = \sigma_\xi(x_1)e^{i(k \cdot x_1 \cdot \omega t)} , \quad 3.92 \]

where we define

\[ U_\xi(x_1) = A_\xi e^{i(K_i \cdot x_1)} + B_\xi e^{-i(K_i \cdot x_1)} \quad 3.93 \]

\[ \sigma_\xi(x_1) = iz_\xi \omega [A_\xi e^{i(K_i \cdot x_1)} - B_\xi e^{-i(K_i \cdot x_1)}] , \quad 3.94 \]

and

\[ K_\xi = k_\xi \pm k . \quad 3.95 \]

The functions \( U_\xi(x_1) \) and \( \sigma_\xi(x_1) \) are continuous across the layer interfaces and do not depend on time. Thus the Floquet theorem (Bedford and Drumheller, 1994) states that they must be periodic functions of \( x_1 \) with period equal to length \( d = a + b \) of the unit cell. This means that
\[ U_a(-a) = U_b(b) \] \[ \sigma_a(-a) = \sigma_b(b). \]

Combining these two conditions with the conditions obtained in 3.84 above in matrix form we have

\[
\begin{bmatrix}
1 & 1 & 1 & 1 \\
z_a e^{-iK_a} & -z_a e^{iK_a} & z_b e^{-iK_b} & -z_b e^{iK_b} \\
z_a e^{-iK_a} & -z_a e^{iK_a} & z_b e^{-iK_b} & -z_b e^{iK_b}
\end{bmatrix}
\begin{bmatrix}
A_a \\
B_a \\
-A_a \\
-B_a
\end{bmatrix} = [0].
\]

Equating the determinant of the coefficients to zero

\[
\cos kd = \cos \left( \frac{\omega a}{\alpha_a} \right) \cos \left( \frac{\omega b}{\alpha_b} \right) - \frac{1}{2} \left( \frac{z_a + z_b}{z_b - z_a} \right) \sin \left( \frac{\omega a}{\alpha_a} \right) \sin \left( \frac{\omega b}{\alpha_b} \right)
\]

This is the dispersion relation for a periodic layered medium. This relation yields real solutions for \( k \) only for values of frequency within distinct bands. Between the bands the solutions for \( k \) are complex. Writing \( k \) in terms of its real and imaginary parts as

\[ k = k_R + k_I, \]

and replacing it in equations 3.91 and 3.92 gives expressions for the displacement and stress fields of the form \( e^{y} \), where \( y = -k x_1 \) indicating that within the frequency bands \( k \) is complex. The amplitudes of the displacement and stress decrease or attenuate exponentially with \( x_1 \). For this reason these frequency bands are called stop bands. The bands within which \( k \) is real are called pass bands.

Equation 3.99 is examined in Chapter 9 to investigate under what conditions under which stop bands or pass bands might arise in softwoods. Typical data, based on measurements reported in Chapter 8 is used to examine the hardwood and softwood cases. Experimental evidence for the presence of stopbands is then sought.
3.4 Attenuation and Scattering

The loss factor for materials is frequently used to characterise materials. The form of Hooke's Law given in equations 3.10 and 3.20 makes no allowance for loss or attenuation of the wave as it travels through the medium. In practice there will always be some attenuation of the wave as it travels.

Green (1973) distinguishes between geometrical and intrinsic effects when discussing attenuation. Geometric effects might include such factors the physical size of the test specimen, the parallelism of the opposite faces, the size of the transducer relative to the wavelength of the sound beam, the curvature of the sound beam and other geometrical effects. These factors all exert a strong influence on the propagational characteristics of elastic waves and on the apparent energy loss from such waves. Of course such effects are extrinsic to the material and as such tell us little about the material. It is the intrinsic attenuation, independent of the factors described above which is sought as a descriptor of the material.

Attenuation may be modelled by using a complex modulus to describe the elastic behaviour of the medium. According to this 3.22 would be written:

\[ \sigma_{A} = \left( c_{AB} + j c_{AB}^{''} \right) e_{B}, \]  

so that the elastic stiffness is considered to have an imaginary component which takes into account the loss of the wave as it travels through the medium. In view of the potential complexity of the wave propagation in wood it was decided to use the conventional empirical description of attenuation based on plane wave propagation.

If we consider plane waves, where there is no geometric beam spread, and the incident amplitude is given by \( A_{0} \), this amplitude will decrease to a value \( A \) after travelling a distance \( x \) according to the relationship

\[ A = A_{0} e^{-\alpha x}, \]  

where \( \alpha \) is the amplitude attenuation coefficient. As the intensity \( I \) is proportional to the square of the amplitude, the incident intensity, \( I_{0} \), will decrease to
\[ I = I_0 e^{-2\alpha}, \] 3.103

If the natural logarithm of equation 3.101 is taken then

\[ \alpha x = \ln \frac{A_0}{A}, \] 3.104

where the value of \( \alpha x \) is measured in nepers. Now the attenuation coefficient for the material is obtained by dividing by the distance in metres.

\[ \alpha = \frac{1}{r} \ln \frac{A_0}{A}, \] 3.105

and the value of \( \alpha \) is measured in nepers per metre. Alternatively attenuation may be expressed in decibels. Since \( \log x = \ln x / \ln 10 = 0.434 \ln x \), these units are related as follows:

\[ 1 \text{ Np} = 8.686 \text{ dB}. \] 3.106

In an homogeneous medium such as a gas, liquid, amorphous solid or a single crystal part of the wave energy is absorbed and turned into heat. In an heterogeneous medium additional losses take place in the form of scattering losses. Accordingly the overall attenuation coefficient can be given by

\[ \alpha = \alpha_a + \alpha_s, \] 3.107
where $\alpha_a$ is the absorption coefficient and $\alpha_s$ is the scattering coefficient.

Scatter is due, inter alia, to inhomogeneities having a characteristic impedance different from that of the surrounding material. The scatter coefficient varies with, among other factors, the wavelength to diameter ratio of the inhomogeneities. Three scattering regimes can be distinguished with different behaviour of scatter coefficient (Szilard, 1982). If $\lambda$ is the wavelength of the material waves, $\bar{D}$ the mean diameter of the inhomogeneities, and $f$ the frequency of the material waves the three scattering regimes are given by:

1. Where $\lambda \gg \bar{D}$, known as the Rayleigh scattering range, here $\alpha_s \propto \bar{D}^{-3} f^2$.

2. Where $\lambda \approx \bar{D}$, known as the stochastic scattering range, here $\alpha_s \propto \bar{D} f^2$.

3. Where $\lambda \leq \bar{D}$, known as the diffusion scattering range, here $\alpha_s \propto 1/\bar{D}$.

The boundaries between 'much greater' or 'much less' than the mean scatterer diameter are not clearly defined and also depend on scatterer contrast, shape, orientation and concentration.

As discussed in Chapter 2 wood has an anisotropic inhomogeneous structure. In Chapter 6 of this work signal attenuation in three different species of wood, representing three different type of wood is examined. The woods chosen for this work have different microstructures - a ring porous wood with large vessels in the early wood of each ring; a diffuse porous wood with small vessels spaced throughout the ring and a softwood with no vessels but smaller tracheids and density steps between the annual rings. Thus differences in attenuation between the three species might be expected.
4. ULTRASONIC MEASUREMENT TECHNIQUES

4.1 Introduction

Mc Skimin (1964) reports that the basic problem involved in ultrasonic measurements is that of cyclically straining a small volume element of liquid or solid in a predetermined way and of measuring the mechanical stiffness and energy loss. This may be carried out over a range of temperatures, pressures or samples. The information so obtained can then be related to the physical processes involved. For example, as seen in the first part of chapter 3, the mechanical stiffnesses of a material can be obtained by determining the appropriate acoustic wavespeeds in the material.

The theory described in chapter 3 models what might be termed ideal measurements made on an ideal material. In practice wood is far from an ideal material and so presents many challenges when trying to apply the models described in chapter 3 to it. For example, the theoretical relations developed in chapter 3 are based on the assumption that we are dealing with plane wave propagation in the material. Thus the wave is assumed to be travelling in a semi-infinite material. However, as observed in chapter 6, wood attenuates ultrasonic signals strongly, limiting the size of sample which can be used.

In this chapter some of the experimental techniques which are available for use in determining the elastic properties of materials are examined. The main techniques which have previously been used to measure acoustic wave propagation properties in wood are reviewed. In particular, the compromises that have to be made when selecting particular approaches to measurement are assessed.

This work commences with an overview of a typical ultrasonic measurement system which permits identification of some of the main issues involved in making ultrasonic measurements.
4.2 Generic Ultrasound Characterisation System.

Figure 4.1 below shows a ‘generic’ ultrasound characterisation system of the type used to make measurements in this work.

![Diagram of a generic ultrasound characterisation system]

**Figure 4.1 Generic Model Of Ultrasonic Measurements System In Through Transmission Configuration**

The role of the main elements in the diagram is outlined below:

- **Pulser.** This is the source of excitation for the transmitting probe. It may provide a ‘spike’ voltage signal with many frequencies in it for broadband measurements, or it may provide a ‘tone burst’ of several cycles of a single frequency for quasi-monochromatic measurements (see section 4.4.1).

- **Source or transmitting transducer.** This element turns the excitation signal provided by the pulser into physical vibrations. Depending on its construction it may respond over a relatively wide range of frequencies (broadband) or it may respond to a limited range of frequencies (narrow-band) (see section 4.4.1).

- **Coupling interfaces.** The interfaces between the transducer and the sample are a crucial part of the measurement system. The interface between the transducer and the samples may significantly affect how much of the vibrational energy generated by the source is coupled into the sample. Similarly at the receiving end the amount of energy picked up by the receiving transducer is affected greatly by the interface between the sample and the receiving transducer. The coupling interfaces are also...
potential sources of uncertainty when making velocity and attenuation measurements on signals which have passed through samples.

- Receiving transducer. This is used to re-transduce the physical vibrations at the material interface into an electronic signal. Often the receiving transducer is identical in construction to the transmitting transducer so that the two overlap in terms of bandwidth and other transduction properties.

- Receiver amplifier. The receiver amplifier is used to amplify the signal from the receiving transducer. Amplifications of the order of 60dB or more are often required to deal with the attenuation experienced in wood. Many ultrasonic receivers incorporate an attenuator which permits electronic attenuation of the signal in a controlled fashion over ranges of several decades of dB.

- Measurement System. The amplified signal is fed to a measurement system. This may take the form of a simple digital readout which indicates the time at which a signal has reached a particular threshold. The measurement system may take the form of an oscilloscope, generally nowadays a digital storage oscilloscope, which permits on-screen examination and measurement of the signal. Increasingly the received ultrasonic signal is digitised and fed to a computer for measurement, storage and analysis (see section 4.3.3 for further comments).


The velocity of a wave is usually associated with the phase difference between the vibrations observed at two different points during the passage of the wave. In chapter 3 it was noted that a plane harmonic wave of amplitude A, angular frequency \( \omega = 2\pi f \) and wavelength \( \lambda = 2\pi/k \) propagating in a non-attenuating medium may be represented by \( A_0 e^{i(\omega t - kx)} \). The phase velocity of the wave is then given by \( v = \omega/k \) (Brillouin, 1960). For monochromatic or non-dispersive waves the problem of velocity measurement becomes one of determining the length of time an identifiable element or phase of the wave takes to propagate over a known or measurable distance.
When the phase velocity of a wave is a function of its frequency then the wave is dispersive. A pulse propagating through a dispersive medium will not retain its original shape. This is because the different frequency components making up the pulse propagate at different speeds causing the pulse to change its shape as it propagates.

For such pulses the concept of group velocity is important. Brillouin (1960) defines a group velocity as the velocity of a modulation imposed on a carrier. The carrier moves with the phase velocity and the modulation moves with the group velocity. If the modulation is imposed on a number of superimposed carriers forming a pulse then the pulse moves with a group velocity $U$ defined by

$$U = \frac{d\omega}{dk} = v + k \frac{dv}{dk}.$$  \hspace{1cm} (4.1)

In dispersive media the received pulse will not be identical in shape to the transmitted pulse. This presents a problem when determining the time of flight of the pulse through the sample. If the received signal is not identical to the transmitted pulse then how does one select an identifiable element of the received wave for timing purposes?

One approach to dealing with this problem may be to use an almost monochromatic signal composed of a long toneburst of a single frequency for the purposes of velocity measurement (McSkimin, 1964). Papadakis (1976), proposes a technique whereby the transmitted and received pulses are overlapped on a screen permitting the experimenter to make a judgement on the overlap of the wave packet. More recently frequency domain techniques for determining ultrasonic phase and group velocity from ultrasonic pulse propagation has been reported (Sachse and Pao, 1978; Chivers et al., 1980; Pialucha et al. 1989).

A further complicating factor when determining the velocity of material waves in a complex material such as wood is the presence of other waves propagating in modes other than the mode under measurement at a particular time. As is discussed in section 4.3.3 when propagating shear waves in wood, for example, longitudinal and indeed other modes are often also excited.

Thus when making measurements of pulse arrival time one must ensure that the correct pulse is detected and measured. This precludes the use of several techniques such as the sing around technique (McSkimin, 1964) and the phase lock loop technique (Yost
et al., 1992). These techniques can achieve high levels of accuracy (up to 1 part in $10^8$ for the phase lock loop technique) for velocity measurements. However, the presence of competing modes of propagation can confound some of these techniques.

A question also arises as to the accuracy required for ultrasound velocity measurements in wood. The biological origin of wood means that it has much greater natural variability than manufactured materials. For example, in chapter 8 of this work, four sets of thirty samples from four species of wood were measured for longitudinal ultrasonic pulse velocity in the longitudinal direction. The samples were selected for quality and straightness of grain from high-quality joinery stock. Thus, one might expect reasonably uniform behaviour from the samples. The velocity results obtained from velocity measurements show remarkable scatter, ranging from 3,700 m/s to 4,700 m/s in Oak. Such scatter is not considered unusual, however, for workers carrying out measurements in the field of wood and timber research (Desch and Dinwoodie, 1997; Ross et al., 1996, 1997; Sandoz, 1989). Feeney (1987) reports significant variations in velocity for measurements of longitudinal velocity carried out on different parts of the same 2cm x 2cm x 30cm samples. This was observed for several samples each of which had been selected for straightness of grain and uniformity. It appears more sensible instead to try to understand what is being measured when the velocity and attenuation of a material wave propagating through wood is determined.

4.3.1. Through Transmission Techniques versus Pulse Echo Techniques.

One of the first decisions faced by an experimenter selecting an ultrasonic measurement technique is whether to use a pulse echo measurement technique or a through transmission technique. Figure 4.1 above is a diagram of a through transmission system since this is the system most commonly used in this work.

Pulse echo techniques involve using a single transducer as a source and receiver. An exciting signal is applied to the transducer causing it to vibrate in the appropriate fashion. The vibrational energy is then coupled into the sample of material under investigation. The vibration passes down into the sample and is reflected at the
backwall of the sample producing the 'echo'. The echo is received by the transducer and displayed.

In the through transmission technique separate transducers are used for transmission and detection. The source transducer generates the appropriate vibrations which are then detected by the receiving transducer placed on the opposite face of the sample (figure 4.1). The received signal is displayed in relation to a trigger signal derived from the outgoing pulse.

The pulse echo system has several advantages. Usually front and backwall echoes are available, making transit times in the material easy to determine. In some cases echoes from multiple reflections in the sample are obtainable permitting measurement of attenuation independent of coupling losses.

However the pulse echo system is almost never used with wood. Wood is highly attenuating so that the echo signal is generally too small for reliable measurement, even with thin samples. Pulse transmission velocities in wood are high, particularly in the longitudinal direction so the echo signal may return before the single transmit/receive probe has recovered from the outgoing pulse. Thus the through transmission system is generally the preferred technique for making measurements on wood. There are certain disadvantages to this. For example phase and amplitude changes are indeterminate at the interfaces, unlike in the pulse echo system when looking at multiple echoes.

4.3.2 Review of Some Commonly used Ultrasonic Velocity Measurement Techniques

Several different techniques exist for the determination of velocity of ultrasound in materials. One classic technique is the sing around technique (McSkimin, 1964). In this technique the received pulse from one passage of a pulse or toneburst through a sample is used to trigger the next outgoing signal. The delay time of the system is then the inverse of the repetition frequency of the transmitted pulses. A time with no sample in place can be measured and subtracted from the time with the sample in place to give the transit time in the sample.
The sing around technique was used by Sasaki et al. when examining higher order elasticity in wood (see section 5.6.2). These measurements were made using longitudinal waves along the longitudinal axis of the tree. As can be seen from the measurements reported in chapter 6 these modes are the least attenuated and fastest modes transmitted by wood. Thus they provide a suitable trigger for the operation of the sing around technique. The advantage of the sing around technique is that one effectively counts the time taken for a number of trips (typically 1000) through the sample. Then by calculating the average time per trip one the precision of the technique is enhanced.

However, as can be seen from section 4.4.3 below other modes than the mode of interest may be excited. Thus when measuring shear waves, for example, a faster longitudinal mode of significant amplitude may be excited. This may be of sufficient amplitude to switch the triggering mechanism of the sing around technique.

The Pulse-Echo-Overlap Technique developed by May, 1958 and extended by Papadakis, 1964, is reported as being capable of measurement of phase delay to within less than 10° of phase delay. In this technique the time delay is measured over a certain path by overlapping the ultrasonic signals at the beginning and end of that path. The overlapping is performed on the face of a monitoring oscilloscope by driving the x-axis sweep of the oscilloscope at a frequency set such that the period of the sweeping frequency is equal to the delay time. Again measurement of the sweep frequency gives the time delay within the system. Sakai (1990) reported problems when trying to use the conventional pulse echo overlap technique due to the difficulty in receiving the pulse and echoes separately. A through transmission adaptation of the technique is reported (Papadakis, 1990) for dispersive materials, but budgetary constraints did not permit its investigation for the current set of measurements.

4.3.3. Measurement of Time of Flight.

In section 4.3 it was noted that the determination of time of flight in the time domain requires identifying a point of similar phase in the transmitted and received signals and measuring the time difference between the two points. There are three types of location in a typical signal which are commonly used for the purposes of time delay measurements - (i) the onset of the signal, (ii) peaks within the signal and (iii) zero
crossings within the signal. In this section the effect of choosing one location of a signal against another location of the received signal on the time delay recorded is considered.

Figure 4.2 shown below shows received signals obtained using 100kHz longitudinal, broadband probes. A 200V pulse was applied in each case and the wave propagated through 75mm of Pine in the radial direction. The only difference in the two received signals is an extra 10dB electronic attenuation inserted in the smaller signal after reception and amplification. Thus the coupling of the probes to the sample and other settings were not changed between recording the two signals. Since nothing else has changed one would expect the pulse arrival time to be the same in both cases.

\[\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure4.2}
\caption{Received Signals Through 75mm Pine- Longitudinal Wave In Radial Direction. (Smaller signal has had 10dB extra attenuation applied, other settings and coupling not disturbed between measurements.)}
\end{figure}\]

Time delay is frequently measured by locating the onset of the received signal. As noted by Kamioka and Katioka (1982) extreme care is necessary in order to determine the onset point correctly. In practice often this onset is automatically determined once the signal has reached a particular threshold and displayed digitally (with great precision). However as is clear from the two signals above using a fixed threshold to determine pulse onset will yield two different pulse onset times. Indeed in this experiment the pulse onset was recorded, with the aid of a cursor to be 48.36µs for the attenuated signal and 49.06µs for the un attenuated signal. This corresponds to calculated velocities of 2261m/s and 2214m/s respectively, a difference of approximately 2% in this case. Of course if the propagation distance is sufficiently long then this error becomes less significant. However the sample shown above represents
an almost optimal situation where nothing has been changed between the measurements.

The thresholded pulse onset measurement, which is frequently used in commercial pulse velocity instruments, can be considered in some respects to be a combined measurement of time delay and attenuation. Indeed in some cases where a weak signal is being detected and a toneburst or similar signal is used the first cycle of the toneburst can fall below the threshold resulting in an error in measurement of 1 cycle (Peterson et al, 1997).

Returning to figure 4.2 above it is clear that the received peak position has not changed even when the signal has been attenuated. However the problem with using the position of the peak for timing is that the received peak is not sharp resulting in uncertainty in its location, particularly in the case of the attenuated peak. The zero-crossing after the peak crosses the axis in a well defined location that does not appear, in this example, to change with attenuation. Many workers making accurate phase variation measurements use zero-crossing locations (Micheletti, 1991). In the example above the peak of the received signal was determined to be at 51.00μs and 50.97μs for the unattenuated and attenuated signals respectively (an error of 0.06%). The zero-crossing after the first peak was determined to be at 52.26μs and 52.27μs for the unattenuated and attenuated signals respectively (an error of 0.02%).

4.3.3.1 Identification of Correct Received Signal for Measurement Purposes.

In practice it is impossible to generate pure single modes for most real samples. Using high quality probes usually ensures that the desired mode is the predominant mode generated. However under certain conditions significant energy may be excited in other modes. In this case the received signal must be examined carefully to identify the correct mode before making a measurement of time of arrival for the purposes of velocity measurement.

The signal displayed in figure 4.3 (a) was obtained using two normal shear wave probes in a through transmission arrangement with a 5mm piece of plastic sandwiched between the probes. The signal displayed in fig 4.3 (b) is the signal received using the same pair of shear wave probes on a 35mm piece of Norway spruce wood. The
direction of propagation was along the longitudinal direction, with the wave polarised in the tangential axis (an LT shear wave). The largest pulse in the time window is due to the LT shear wave. It is preceded by a smaller wave which can be shown to have the same velocity as a pure longitudinal wave propagating along the longitudinal axis of the same tree. In figure 4.3 (c) where an LR shear wave is excited the longitudinal mode also present.

![Shear Wave Probes Signal - 5mm Plastic](image)

**Figure 4.3 (a) Shear Wave Signal Through 5mm Plastic.**

![LT Shear Wave Signal Received Through 35mm Norway Spruce Wood](image)

**Figure 4.3 (b) LT Shear Wave Signal Received Through 35mm Norway Spruce Wood.**
Figure 4.3 (c) LR shear wave signal received through 35mm Norway spruce (Epicea) wood.

Other types diversion of energy from the directly excited mode can also be observed. In the trace shown below (figure 4.4) a TR and a TL signal received through Sitka spruce are displayed on the same graph. The TR wave displays a significant amount of energy in the TL mode. It is not clear that the reverse process occurs, however, as the TL wave appears to display only minor amounts of the TR wave.

Figure 4.4 Plot Of TR And TL Signals For Sitka (Sample Number 23)

A TL shear wave propagates at right angles to the annual rings with the particle motion in the longitudinal axis (figure 4.5(a)). A TR wave propagates in the direction of the annual rings with the particle motion polarised in the radial direction (figure 4.5(b)). From the presence of the TL mode when the TR mode is excited one may conclude the shearing motion at the surface of the sample in radial direction set up a shearing motion in the longitudinal direction via an interaction with the stiff bands of annual rings. The
opposite effect is not observed to any significant degree since the shearing motion of the TL wave does not interact with an significant structures aligned in the radial direction.

Figure 4.5(a) TL Waves Propagate Through Wood With Vibration In Longitudinal Direction. No Structure To Cross Couple Into TR Mode (Except Small Amount Of Rays).

Figure 4.5(b) TR Waves Propagate Through Wood With Vibration In Radial Direction. Interaction Of Radial Shear With Plates Of Stiff Latewood Results In Significant TL Wave.

The examples here illustrate the process of diversion of energy from one wave mode to another. The amount of energy diversion may not be constant with species, ring width or other variable. However it is the experience of the author that an LL wave generally accompanies an LT or LR shear wave although its magnitude may vary.

Clearly when carrying out velocity and attenuation measurements in wood the experimenter must be careful to identify the correct peak for measurement. It is also clear that measurements of attenuation can be affected by diversion of energy from the intended mode into other modes of propagation. That mode conversion and other factors which influence the shape of the received signal may vary consistently from species to species is the hypothesis on which the neural network classification study reported in chapter 8 is based.

For the remainder of this chapter where velocity and attenuation is determined by the time of flight through a sample of known dimension it is assumed that the appropriate signal was identified and measured. It should be pointed out that in practice, for the
reasons set out above, this may be difficult and require an experienced worker. Indeed when considering off axis propagation the task is further complicated by the fact that the wave under consideration on a particular slowness surface may change from a quasi-longitudinal to a quasi-shear wave and vice versa (Lanceleur et al., 1998).


Perhaps one of the most significant experimental design decisions to be made is the choice of propagation frequency to be used for the material waves. As noted in section 3.4 scattering attenuation depends greatly on the wavelength to diameter of scatterer ratio. Clearly as one uses a higher frequency the influence of any inhomogeneities becomes more important, with more and more of the interrogating signal being lost due to scattering.

For this reason many workers employ low frequencies in the 100kHz range for making measurements on wood. The model of elastic wave propagation derived in chapter 3 assumes plane wave propagation. Read and Dean, 1978, state that the material dimensions should be at least 5 times the wavelength to ensure that the assumption of plane wave propagation is valid. Kamioka and Kataoka, 1982, presented an experimental graph of the velocity in a finite rod shaped piece of material normalised to the bulk wave velocity as a function of radius wavelength ratio. They found that as the radius-to-wavelength ratio passes 2.5 approximately then the velocity of the wave in a rod shaped piece of material approaches the bulk wave velocity.

As stated in section 3.2.2.2 a pure rod wave is propagated when the diameter of the rod is less than 0.1 of the wavelength. The region where the diameter is greater than 10% of the wavelength but is less than 5 times the wavelength is a transition region where the wave velocity is less than the bulk wave velocity and depends on the diameter to wavelength ratio.

Thus when attempting to determine velocity values which are independent of sample size, wavelengths corresponding to the transition region between rod or plate waves
and bulk waves should be avoided. Experimental studies which employ modes which are neither pure bulk nor pure plate modes only have a validity for the particular set of experimental conditions in which they were carried out. It is difficult to make generalisations from such studies.

The value of the wavelength depends not only on the frequency used, but also the wavespeed for the material and the mode of propagation of interest. The results presented in chapter 6 show that the latter may vary by as much as a factor of 4 in wood. For convenience a set of curves for determining the wavelength, $\lambda$, given the frequency and wavespeed is included here as figure 4.6.

A propagation frequency of 100kHz with velocities ranging from 800m/s to 5000m/s depending on propagation direction implies wavelengths in the material of the order of 1cm to 5cm approximately. This would require samples of the order of 5cm to 25cm along the direction of propagation to fulfil the assumption of plane wave propagation.

Bodig and Jayne (1982) report typical tracheid radii in softwoods to be of the order of 25$\mu$m to 80$\mu$m. If we take 'much greater than' to mean 'an order of magnitude greater than' then this implies using wavelengths of the order of 0.8mm or greater in order to remain in the Rayleigh scattering regime, where scattering may be taken to be less influential. This has implications for the propagation frequency particularly in the radial and tangential directions. Wavelengths of greater than 0.8mm implies frequencies of less than 1MHz and 1.8MHz for waves propagating in the tangential (>800 m/s) and radial (>1500m/s) directions respectively if significant scattering is to be avoided.

Propagation in the longitudinal direction presents a different problem. In this case the propagation is along the tracheid lengths for which Bodig and Jayne report typical figures of 2.5mm to 7mm respectively. Using the guidelines in the previous two paragraphs would restrict the useable frequencies to less than 70kHz for a 5000m/s velocity. However, tracheids are normally modelled as elastic cylinders which are much less compressible along the longitudinal axis (Lee, 1958; Desch and Dinwoodie, 1997; Kahle and Woodhouse, 1994). Thus they do not appear to act as scatterers in the longitudinal direction.

As is clear from the results reported in chapter 6 much less attenuation is experienced in the longitudinal direction than is experienced in the tangential and radial directions.
Figure 4.6 (a) Plot Of Wavelength Against Wavespeed For Typical Range Of Frequencies Applied To Ultrasonic Measurement Of Wood.

Figure 4.6 (b) Plot Of Wavelength Against Wavespeed For Higher Frequencies Applied To Ultrasonic Measurement Of Wood.
As a result, in practice, higher frequencies can be used in the longitudinal direction. A wave travelling in the longitudinal direction is travelling through material consisting of concentric rings of dense latewood and less dense earlywood. Propagation in this direction is given further consideration in section 4.7 as the ‘phase cancellation artifact’, and in chapters 8 and 9 on the inhomogeneity in wood.

Having set limits on the appropriate frequencies and sample sizes which should be used in characterising wood using material wave propagation it should be borne in mind that practical difficulties associated with obtaining suitable samples may sometimes over-ride these constraints.

4.4.1 Broadband or Narrow Band Measurements?

A further factor to be considered along with propagation frequency is whether to use a broadband propagation or a narrow band propagation. Broadband signals are composed of a range of frequencies (Laithi, 1989). Broadband transmission requires broadband excitation and a broadband transducer. The most common broadband excitation signal is a narrow voltage spike or pulse. This may considered to be constructed from a large number of sine waves and so provides excitation to the transmitter over a wide range of frequencies (Lathi, 1989).

The broad band transducer typically consists of a resonant piezoelectric element with a very dense backing to damp the crystal heavily. This heavy damping broadens the range of frequencies over which the transducer can respond, but reduces the level of signal produced. The bandwidth of a transducer is the range of frequencies for which it responds. It is usually defined as:

\[
Bandwidth = \left( \frac{f_a - f_b}{f_o} \right) \times 100\% 
\]

where \( f_a \) and \( f_b \) are the frequencies above and below the maximum response of a transducer at which the magnitude of the response function fall to 50% of the maximum value and \( f_o \) is the centre frequency of the transducer (Sachse and Hsu, 1986).
Narrowband transmission is generally achieved by exciting an undamped piezoelectric element with a quasi-monochromatic signal such as a sinusoidal tone burst at the resonant frequency of the crystal. If pulse excitation is used the transducer will still resonate at its main frequency but the harmonics of the main resonance may also be excited giving a less pure signal. Pulse excitation also results in a lower proportion of the energy of the excitation signal being converted into vibrational energy.

In Chapter 6 of this work quasi-monochromatic signals are obtained from broadband probes by driving them with a toneburst. This is less efficient than using narrow-band transducers but was a compromise since it was desired to carry our measurements over a range of frequencies, and buying a range of narrow-band transducers was not financially feasible. It also had the advantage of retaining the same physical coupling conditions for measurements at the different frequencies chosen (section 4.5).

Broadband signals have potential problems associated with measuring group delay in a dispersive medium as noted at the beginning of this chapter. On the other hand when used in association with frequency domain techniques they can give access to attenuation as well as phase velocity information (Sachse and Pao, 1978). Narrowband techniques typically use a ‘toneburst’, that is a quasi-monochromatic sinusoidal signal of a fixed number of cycles. The aim of such signals is to give the phase velocity and a constant amplitude at the frequency of propagation, and reduce the problems associated with dispersion.

4.5 Choice of Coupling Technique

Coupling generally involves ensuring maximising the transfer of energy from the transducers into and out of the sample under investigation. Clearly where significant attenuation is encountered, as is the case when propagating ultrasound through wood, this is a topic of crucial significance. For most solid materials satisfactory coupling of ultrasound into dry samples involves using a gel or liquid at the transducer - sample interface. This thin layer of liquid is sufficiently thin to have a negligible effect on the ultrasound passing through the interface while ensuring that air is expelled from the interface.
The elimination of air from the interface is crucial because the impedance of air is hugely different to that of most solids. Most air-solid interfaces have reflection coefficients of the order of 99% or greater. Thus where air is present at an interface most of the energy will be reflected at the interface rather than propagating into the interface.

Unfortunately when working with dry moisture conditioned wood samples it is generally not advisable to use a liquid or gel couplant directly on the surface of the sample. This is because dry wood will rapidly absorb most gels and liquids. If a large sample is under investigation and only a small part of the sample is affected by absorption then this effect can be ignored. However in this work the samples used were too small to ignore the potential effect of absorption of couplants.

The issue of coupling of ultrasound into wood samples is further complicated by the relative roughness and variable nature of the surface of the wood. The roughness of the surfaces of a sample causes problems for the elimination of air when coupling the sound into the sample as mentioned in the preceding paragraphs. This problem can be reduced, but not eliminated, by careful finishing of the surfaces of the samples to provide a smooth surface. Since this work has started the availability of high speed tungsten tipped circular saws has increased dramatically making the preparation of samples with good surface finish easier, although still requiring considerable skill.

Many different coupling techniques have been employed by workers aiming to maximise energy transfer form the sample to the measurement system and vice versa. Bucur, (1981),and Sakai, (1990), have used a combination of a gel and a plastic or cellophane layer to eliminate air and prevent the gel affecting the sample. Olivato (1993) used sanded samples and applied silicone grease to the surface. He does not record if this had a significant effect on the moisture content study. Sandoz, 1989, used a transducer with a conical tip which was hammered into the samples. He worked with relatively long samples, 28-44cm, reducing the error due to coupling variations. Simpson, 1998, used rubber face roller probes. The soft rubber faces make good contact with the relatively rough surface of the wood and are effective for coupling low frequencies such as the 84kHz emitted by the transducers in question. Halebe et al. report the use of petroleum jelly as a couplant with constant pressure applied using a
combination of clamps and load cells. Again the effect of penetration of the couplant into the sample is not discussed.

Kamioka and Kataoka, 1982, examined the influence of using different couplants (Petroleum Jelly, grease, Machine Oil, Sewing Machine Oil, Water) on the surface of wood. They found typical velocity differences of the order of 5% in comparison to using non-invasive coupling. Kamioka and Kataoka also investigated using aluminium tape and plastic tape in combination with grease and again found a significant measurement effect of up to 5%.

4.6 Choice of Transducer Dimensions.

Although commercially available transducers may have rectangular piezoelectric elements, the majority appear to have circular elements. Of necessity the elements are finite in size, and this causes the fields radiated by the transducers to be diffractive and to deviate from the ideal plane bulk waves implicitly assumed in the signal analysis. Diffraction corrections (Papadakis, 1975) have been proposed to account for the finite size of the transmitting and receiving transducers for ultrasonic wave measurements in fluids. They assume ideal behaviour of the transducers (which is unlikely to occur and difficult to measure (Aindow et al., 1985). Furthermore while the application of these corrections to isotropic homogeneous solids would appear to be straight-forward, there may be losses due to mode conversion of those waves that are not emitted exactly along the axis. The problem does not appear to have been investigated for shear wave transducers, or for anisotropic solids, let alone those that are, additionally inhomogeneous. Nevertheless the diffraction effects will be controlled in the first instance by the ratio of the dimensions of the transducing element to the wavelength. Generally speaking it is sensible to work within the collimated near field of the transducer, i.e. within a distance \( \frac{a^2}{\lambda} \) for a disc sample where \( a \) is the radius and \( \lambda \) the wavelength.

Reducing the size of the transducer to attempt more refined measurements or small samples, such as the incremental cores described in chapter 7 thus limits the length of the samples over which measurements can be made. This generally reduces the accuracy of the measurements. Attention must be paid to the wave modes whose measurement is being attempted since, as is shown in chapter 6, the wavespeeds which
determine the wavelength at a given frequency can vary by a factor of 4 or more in a given material (see also figure 4.6).

4.7 Measurement of Attenuation in Solids.

In section 3.4 aspects of attenuation were considered. Attenuation of the received signal due to geometrical effects was distinguished from intrinsic wave attenuation due to material effects. Overall intrinsic or material attenuation was seen to be composed of attenuation due to absorption and attenuation due to scattering. Both of these parameters can give important information when characterising a material, although separating the individual contributions may be problematic, as indeed may separating geometrical effects from intrinsic effects.

Attenuation due to scattering is not specifically measured in this work. However the presence of scattering cannot be ignored. Scattering is generally accepted as being caused by inhomogeneities in the material through which the material waves are propagating (Szilard, 1982). As mentioned in section 3.4 the scattering coefficient varies with the wavelength to diameter ratio of the inhomogeneities and the contrast between the inhomogeneities and the material through which the acoustic waves are passing. There is some evidence to suggest that the main sources of scatter are considered to be the air voids in the cells of the wood. Indeed one of the main differences between the three species for which attenuation measurements are reported in Chapter 6 is the size of the cells such as vessels and tracheids within the wood.

As can be seen in chapter 5 which reviews the applications of ultrasound to the characterisation of wood very few measurements of attenuation of ultrasound in wood are reported. Many of those measurements which are presented report received signal amplitudes rather than actual attenuation figures, and those that do report attenuation figures caution that the measurements are specific to the apparatus, technique and samples used.

Many of the standard attenuation techniques reported rely on pulse echo measurements or immersion measurements (McSkimin, 1964; Papadakis, 1976). Pulse echo techniques are generally not suitable for use in wood due to the severe attenuation
experienced by material waves propagating through wood. Immersion techniques are not appropriate for testing wood which will be used in a dried state.

Problems associated with the variability of wood and its surfaces mean that repeatability is an problem when carrying out measurements on wood. This is generally worse for amplitude measurement than it is for time of flight measurement. Coupling problems (section 4.5) also have a bigger impact on attenuation measurement than time of flight measurement.

The attenuation measurements reported in this work are based on a simple substitution technique. The amplitude of the received signal with no sample present is measured. The sample is then placed in the measuring apparatus and the received signal again measured. The relations reported in section 3.4 are then employed to calculate attenuation in dB/cm.

Accurate and meaningful attenuation measurements on materials such as wood are difficult to obtain. In part this has to do with the difficulty in achieving repeatable coupling discussed in section 4.5. Also it is not possible to manufacture wood specimens for measurement in controlled conditions. Wood samples have to be obtained by selection from grown material. Thus each sample is unique and only approximates the ideal of orthorhombic symmetry.

There appear to be three mechanisms associated with wave propagation in wood (as an anisotropic, inhomogeneous solid material) that can affect the amplitude of a received signal from which attenuation measurements are derived. The first concerns the fact that the plane wave normal transmission and reflection coefficients of polarised shear waves are likely to depend on the structure and orientation of the microstructure at the surface of the sample. This is a problem that appears to have received little attention and may be relatively small in the magnitude of its effect.

The second mechanism concerns the possibility of energy being deviated out of the propagation mode of interest by mode conversion processes, as discussed in sections 4.3.3.1 and 4.6 above.

The third mechanism concerns the possibility of the effects of a combination of waves impinging on the receiving transducer. Two obvious possibilities arise here. The first occurs in the presence of mode conversion just mentioned. In this case one may
envisage two waves of different types both impinging on the (whole of the) receiving transducer surface but interfering as they do so. The resultant effect would depend on the actual modes involved, their relative amplitudes, the relative sensitivity of the receiver to the two modes, the wavespeeds of the two modes and the length of the specimen through which they have propagated. The second possibility may be identified as due to the presence of inhomogeneities within the sample, such as the annual growth rings, which cause a single mode of wave to travel at different speeds through different parts of the interrogated specimen volume, thus arriving with different phases on different parts of the receiving transducer.

The integrating process of the conventional piezoelectric receiver will produce an effective interference of the electrical signals produced by the component wavefronts leading in general to a reduction in detected signal amplitude. This is the well known 'phase cancellation artefact' (Chivers, 1991). It should of course be noted for completeness that both of the above two mechanisms could in principle occur simultaneously.
5. REVIEW OF APPLICATIONS OF ULTRASONIC AND MATERIAL WAVE TECHNIQUES TO WOOD.

5.0 Introduction.

Wood is a material whose potential for use as an engineering material has to be tempered by conservative specification owing to the natural variability of the material. Significant effort has been expended by workers trying to arrive at evaluation techniques which would permit tight quality control on those specimens to be used in critical applications. Strength parameters such as the Modulus of Rupture (MOR) are considered to be the definitive figures of merit for timber in use. On the other hand, Modulus of Elasticity is the parameter measured by many static and non-destructive testing techniques. A strong statistical link between strength properties and the Young's Modulus or Modulus of Elasticity has been demonstrated by many workers (Bell et al., 1954; Galligan and Corteau, 1965; Pellerin and Galligan, 1973; Gerhards, 1982). This link has then been used to justify the use of secondary non-destructive evaluation techniques for the assessment of structural lumber. These secondary techniques would encompass machine stress grading and material wave propagation techniques for determining MOE and MOR.

Material wave techniques have been used for the characterisation of many other materials. Elastic constants, flaws and microstructure have all been evaluated by measuring the velocity and attenuation of material waves propagating through liquids, metals and other solids. It seems natural therefore to adapt these techniques for use on wood. Ross and Pellerin (1994) in their comprehensive review of non-destructive testing for wood members in structures attribute the fundamental hypothesis for the application of NDT techniques to Jayne (1959), who proposed that the energy storage and dissipation properties of wood which are measured non-destructively are controlled by the same mechanisms which determine the static behaviour of wood.
However, while it is possible to quote a specific figure for the velocity of longitudinal waves in a high quality steel, for example, the natural variability of wood means that it is not possible to quote a single figure for high quality wood. The anisotropy and inhomogeneity of wood also means that care must be taken with sample selection, orientation and dimensions when exciting material waves in wood. Wood has also a high percentage of air filled voids which scatter ultrasound strongly resulting in attenuation, particularly at higher frequencies.

When reviewing the approaches of different workers to the problem of using material waves to characterise wood certain themes recur, making it possible to break down the body of work in the field into separate sections, as outlined in the next section. It is clear also from the literature that many subtly different experimental approaches have been adopted so that measurements have been made on a wide range of species, on many different samples sizes, using many different propagation frequencies. This makes comparison of work reported by different researchers difficult as it is often difficult to separate the results reported from the particular experimental set-up used to achieve the result. In many cases, vital experimental details are omitted significantly reducing the scientific value of the reports.

5.1 Approaches to Applying Materials Wave Techniques to the Characterisation of Wood.

The most direct approach taken by many workers is to adapt a measurement technique which has been applied to characterising other materials and evaluate its efficiency. Generally such workers have some target physical property, such as the bending strength of the wood, in which they are interested. The ability of ultrasonic velocity or attenuation measurements to measure this property in comparison with some other standard or widely accepted measurement technique is then evaluated. While the theoretical background described in chapter 3 may form the basis for using ultrasound in the characterisation process, the models described in chapter 3 are not used in such studies which rather derive the validity from empirical statistical linkages of the measurements to the target property. Work of this type is described in section 5.3 ‘Empirical Relationships between Material Wave Properties and Physical Properties of Wood’.
Other workers use the models described in chapter 3 as a basis for measuring engineering constants, specifically Modulus of Elasticity. Their approach is driven by the need to arrive at evaluation techniques for direct use in the wood industry. Generally the models are considered to ensure that the measurements being performed are valid to the extent of the assumptions on which the models are based. Usually this type of study is carried out at relatively low frequency on large dimension samples, for example, so that the assumption of material homogeneity is not seriously infringed. Again large numbers of samples may be measured in this type of study to take account of the variability of the material. These studies are reviewed in section 5.4 ‘Material Wave Techniques Aimed at the Determination of Engineering Constants in Industry.’

While the work reported in this thesis is based on measurements on clear ‘flaw free’ wood, the detection of flaws such as knots, splits and rot is clearly of importance when characterising wood for engineering use. Several workers have carried out studies using ultrasonic techniques to determine the presence and location of flaws in wood. This work is considered in section 5.5 ‘Ultrasonic techniques for the detection and location of flaws in wood.

Another body of work which can be identified is that carried out on characterising the nature of the interaction of wood and ultrasound. Included in this might be work to determine the full set of elastic constants described in chapter 3, as well as work which takes into account the inhomogeneous nature of wood. This is described in section 5.6 ‘Towards the fuller characterisation of the interaction of material waves with wood.’

5.2 Early Work on the Use of Material Waves to Characterise Wood.

Some of the earliest reported work on the use of material wave techniques for the determination of wood quality is discussed by Ross and Pellerin (1994) in their review of nondestructive testing for assessing wood members in wood structures. In this article work by Bell, 1950, on the determination of Young’s modulus is reported as showing strong correlations between stress wave modulus of elasticity values obtained from time of flight measurements and the static modulus of elasticity of clear wood. Jayne, (1959), worked on small clear specimens of Sitka spruce measuring the bending strength and the modulus of rupture using a force transverse vibration technique. In
this work, Jayne showed a link between resonant frequency and modulus of rupture (MOR), as well as a link between resonant frequency and modulus of elasticity (MOE).

In an extensive piece of work, Lee (1958), reported measurements of the velocities of longitudinal ultrasonic waves in six species of wood. The species measured were two softwoods - Douglas fir and Sitka spruce - and four hardwoods - Gurjun, Iroko, Mahogany and Teak. Lee made ultrasonic velocity measurements on three 4 inch (10cm) diameter disc samples cut from the principal planes of the trunk (LR, LT and RT planes. The LR and LT discs were 2 (5cm) inches thick and the RT disc was three inches (7.5cm) thick. Lee then measured the velocity of longitudinal waves along the principal axes and at ten degree intervals between the principal axes. Lee used a through-transmission technique and a relatively low carrier frequency of 150kHz to deal with the high attenuation experienced when propagating ultrasound waves in wood. It is not clear whether a broadband or narrow band measurement technique was used.

Lee measured velocities in the range 5850m/s to 1300m/s, corresponding to a wavelength range of 4cm to ~1cm. He developed an expression for evaluating the Young's modulus at any angle in a principal plane provided that the value at 0°, 45° and 90° was known. He then used this relation and values of Young's modulus estimated from ultrasonic velocity measurements at 0°, 45° and 90° to estimate the Young’s modulus at different angles. The velocity recorded at intermediate angles was then used to generate a Young's modulus and this was compared with the estimated version obtained from the orthorhombic model. Lee found significant agreement between his theoretical values estimated from measurements made at 0°, 45° and 90° in the principal planes and the measured velocities at the intervening angles. Lee took this to represent a verification of the orthorhombic elastic behaviour of wood as described by Hearmon (1941).

Lee also observed that the moduli determined by the ultrasonic technique were generally higher than moduli determined using static test techniques. He ascribed this difference to the reduction in apparent modulus measured by the static testing procedure due to creep and moisture displacement effects in wood under stress. Work by other researchers showed evidence of a link between modulus of elasticity and bending strength (Hoyle, 1961; Pellerin 1963).
Hearmon (1965) carried out work on relating elastic constants to static test results. He presented a detailed consideration of some of the issues facing the worker interested in measuring all nine elements of the stiffness matrix. He pointed out that only six elements of the elastic matrix could be determined from ultrasonic velocity measurements carried out on the principal axis. Determination of the other three elements of the elastic stiffness matrix would require measurements of off-principal-axis velocities. Hearmon reports that such measurements have additional difficulty associated with them since off-axis modes of wave propagation are generally not pure modes and also have energy flux deviation associated with them.

Hearmon also presented slowness curves and sections of the wave surface for Spruce and Beech calculated from a computer model based on the elastic constants determined statically. He reported propagation velocities for longitudinal and shear waves along the principal axes in Beech and Spruce. It should be noted that these were calculated from the static data used to generate the slowness curves rather than measured.

In other early work Galginaitis et al. (1953) tested laminated samples using continuous waves at frequencies of 300kHz to 500kHz to locate breaks in glue lines. This early example of flaw detection in timber based products used the reduction in amplitude of the waves as the basis for locating flaws. Some problems were reported with coupling and with the interpretation of received signals.

Ultrasonic techniques are well established in the field of flaw detection in other materials and have also been applied with some success to timber. Lee (1965) reported on a study carried out on the timbers of an 18th century mansion, some of which had been affected by wet rot (fungal attack) and Death Watch Beetle. In order to establish a baseline representative samples of timber were extracted and measured using static testing techniques as well as ultrasonic velocity techniques (50kHz-250kHZ). It was possible to show using ultrasonic techniques that most damage was superficial with the timbers retaining their physical integrity. The calibration study carried out may be used to check for future deterioration at a later stage. This approach gives one possible method for overcoming the problems associated with variability in wood samples when checking in-service degradation of timber products. If each vital element is measured at the beginning of its service life then later, tests have a baseline to work from. Obviously the extra effort this entails would have to be economically justified.
After this early work in the field three significant advances had been made. Firstly the model of orthotropic symmetry had clearly been established as being relevant to wood (Lee, 1958). Secondly it was seen that a full determination of the elastic constants for wood would require a sophisticated series of off-principal-axis as well as on-axis velocity measurements (Hearmon, 1965). Thirdly it was seen that defect detection was possible using ultrasonic techniques (Galginaitis, 1953; Lee, 1965).

While the work outlined in the previous paragraphs provides an excellent basis on which to approach the challenge of applying non-destructive testing techniques to wood many challenges remained before a fuller understanding of the interaction of ultrasound and wood could be gained. These challenges include

- dealing with environmental factors such as changes in temperature or moisture content.
- taking into account the natural variability of the material.
- assessing the impact of inhomogeneity on wave transmission.
- examining the influence of frequency of wave propagation in wood.


This section presents work on measuring wood properties by material wave techniques whose validity is derived from empirical statistical relationships rather than fitting of data to predictions from a model. Several physical parameters have been studied in this way.

5.3.1 The Influence of Moisture Content on Wave Propagation in Wood.

That the strength properties of wood vary with moisture content is well established (Desch and Dinwoodie, 1996; Bodig and Jayne, 1982). This is of importance not only for the preparations of specimens prior to measurement but has implications for
coupling as indicated in chapter 4. The moisture content of a wood sample is most often defined in relation to its oven dry weight by the relation:

\[
\text{M.C. \%} = 100 \left( \frac{W_{\text{Moist}} - W_{\text{dry}}}{W_{\text{dry}}} \right)
\]

Where M.C. \% is the moisture content percentage, \( W_{\text{Moist}} \) is the weight at the moisture content under measurement and \( W_{\text{dry}} \) is the oven dry weight of the sample. Using this definition it is not unusual for moisture contents in the range 0\% to 200\% to be reported. As demonstrated by Gerhards, 1975, (Figure 5.1) the Modulus of Elasticity (MOE) determined using static techniques can be shown to vary with moisture content up to a point known as the ‘fibre saturation point’ (FSP) and to be constant thereafter (Desch and Dinwoodie, 1996; Gerhards, 1975). The mean ‘fibre saturation point’ varies from species to species but is typically in the range 20\% to 50\% moisture content.

![Figure 5.1 Effect of moisture content on static modulus of elasticity. Data points are indicated by specimen number (Gerhards, 1975).](image)

Below the FSP wood is understood to be hygroscopic, with all the water in the wood chemically bound to the hydroxyl groups in the cell walls of the wood. Increases in moisture content below the FSP are associated with swelling of the specimen and consequent changes in density and cross section. After allowing for these changes the modulus of elasticity is seen to decrease with increasing moisture content (Gerhards, 1975) as the stiffness of the cell wall decreases. Above the FSP the water in the wood is called ‘free water’ occupying the cavities in the cells of the wood. In static testing this additional moisture is not seen to have a significant effect on stiffness.
Burmester (1965) was one of the first workers to demonstrate a link between stress wave velocity and moisture content in wood. Burmester reported on the speed of longitudinal stress waves in Pine as moisture content varied from 0% to around 30% (approximate FSP). One further longitudinal stress wave velocity measurement was made under saturated conditions (around 150% for these samples). Stress wave velocity was observed to decrease from 6,000 m/s to 5,200 m/s as the moisture content increased from 0% to 30% (Figure 5.2). It decreased further to 4,500 m/s at 150% moisture content.

![Figure 5.2 Speed of Stress Waves in Longitudinal Direction in Pine. (Burmester, 1965- Note x10^5 multiplier omitted from in/s scale)](image)

Gerhards (1975) used the data given by Burmester to generate a dynamic modulus of elasticity. The stress wave velocity data was converted to a dynamic modulus using the relation:

\[ C_L = \sqrt{\frac{E}{\rho}} \]  \hspace{1cm} 5.2

where \( C_L \) is the stress wave velocity, \( E \) is the dynamic modulus of elasticity and \( \rho \) the density including the moisture content. The plotted dynamic modulus against moisture content shows a minimum at the fibre saturation point (Figure 5.3).
Gerhards concluded from figures 5.1 and 5.3 that the dynamic modulus calculated from the stress wave velocity can yield a very much higher value than the static bending modulus of elasticity. Thus the stress wave technique may overestimate the static E of incompletely dried lumber. Equally, as Gerhards points out, dry lumber (below 30% moisture content) containing wet pockets may be unnecessarily downgraded by stress wave or ultrasonic methods.

Wen and Moshenin (1970) measured the influence of moisture content on longitudinal ultrasound pulse propagation in the longitudinal direction in Yellow poplar. They made measurements for moisture content under the fibre saturation point in the range 4% to 19% moisture content. A pulse propagation frequency of 40kHz, 5μs duration pulse was used on 1inch (2.54cm) cube samples were used. A silicone grease couplant was used. Wen and Moshenin found a linear decreasing relationship between the Young’s modulus derived from pulse velocity and moisture content. Since these measurements were carried out below FSP this is in line with other workers. Velocities reported in this work are of the order of 5,000m/s to 5800m/s, which for a propagation frequency of 40kHz corresponds to wavelengths of 12.5cm to 14.5cm so it is probable bulk wave propagation was not involved. Wen and Moshenin use the rod wave relationship given in 3.75 for calculating the Young’s modulus:

\[ V_{rod} = \sqrt{\frac{E}{\rho}} \]  \hspace{1cm} 3.75
It is more likely that using a 12.5cm wavelength wave on a 2.54cm cube falls into the transition region between pure rod or plate waves and bulk waves, but since the wavespeeds are the same this may not cause any measurement problems.

In 1974 Facaoaru and Bucur demonstrated a link between moisture content and ultrasound pulse velocity in Black Poplar. Longitudinal velocity measurements were made along each of the principal axes at 100kHz on 4x6x40cm samples extracted from 11 trees. The velocity of longitudinal waves along each axis was shown to be dependent on moisture content over the range 200% moisture content to oven dry. Velocities varied between 6,000m/s and 2,500m/s in the longitudinal direction, between 2,400m/s and 1,400m/s in the radial direction and between 1,700m/s and 1,900 m/s in the tangential direction. Facaoaru and Bucur fitted an exponential model to their experimental results, although a preliminary inspection of the data produced by Facaoaru and Bucur indicates that the bi-linear model proposed by Gerhards (1975) may also fit. Resonant frequency measurements carried out on the same samples also showed correlation with moisture content. Facaoaru and Bucur suggested that the variation in velocity with moisture content could be used to monitor drying.

Sakai et al. (1990) reported on the effect of moisture content on ultrasonic velocity and attenuation in the longitudinal direction in nine species of woods including two softwoods. They used 1MHz quartz based longitudinal transducers to measure velocity and attenuation in 4 x 4 x 1 cm samples (with the 1cm dimension corresponding to the longitudinal dimension). They found a bilinear relationship between ultrasonic pulse velocity and moisture content. For moisture contents above the FSP, ultrasound velocity was seen to decrease slowly with increasing moisture content in a linear fashion. For moisture contents below the FSP, ultrasound velocity was seen to decrease rapidly with increasing moisture content in a linear fashion, similar to that measured by Gerhards, 1975.

Sakai et al. pointed out that, as moisture content increased, attenuation plots showed a change in slope slightly before the velocity plots. In the case of attenuation moisture content had little influence on signal amplitude until the FSP was reached. After the FSP a sharp increase in attenuation was observed. Sakai attributed the fact that attenuation plots change slope sooner than the velocity plots to the small amount of free water present having a much stronger influence on attenuation than on velocity.
He proposed that the free water was causing irreversible acoustic loss due to capillary action. On the other hand more free water is required before the stiffening effect of free water displacing air is observed.

Sakai also plotted elastic constants derived from velocity measurements against moisture content. The plots have the same form as those shown by Gerhards (1975), although Sakai has many more data points per sample for the region above the FSP. The curves of longitudinal modulus against moisture content plotted by Sakai show variations in absolute value from species to species as well as variations in slope from species to species.

Sakai et al. also observed greater scatter in measurements on softwoods and attributed this to their heterogeneous nature. He also postulated that this was due to interference effects but did not pursue the implications of this idea. The ‘interference’ effect he postulated would in fact only become apparent due to the integrating effect of the transducer. It presents itself as the classical ‘phase cancellation artefact’ discussed in section 4.7. The practical results of such phenomena are given some experimental attention in Chapter 8.

Sandoz, 1993, measured the influence of moisture content on pulse velocity along the longitudinal axis of 580 samples of construction timber (Spruce beams). Sandoz, working at a frequency of 50kHz, also found a bilinear relationship between ultrasonic pulse velocity and moisture content. Velocities ranged in the region 4,600m/s to 6,000 m/s for beam samples with dimensions 10cm x 14cm x 300cm. Again, Sandoz attributed the bilinear nature of his results to the removal of free water not significantly affecting the elastic nature of the material, except insofar as it acted as a stiffening agent. On the other hand removal of the bound water from the cell walls had a more profound effect on the elastic nature of the wood in the samples.

The influence of moisture content variation in wood on ultrasound longitudinal velocity has also been investigated by Mishiro (1996) and Booker et al. (1996). Mishiro investigated the influence of variation of moisture content within the samples and noted different behaviour for different species. Booker et al. carried out an extensive study on the influence of moisture content on ultrasonic velocity in Radiata Pine. Booker et al. worked on 20x20x300mm samples using 54kHz ultrasound. The study involved 26 samples taken from 4 boards. They found a similar bi-linear relationship to that found
by Sakai (1990). However the aim of the work of Booker et al. was not to discover empirical relationships but to use velocity measurements to determine the elastic constants and thereby to investigate the mechanisms by which moisture contributes to the strength of wood. This study is considered further in section 5.6.1.

The influence of moisture content on propagation in wood was also studied by Olivato (1993) who measured the velocity and amplitude of received longitudinal pulses as a function of moisture content. Olivato measured along the radial and longitudinal axes of symmetry using 54kHz pulses on 15cm cubes of Poplar. He concluded that ultrasonic pulse velocity was a viable method for assessing wood moisture content and that pulse amplitude measurement was a viable method for assessing the presence of flaws. Olivato also reported that received signal amplitude in the radial direction was affected by cracking as the timber dried. Olivato used three sets of three samples in this study. Significant scatter is not observed in his plots of velocity against moisture content. However in view of the scatter in velocity and amplitude reported by other workers there are fundamental reasons why Olivato’s proposal may not be realised in practice.

Kabir et al. (1997) carried out a series of measurements on the tropical hardwood, Rubber wood using 45kHz longitudinal waves on 2x2x2cm samples. Kabir also measured variations of velocity with grain angle and moisture content using semi-circular samples of unspecified dimensions. Again ultrasonic pulse velocity displayed a decreasing trend with increasing moisture content. The FSP is once again clearly visible, particularly for propagation along the longitudinal axis. Pu and Tang (1997) reported changes in relative humidity leading to changes in moisture content and elasticity of laminated veneer lumber, demonstrating how the properties of wood can vary in response to environmental conditions.

Simpson (1998) monitored the time of flight of longitudinal ultrasonic signals in Red oak and Hard maple during kiln drying. Simpson carried out measurements on samples of red oak whose dimensions ranged from 1 x 6 x 30 inches to 1 x 3 x 14 inches and samples of hard maple with dimensions of 1½ x 6 x 14 inches. Simpson measured five groups of samples with 4-6 samples in each group. Simpson measured in the longitudinal and tangential directions using roller probes with a reported frequency of 84kHz. It is not reported but such probes are typically narrow band in their operation.
Simpson gives plots of moisture content with velocity. This moisture content is the average moisture content of the sample and was not allowed to come to equilibrium within the samples. As such there would be significant variations of moisture content within the sample, with the outside generally drying first. The aim of the work was to see if transit time could be of assistance for monitoring the drying of wood in kilns so the procedure of not allowing samples to come to equilibrium best simulates kiln conditions. Simpson found that transit time in the longitudinal direction was sensitive to changes in moisture content above 30% moisture content and showed some potential as a feedback element for a control loop. On the other hand tangential transit time was not significantly sensitive above 30% moisture content. Simpson attributed this to the uneven drying of the sample.

In all these cases there is a clear link between moisture content and ultrasonic longitudinal pulse velocity. It is not so clear how this can be used to determine moisture content from ultrasonic pulse velocity measurements because of the scatter of ultrasonic pulse velocities and elasticities which are encountered in practice even within a species. On the other hand it could be helpful to use the relationships measured to correct subsequent measurements of ultrasonic pulse velocity for variations in the moisture content. This would need to be done on a species by species basis, but much more good quality data is needed. When it is available it can then be used to generate a calibration curve of moisture content against pulse velocity. This can then be used to correct ultrasonic measurements made at different moisture contents to a standard moisture content for comparison or grading purposes as has been demonstrated by Facaoaru and Bucur, 1974; Sandoz, 1993. Unfortunately it is difficult to compare results between workers since many species, samples sizes and propagation frequencies were used. As a rule of thumb the velocity decreases typically by about 15% from the fastest value for the region below the fibre saturation point in the longitudinal direction as moisture content increases. This corresponds to a decrease of 25m/s per % increase in moisture content for a sample with an FSP at 30%. Above the FSP the decrease in velocity with moisture content is much less marked with decreases of the order of 100m/s for changes in moisture content of the order of 100%. This corresponds to a decrease of velocity of 1m/s per 1% increase in moisture content.
It is also clear that when using ultrasonic pulse velocity and attenuation to measure factors other than moisture content in wood then these measurements should be carried out at constant humidity, since variations in humidity will lead to variations in sample moisture content. There appear to be no reports of measurements of the relationship between shear wave velocities and moisture content.

5.3.2 The Influence of Temperature on Ultrasound Velocity in Wood.

Sandoz (1993) measured the influence of temperature on the propagation of longitudinal waves in the longitudinal direction in Spruce beams using 50kHz waves. He found a linearly decreasing relation between ultrasound velocity and temperature. These measurements were made with samples held at constant moisture content. This was necessary since the temperature effect over the measurement range (-20°C to 60°C) yielded around a 10% variation in velocity compared to a 20% variation due to moisture content variations over the range 10% to 70% moisture content. The apparent decrease in elastic modulus as measured by the decrease in ultrasound velocity is reflected in static MOE and MOR values as reported by Barrett et al. (1989) when making recommendations for timber graders. Similar influences of temperature on pulse velocity are reported by Bucur (1995). Thus the order of magnitude of the effect is 0.125% per degree C and, for example, with a wave speed of 4,000m/s a one degree change of temperature would produce a change of 5m/s. As in the case of moisture content it is clear that a constant temperature regime is necessary for characterising wood using material wave measurements.

5.3.3 Other Wood Parameters Measured using Correlation Techniques.

A number of other studies measuring physical properties of wood using the propagation of ultrasound have been reported. In 1984 Polge, using 80kHz waves, reported a strong link between fibre length in Cherry Wood and longitudinal velocity in the longitudinal direction. In 1982 Bucur noted a correlation between the tangential dimension of 5mm increment cores (See section 4.5) and ultrasonic velocity. This correlation was attributed to the presence of growth stresses within the tree. The measurements were carried out using 80kHz waves on Beech samples taken from 11 trees. Bucur (1995) has also reported a relationship between annual ring width and
shear wave velocity in propagation along the tangential axis, polarised in the radial axis in Spruce.

In 1996 Mishiro reported on the relationship between density and ultrasonic longitudinal velocity in wood. Mishiro carried out measurements on 19 species of wood, including softwoods, ring porous woods and diffuse porous woods (See Fig.2.5). Between three and five samples of each species was used. The samples were described as having dimensions of ‘30mm on a side’. 2.5MHz ultrasound was used for the measurements along each of the three principal axes. Mishiro found that when the two extreme species of wood (in density terms), Balsa and Lignum Vitae, were excluded from the results there was no significant correlation between ultrasonic velocity and wood density, although there was a wide scatter of the data. Mishiro only studied between three to five samples of each species so it is quite possible that species to species variation in structure, and within species scatter of physical properties masked any underlying relationship between ultrasonic velocity and density.

Urakami and Asai (1996) measured the longitudinal velocity of ultrasound in laminated wood samples. They modelled the latewood and early wood velocity of wood by laminating samples formed of layers of ‘high speed’ wood (generally samples oriented for propagation along the longitudinal axis) and ‘low speed’ wood (mostly samples oriented for radial propagation with some tangential samples). Urakami and Asai used longitudinal, tangential and radial samples of 5 oriental species of wood. They found a good correlation between dynamic modulus as measured by ultrasound velocity and static modulus of elasticity. They correlated the velocity of their model samples to the velocity of the individual samples. They found, as might have been expected, that for samples of layers of low velocity and high velocity in series the resultant overall time of flight was equivalent to the sum of the times of flight in each layer. On the other hand for samples constructed in parallel the resultant time of flight was close to that for the faster layer.
5.4 Material Wave Techniques Aimed at the Determination of Engineering Constants in Industry.

In this section we will discuss techniques aimed at providing quality measurements in an industrial context. For the purposes of this section quality is taken to mean bending strength or breaking strength. Detection of flaws is a quality issue discussed in a later section (5.5).

Stress wave techniques have been used as a method of determining MOE since 1954 (Bell et al., 1954) when a strong correlation ($r = 0.98$) was reported by stress wave velocity and static MOE. In this paper and all those cited in this section the stress waves used were longitudinal waves. The stress wave velocity along the longitudinal axis is generally measured. Stress waves are introduced into the specimen under test by some form of repeatable impact on the end of the specimen under test. In general no account is taken of the spectral content of the stress pulse. The time of flight of the wave is then determined using a receiver and some form of time of flight measurement system. Determination of the elastic constant then requires only a knowledge of the dimensions of the specimen and its weight. Wave attenuation can also be determined from the rate of decay of the amplitude pulses, although these measurements are more problematic (Ross and Pellerin, 1994).

Stress wave velocity measurement techniques were applied to structural lumber with knots, splits and grain deviations (Galligan and Corteau, 1965). A good correlation (correlation coefficient, $r = 0.96$) was recorded between stress wave velocity and bending strength in this case. A similar relationship between stress wave velocity and strength qualities of lumber was also found by later workers Porter et al., 1972; Pellerin and Galligan, 1973; McAlister, 1976). Gerhards (1982) showed that knottiness has an influence on the strength of the relationship between the stress wave velocity and the elastic strength properties.

Jung (1982) used stress wave velocity to grade veneers before assembling parallel laminated veneer lumber. He used 5"x1/4"x8’ samples of Douglas fir and a signal from a pulsed 50kHz piezoelectric crystal to measure velocity in the longitudinal direction. Jung found that the stiffness of the lumber could be predicted from the elastic constants of the individual veneers. However the relationship between the stress wave velocity
measurements and the strength properties of the lumber was not a strong one. This was postulated to be due to the use of high quality veneers not giving a representative scatter of values. Later work on more variable material reported by Pu and Tang (1997) indicated that the MOE of laminated veneer lumber (LVL) predicted by stress wave propagation was influenced by veneer grade, with better veneers giving higher value MOE LVL. Good correlations were reported between static MOE and stress wave derived MOE.

Paschalis (1978) reported measurements of elastic constants using ultrasonic pulse velocity for 500kHz waves propagated along the longitudinal axis. Paschalis noted a correlation between the elastic modulus determined using resonance testing and the elastic modulus determined using ultrasound.

Sandoz, 1989,1993, reported on the use of velocity of ultrasound to grade timber. Sandoz’ measurements were made using longitudinal waves (propagation frequency 50kHz) along the longitudinal axis of the timber. Sample dimensions varied between 10x14x280cm to 10x22x440cm and a total of 341 specimens were used. Sandoz compared the results obtained by ultrasonic grading to those obtained by a panel of timber graders. Sandoz found that the ultrasonic technique was shown to be more reliable than visual stress grading in grading timber and more reliable than density as a measure of MOE. Sandoz evaluated the influence of knots on ultrasound propagation. He found that the samples with the highest velocity in the longitudinal direction had few knots and were of the highest bending strength. He found that low velocity could be attributed to knottiness or low quality knot free wood. This work has led to the designation of a new high strength grade for Swiss timber which is graded ultrasonically. Sandoz reported a correlation factor of \( r = 0.82 \) for velocity squared against MOE and \( r = 0.68 \) for velocity against MOR in his tests.

Halebe et al. (1995,1997) carried out work relating stress wave velocity measurements on green, (undried) wood to the corresponding dried wood. Green stress wave velocity and MOE were shown to correlate with dry static bending MOE with correlations of \( r = 0.62 \) and \( 0.78 \) respectively for a sample of 100 samples of Southern Pine lumber (50mm x 100mm x 2.4m).

In the same work Halebe et al. reported poor correlation between ultrasound velocity measured in the samples and static MOE. In both green and dry lumber (\( R^2 = 0.29 \) and
This conflicts with the findings of Sandoz (1989,1993) but may be due to the measurement technique adopted by Halebe et al. This technique, which is described as a ‘P-wave’ measuring technique, involved placing two 125kHz transducers on the same face of the plank separated by 300mm. The transducers were placed along the longitudinal axis of the plank and the transmission time of a pulse between the transducers measured. This was carried out at the two ends and the middle of the plank. As pointed out by Halebe et al. this does not test the whole material of the 2.4m plank in the same way as the stress wave technique does, so that this may account for the lack of correlation. This could be checked by measuring the variability of pulse velocity along a few samples by measuring more intensively along their length. However the lack of correlation observed between ultrasound velocity and MOE suggests that some other factors may at work as well as variability along the length of the sample. Indeed it is open to question whether the wave measured by the ‘P-wave’ technique gives a response representative of the bulk of the sample. It is quite probable that it is primarily a surface wave velocity (see section 3.2.2.1) which is being measured, which could be particularly sensitive to the surface finish of the specimen.

The interest in checking the correlation between green wood measurements and dry wood measurements is strong because it permits selection of the best material for drying purposes thus providing a potential cost saving for the timber industry. This can be taken a stage further by testing logs before their conversion to green lumber. Ross et al. (1997) reported correlations between log and lumber modulus of elasticity measured using a stress wave technique. In a study carried out on 95 Balsam-Fir and 98 Eastern Spruce logs, with moisture contents varying between 56% and 153%, the MOE of the log was found to correlate with the average MOE of lumber obtained from the log. When considering individual boards this relationship was maintained but not as strongly for each individual board obtained from the log. This may be expected as intra tree variations in wood quality would introduce an extra variable factor which would tend to reduce correlation between measurements on individual boards and stress wave measurements for the whole log (Desch and Dinwoodie, 1997; Olesen, 1977). The assessment of intra-tree variations is addressed in Chapter 7 below.
5.5 Ultrasonic Techniques for the Determination of the Presence and Location of Flaws in Wood.

As anyone who has tried to extract clear wood samples will appreciate, most large dimension wood contains flaws such as knots and twisted grain. Drying timber is often associated with the introduction of splits and shakes in timber. Rot due to fungal and bacterial attack of the timber is an ever present threat to the integrity of structural lumber. It is widely accepted that all these defects can have a serious impact on the quality of the timber as a glance at timber grading standards will quickly show (Desch and Dinwoodie, 1997; Davidson, 1987).

5.5.1 Location of Decay using Material Wave Techniques.

Stress wave techniques have been applied to locate deterioration in wood quality in situ. Several successful applications to timber structures are reported in Ross and Pellerin (1994), including location of decay in a wooden spectator stand, piers and bridges. In 1997 Klinkhachorn et al. reported successful development of a hand held ultrasonic test unit used to monitor decay in bridge timbers. The device uses velocity and attenuation measurements to localise decayed wood. Attenuation is measured using the fast Fourier transform (FFT) technique first applied to wood by Halebe et al. (1994).

Bauer et al. (1990) reported that fungal attack on pieces of timber could be detected by a decrease in velocity of both longitudinal (0.5MHz) and shear waves (1MHz). They further reported that this decrease in velocity could be detected earlier and more significantly than by other rot progress measurement techniques such as weight loss in the samples. Ross et al. used stress waves to determine the presence of ‘wetwood’. They measured transit time in the tangential direction using a standard impact hammer technique to excite the stress waves. Wetwood is bacterially infected wood prone to developing defects when dried. It is often not visible on the surface of lumber so early detection is of advantage to the timber drier. Ross found that the stress wave measurements identified infected heartwood in green Red oak lumber with an average accuracy of 84%. Ross et al. noted that the detection rate was higher with Red oak
than with White oak. They attributed this to differences in the types of bacteria infecting each species. The bacteria infecting the Red oak tended to attack the cell wall more which was more easily detected by the ultrasound.

Halebe et al. (1993) used a dry coupled ‘P-wave’ technique, described in 5.4 to locate flaws in wood. Measurements were made in the radial and tangential directions on 12 samples of Oak and 7 samples of Pine. It was not possible to discriminate between knots, rot and clear wood using radial velocity, whereas some discrimination of rotten areas and clear areas was possible using tangential velocity as a guide. The work was based on relatively small samples and significant scatter was evident in the results.

Marcok et al. (1997) used longitudinal ultrasonic waves along the longitudinal axis in wood to monitor the progress of decay due to brown rot in Spruce. They used 10mm x 10mm x 120mm samples and a 54kHz longitudinal ultrasonic pulse. Marcok et al. concluded that it was possible to detect the onset of decay at an early stage using ultrasound velocity but that this required a knowledge of the ultrasound velocity in the particular sample in its sound state.

Wooden utility poles have also been the subject of a number of studies. There is a huge quantity of these poles in use all over the world and a reliable technique which would permit extension of the service life of a pole by verification of its integrity in situ would be of enormous value. Dunlop (1981,1983) reported on acoustic techniques for the determination of rot in poles. In 1981 he used a pulse velocity technique but encountered some problems in definitely measuring significant decay. In 1983 he proposed a resonance technique for testing poles in situ. The technique consisted of driving the pole over a range of frequencies, up to 4kHz, and observing the resonance effects. The technique was compared with a visual inspection technique carried out by trained pole inspectors. The techniques classified 18 poles correctly according to the pole inspection grading and 10 poles incorrectly. This study highlights some of the problems associated with developing non-destructive evaluation techniques to replace existing techniques in that while the results appeared poor, further examination showed that the pole grading techniques had incorrectly classified some of the poles. Sandoz, 1989, observed similar occurrences when comparing lumber MOE measurements with results from a panel of timber graders (see section 5.4).
Pines, 1997, also reported a technique to measure utility pole rot damage by measuring the reflection coefficient of the buried end using stress wave techniques. He presented a theoretical model for pole behaviour which was confirmed by a study of two poles under laboratory conditions. Obviously more practical work needs to be carried out to confirm this work and to assess its utility. The literature in this area of clear commercial importance is tantalising in that while it reveals a number of promising studies, it appears to lack the definitive investigation that is needed. Again the relatively small number of reports of shear waves is an area that needs attention.

5.5.2 Location of Defects using Material Wave Techniques.

McDonald (1978) reported on using a through transmission ultrasonic velocity measurement technique to detect knots in lumber. Frequencies in the range 200kHz to 1MHz were used to determine knot location. The technique established that defect detection using ultrasound was possible. Syzmani and McDonald (1981) reviewed defect detection in lumber including optical, ultrasound, microwave, X-ray and neutron based scanning techniques. They concluded that no one technique provided sufficient performance to be applicable for industry. They reported on measurements using ultrasonic systems working at frequencies between 150kHz and 1MHz. They found the systems to be sensitive to slope of grain but not able to distinguish features such a splits, cracks and worm holes.

Schmoldt et al. (1994) investigated the possibility of inspecting the pieces that go to make wooden pallet parts using an ultrasonic technique. The aim was to provide a combined automated sorting/grading system which would permit the construction of high quality more durable pallets. Measurements were made on sixteen 52 inch x 3.25 inch x 1.75 inch boards using a through transmission technique from edge to edge of each board. Each board was measured at 2 inch intervals and 250kHz ultrasonic probes were used, coupled to the boards using petroleum jelly. The propagation direction through the board varied from radial to tangential and including angles in between, depending on how the board under test had been cut. Wide scatter in the velocity and amplitude results was observed. Clear wood was observed to exhibit ultrasound velocities at the mean level or below whereas sound and unsound knots displayed
above average velocity. Unsound knots and splits/checks and shakes had amplitudes below the mean. No information was reported on the reliability of these classifications.

In 1997 Schmoldt reported a further study aimed at flaw detection in pallet wood this time using roller probes with a range of frequencies (84kHz, 500kHz, 1MHz) to scan ‘feature rich’ areas of four sample pallet decks. Time of flight was recorded for each sample point. The 84kHz transducers produced more statistically significant differences in time of flight between clear areas and knotty areas than the other frequencies and provide the basis for further study.

In 1994 Halebe et al reported ultrasonic measurements using time and frequency domain analysis for non-destructive analysis of wood. Velocity was measured using a standard time of flight technique but ‘attenuation’ was measured by integrating the area under the FFT amplitude curve of the received pulse signal. Halebe reported that the area under the FFT curve was more sensitive to the presence of knots and rot than the amplitude of the received signal. Measurements were made in the tangential and radial directions. Halebe (1995, 1997) reported an extension of this technique to determine ‘attenuation’ by plotting the area under the FFT curve versus distance using a regression line obtained from experimental data. Scatter was evident in the results indicating that a larger scale study would be necessary before definite conclusions could be drawn.

Han, 1992, reported on an ultrasonic system for scanning Scots’ pine logs. Han used three approaches to ultrasonic measurements. Firstly a 750kHz air borne ultrasound system was used in pulse echo mode to determine the shape of the log. Secondly a 125kHz water coupled tone burst system was used for through-transmission measurements in the radial direction. Thirdly a ‘grain sound tracing’ approach was adopted. This involved using a 125kHz toneburst injected at the end of the log. The sides of the log were then scanned and signals picked up at points where knots had provided a path along the grain for the sound to travel. Han used an artificial approach to combine the measurements to permit classification of defects by received signal. He reported some success although the system does not appear to have been commercialised.

Han 1997 has also reported on log quality evaluation by lengthwise material wave measurements, although this time with an ultrasonic technique rather than a stress wave.
technique. He used three Scots pine logs and three Norway spruce logs for this study. Han employed 54kHz transducers applied to the ends of logs up to 4m long and measured longitudinal velocity along the longitudinal axis. Han divided the ends of the trunk into 8 sectors and measured the velocity from top to bottom of the trunk at the centre of each sector. Han assumed that low quality would be indicated by a longer transmission time as the wave would travel longer to pass round a knot or through non-straight grain. The logs were cut up after measurement and the features noted. Han obtained a correlation of $r = 0.7$ between ultrasonically detected flawed or low quality wood and manually observed flawed or low quality wood.

Fuller et al. (1995) demonstrated the utility of ultrasonic techniques for detecting honeycomb and surface checks in Red oak lumber. Honeycomb and surface checks are drying defects which may pass unnoticed before conversion of the lumber into high quality products. The technique used 84kHz roller probes in a through transmission arrangement and so is adaptable for use in an industrial environment. Anderson et al. (1997) have evaluated the financial case for applying this technique in industry and indicate that it has the potential to give an economic return.

Beall (1989) and Biemacki and Beall (1993, 1996) have reported development of 'acousto-ultrasonic techniques' for the nondestructive evaluation of wood and wood laminates. The techniques use ultrasound in that there is a source and receiving transducer but they are not necessarily aligned. In addition measurement parameters are obtained by processing the whole of the received signal waveform. Thus the parameters measured are aimed at detecting such quantities as the total received energy rather than the time of flight or the amplitude of the received signal. In some senses this analysis technique can be compared to the area under the FFT curve measurements carried out by Halebe et al. (1995,1997) mentioned earlier in this section. Biernacki and Beall (1993,1996) found that the system could measure adhesive bond curing and detect the presence of non-adhesive or 'kissing' bonds if the acousto-ultrasonic technique was used during the clamping and unclamping processes of glued laminated timber (glulam) formation. Tiitta et al. (1998) reported on an 'acousto-ultrasonic' through-transmission technique for evaluating brown rot decay in Douglas fir glulam (glued laminated) beams. The samples used were 125 x 460 x 640 mm in dimension and contained knots, splits and growth ring angle variations. A narrow-band 175kHz
transmitter probe was used and a wideband 175kHz receiver was used. A silicone rubber disc was used between the probe and the samples as a coupling agent. Decayed specimens were indicated by substantial decreases in received signal of up to two orders of magnitude. The frequency domain showed loss of high frequency content.

Tiittaa et al also examined the effect of growth ring angle variations and moisture content variations on 'acousto-ultrasonic' parameters. They found received signal energy to be most affected by growth ring angle but transit time to be least affected by growth ring angle. Tiittaa et al. found both frequency and time parameters to be affected by moisture content variation. The 'acousto-ultrasonic' parameter measured appear to be based on the experience of the workers rather than on any specific model of propagation for wood. Thus the relationships obtained appear to be specific to the experiments carried out.

5.6 Towards the Fuller Characterisation of the Interaction of Material Waves with Wood.

A great deal of the work in the previous sections is aimed at providing techniques for direct use in the wood engineering industry. Thus the focus is on using the simple techniques, such as stress wave velocity measurement, which is an index of the primary parameter of interest to the wood industry, strength. It can also be easily deployed for field measurements. In this section techniques are reviewed which aim to provide a more complete characterisation of wood and its elastic properties. These techniques tend to be more laboratory bound, analysis based, techniques which may be viewed as providing the basis for understanding the limits and potential for the future development of material wave techniques to the area of wood characterisation.

5.6.1 Elastic Constants of Wood using Ultrasonic Pulse Velocity Measurement.

Bucur (1983) cites Savart in 1810 as the first to put forward the idea that wood can be considered to have three mutually perpendicular planes of elastic symmetry. As described in chapter 2 this model leads to the results that a samples of wood can completely characterised elastically by measuring nine independent elastic moduli.
As detailed in section 5.2, Lee, 1958, reported one of the first sets of elastic constants determined by acoustic velocity measurements for wood in the form of Young’s moduli measured over a range of angles. Lee made measurements with longitudinal transducers at 150kHz which permits determination of the first three terms of the diagonal matrix only. Lee found a good fit between models describing the variation of velocity with angle and actual measurements of velocity made over a range of angles.

Musgrave, 1970, reported slowness surfaces for Spruce and Oak which vividly outlined the anisotropic nature of wood. No experimental data or conditions were reported and it appears that the slowness surfaces may have been constructed using a computational model with statically determined constants as the input. Musgrave cautioned that softwoods such as Spruce display such a degree of anisotropy that distinctions between quasi-shear and quasi-longitudinal waves may become meaningless for material waves propagating along certain off-axis propagation directions.

Bucur (1981) reported measurements of the three stiffness moduli and three shear moduli determined using ultrasonic pulse velocity measurements. This study was carried out on samples taken from nine dominant Beech trees. Bucur carried out measurements using 80kHz waves on 36 samples of 5mm diameter increment cores as well as thirty six 20x20x300mm samples of clear wood extracted from adjacent points in the stem. The aim of this study was to determine if ultrasonic measurements on increment core samples could be used to assess the elastic quality of the wood of a tree. Since increment core samples can be extracted from a tree without compromising its viability such measurements offer the possibility of determining the quality of standing trees.

The velocity-derived stiffness measurements carried out on the increment core samples generally correlated with the measurements carried out on the cube samples although significant scatter was evident from the plots given. The stiffness moduli measurements derived from increment core velocities were shown to have some correlation with static test results except in the radial direction.

Measurements were carried out at 80kHz and 2MHz for longitudinal waves. Shear wave measurements were carried out at 1MHz. Longitudinal wave velocity was seen to increase significantly between 80kHz and 2MHz for propagation in the longitudinal direction. For the radial and tangential directions longitudinal wave velocity was seen
to drop significantly with increasing frequency. Bucur attributed this drop to the wavelength becoming similar to the dimensions of the anatomical elements in the wood. It is interesting that no correlation was found between velocity measured in increment cores in the radial direction at two different frequencies, 80kHz and 2MHz. Indeed the correlation coefficient, $r^2 = 0.474$, determined for the correlation between longitudinal velocity in the longitudinal direction at 80kHz and longitudinal velocity in the longitudinal direction at 2MHz, while statistically significant is not as high as one might expect. Also the correlation coefficient, $r^2 = 0.40$, determined for the correlation between longitudinal velocity in the tangential direction at 80kHz and the longitudinal velocity in the tangential direction at 2MHz seems quite low, though once again statistically significant.

According to Bucur, possible explanations for the low correlations might be scatter in the results due to difficulty in aligning such small samples as increment cores. The fact that no correlation was found for the radial direction may be attributed to the influence of the inhomogeneity presented by the annual rings encountered in this direction. It is also doubtful what type of wave is travelling in 5mm samples when 80kHz waves or indeed 2MHz waves with velocities between 1000m/s and 5000m/s are used. Indeed in this work Bucur demonstrated a dependence of velocity on sample size when making measurements on a samples which is reduced in dimension after each measurement. Bucur also noted that it can be difficult to identify correctly the onset of the appropriate pulse, particularly for shear wave measurements.

Bucur and Archer (1984) made the first reported measurement of the complete stiffness matrix for six species of wood (Douglas-fir, Spruce, Pine, Beech, Oak and Yellow poplar). Measurements were carried out at 0.5MHz and 1MHz for longitudinal waves and shear waves, respectively. The samples used were 16mm cubes of clear wood. The cubes were extracted aligned along the principal axes as well as at angles of 15°, 30°, 45° to the main symmetry axes. This permitted measurement of off-axis velocities in order to compute the off-diagonal terms of the stiffness matrix (see table 3.2).

Problems were reported with this procedure, for example using velocities obtained from quasi-longitudinal waves lead to some constants having imaginary values. Bucur and Archer reported that when inverting the stiffness matrix to obtain the compliance
matrix for most conifers the matrix was close to being singular. An optimisation procedure was adopted to give physically sensible values of the technical constants. The implications of measuring at two different frequencies perhaps need to be explored further. This would require a study of dispersion in the frequency range. When analysing their results Bucur and Archer indicated that the diagonal terms would have accuracies of the order of 3-4% whereas for the off diagonal terms of the stiffness matrix would the accuracy would be of the order of 4-20%. This is because of an accumulation of errors through the calculation procedure since calculation of the off-diagonal terms of the stiffness matrix required prior knowledge of the diagonal terms of the stiffness matrix.

Bucur and Archer also compared experimentally derived slownesses to theoretical slowness curves for Beech and Douglas fir. The theoretical slowness curves were generated from the stiffness matrix which had been derived from the velocity and density measurements. The experimental values were generally of the correct order and followed the approximate shape of the theoretical slowness curve although significant deviations can be seen for off axis measurements particularly in the TR plane of Beech and the LT plane of Douglas fir.

In 1987 Bucur and Rocaboy proposed using surface waves to determine the off diagonal terms of the stiffness matrix. Using a mode conversion technique to generate surface waves Bucur and Rocaboy reported reasonable agreement between off diagonal terms of the stiffness matrix measured using surface waves and off-axis terms measured using bulk waves and specially prepared samples. The surface wave technique has the advantage of not requiring off axis samples to be prepared. The surface wave measurements were carried out on 600x180x90mm samples of Beech and Spruce. The surface waves were excited by placing a 1MHz compression probe on an appropriate edge of the block which had been machined to give a 45° contact surface.

In 1987 Sinclair and Farshad reported the results of a small study (5 samples, cut from a single block of Douglas fir) comparing ultrasonic, resonance and static techniques for determining elastic constants of wood. In one of few comments by workers on the alignment of the grain in their samples Sinclair and Farshad report that the samples were aligned along the main symmetry axes to within ±4° for 95% of the surface of the sample. The shear waves were generate by normal incidence shear wave probes with a
central frequency of 1MHz. The longitudinal waves were generated with 250kHz probes. A question arises as to whether one can treat results obtained from two different frequencies as giving the same elastic constants. Clearly a study of dispersion in the frequency range of interest is justified.

Specimen sizes used ranged from dimensions of 20cm (L) by 6cm (R) by 5.5cm (T) to 6cm by 3cm by 2.4cm. Given the experience of other workers, the propagation frequencies used and sample dimensions, using samples of different dimensions may well have had a bearing on the results obtained. Sinclair and Farshad reported difficulties in determining the location and onset of various shear waves. Difficulties were also reported in comparing constants obtained from RT shear waves to those obtained TR shear waves which, from the assumptions of the orthotropic model would be expected to give the same result. Otherwise the study was too small and limited for significant conclusions to be drawn.

Bucur and Chivers (1991) reported on acoustic properties and anisotropy of 12 Australian wood species (11 hardwoods and one softwood). Three samples of each species were used of dimensions 6 x 20 x 125 mm. Measurements were carried out using longitudinal and shear waves at 1MHz. Moisture content was reported to be 10% for all samples. Bucur and Chivers reported elastic constants for the diagonal terms of the stiffness matrix. They also plotted longitudinal wave velocity in the longitudinal direction against density reporting a correlation of $r = -0.647$ and shear wave velocity for a shear wave propagating in the longitudinal direction polarised in the radial direction reporting a correlation of $-0.595$. Both these correlations were reported to be statistically significant at the 5% level and showed significant scatter. It is not perhaps surprising to observe significant scatter when comparing between species since wood of different species is really a collection of materials of similar structure rather than a single structure. Indeed chapter 10 of this work examines the possibility that it is possible to identify the species through which a signal has propagated from an examination of the signal using neural networks techniques. Thus even though two samples might have similar velocities and amplitudes associated with them the received signals still retain information which can be related to the different structures of the wood through which they have propagated.
Gorbatsevich, 1990, reported a technique for determining the type of symmetry and elastic constants of anisotropic media. Based on an instrument called an acousto-polariscope which measures the amplitude of 0.5MHz polarised shear waves after passing through the sample, Gorbatsevich reported measurements on a specimen of 'ordinary wood' which demonstrated the anisotropy of the sample. He reported that the amplitude of the vibrations perpendicular to the fibres was 5 times smaller than the amplitude of the vibration parallel to the fibres.

In section 5.3.1 work relating moisture content to variations in velocity was considered. While most of this work was aimed at establishing an empirical relationship several workers were interested in taking this further in order to understand the influence of moisture content on the elastic stiffness moduli of wood as derived from ultrasonic velocity measurements. These elements of their work are treated in the next few paragraphs.

Sakai (1990) reported that moisture above the fibre saturation point (FSP) has an apparent stiffening effect on the longitudinal modulus. It should be pointed out that this apparent stiffening is in fact due to the contribution of free water in the cells rather than any intrinsic stiffening of the wood itself. High moisture contents in practice degrade the elastic moduli of wood and special tables have been constructed to take this into account (Bodig and Jayne, 1982; Desch and Dinwoodie, 1996). Sandoz, 1993 also observed this effect which it is important to understand lest a specimen with high moisture content be attributed high elastic coefficients.

Booker et al., 1996, studied the influence of moisture content on the velocity and stiffness moduli in Radiata Pine along the three principal directions. They showed that 60% of the variation in elastic modulus with moisture content below the FSP can be attributed to shrinkage/ swelling of the specimen cross-section. Booker et al. proposed an adaptation of the Biot theory of propagation in a porous medium which assumed no relative motion of the cell walls and the water in the cell luminae.

Third order elastic coefficients are important guides to the behaviour of a material under stress (Murnaghan, 1951; Einspruch and Manning 1964). Potentially measurements of ultrasonic velocity can give the stress state of a material (Green, 1973). Bucur (1979, 1983) demonstrated the influence of increasing load on longitudinal velocities in the three principal axes in wood. Bucur measured 2x2x30cm samples of Spruce and Maple using 50kHz waves. In each case Bucur observed four regimes: in the initial regime velocity increased slightly, this was followed by a plateau of constant velocity, next there was a small decrease in velocity and then a sharp decrease in velocity.

Bucur (1979, 1983) also measured the response of velocity to load over time and noted that the change in velocity stabilised approximately 10 days after application of a load. Bucur attributed at least some of the improvement in the quality of sound from violins with age to this effect. She also reported a link between annual ring size and velocity in the longitudinal direction, with velocity decreasing with increasing annual ring size. The number of samples used in these studies is not reported.

Peterson et al. (1997) carried out an investigation of higher order elastic coefficients in timber. Their aim was to assess timber used to construct railroad bridges. Peterson et al., using 500kHz roller probes, observed changes in longitudinal velocity in the laboratory and in situ when the timber elements were stressed but did not observe any correlation between ultimate compressive strength and stress wave speed. The laboratory study was based on ten 12’x4”x4” samples of Douglas fir.

Peterson et al. attributed the lack of an observed correlation between stress wave speed and compressive strength partly to the cross-correlation techniques used to determine the time of flight which they took to measure a different quantity that either pulse onset measurement or peak measurement. In the case of pulse onset Peterson et al. reason that this effectively measures a combination of time of flight and attenuation. On the other hand dispersion may cause difficulties for identification of the received peaks.
Sasaki et al. (1997) have also measured the effect of compressive stress on the velocity of 0.5MHz longitudinal waves in wood, measured using the sing around technique. Sasaki et al (1997) reported changes in velocity similar to those reported by Bucur (1979) but over a wider range of samples and species. Sasaki et al report that the sensitivity of ultrasound velocity in wood to applied stress is greater than that observed in metals.

5.6.3. Ultrasonic Attenuation Measurements in Wood.

As noted in chapter 4 reliable measurements of ultrasound attenuation in wood are more difficult to achieve than measurements of velocity. Variability in the material and in coupling to the material all contribute to the greater scatter of ultrasonic attenuation measurements. On the other hand attenuation has been shown to have the potential to give information on anisotropy (Bucur and Feeney, 1992), flaws (Halebe et al., 1997; Biernacki and Beall, 1996) and on the onset of the fibre saturation point when moisture content varies (Sakai et al., 1990). Some of these workers quote figures in terms of reduction of relative amplitude rather than attenuation units.

Okyere and Cousin (1980) quoted figures for radial and longitudinal attenuation at three frequencies in four species. In general an increase in attenuation with frequency was observed, with Spruce and Pine (softwoods) displaying more attenuation than Beech and Oak (hardwoods).

Bucur and Feeney (1991,1992) reported measurements of attenuation of both longitudinal and shear waves over a range of five frequencies (between 100kHz and 1.5MHz) and different angles of propagation using a toneburst technique. The attenuation was shown to be frequency dependent with some anomalies in the relative attenuation of shear waves. This work is treated in more detail in chapter 5 of this thesis, and probably represents the most systematic study reported to date.

Bucur and Bohnke (1994) report some attenuation measurements deduced from frequency domain measurements obtained using broadband pulses and a spectrum analyser. They investigated the variation in peak frequency with length of specimen and found, as might be expected, that high frequencies were not transmitted along the longer specimens. The specimens used were cylindrical samples of beech with 20mm
diameter and lengths ranging from 50mm to 200mm as well as 20mm cubes. The ultrasonic transducers used were 14mm diameter 5MHz transducers and 1MHz 14mm diameter transducers. Bucur and Bonhke reported measurements for Maple, Spruce, Beech, Douglas and Poplar with the most extensive results reported for Maple and Spruce. Some of the spectra published by Bucur and Bonhke show periodic dips which they postulate may be due to resonance of fibres and may permit measurement of fibre length. However, as dealt with in Chapter 4, the periodic dips observed are more likely due to the presence of two modes of propagation in the received signal which overlap in the time domain. Clearly this would have some impact on the reported accuracy of the measurements.

Sakai (1990) reported the use of attenuation measurements to determine FSP under conditions of changing moisture content. Sakai attributed greater scatter observed in measurements in softwoods to their greater inhomogeneity. He postulated that interference effects arise from slow waves travelling in earlywood in parallel with faster waves travelling in latewood when propagating in the longitudinal direction.

5.6.4 Developments of other Ultrasonic Measurements and Measurement Techniques for Wood.

In this section a number of works are considered which consider some of the problems associated with making measurements in wood are addressed.

Bucur and Perrin, 1989, published a technical note showing how an ultrasonic technique could be used to make slope of grain measurements in living trees and timber. The measurements were made using 80kHz stress waves and were predicated on finding the direction of maximum longitudinal velocity in the longitudinal direction.

Berndt and Johnson, 1995, reported briefly on wave propagation in wood from a microstructural perspective. They used a pulse echo system in a water tank to examine reflections from the annual ring interface in wood. By progressively planing their sample they were able to show the influence of removing an annual ring from their sample. Berndt and Johnson also reported frequency domain based attenuation measurements and postulated the possibility that the quasi-periodic layered structure of wood could give rise to acoustic stop bands.
5.7 Summary

It is clear that material wave measurement techniques have the potential to be useful tools for the wood industry both as non-destructive evaluation techniques and as tools for gaining a greater understanding of the nature of timber. Overall the main successes in terms of applications of ultrasound or material waves to timber has been the use of stress waves to grade samples for laminated veneer lumber (Ross and Pellerin, 1994). Sandoz (1989, 1993) has pioneered the introduction of ultrasonic stress grading in Switzerland but this has not been widely accepted in the general market.

As detailed in section 5.4 stress and ultrasound wave measurements have been successfully applied in industry to problems of measurement of the bending strength of logs and lumber. Some degree of success has been reported for the detection of flaws such as rot, knots and splits and other flaws using velocity and attenuation measurement techniques (section 5.5).

In many of these cases a direct and simple measurement approach has been taken to a problem. Some success has been reported but the measurement system has failed to find general application. This may be due to several factors. Firstly the reported work is often specific to the particular experimental set-up used. That is to say that frequencies and sample sizes are employed which make it difficult to determine exactly what mode of propagation is used and to extract material effects from experimental effects. Secondly no account is generally taken of the inhomogeneity of the material save for an assumption that it is not of consequence for frequencies of around 100kHz-200kHz. Thirdly the variation of acoustic properties within a tree and at a microstructural level has received little attention.

It will become clear that the main contributions of the novel experimental work described in the following chapters has concentrated on the scientific problems concerned with fundamental interactions between ultrasonic waves and the internal structure of wood.
6. MEASUREMENT OF VELOCITY AND ATTENUATION IN WOOD SAMPLES.

6.1 Introduction

As discussed in Chapters 1 and 5 the velocity and attenuation of ultrasound in a material are well established potential descriptors of the physical nature of a material. In the case of wood significant work has been carried out using ultrasonic pulse velocity to evaluate the Young’s modulus in the longitudinal direction, $E_L$ (Sandoz, 1989, Green 1992, Ross et al. 1996). The elastic anisotropy and angular variation of Young’s moduli of wood has been studied (Lee, 1958). Some work also discusses the measurements of the full nine elastic constants required to characterise fully a sample of wood elastically (Bucur and Archer, 1984; Bucur, 1987; Sinclair and Farshad, 1987). While some success has been reported in velocity measurements some lacunae remain, one of which is an assessment of the role of frequency of propagation in making measurements. Relatively little attention has also been paid to the measurement of attenuation in wood although some work is reported (Okyere and Cousin, 1980, Bucur and Bohnke, 1991).

In this chapter of the thesis a series of velocity and attenuation measurements carried out on samples of three different species of wood is presented. The measurements were carried out using a tone-burst technique which may be taken as an approximation to a single frequency measurement technique. Measurements were carried out at 5 frequencies in the range 100kHz to 1.5MHz.

6.2 Selection and Preparation of Samples.

The purpose of this set of measurements was to study the influence of propagation frequency on ultrasound propagation in different types of wood as well as to examine the variation of attenuation with frequency and propagation angle. The three species examined were Horse chestnut, Maple and Norway spruce. Horse chestnut is a ring porous hardwood, Maple is a diffuse porous hardwood and Norway spruce is a softwood. Figures 2.5(a)-(c) shows micrographs of an RT cross-section of each type of
wood. These samples and species were chosen as reasonably standard representatives of each type of wood (Bucur, 1991; Gnaggs, 1997).

Horse chestnut (Aesculus hippocastanum) is a ring porous hardwood. In general it has uniform straight grained wood (Desch and Dinwoodie, 7th edition, 1996). The ring porous structure has a ring of large diameter vessels at the beginning of each annual ring. Typical dimensions of these vessels are of the order of 200-300µm (Bodig and Jayne, 1982). It is generally less stiff than Maple.

The Maple (Acer saccharum) wood used is a diffuse porous hardwood which typically has small vessels (20µm to 30µm) distributed throughout the annual ring (Desch and Dinwoodie, 6th edition, 1982). The wood is generally uniform and straight grained.

Norway spruce (Picea abies) is a softwood with significant density variations in its annual rings (Olesen, 1977; Harvald and Olesen, 1987). The transition between earlywood and latewood at the end of the growing season is a sudden one with a pronounced density step. As with all softwoods a pronounced density step is also experienced at the start of the following growing year between the latewood and the earlywood (Bodig and Jayne, 1982). The diameter of the tracheids in such a species is typically of the order of 20-60µm.

The particular species were selected as the different microstructures of each species might be expected to have a different influence on attenuation and possibly dispersion with increasing frequency. Horse chestnut, with its rings of large vessels (200-300µm) might be expected to scatter ultrasound strongly with increasing frequency. Maple with its diffuse porous structure and small vessels (20-30µm) has a more uniform structure and might be expected to scatter less strongly with increasing frequency. The tracheids diameters in Norway spruce are of the order of 20-60µm and so might be expected to attenuate ultrasound less than Horse chestnut, provided one ignores the influence of annual rings.

Each set of samples used in these experiments was taken from a single piece of straight grained mature wood which had narrow uniform annual rings. For each species a set of three disc like samples were prepared for measurement, using a high speed tungsten tipped spindle saw. These disks has a diameter of 35mm and a thickness of 20mm. The major flat surfaces of the disk were aligned along the planes of symmetry within the
Thus there were Longitudinal-Radial (LR), Longitudinal-Tangential (LT) and Radial-Tangential (RT) sample discs for each tree. The edges of the discs were made flat to permit measurements at 15° intervals. The flat edges measured 20mm by 9mm. A typical sample is shown in Figure 6.1 below.

Figure 6.1 Outline Of 35mm Discs Used In Velocity And Attenuation Measurements.

The sample dimension was chosen so that measurements would be carried out over a consistent piece of wood. The elastic properties of the wood within a tree varies significantly depending on where within the tree the wood is selected from (Bodig and Jayne, 1982). Indeed in Chapter 6 of this work the extent of this variation in terms of ultrasound velocity is reported. A number of samples were required to access a reasonable selection of the wide range of propagation modes observed within wood (Bucur and Archer, 1984). Thus it was necessary to use three small samples obtained from within a small area of one tree. Small samples were also necessary since ultrasound is severely attenuated in some propagation directions.

The samples are quite small and, particularly compared to the wavelength of some of the waves passing through them. This may be a problem for the lower frequency longitudinal wave measurements along the longitudinal axis where the usual minimum
constraint of using a wavelength an order of magnitude smaller than the sample is only satisfied at frequencies of 1MHz and higher. Ideally this could be overcome by using a larger sample size however two factors militate against this. Firstly use of a larger sample would preclude measurements along those directions where attenuation is greatest. Secondly wood is a naturally occurring material with curvature inherent in its structure. It is extremely difficult to produce large samples with perfect alignment of the grain throughout the sample over large distances. Since velocity measurements are extremely sensitive to grain alignment this necessitates the use of well aligned samples. Consideration of the results obtained indicates that the 100kHz results in particular should be treated with caution. While they agree qualitatively with the anisotropy displayed at higher frequencies these readings were not used when considering dispersion (see sections 6.7 and 6.13).

Only three disc samples were used for each species (one for each orientation with respect to the principal axes of the timber). For each sample, measurements were made at each angle for three waves (a longitudinal wave and two polarisations of transverse waves). The particular advantage of the shape of specimen used is that the geometry of the specimen is essentially the same for each of the waves measured (although variations in the wavespeeds effectively scale the dimensions). However for each measurement the specimen had to be hand mounted and adjusted. Since the three discs for the three species alone involved over 1000 measurements it was decided at the outset not to use a number of samples for each species. Evertsen (1986) suggests that it is necessary to have at least 7-8 specimens to obtain a sample representative of one group of trees. This would have increased the time taken for this part of the work by almost an order of magnitude. Since it was the first study of its kind in the literature it was felt better to obtain a single comprehensive set of results and analyse them with a view to constructing hypotheses for more extensive and specific testing in future work.

6.3 Ultrasonic Velocity and Attenuation Measurement Techniques.

Velocity and received signal amplitudes were measured using a direct contact through-transmission technique. Both longitudinal and shear wave measurements were carried out. Broadband Panametrics probes were used for measurements. Longitudinal wave 1MHz (V103) probes (nominal diameter 20mm) were used to excite longitudinal
waves. Normal incidence shear wave probes 1MHz (V153) (nominal diameter 20mm) were used for the shear wave measurements.

For the longitudinal wave measurements a 5mm thick plastic buffer plate (larger than the transducer element size) was attached to the transmitting transducer while the receiver was coupled with a piece of cellophane (approx. 0.02mm thick). In both cases a layer of vaseline was next to the transducer face. A similar arrangement was used for the shear wave measurements. In both cases a constant pressure was applied to the transducers using a specially designed clamp.

An outline diagram of the measurement arrangement is given below (figure 6.2). The transmitting probe was excited using a four cycle sinusoidal tone burst generated by a Schlumberger 4432 pulse generator. Measurements were made at 100kHz, 250kHz, 500kHz, 1000kHz and 1500kHz, with the received signal measurements carried out on a Schlumberger 5220 oscilloscope. This oscilloscope had a manually positioned cursor with a digital readout in the time domain. Time delay measurements were made by marking the position of the first peak of the tone burst with the cursor. This permitted phase velocity and attenuation measurements to be made at each frequency. Velocity was calculated simply by dividing the distance the pulse travelled within the sample by the time delay experienced by the pulse in the sample.

Attenuation was calculated using the ratio of the received signal amplitude with the transducers in contact to the received signal amplitude with the sample in place in the relation:

\[ A = 20 \log \left( \frac{V_{\text{sample}}}{V_{\text{no\_sample}}} \right) \quad 6.1 \]

where d is the geometric path length covered by the ultrasound in cm. The received signal amplitude was taken to be the amplitude of the first positive going peak in the pulse measured on an analogue oscilloscope. The relation 6.1 gives attenuation figures in dB/cm. As discussed in chapter 4 this technique for attenuation evaluation may not yield absolute values of attenuation but is reproducible and should give a good indication of the variation of attenuation within and between samples of clear wood.
6.4 Preliminary Considerations for Velocity Measurements.

6.4.1 Presentation of Results and Nomenclature.

The large amount of data produced by the measurements cannot be summarized by conventional (statistical) data reduction techniques since each measurement is unique. The velocity measurements form the bulk of the data. For convenience of visual interpretation they have been plotted as angular plots of velocity and as slowness curves (see section 3.2.1) with frequency as a parameter. This permits dispersion within and between species to be assessed rapidly.

As mentioned in section 6.2 the orientation of each disc within the tree was identified by two letters indicating the principal plane within which it lay, i.e. LR, LT, or RT. The angular axes of the displays which follow in this chapter have been constructed so that 0° corresponds to the axis indicated by the first letter and 90° corresponds to the axis indicated by the second letter. Thus for an LR disc, 0° is along the longitudinal axis of the wood and 90° is along the radial axis of the wood. In practice measurements were only taken at the seven angles representing 15° steps between 0° and 90°. The curves have been shown as 360° by assuming symmetry simply for ease of visual appreciation.
6.4.2 Experimental Error in Velocity Determinations

The velocities reported in this chapter were calculated from the transit time of the pulse in the sample and the thickness of the sample. The thickness of the sample, \( d \), was measured directly using vernier callipers for each orientation. The transit time in the sample, \( t_s \), was calculated from the difference in the transit time with a 5mm piece of plastic between the probes (the zero time, \( t_z \)) and the transit time with the sample and the 5mm piece of plastic between the probes (the total time, \( t_t \)).

The error in the thickness determination was ±0.01mm, which given a nominal sample dimension of 35mm equates to an error of less than 0.03%. The transit times of the pulse were measured using a peak location technique with the aid of a cursor which had a digital read out with a stated accuracy of ±0.05μs. Thus the total uncertainty for transit time measurements was ±0.01μs. Transit times ranged between 6.5μs for longitudinal waves in the longitudinal direction to 68μs for some shear waves in the RT plane. The 6.5μs transit time gives an uncertainty in percentage terms of 0.15%. Rounding up the total measurement errors should be less than 0.2%, or 10m/s for a velocity of 5000m/s.

Repeatability of measurements was raised as an issue in section 4.5 in relation to waves coupling problems. A repeatability study carried out at 500kHz using longitudinal on the Maple RT disc.

The results obtained are shown in table 6.1. below. Repeatability is best for the on-axis measurements with a standard deviation of less than 1%. For the off-axis measurements the repeatability degrades to a standard deviation of around 2.5%.

<table>
<thead>
<tr>
<th>Radial</th>
<th>Tangential</th>
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<tbody>
<tr>
<td>( 0^\circ )</td>
<td>( 15^\circ )</td>
</tr>
<tr>
<td>Run 1</td>
<td>1847</td>
</tr>
<tr>
<td>Run 2</td>
<td>1846</td>
</tr>
<tr>
<td>Run 3</td>
<td>missed</td>
</tr>
<tr>
<td>Run 4</td>
<td>1840</td>
</tr>
<tr>
<td>Average</td>
<td>1844</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>4.018</td>
</tr>
</tbody>
</table>

Table 6.1 Results of repeatability study on measured longitudinal velocity for RT maple disc.
In addition to the information gained from the above study, the method of taking the measurements provided additional information on the reproducibility of the measurements. For longitudinal wave propagation results from each pair of the three specimens of a particular species contain two sets of data for propagation along one of the principal axes. In addition to the intrinsic precision of the measurement techniques, and the reproducibility of measurements on the same specimen discussed above, these data also include the possible effects of variation between samples of the same species. The data collected on this variation is discussed after the measured velocities are presented in the following sections. They are particularly relevant in relation to the question of velocity dispersion discussed in section 6.7.

6.4.3 The Influence of Sample Dimensions on the Mode of Wave Measured for The Velocity Results.

In section 4.4 it was pointed out that for bulk wave propagation one requires a sample whose dimensions are of the order of 5 times the wavelength of the wave being measured. Waves propagating in samples whose dimensions are too small to fit this criterion but whose dimensions are too large for rod or plate wave propagation (section 3.2.2) propagate with a transitional form to either bulk or plate waves. This transitional form tends to have a lower velocity than the bulk wave velocity. In this section some of the velocities reported in the main results sections are extracted and the form of wave likely to have propagated is discussed.

The velocities in the longitudinal direction range between 3200m/s to 4450m/s at a propagation frequency of 100kHz over the three species (Appendix 1). This corresponds to wavelengths of the order of 3-4.5cm which given, that the samples are 3.5cm discs, corresponds to non-pure bulk wave propagation as dealt with in section 4.4. These velocities are slower than would have been measured if pure bulk wave propagation had been involved. Again at propagation frequencies of 250kHz velocities recorded are in the range 3650m/s to 4800m/s corresponding to wavelengths of 1.5cm-2cm. Thus there are approximately 2-3 wavelengths within the sample dimension, still short of the five wavelengths requirement (Read and Dean, 1978).
In the radial direction the velocities are between 1,600m/s for Spruce and 2000m/s for Chestnut, corresponding to wavelengths of 1.5-2cm, similar to those observed for the 250kHz frequency in the longitudinal direction and close to the bulk wave propagation requirement of 5 wavelengths in the sample.

Thus at 100kHz as one moves from considering propagation in the longitudinal direction to propagation in the radial direction, it can be seen that the wavelength decreases from a wavelength which is around the same size as the sample to a wavelength which is 2-3 times smaller than the sample. Thus propagation in the longitudinal direction is likely to be more retarded by the small dimensions of the sample than propagation in the radial direction. This would result in slowness and velocity plots which show apparently lower LR anisotropy at 100kHz than at higher frequencies. Thus the apparently lower anisotropy observed at 100kHz could be, at least in part, an artefact of the sample dimension chosen.

The major effect of sample dimension on propagation is seen for the 100kHz waves in the longitudinal direction. For radial waves at 100kHz or longitudinal waves at 250kHz the wavelength is not far from that required for bulk wave propagation, and for frequencies above this the waves measured may be assumed to be bulk waves.

6.5 Longitudinal Wave Velocity and Slowness Curves

6.5.1 Longitudinal Wave Velocity in the LR discs

Shown below in figure 6.3 are velocity and slowness curves for ultrasound propagation in the LR disk for the Horse chestnut, Maple and Norway spruce samples. A number of observations may be made. Firstly, for all species, \( V_{LL} \), the longitudinal velocity in the longitudinal direction is generally more than twice as fast as \( V_{RR} \), the longitudinal velocity in the radial direction, confirming the anisotropic nature of the material discussed in chapter 2. Secondly dispersion is observed in both radial and longitudinal directions with velocity increasing with frequency in all cases. However some of the 'dispersion' observed in the longitudinal direction may be an artefact caused by the
choice of sample size as discussed in section 6.4.3 above. This is discussed further in
the next paragraph. Thirdly $V_{ll}$ exhibits a stronger frequency dependence than $V_{rr}$.

In comparing the results, illustrated in figure 6.3 and recorded in Appendix 1, between
species it is clear that propagation in Norway spruce becomes increasingly difficult as
the radial direction is approached, with no signal at all being detected at 1MHz and
1.5MHz for slightly off radial axis propagation. This can be contrasted with Horse
chestnut which has larger internal vessels but for which a signal is always received.
Norway spruce is a softwood with pronounced density steps observed at the annual
ring boundaries (Kucera, 1994). As the radial direction is approached it appears that
attenuation due to interaction with the density steps presented by the annual rings
appears to increase. This is consistent with the qualitative observation of Berndt and
Johnson (1995). This possibility is investigated further in Chapters 7 and 8.

The Maple velocity and slowness curves present a lower anisotropy than the Horse
chestnut curves. This is in agreement with the observation that Maple is reported as a
more uniform and homogeneous wood than either Horse chestnut or Norway spruce.

Longitudinal velocity in Horse chestnut increases from 4288m/s at 500kHz to 5013m/s
at 1.5MHz whereas longitudinal velocity in Maple varies between 4270m/s and
4478m/s and longitudinal velocity in Norway spruce varies between 5330 and 5400m/s.
Horse chestnut appears to display more dispersion of the longitudinal waves travelling
in the longitudinal direction than either Maple or Norway spruce. This may be due to
its ring porous nature and larger vessels causing scattering of the wave.

In the radial direction in Maple radial velocity is almost constant at around 1850m/s
whereas the Horse chestnut and Norway spruce samples both show an increase in
velocity with frequency of the order of 12-15%. Maple has a uniform annual ring
structure whereas Horse chestnut has a ring of pores at the beginning of the annual ring
and Norway spruce has annual rings with large variations in density and density steps
within them. Thus there are structures present in both Horse chestnut and Norway
spruce to which the observed dispersion can be attributed.

The experimentally determined slowness curves illustrated here have the same form as
those reported by Hearmon (1965) and Musgrave (1970). The slowness curves
reported by Hearmon and Musgrave were computed from on-axis stiffness data
obtained from static tests and not actually measured. The slight 'pinching' of the curve at the longitudinal axis for Horse chestnut (figure 6.3(a)) and Norway spruce (figure 6.3(c)) differs from the model data reported. The model data (Hearmon, 1965; Musgrave, 1970) follows the form of the Maple sample (figure 6.3(b)). The 'pinching' observed is actually a reduction in slowness or increase in velocity for the on-axis and 15° measurements. It is very possible that the curve looks pinched because the stiffening effect of fibre alignment comes into play strongly in the last two measurements rather than gradually with angle. The models of Hearmon and Musgrave would ignore these microstructural considerations.

Bucur and Archer (1984) report experimentally determined slowness curves which also appear to show a small 'pinching effect' at the longitudinal axis. Bucur and Archer used a range of longitudinal and shear wave measurements at different propagation angles to determine the full elastic stiffness matrix (Section 3.2.1). From this they generated a set of model slowness curves, which have a similar form to those generated by Hearmon (1965). It should be noted that the measurements reported by Bucur and Archer were made at 0.5MHz and 1MHz, which for typical longitudinal bulk wave velocities of the order of 5,000m/s would correspond to wavelengths of 10mm to 5mm. Thus the sample dimensions (916mm cubes) can be expected to have played a role in underestimating the experimentally determined anisotropy and indeed the elastic constants reported. Clearly the 1MHz measurements represent a closer approximation to bulk wave propagation.
Figure 6.3 Plot of Slowness and Velocity Curves for LR Discs.
6.5.2 Longitudinal Wave Velocity in the LT Discs

Shown below in figure 6.4 are velocity and slowness curves for ultrasound propagation in the LT disk of the Horse chestnut, Maple and Norway spruce samples. A number of observations may be made. Firstly $V_L$, the longitudinal velocity in the longitudinal direction is generally more than twice as fast as $V_T$, the longitudinal velocity in the tangential direction. Secondly dispersion is observed in the longitudinal, but not to a significant degree in the tangential direction.

The same caution as applied in section 6.5.1 to the type of wave propagating in the longitudinal direction at 100kHz applies here. Again the effect is an underestimation of the anisotropy of the specimens when examining the 100kHz plots. Similarly the dispersion in the longitudinal direction is most significant for the Horse chestnut sample.

Comparing between species, it is clear that propagation in Norway spruce becomes increasingly difficult as the tangential direction is approached. The Maple velocity and slowness curves again present a lower anisotropy than the Horse chestnut or Norway spruce curves. This again concurs with the reported uniformity of Maple as a wood.

There is no apparent trend in the variation in velocity in the tangential direction with frequency for both Horse chestnut and Maple. It is not possible to comment on dispersion for Norway spruce as above 100kHz no signals were received above the noise level. This is discussed further in section 6.10 where attenuation in this sample is considered.

Comparing these results to those reported by Bucur and Archer (Hearmon did not report results for the LT plane), it is clear, once again that the faster axis, the longitudinal axis in this case, has a ‘pinched’ form in the slowness curve for both Horse chestnut (above 100kHz) and Norway spruce. Again the results for Maple follow the model more closely.
Figure 6.4 Plot of Slowness and Velocity Curves for LT Discs.
6.5.3 Longitudinal Wave Velocity in the RT Discs

Shown below in figure 6.5 are velocity and slowness curves for ultrasound propagation in the RT disk of the Horse chestnut, Maple and Norway spruce samples. A number of observations may be made. Firstly $V_{rr}$, the longitudinal velocity in the radial direction is generally higher than $V_{tt}$, the longitudinal velocity in the tangential direction. Secondly dispersion is apparent in the radial, but is not apparent in the tangential direction. Thirdly, a greater anisotropy as expressed by the ratio of $V_{rr}/V_{tt}$ is observed in Horse chestnut than in Maple or Norway spruce. Indeed in the case of Maple the degree of R-T anisotropy is very small.

Dispersion is again observed for propagation in the radial direction for Horse chestnut as the velocity at 250kHz was measured to be 2049m/s increasing until 2188m/s at 1.5MHz. Dispersion was not observed in the radial direction for Maple where the velocity remained around 2330m/s from 250kHz to 1.5MHz. Dispersion was observed in Norway spruce in the change in velocity from 1920m/s at 250 kHz to 2060m/s at 1.5MHz.

In the tangential direction dispersion is not significant in the tangential direction for Horse chestnut and Maple. Again in the tangential direction it was not possible to obtain sufficient results to make a comment. As the tangential propagation direction in Norway spruce is approached at frequencies of 500kHz and higher, the signal level decreases below the noise level, indicating an high attenuation.

The slowness curves presented here are similar in form to those presented by Hearmon (1965) and Bucur and Archer (1984). Again the Maple curve follows the theoretical form most closely with the Chestnut and Spruce models showing the a minor 'pinching' on the radial axis.
Figure 6.5 Plot of Slowness and Velocity Curves for RT Discs.
6.6. Shear Wave Velocity and Slowness Curves

In this section results describing the variation of shear wave velocity with frequency and propagation direction are presented. In each disk the polarisation measured is that in which the plane of vibration concurs with the plane of the disk. Thus in the LR disk at 0° the normal incidence shear wave probes were set to excite a wave propagating in the longitudinal direction, polarised in the radial direction, whereas at 90° the wave excited propagated in the radial direction and was polarised in the longitudinal direction.

6.6.1 Shear Wave Velocity in the LR Discs

Shown in Figure 6.6 are velocity and slowness curves for shear wave propagation in the LR disks in each of the three species. The velocities recorded in this section are in the range 1350m/s to 1450m/s for on-axis propagation at 100kHz, corresponding to wavelengths in the range 1.4-1.5cm. Wavelengths for higher frequencies are 2-10 times shorter than these wavelengths. Thus the sample dimensions should only have a small effect at 100kHz and a negligible one for higher frequencies in terms of bulk wave propagation.

In general higher velocity is observed for the quasi-shear waves propagating off axis than for the waves propagating on axis. Except for the 100kHz curve a minimum in off-axis velocity is observed at the 45° measurement between the L and R axes for all species.

Waves propagating in the longitudinal direction in Norway spruce, polarised in the radial direction display a faster velocity at 1MHz and 1.5MHz (∼1800m/s) compared to the velocity at lower frequencies (∼1370m/s). This is not observed for the RL wave. It is not clear whether this is a real effect linked to the fact that in the LR wave the vibration of the waves is interacting with the annual rings or merely a measurement error.
According to the symmetry considerations outlined in section 3.2, $c_{LR} = c_{RL}$. Thus from section 3.3 a shear wave propagating in the longitudinal direction, polarised in the radial direction should have the same velocity as a shear wave propagating in the radial direction, polarised in the longitudinal direction. Consideration of the velocity and slowness curves for each species shows that this supposition generally holds through with variation between $V_{RL}$ and $V_{LR}$ being within the limits of error.

Comparing the results obtained from this study with those reported by Bucur and Archer, the overall form of the curves are similar.
Figure 6.6 Plot of Shear Wave Slowness and Velocity Curves for LR Discs. A,B: Horse chestnut. C,D: Maple. E,F: Norway spruce.
6.6.2 Shear Wave Velocity in the LT Discs

Shown below in figure 6.7 are velocity and slowness curves for shear wave propagation in the LT disks in each of the three species. Wavelengths at the 100kHz frequency are of the order of 1cm-1.3cm which is close to the criterion for bulk wave propagation with frequencies above this comfortably fulfilling the wavelength criterion for bulk wave propagation.

The velocity and slowness curves displayed by the Maple sample show uniform velocity regardless of propagation angle, with a dip in velocity at 45° for the 100kHz reading only. The 100kHz curve in Maple displays consistently lower velocity than the other frequencies which are constant with frequency. The pattern in general is a confirmation of the uniformity of the elastic properties and structure of maple as observed in the longitudinal wave measurements.

The LT Horse chestnut curve displays more variability with maximum velocity observed off axis. The velocity curve is also significantly more variable. This may be attributed to the interaction of the shear waves with the ring of large vessels in earlywood present in Horse chestnut.

The Norway spruce curve is significantly more anisotropic with a maximum velocity observed at 60° and a minimum observed at 45°. Again it is possible to attribute this behaviour to an interaction between the annual rings and the waves as the direction of propagation and polarisation varies.

According to the symmetry considerations outlined in section 3.2 $c_{LT} = c_{TL}$. Thus from section 3.3 a shear wave propagating in the longitudinal direction, polarised in the tangential direction should have the same velocity as a shear wave propagating in the tangential direction, polarised in the longitudinal direction.

Consideration of the velocity and slowness curves for each species does not show that this supposition necessarily holds. In general $V_{LT}$ is observed to be larger than $V_{TL}$, with the difference most pronounced at 1.5MHz. This is particularly true of Norway spruce where the $V_{LT}$ is 1330m/s and $V_{TL}$ is 1210m/s (for Horse chestnut $V_{LT}$ is 1250m/s and $V_{TL}$ is 1190m/s and for Maple $V_{LT}$ is 1450m/s and $V_{TL}$ is 1370m/s), with
all measurements quoted measured at 1.5MHz. These differences appear to be outside the (conservative) error estimates of ±2.5% from section 6.4.2, but only just!

The overall form of the LT curves for Maple is uniform for frequencies above 100kHz. When the slowness curves reported here are compared with the theoretical slowness curves reported by Bucur and Archer (1984) the Maple curve fits best. The experimental velocities reported by Bucur and Archer show a fair degree of divergence between the theoretical curves and the experimental results. The Horse chestnut and Norway spruce curves display a peak in slowness at the 45° propagation angle.
Figure 6.7 Plot of Shear Wave Slowness and Velocity Curves for LT Discs. A,B: Horse chestnut. C,D: Maple. E,F: Norway spruce.
6.6.3. Shear Wave Velocity in the RT Discs

Shown in figure 6.8 are velocity and slowness curves for shear wave propagation in the RT disks for each of the three species. Velocities range from 1200m/s in Norway spruce to 500m/s in Horse chestnut, indicating wavelengths in the range of 1.2cm to 0.5cm at the 100kHz propagation frequency.

Once again, the velocity and slowness curves displayed by the Maple sample show uniform velocity regardless of propagation angle. The 100kHz curve displays slightly lower velocity than the other frequencies.

The picture in the Horse chestnut sample is not so simple. Velocity is highest at the 60° propagation angle. A lower velocity is measured at the 100khz frequency than at the other propagation frequencies. The signal level decreases below the noise level for the on axis RT wave at 1MHz and 1.5MHz respectively in Horse chestnut, indicating an high attenuation. In these samples waves initially (0°) propagate in the radial direction and are polarised in the radial direction. At the 90° angle propagation is in the tangential direction, polarisation in the radial direction. It is possible that the maximum in velocity observed at 45° (800m/s compared to about 600m/s for on-axis measurements) can be attributed to the ring porous nature of this wood but a mechanism for this is not clear.

In Norway spruce for propagation at 1MHz and 1.5MHz the signal level disappeared into the noise. Indeed only the 100kHz signal was transmitted at the 60° propagation angle.

According to the symmetry considerations outlined in section 3.2 \( c_{RT} = c_{TR} \). Thus from section 3.3 a shear wave propagating in the radial direction, polarised in the tangential direction should have the same velocity as a shear wave propagating in the tangential direction, polarised in the radial direction. Consideration of the velocity and slowness curves for each species shows that this supposition holds, though with variation between \( V_{RT} \) and \( V_{TR} \) generally within the limits of error for Maple and Horse chestnut. Measurements for Norway spruce show significant differences between the TR and the RT velocity for 100kHz and 250kHz with the RT wave faster than the TR wave. The difference diminishes at 500kHz and no measurements were possible at higher frequencies. Sliker (1988) used a compression technique and strain gages to measure
RR, TT, RT and TR strains in hardwoods and softwoods. Sliker reported that for hardwoods the $S_{TR} = S_{RT}$ model fitted well but that softwoods deviated somewhat from this behaviour.

The RT slowness curve observed for Horse chestnut is similar in form to that suggested by Hearmon (1965) and Musgrave (1970) for an anisotropic wood such as Spruce. Norway spruce might be expected to display a similar curve but it was not possible to make reliable measurements for Norway spruce for most of the RT plane. Bucur and Archer (1984) have also reported slowness curves for Beech and Fir. The Horse chestnut measurements are similar in form to the theoretical model proposed by Bucur and Archer for Douglas fir at 0.5MHz, although Bucur and Archer’s results do not fit this model very well. Douglas fir is a softwood and as such would be highly anisotropic. Horse chestnut has displayed significant anisotropy in the previous sections so it is not surprising that its slowness curves follow those of the Douglas fir.

The Maple results presented here follow the form of those presented for Beech by Bucur and Archer and are in keeping with the uniform structure of Beech. The Norway spruce results are incomplete except for the 100kHz frequency. When making these measurements, in particular, it was extremely difficult to identify the correct signal for measurement purposes as the signals were very small and often several candidate signals presented themselves. Clearly the annual ring structure disrupted the wavefront at higher frequencies making identification of the received signal difficult.
Figure 6.8 Plot of Shear Wave Slowness and Velocity Curves for RT Discs.
6.7 Velocity Dispersion in the Specimens

In view of the potential uncertainty as to the exact modes of the waves being propagated and detected at angles not aligned with the principal axes of the timber attention will be restricted to consideration only of the data from Appendix 1 for waves propagating along the principal axes. In the tables in Appendix 1 this means waves at 0° and 90°.

The assessment of velocity dispersion has to be made in the light of the uncertainties that are associated with the measurements. In addition to the data from the reproducibility experiment reported in section 6.4.2 above, the procedure for taking the measurements effectively duplicated those of longitudinal wave velocities along the three principal axes for each of the three species. The percentage differences observed in these measurements are tabulated in table 6.2. There is a general trend for the figures for Maple to be higher than those for Horse chestnut, with Norway spruce clearly being more variable than both of these.

These data (extracted from Appendix 1) are plotted in figures 6.9 to 6.11 for the LL, RR and TT waves respectively. Bearing in mind that, for the reasons given in section 6.4.3, the results at 100kHz may be less reliable, there is clear evidence of velocity dispersion for longitudinal waves in Horse chestnut propagating along each of the three principal axes. The data for Maple is uncertain. It would suggest that the dispersion above 500kHz is very low but in all cases the data point at 250kHz appears to be significantly lower than this 'high frequency' level. This may be an indication of dispersion in this frequency range or could possibly be an artefact of the specimen dimensions. This would require further investigation to elucidate the situation. A similar result is found for propagation along the longitudinal axis in Norway spruce. However along the radial direction there is a suggestion that the two specimens show similar slopes of dispersion but at different magnitudes of velocity. No data was available for Norway spruce along the tangential axis.

Analysis of the data for shear wave propagation from Appendix 1 was limited to shear waves propagating along the principal axes. Since there were no direct measurements of reproducibility an arbitrary threshold of a 3% change was used, based on the figures
in section 6.4.2. Only the data at 250kHz and above was considered. If the velocity increased monotonically from 250kHz to 1500kHz and the change was greater than 6% it was considered that there was evidence of dispersion. If the increase lay between 3% and 6% it was considered that dispersion was possibly present, and if the change was less than 3% it was felt unlikely that there was sufficient dispersion to be detected. A summary of these classifications is given in table 6.3.

Only two sets of data give evidence of dispersion. LT waves in Maple and RT waves in Norway spruce. Possible dispersion of LR waves was observed in all three species, otherwise there appears to be no obvious pattern to the results.

However the fact that some species can clearly show velocity dispersion has a clear implication for experimental work, namely that the measurements made (Bucur, 1981) of longitudinal wavespeeds at one frequency (80kHz and 2MHz) and shear wavespeeds at another (1MHz), even if on the same samples, should not be combined to attempt to derive elastic constants.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
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<tbody>
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<td>Axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horse</td>
<td>L</td>
<td>8.4</td>
<td>1.0</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>chestnut</td>
<td>R</td>
<td>1.2</td>
<td>2.0</td>
<td>2.2</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>T</td>
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<td>0.5</td>
<td>0.3</td>
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</tr>
<tr>
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<td>L</td>
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<td>5.9</td>
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<tr>
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<td>5.3</td>
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<tr>
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<td>9.6</td>
<td>10.7</td>
<td>6.6</td>
</tr>
<tr>
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<tr>
<td></td>
<td>T</td>
<td>8.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.2 Percentage Differences Of Longitudinal Wave Measurements Propagating Along The Principal Axes.
Figure 6.9 Longitudinal Wavespeed v Propagation Frequency in the Longitudinal Direction for (A) Horse chestnut, (B) Maple and (C) Norway spruce.
Figure 6.10 Longitudinal Wavespeed v Propagation Frequency in the Radial Direction for (A) Horse chestnut, (B) Maple and (C) Norway spruce.
Figure 6.11 Longitudinal Wavespeed v Propagation Frequency in the Tangential Direction for (A) Horse chestnut, and (B) Maple.

<table>
<thead>
<tr>
<th>Wave Polarisation</th>
<th>Longitudinal</th>
<th>Shear</th>
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</thead>
<tbody>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
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<td>-</td>
</tr>
<tr>
<td>R</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>T</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Maple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>R</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>T</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Norway spruce</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>T</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 6.3 Summary of evidence of dispersion of different waves propagating along the principal axes between 250kHz and 1.5MHz.

Key: ✓ = Clear; (✓) = Possible; X = Unlikely.
6.8 Calculation Of Elastic Constants

It is clear that with the extensive set of velocity measurements reported here, it would be possible in principle to determine a full set of elastic constants for each of the species as discussed in section 3.2.2. The evidence of dispersion in some of the velocity measurements identified in the previous section indicates that this would need to be done for each of the five frequencies at which measurements were made.

While calculation of the constants on the diagonal of the matrix (Table 3.1) are relatively straightforward to calculate, the off-diagonal terms can present serious problems. As a result, probably, of the mixed mode propagation that occurs in off-axis propagation, the values for the velocities measured are not those assumed by the theoretical model. Thus it is common for imaginary values (which have no physical meaning) to be derived by the conventional analysis. Bucur and Archer (1984) were forced to use an optimisation technique in their analysis, which gives the values determined the character of best estimates rather than directly measured quantities. In view of this it was not clear that at the present time, the effort involved in calculating these estimates was worthwhile.

Nevertheless, in case, it should prove to be a valuable exercise at some stage in the future, then all the relevant data that is needed is to be found in appendix 1 with the exception of values for the densities of the samples. These are given in Table 6.4 below (Bucur, 1992).

<table>
<thead>
<tr>
<th>Species</th>
<th>Horse chestnut</th>
<th>Maple</th>
<th>Norway spruce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>510</td>
<td>700</td>
<td>485</td>
</tr>
</tbody>
</table>

Table 6.4 Densities of Specimens used for Velocity and Attenuation Measurements.
6.9 Preliminary Considerations for Attenuation Measurements.

6.9.1 Presentation of Results.

In the following section the values for attenuation obtained are plotted against propagation angle for the various propagation frequencies used. First the attenuation of longitudinal waves is considered in the three species. Then the attenuation of transverse or shear waves is considered.

6.9.2 Experimental Errors in Attenuation Measurements.

Measurements were carried out using an analogue oscilloscope with a digital cursor read out for time. Amplitude was read using the graticule of the oscilloscope. Reading accuracy was of the order of 0.1mV. Some of the signals received were very weak and of the order of 1mV in amplitude. For these readings the error in amplitude measurement would be of the order of 50%. Amplitudes up to 70mV were recorded, which would be measured to a precision of 0.15%. Clearly the precision of the voltage amplitude measurement is dependent on the amplitude of the measurement.

Taking some of the RT shear waves measurements in Horse chestnut as an example, a received amplitude of 0.1V corresponded to an attenuation figure of 28.3dB/cm whereas a received amplitude of 0.2V corresponded to an attenuation result of 26.6dB/cm. On the other hand a received amplitude of 14mV corresponded to an attenuation measurement of 16.0dB/cm, as did a received amplitude measurement of 14.5mV. Thus for measurements greater than 25dB the precision is of the order of 1dB whereas as the amplitude increases to 14mV the precision is around 0.05dB.

A repeatability study was also carried out using the same RT Maple measurements reported in table 6.1. The results obtained are given in table 6.5 below.
<table>
<thead>
<tr>
<th>Trial</th>
<th>Longitudinal</th>
<th>Propagation Angle</th>
<th>Tangential</th>
</tr>
</thead>
<tbody>
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<td>2.438</td>
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<td>2.125</td>
</tr>
<tr>
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<td>3.25</td>
<td>2.938</td>
</tr>
<tr>
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<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.063</td>
<td>2.438</td>
</tr>
<tr>
<td>Run 4</td>
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<td>2.25</td>
<td>1.75</td>
</tr>
<tr>
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<tr>
<td></td>
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</tr>
</tbody>
</table>

**Table 6.5:** Repeatability study carried out to determine the repeatability of received signal amplitude in volts.

There does not appear to be any systematic variation with angle. A standard deviation of the order of 15% (corresponding to ±1.4dB) is evidenced where 4 readings were recorded. Since the distance traversed by the waves was always 3.5cm, this corresponds to an uncertainty of approximately ±0.4dB/cm.

As was mentioned in section 6.4.2, the procedure for taking measurements incorporated a duplication of measurements of longitudinal wave attenuation along the principal axes. Any variation observed between the two nominally identical measurements includes the effects of variations between different specimens of the same piece of timber. These variations are discussed in section 6.12.

### 6.10 Longitudinal Wave Attenuation Results.

#### 6.10.1 Attenuation of Longitudinal Waves in LR Disks.

Shown below (figure 6.12) is a plot of attenuation against propagation angle for the LR disk for each of the three species measured. Attenuation of the LL wave appears to

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1 These measurements were carried out at 500kHz. At 1MHz and 1.5MHz the uncertainty may be greater, approaching 5dB/cm.
be slightly lower than attenuation of the RR wave. In general attenuation increases with frequency, except for the off-axis 100kHz signals in Horse chestnut.

For Horse chestnut, on-axis attenuation appears to be slightly lower than off-axis attenuation. This may be due to an interaction between the large ring of earlywood vessels and the off-axis waves which would encounter these vessels at an angle.

The Maple plot shows a flatter response with propagation angle than the other two species. This may be attributed to the uniform structure of maple, which displayed the least anisotropy in the velocity measurements.

For the 1.5MHz signal in the radial direction in Norway spruce the signal levels disappear into the noise. Tracheids in Norway spruce are typically of the order of 20-30μm in diameter. Radial velocities of the order of 2,000 m/s correspond to wavelengths of 1.3mm at a 1.5MHz frequency, which is more than an order of magnitude greater than the reported tracheid dimensions. Normally an assumption of homogeneity is considered to be valid if the inhomogeneities present in a medium are an order of magnitude less than the wavelength of the wave propagating. Indeed if it was scattering inhomogeneity that was dominating attenuation one might expect Horse chestnut with its ring porous structures to display more attenuation than Norway spruce. Clearly another explanation must be sought for the severe attenuation displayed for the radial direction in Norway spruce.

The annual ring structure of Norway spruce is proposed as the source of the excess attenuation observed here. Annual ring widths can vary between 1mm and 10mm and are of the right dimension to be considered an inhomogeneity for waves in the range 500kHz to 1.5MHz. The inhomogeneity of wood caused by annual rings and its potential influence on ultrasound propagation in wood is considered in Chapters 8 and 9.
Figure 6.12 Attenuation of Longitudinal Waves in LR discs.
6.10.2 Attenuation of Longitudinal Waves in LT Disks.

Shown below (figure 6.13) is a plot of attenuation against propagation angle for the LT disk for each of the three species measured. An increasing trend of attenuation with frequency is observed in all cases.

Horse chestnut displays increasing attenuation as propagation direction moves from longitudinal to tangential, indicating a possible scattering role for the earlywood vessels at the wave propagates across them.

The Maple sample displays a fairly flat response with propagation angle, again in line with its reported uniform structure.

Norway spruce also displays an increasing trend in attenuation as propagation moves from the longitudinal axis to the tangential axis. The received signal disappears into the noise for all but the 100kHz signal in the tangential direction. This may be due to the annual ring structure in the form of a phase cancellation artefact as some parts of the wave move through earlywood and some through latewood.
Figure 6.13 Attenuation of Longitudinal Waves in LT discs.
6.10.3 Attenuation of Longitudinal Waves in RT Disks.

Shown below (figure 6.14) is a plot of attenuation against propagation angle for the RT disk for each of the three species measured. Attenuation is severe and fairly constant with propagation angle in these specimens. In general there is an increasing trend between frequency and attenuation although there are some exceptions to this.

In Horse chestnut attenuation is lowest for the RR wave and uniform for all angles after this.

In Maple the attenuation appears to be uniform with angle.

Again, no signal was received high frequencies in Norway spruce in the tangential direction. This is similar to what was observed in the LT disk and again a phase cancellation artefact may be responsible.

Signals are received for a full range of frequencies in the radial direction in Norway spruce. This is not as was observed for the LR disk, where a radial signal was not received for 1.5MHz.
Figure 6.14 Attenuation of Longitudinal Waves in RT discs.
6.11 Shear Wave Attenuation Results

6.11.1 Attenuation of Shear Waves in LR Disks.

Shown below (figure 6.15) is a plot of attenuation of shear waves against propagation angle for the LR disk for each of the three species measured. In these measurements the 0° angle corresponds to a shear wave propagating in the L direction polarised in the R axis, whereas the 90° measurement corresponds to a wave propagating in the radial direction, polarised in the longitudinal axis.

The Horse chestnut sample displays significantly higher attenuation than the other two species. Attenuation also falls for the RL wave compared to the LR wave in Horse chestnut, whereas it is fairly constant with propagation angle for the other two species.

In Horse chestnut attenuation of the LR shear wave is greater than attenuation of the RL wave. For the LR wave the vibration is polarised in the radial direction and interacts with the vessels of the ring porous structure of Horse chestnut. Propagation of the RL wave involves vibrations in the longitudinal direction.

For pure longitudinal vibrations less attenuation was observed for waves vibrating in the longitudinal direction in Horse chestnut than for waves vibrating in the radial direction. It appears that this is also true here with the mode which has its vibration in the longitudinal direction suffering less scattering than the mode with its vibrations across the earlywood vessel structure.

On the other hand in Norway spruce, attenuation of the LR shear wave is less than attenuation of the RL wave, a feature not apparent in the longitudinal wave attenuation along the longitudinal and radial axes of symmetry. The higher attenuation when propagating in the radial direction may be attributable to the density step encountered in this species at the annual ring boundaries (see Chapters 8 and 9).
Figure 6.15 Attenuation of Shear Waves in LR discs.
6.11.2 Attenuation of Shear Waves in LT Disks.

Shown below (figure 6.16) is a plot of shear wave attenuation against propagation angle for the LT disk for each of the three species measured. The 0° measurement corresponds to a wave propagating in the longitudinal direction, polarised in the tangential direction, while the 90° angle corresponds to a wave propagating in the tangential direction, polarised in the longitudinal direction.

In Horse chestnut and Maple the LT attenuation is higher than the TL attenuation, with Horse chestnut displaying a greater drop with frequency. As in the case of the LR and RL waves we may postulate that the lower attenuation displayed by the mode vibrating in the longitudinal direction may be attributed to the interaction with the ring porous structure.

Norway spruce displays a flatter response with propagation angle with a slight maximum of attenuation at propagation angles around 45°. Attenuation of the LT shear waves in Norway spruce is significantly lower than in the other two species.
Figure 6.16 Attenuation of Shear Waves in LT discs.
6.11.3 Attenuation of Shear Waves in RT Disks.

Shown below (Figure 6.17) is a plot of shear wave attenuation against propagation angle for the RT disk for each of the three species measured. The 0° measurement corresponds to a wave propagating in the radial direction, polarised in the tangential direction, while the 90° angle corresponds to a wave propagating in the tangential direction, polarised in the radial direction.

In Horse chestnut attenuation of the RT shear wave is less than attenuation of the TR wave. Propagation of the TR wave requires particle motion in the radial direction, while propagation of the RT wave requires particle motion in the tangential direction. If we then consider the attenuation of pure radial waves in Horse chestnut we can see that is was much less than the attenuation of pure longitudinal waves observed in the tangential direction. This has been attributed to the better alignment of cells (Kahle and Woodhouse, 1994) along the radial axis which appears to cause less attenuation of radial motion than tangential motion.

The Maple sample displays little difference in the attenuation of either wave, this may be attributable to the uniformity of the species in the RT plane.

Propagation in the Norway spruce Sample is severely attenuated for off axis propagation except at 100kHz. In contrast Norway spruce attenuation of the RT shear wave is less than attenuation of the TR wave, a feature not apparent in the longitudinal wave attenuation along the tangential and radial axes of symmetry. Again it is proposed that motion in the radial direction in this species is hampered by the large density steps at the annual ring interfaces.
Figure 6.17 Attenuation of Shear Waves in RT discs. 
6.12 General Remarks on the Attenuation Measurements.

In addition to the detailed remarks on the individual results given above, some general observations can be made. Firstly attenuation can be seen to increase significantly with frequency in nearly all cases. Secondly shear wave attenuation appears to be less than longitudinal wave attenuation.

On a species to species basis Norway spruce is clearly the most attenuative species in general. In many cases there is no detectable received signal for Norway spruce. For longitudinal wave propagation in the longitudinal direction Norway spruce is not the most attenuative species, that role being taken by Maple.

Indeed the measurements in Maple show it to be highly attenuative for all directions. Yet there are relatively few occasions when it was not possible to identify and measure the received signal. Also there is relatively little variation in attenuation with propagation angle and mode observed for Maple. This may explained by the diffuse porous structure of Maple with small vessels evenly distributed throughout the ring. It also displays more uniform elastic structure than the other two species measured, as indicated by the range of velocities measured.

The results for Horse chestnut show a much greater range of variation with propagation angle than for Maple. This may be attributed to the extra anisotropy introduced by the ring porous structure of Horse chestnut.

A comparison of the data in Appendix 1 permits us to assess the variation of the attenuation for longitudinal waves along the principal axes using two different specimens. This is summarised in table 6.6. It can be seen that the results for Horse chestnut lie near or just above the uncertainty limits established in section 6.9.2 (i.e of the order of 0.4dB/cm), while those for propagation along the longitudinal axis in maple are significantly higher. The differences tend to increase slightly (up to 3.5dB/cm) for the radial and tangential directions in both Horse chestnut and Maple. However in Norway spruce, where data is available, the lowest difference recorded is 3.4dB/cm and the highest is 6.8dB/cm. There is no apparent reason to suppose that the marked systematic variation from species to species is caused by coupling problems.
(although there may be a small contribution to this as discussed in section 4.2.6). Nor would this systematic variation appear to follow a trend in the attenuation levels being measured, since a glance at Appendix 1 reveals that the values recorded for the three species are all very similar.

It may be that the greater scatter observed for the two sets of Norway spruce readings can be attributed to a form of phase cancellation artefact as the early wood and latewood in Norway spruce are two distinct regions compared to the more uniform nature of Maple and Horse chestnut.

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<tr>
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<td>1.1</td>
<td>0.7</td>
<td>1.0</td>
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</tr>
<tr>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 6.6 Difference (dB/cm) Between Longitudinal Attenuation Measurements taken on Two Samples for Propagation Along the Principal Axes.

6.13 Frequency Dependence of Attenuation

6.13.1 Introduction.

In considering the extent to which the measurement results give evidence of frequency dependence of the attenuation, two factors need to borne in mind. In the first place, the cautionary remarks in section 6.4.3 about the specimen size causing the lowest frequency (100kHz) waves to propagate in a way which does not strictly conform to the bulk waves assumed by the analysis are also potentially relevant to attenuation measurements. Thus less weight should be attached to these results.

Secondly consideration has to be given as to the appropriate uncertainties to attribute to each measurement. While this latter task can not be done with any rigour at the
present time, the level of uncertainty may be taken to be somewhere between the values obtained in the reproducibility of section 6.9.2 and the typical figures presented in Table 6.6. It is suggested that since the latter include inter specimen variations, appropriate figures for the uncertainties would be closer to the former values of 0.4dB/cm. As in the section 6.7 detailed consideration is only given to variation of on-axis measurements with frequency.

When considering longitudinal wave propagation it is clear from the data in Appendix 1 that there is significantly higher attenuation at 1.5MHz than there is at 250kHz for all species. However in horse chestnut the most significant rise in attenuation occurs between 1MHz and 1.5MHz, whereas in Maple the jump to higher values of attenuation occurs at lower frequencies of 1MHz or 500kHz. In Norway spruce the increase in attenuation is monotonic for the longitudinal direction and the radial direction with insufficient data being available for propagation in the tangential direction to form a judgement.

For shear waves again the picture is one of significantly increasing attenuation with frequency for nearly all cases. In Horse chestnut attenuation increased significantly with frequency for all three waves measured with the LT and RT waves showing the greatest frequency dependence (more than 5dB/cm increase from 250kHz to 1.5MHz). In Maple an examination of appendix 1 gives a similar picture with increases in attenuation with frequency from 250kHz to 1.5MHz of the order of 3.5-5.5dB/mm for on-axis propagation. Norway spruce also displays frequency dependent attenuation with increases in attenuation of the order of 4-5.5dB/mm for increases in frequency in the range 250kHz to 1.5MHz. Insufficient data was recorded for the RT disc in Norway spruce to make a judgement.

6.14 Discussion of Velocity and Attenuation Results.

The results reported in this chapter are the outcome of a study based on standard through transmission techniques designed to investigate a number of questions. Three type of wood - hardwood, ring porous; hardwood, diffuse porous; softwood were selected for investigation. Information was sought on the following

- Possible causes of attenuation in solid wood.
• The presence of dispersion in solid wood.

• Propagation characteristics of different types of wood.

• Whether the data fitted the orthorhombic model proposed.

In terms of attenuation it was observed that scattering due to the cellular structure could not alone explain attenuation in wood, especially when comparing the attenuation in Horse chestnut to the attenuation in Norway spruce. Thus the annual ring structure is proposed as a source of attenuation. This proposal, and some of its implications, is investigated further in Chapters 8 and 9 of this work.

Attenuation of shear waves was also seen to be dependent on the type and orientation of the microstructure of the wood under investigation. Thus the earlywood vessels of Horse chestnut for example was seen as giving rise to an asymmetry in the attenuation of RT vs. TR waves whereas the same asymmetry was not observed for RT and TR waves in Maple. The microstructure is also seen as responsible for the strong frequency dependence of attenuation reported in section 6.13.

The longitudinal wave measurements at 100kHz were generally found to be slower than measurements at other frequencies. This was attributed to the samples not being large enough to support bulk waves for the wavelengths propagated at this frequency. The degree of misfit between sample size and bulk wave propagation was seen to be worse for longitudinal direction waves (owing to their higher velocity and longer wavelength) than for radial direction or tangential direction waves. The anisotropy of a sample would be underestimated by using such non-pure bulk waves for an anisotropy determination since the ultrasound velocity in the longitudinal direction would be more affected than the ultrasound velocity in the radial or tangential directions. This illustrates the need for care when selecting sample sizes and frequencies.

Velocity dispersion was observed for longitudinal waves propagating along each of the three axes in Horse chestnut. For Maple and Norway spruce possible velocity dispersion was observed although further work would be needed to elucidate this. The evidence for velocity dispersion in shear wave propagation was mixed with some propagation modes showing stronger effects than others. The RL mode generally showed velocity dispersion just above the uncertainty levels for the measurements. A
broadband pulse type study might be appropriate to investigate the velocity dispersion phenomenon further.

A number of deviations from ideal orthotropic behaviour were observed. For example discrepancies between measured values of $V_{LT}$ and $V_{TL}$ were observed for shear wave velocities whereas the theoretical model predicts that material symmetries lead to the conclusion that these two velocities should be equal.

Similarly the form of the slowness curves was seen to deviate from the ideal curves generated by Hearmon (1965) and Bucur and Archer (1984). This is evidence that the orthorhombic model may not be adequate in the form in which it is currently applied to wood. In particular the annual rings and the fibres in cells represent levels of microstructure and ultrastructure which may play a role which is not fully accounted for by the orthotropic model. Musgrave, (1988), has proposed that a model which relaxes some of the symmetry conditions applied to the orthorhombic model as applied to wood. This results in a model with fifteen non-zero stiffnesses which Musgrave suggests can be used for dealing with inconsistencies thrown up by the nine stiffness orthorhombic model. Before considering the application of more complex elastic models it was felt necessary to examine the inhomogeneity presented by wood.

Significant dispersion was observed for longitudinal waves propagating in the radial direction in both Horse chestnut and Norway spruce. The source of this dispersion in both cases is attributed to inhomogeneity in the radial direction. In the case of Norway spruce the inhomogeneity presented by the annual rings was seen as the main potential source of this dispersion. This idea is tested further in chapters 8 and 9. In Horse chestnut the large latewood vessels of the earlywood are put forward as a potential source of scattering based dispersion. Indeed this idea is supported by Berndt and Johnson (1995) who made measurements on a ring porous wood.

The origin of scattering based dispersion in ring porous hardwoods could be investigated further by an immersion tank based scattering study.

The work reported in chapter 10 was also inspired by the experience of the investigator in carrying out measurements reported in this chapter among others. In that chapter the idea the different microstructures of the different species give rise to signals characteristic of that species is explored.
7. VARIATIONS IN ULTRASOUND VELOCITY WITHIN TREES.

7.1 Introduction.

In this chapter the variation of longitudinal ultrasonic velocity within Sitka spruce Picea Sitchensis (Bong.) Carr., trees is investigated. Sitka spruce was chosen for this study as it is one of the most significant commercially grown species within the British Isles. That the wood taken from different parts of Sitka spruce trees varies in strength and density is a well established fact (Bryan and Pearson, 1954; Evertsen, 1986). This is true for most wood species (Bodig and Jayne, 1982; Desch and Dinwoodie, 1997). The wood laid down in the first ten to fifteen years of the life of a tree is called juvenile wood, and is considered to be of inferior quality to wood laid down in the later years. Characteristically the density of the juvenile wood is variable in nature whereas in mature wood the density patterns are seen to be reasonably consistent (Olesen, 1977; Harvald and Olesen, 1987; Kucera, 1994). On a macroscopic scale this variability manifests itself as lower grade structural timber.

While the microscopic variability of density throughout the tree has been measured and presented by a number of workers mentioned above there has been much less work has been carried out on the equivalent measurement and analysis of the variation in elastic properties of wood at the level between the microscopic and the macroscopic. It was decided to study the variation in acoustic properties in the longitudinal direction since a significant amount of complementary data from other techniques is available. The data reported in this chapter were obtained from increment core samples which are samples which may be extracted non-destructively from living trees. Some of the first work carried out in this area was carried out by the current author (Feeney, 1987) and was reported by Bucur 1995. Subsequent work by Bucur 1991 largely confirms the findings of this work. The measurements carried out by Feeney in 1987 are reported here together with a new analysis to place the measurements in the context of density and microfibril angle variations within Sitka spruce.
The methods of measurement used are discussed first and are followed by the results. Then the patterns of ultrasonic velocity variation observed are compared to other physical parameters which vary within the tree. In this chapter some insight is gained into the variations of elastic properties from pith to bark of the tree. The likely origins of this variation are also discussed.

7.2 Specimen Selection and Preparation.

This study was part of an overall study to look at the wood quality information which can be gathered from standing trees. For this series of experiments increment core type samples were taken from seven trees. Increment core wood samples are normally extracted from standing trees by boring the sample from the trunk of the tree using a special instrument. This technique is non-destructive, in so far as the tree is largely unaffected by the extraction of the sample. The resultant sample is a 5mm diameter sample of wood running from the pith to the bark of the tree. The samples are then typically analysed for density which is taken as a measure of wood quality.

For the present study the samples were extracted by sawing using a high speed twin bladed spindle saw. They were taken from the trunks of seven trees which were available in the Forest Products department of Forbairt. The sawing technique was used to extract these increment core type samples because ultrasonic measurements obtained from the increment core samples were to be compared with MOE results obtained from small clear specimens (2 x 2 x 30 cm) taken from adjacent points in the tree stems. This was part of another study reported by the author (Feeney, 1987). The sawn increment core type samples were 5mm thick in the longitudinal dimension and 5mm wide in the tangential direction. The radial dimension corresponded to the pith to bark distance at the point of extraction.

The trees used in these experiments were selected from a stand of Sitka spruce using a diameter at ‘breast height frequency distribution’ selection procedure. This selection procedure requires measuring the diameter of the trees in a stand at breast height (1.30m), then a number of trees with a representative distribution of diameters is selected from the stand. This then gives a representative sample of a particular stand of trees (Evertsen, 1986).
Each tree was sampled at three levels (1) 'Breast height'; defined as 1m30 above ground level, (2) 'mid point'; halfway between breast height and top diameter and (3) '15cm top diameter'; where top is defined as the point where the diameter of the tree trunk has narrowed to 15cm diameter. Once extracted the samples were conditioned to 12% moisture content in a constant humidity cabinet.

7.3 Ultrasonic Pulse Velocity Measurement Technique

A through-transmission technique was adopted to measure the transit time of the pulses through the material. Vernier callipers were used to determine the physical distance travelled through the sample. Velocity was then simply obtained by dividing distance travelled by time taken. Two identically specified, 20mm element diameter longitudinal ultrasound transducers of nominal frequency 2MHz, obtained from Mateval Ltd., were employed as transmitter and receiver. The 2MHz transmission frequency chosen was a compromise between using a sufficiently small wavelength to obtain an approximately plane wave (section 4.4) in the 5mm thick increment core samples without the severe attenuation experienced at higher frequencies. The ultrasonic probes were supplied with detachable conical perspex guides with 4mm diameters and 2mm diameters respectively (figure 7.1). These tips permitted selection of a single annual ring at a time for measurement.

The ultrasonic pulse velocity was measured through the latewood of each annual ring, for each increment core. Pulse velocity was determined for propagation along both the
longitudinal and tangential axes. The latewood part of the annual ring was used for measurement as this region was found to have the lowest attenuation associated with it. The addition of the perspex tips provides opportunities for multiple reflections and mode conversions and would appear to have the potential to significantly complicate the signal emerging from the probes, making analysis of the received pulses difficult. However these probes were used to measure longitudinal velocity which is the fastest mode of propagation along any symmetry direction. Thus by measuring the first pulse received it was considered that it was the pure longitudinal wave that was being detected.

The location of the received pulse in time was determined automatically by the Krautkramer pulser receiver unit used for measurements. This supplied an analogue voltage signal representative of the position of the received pulse within a time window set up by the user. This is effectively a threshold type measurement of pulse arrival time as discussed in 4.3.3. The analogue voltage corresponding to the position of the pulse was converted to a digital number via an analog to digital converter. This analogue to digital converter was specially constructed for the project. Specially machined steel samples (5mm and 6mm thick) were used to provide calibration times for the system. Typically five measurements were made at each location and averaged. The overall accuracy of the measurements is estimated to be ±0.5%.

Coupling of the sound into the increment core samples was achieved using a specially constructed sample holding jig and a torque wrench (figure 7.2). This provided consistent coupling and alignment. Vaseline was used between the transducer faces and the perspex tips but no couplant was used between the perspex tips and the wood as this could have penetrated the samples, potentially changing their propagation properties (see section 4.5). The torque wrench was set to $100 \text{ cN.m}$. 

Figure 7.2 Specially constructed jig for holding increment cores with screw mechanism for torque wrench to allow consistent coupling.

7.4 Results of Longitudinal Velocity Measurements along the Longitudinal Axis on Increment Cores.

In this section the results of the measurements of ultrasonic pulse velocity in increment cores are presented. The results are presented in figure 7.3. The data used to form the graphs are presented in Appendix 2. The graph represents the plot of mean velocity over seven trees. Level 1 measurements were made on increment cores extracted at 1.3m above ground level. Level 3 measurements were made at the 15cm diameter point of the trunk, near the top of the tree. Level 2 measurements were made at the half way point between the level 1 measurements and the level 3 measurements.

Figure 7.3 Mean Longitudinal Velocity along the Longitudinal Axis for Increment Core Samples from Different Levels Within the Tree.
Level 1 = 1m30, Level 2 = midpoint; Level 3 = 15cm diameter.
A number of observations can be made about this plot. Firstly ultrasonic velocity displays an initial rising trend with annual ring number, with the rise being steepest in the first few years. Secondly the systematic rise in velocity appears to diminish and disappear after about 5-10 years depending on the level within the tree under consideration. Thirdly the lowest level (1.30m above ground level) within the tree displays significantly lower velocity than the other two levels (mid-point and 15cm top diameter). The finding of rapidly increasing velocity for the first few years of growth followed by a levelling off of velocity has been reported also for Pine (Bucur, 1991), although Bucur did not investigate the variation with height in the tree.

Bryan & Pearson (1955) and Harvald & Olesen (1987) reported on the variation of basic density in Sitka spruce with annual ring number. Basic density was determined as the weight after drying at 103°C until a constant weight was reached, divided by the 'green volume' as measured by a water displacement method.

The patterns of variation reported by both sets of authors are similar. The results obtained by Harvald and Olesen are given in figure 7.4 below. The results shown were obtained at 1.3m above the ground. Harvald and Olesen also measured at 3.0m, 5.0m and 9.0m above the ground. The Sitka spruce plot is based on an analysis of 25 trees from a single stand and the Norway spruce plot is based on an analysis of 120 trees. In this case a rapid fall in density was noted for the first 6-8 years, followed by a steady increase in density to year 12-15, after which basic density becomes reasonably stable.

Harvald and Olesen also report in the same work that basic density increases with increasing height from the ground. It should be noted that basic density is quite variable. For example density in Sitka spruce rings shows an inverse relationship with ring width (Brazier, 1967; 1970; Harvald and Olesen 1987). Density is also related to several other factors such as the ring width, genetic origin, stand location, climate, the presence of neighbouring trees and any treatments applied to the trees (Desch and Dinwoodie, 1996).

Clearly the variation in velocity observed in the longitudinal direction cannot be completely explained by the density variation pattern. An examination of the theoretical models given in Chapter 3 leads one to expect velocity to vary inversely with the square root of density, but also shows that the longitudinal stiffness plays a role. Thus we
must turn to the variation of the elastic properties of the material from pith to bark for a more complete explanation of the velocity variation. From table 3.1 we find that the longitudinal stiffness in the longitudinal direction is related to the density and velocity by:

\[ \nu = \sqrt{\frac{c_{11}}{\rho}} \]  

The implication of this is that some factor which controls the elastic modulus in the longitudinal direction would appear to display significant variation as we move between the pith and the bark of the tree.

Factors of potential interest, which vary from the pith to the bark of a tree, are the microfibril angle and the tracheid length (Chapter 2). The orientation of microfibril angle in cell walls, particularly the S2, middle cell wall layer is seen to play a crucial role in determining the mechanical properties of wood fibres (Bodig and Jayne, 1982; Desch and Dinwoodie, 1997; Bachelor et al. 1997; Tang and Hsu, 1973). Theoretical
and experimental work has shown that the elastic modulus and strength of fibres are approximately constant at very low fibril angles with respect to the axis of the tree and that the elastic modulus and strength fall rapidly for fibre angles beyond 5°-10° to the axis of the tree (Page et al., 1977; Salmen and de Ruvo, 1985). Microfibril angle, in the S₂ layer, has been shown to vary with ring number for several species, including Sitka spruce, with greater angles observed near the pith of the tree (Cowdrey and Preston, 1966; Shupe et al., 1996). Thus it seems safe to suppose that microfibril angle may be the factor having a significant influence on the ultrasonic pulse velocity pattern observed in figure 7.3 above. The measurement of microfibril angle has been the subject of much interest (Cave, 1966; Batchelor et al., 1997; Boyd, 1977; Paakkari and Serimaa, 1984) although it is not easy to achieve.. These workers have tried to develop a suitable method for measuring average fibril angle in cell walls in order to use it as a means of assessing wood quality, and its mechanical properties. This is because the standard methods such a Cave's X-ray diffraction method is inaccurate in regions of less than 10° or more than 25° (Yamamoto et al. 1993). Standard techniques are also slow and require careful sample preparation (Batchelor et al., 1997).

It is possible that ultrasonic measurements as outlined above, especially in conjunction with density measurements, can be used to assess variations in elasticity and, by implication, microfibril angle. Relating ultrasonic measurements to the already accepted quality parameter of microfibril angle would give wood quality scientists confidence in ultrasonic techniques as an assessment tool for the elastic properties of small samples. Unfortunately the resources were not available to make microfibril angle measurements on the samples used in this study. However it is clear that some potentially very interesting work remains to be done in this area.

The role of tracheids in wood structure was discussed in section chapter 2 on wood structure at the beginning of this thesis. Several workers report a patterns of increasing tracheid length with annual ring number (Kucera, 1994; Lindstrom, 1997). The pattern displayed is similar to that observed for velocity in the longitudinal axis (figure 7.3). Short tracheid length is known to be associated with a large microfibril angle referred to the axis of the tree (Hiller and Brown, 1967). Thus one would expect to observe a similar correlation between tracheid length and ultrasound velocity as that postulated in this section for microfibril angle and ultrasound velocity.
However even though both tracheid length and microfibril angle vary with ultrasound velocity in the longitudinal direction, it is considered by the present author, that it is the variation in microfibril angle which causes the variation in ultrasonic pulse velocity. This is because microfibril angle has been more closely associated with elastic properties than tracheid length (Tang and Hsu, 1973, Bodig and Jayne, 1982).

7.3 Results of Longitudinal Velocity Measurements along the Tangential Axis on Increment Cores.

The measurements reported in this section were carried out as described in section 7.3. The measurements were carried out on the same increment core samples used in the previous section except that of course in this case the ultrasound was propagated along the tangential axis in the samples. A plot of the mean result over seven trees by level and annual ring number is shown in figure 7.5. The results on which this plot is based are shown in Appendix 2.

A number of observations may be made about these results. The velocity in the tangential direction is significantly lower than that observed in the longitudinal direction (figure 7.3). This agrees well with the macroscopic measurements presented in Chapter 6 where velocity in the tangential direction was generally seen to be significantly less than that in the longitudinal direction (albeit on different species of timber).

There are also a number of points where it has not been possible to make a measurement because a received signal could not be detected. This may be due to several factors. Firstly there are no structural elements in the wood material aligned along the tangential direction. This leads to increased attenuation in this direction. Secondly the curvature of the annual rings in the tangential direction can be severe. Any misalignment of the sample can lead to a situation where the transmitted wave is guided away from the receiver causing no signal to be received.
One consequence of the severe attenuation experienced when propagating in the tangential direction is an increased uncertainty in detecting the received signal. This leads to much greater variation in the measured velocities from one annual ring to the next when compared to propagation in the longitudinal direction. This increased scatter in measured velocity makes determining a pattern in the velocity variation from pith to bark a much more difficult proposition.

The average standard deviation of the individual velocities making up the mean velocity in the tangential direction was of the order of 14% of the mean value. The average standard deviation of the individual velocities making up the mean velocity in the longitudinal direction was of the order of 8%, going down to 5% in the stable outer region. From the plot shown above it is difficult to determine any significant trends apart from a possible slight decrease in velocity from pith to bark.

One potential explanation for this is the variation in microfibril angle from pith to bark mentioned in the previous section. The longitudinal velocity was observed to be lower near the pith. If this is in fact due to large microfibril angle with respect to the longitudinal axis this implies a microfibril more oriented towards the tangential direction, which would produce a higher velocity near the pith for propagation in the tangential direction.
Examining of the results for velocity variation with level for ultrasound propagating in the tangential direction shows that it is difficult to form a definite conclusion about variations in this direction due to the scatter in the results.

It is possible to conclude that density alone is not the only influence on the velocity pattern observed in the longitudinal direction. Otherwise we might expect a similar variation for the velocity measured in the tangential direction which propagated through material of the same density.

A study involving ultrasound pulse velocity measurements, X-ray density measurements and microfibril angle measurements would clearly be warranted. This would help to elucidate the link between microstructure and ultrasound pulse propagation. Such a study would require measurement of a significant number of trees, probably of a number of softwood species. The effort required to carry out such a study could be reduced by combining the study with existing wood quality improvement research.
8 MEASUREMENT OF THE INHOMOGENEITY OF WOOD IN TERMS OF ULTRASOUND VELOCITY

In chapter 6 elastic wave propagation in three species of wood was examined, and the measurements compared with the standard orthorhombic model of wood. While the orthorhombic model was seen as providing an accurate description of the behaviour in most cases, in some respects it was seen not to provide a full description.

In this section of the thesis the limits of the assumption of the homogeneity of the material under investigation are examined. The particular source of inhomogeneity under investigation in this work is that due to the quasi-periodic structure of the annual rings. As discussed in chapter 2 annual growth patterns in wood, particularly woods grown in temperate climate, result in the laying down of rings of less dense and more dense wood. Annual rings in commercially grown softwoods typically have dimensions of the order of 1-10mm (Harvald and Olesen, 1987; Olesen, 1977; Brazier, 1967; 1970). This is of the same order of magnitude as the wavelengths of typical wavespeeds observed in wood. For example 100kHz wave, with a velocity of 2,000m/s as might be observed in the radial direction, would have a wavelength of 20mm. A 5,000m/s wave with a frequency of 1MHz propagating in the longitudinal direction would have a wavelength of 0.5mm (see figure 4.6).

The investigation of the inhomogeneity of wood described in this chapter was carried out by using a well established technique (X-ray densitometry) to measure density variations and a specially adapted acoustic technique (section 8.4) to measure elastic wave variation. The variations are measured in the first case from pith to bark of the tree. In the X-ray densitometry technique the X-ray beam is projected along longitudinal axis of an increment core type sample (section 7.2). If ring curvature is neglected one would expect a beam projected in the tangential direction to record the same density values.

As discussed in chapter 6 acoustic wavespeeds differ markedly depending on whether the sound propagates in the longitudinal, radial or the tangential axis. Thus it is necessary to measure acoustic wavespeeds along each of these axes. This is perfectly
possible for the tangential and longitudinal directions and indeed measurements on a ring by ring basis were reported in chapter 7. Ideally variations of acoustic wavespeed in the radial direction from pith to bark should also be measured, although as discussed in section 8.5 this is a much more complicated task as it requires a means of interrogating sub annual ring thickness samples in the radial direction.

8.2 Samples used for Inhomogeneity Study.

Four stems, two of Sitka spruce, one of Scots pine and one of Larch, were used in this study. This provided samples with different annual ring patterns for testing the resolution of the proposed measurement system. Some samples had wide annual rings and large density variation between late wood and early wood (Bryan and Pearson, 1955; Evertsen:1986, Kucera: 1994). It was felt that this would allow the best chance of measurement of variations within an annual ring.

The samples were green wood samples, that is to say they had not been dried. They were taken from the base of the tree and ranged in diameter from 15-20cm. Green wood samples were used since it was intended to carry out measurements in a water bath and drying and re-wetting samples can result in some splitting of the samples (Desch and Dinwoodie, 1996). The samples were kept wrapped in plastic to retain the moisture within the samples.

When the measurement system was ready for measurement, cross-sectional slices (RT Plane) as well as LR-plane slices were taken from the stems. This was carried out using a band-saw available in the workshops of the Physics Department of the University of Surrey. The samples for longitudinal measurement were 15-20cm diameter discs, nominally 5mm thick. The samples for tangential measurement were typically 20cm squares, nominally 5mm thick. Cutting large thin sections of green wood proved a troublesome task and, in spite of the great care taken some of the samples were not of uniform thickness. It was decided to allow for the thickness variation during the velocity determination stage. The thickness of the samples were measured at 0.5cm intervals along their length using a callipers with a digital readout. Alignment of the samples with respect to the principle axes was generally within 1-2° of the axis. The
samples were stored in a weak (1%) bleach solution for the duration of the measurements. The bleach solution was used to prevent the possibility of decay due to biological attack.

8.3. Measurement of Variation of Density of Wood in a Stem.

As is clear from the theoretical development of the models describing the propagation of ultrasound in section 3.3, the density of the material through which the wave is propagating has a key influence on the wave propagation. In addition, density is often used as a descriptor of wood quality (Bryan, 1955; Kahle and Woodhouse: 1994, Bodig and Jayne: 1982, Harvald and Olesen: 1987). The X-ray microdensitometry technique is the principle technique used as a technique for determining density variations in samples (Evertsen:1986, Kucera:1994).

8.3.1 X-Ray Densitometry Measurements.

X-ray densitometry measurements were carried out using an X-ray densitometer system available in the Forest Products department of Forbairt. The samples described in section 8.2 were arranged on a tray along with a perspex calibration wedge, an identification number, and markers (made from lead) indicating the position of a scan line to be used in the corresponding ultrasonic measurements. A positive print of a typical X-ray image is shown in figure 8.1.

![Figure 8.1 Positive Print Of X-Ray Image Used In Densitometry Measurements (Larch). Note position of ultrasound scan line indicated by image of V-shaped lead markers.](image)

An X-ray film was placed in an envelope under the sample and positioned in an X-ray cabinet. The samples were exposed to 40kV X-rays for 1 minute 15 seconds. The X-
ray films were then developed and placed in an optical densitometer for measurement. The densitometer used was a Joyce-Loebl unit which had an obsolete non-functioning PDP-11 computer interface.

For purposes of this work a replacement interface was constructed by the author which permitted control of and acquisition of data from the densitometer using an IBM compatible computer. The microdensitometer unit and X-ray system had not been calibrated for some years and the resources were not available to do this so the density values obtained are not treated as absolute values.

Scans of density variation in the samples from pith to bark were made for a number of samples using the system. The density scans were obtained as follows: measurements of optical density were carried out at 20μm steps along the film. These measurements were stored in a datafile on a computer for later conversion to gravimetric density. Optical density was related to film density by means a linear correlation equation derived from the perspex calibration stepwedge. The output of a scans converted to density for each of the samples is shown below in figure 8.2.

![Larch Density](chart)

A: Larch.
Figure 8.2 Density from pith to bark for (A) Larch, (B) Spruce ‘B’, (C) Spruce ‘A’ and (D) Pine.
In the larch sample figure 8.2(a) we can see widely spaced annual rings with wide bands of low density interspersed with narrow regions of high density. About 16 annual rings are visible, with ring spacings of the order of 5mm. The transition from less dense early wood to dense latewood is fairly sharp.

The ‘B’ Spruce sample has wide annual rings with annual ring spacings of the order of 7-8mm in the first five years. The transition in density more gradual than it was in Larch. The spruce ‘A’ sample again has wide annual rings at the beginning which narrow after about year 5. The pine sample has a ring spacing of around 4-5mm for the first nine years. This ring spacing decreases rapidly to 2mm or less up to year 20. At this point the X-ray film did not resolve the remaining annual rings clearly as ring spacing decreased to less than 1mm. This is an indication that the X-ray system had not been optimised fully. Unfortunately it was not possible to tackle this problem as the author was not permitted to use the X-ray system in Forbairt unsupervised and the resources were not available to have the system calibrated.

8.4 Measurement of Variation of Longitudinal Ultrasonic Wavespeeds along Longitudinal and Tangential Axes in a Wood Stem.

8.4.1 Introduction

The aim of these measurements was to obtain a measurement of the variation of acoustic wavespeed within an annual ring of the tree. Since the largest annual rings have dimensions of the order of up to 10 millimetres it was necessary to use a measurement technique which would ideally measure over regions significantly less than this.

The longitudinal velocity in the longitudinal and tangential directions was measured for the samples described section 8.2. These planar samples permit the measurement of velocity along a line from the pith to the bark of the sample. The measurement technique used is described in section 8.4.2. A different measurement technique, described in section 8.8 was used for radial velocity measurements. This different
technique was used because it is much more difficult to prepare a sample of material oriented in the radial direction which permits within ring variations to be measured.

8.4.2 Experimental Arrangement.

Measurements were carried out using a through transmission technique for which a block diagram is given in figure 8.3. Measurements were carried out in a Perspex water tank 1.5m long, 1m wide and 1m deep available in the Physics Department of the University of Surrey. A computer controllable stepper motor system permitted x, y and z translation of a holder in 5μm steps. The system had been designed for making precise amplitude and phase measurements for the purposes of transducer characterisation (Aindow et al., 1985). Working in a water tank eliminated many of the coupling problems described in Section 4.5. It also meant that measurements were carried out with the samples in a saturated condition with moisture contents of the order of 150%, although precise moisture content determinations were not carried out.

A weakly focused 2MHz transducer was used as the sound source and a needle hydrophone based measurement system was used as the receiver. The 2MHz source transducer had been well characterised by previous workers and was known to be capable of providing a plane wavefront over a reasonable area at its focus (Adach and Chivers, 1990a;b) The needle hydrophone system was selected to permit measuring within ring variations of annual ring velocities. The hydrophone was a PVdf device (element diameter 500μm) with a wideband preamplifier obtained from Precision Acoustics Ltd..

The cross section (RT plane) and LT plane samples were mounted in a specially designed perspex sample holder in the water tank. It was decided to leave the source transducer and the hydrophone in fixed position and to move the sample within the sound field to interrogate different parts of the sample. This ensured that the measurements through the sample were always made in the same part of the sound field. Although the sample holder was attached to a stepper motor system which permitted movement of the sample in the x, y and z planes, in practice only the x
direction movement was used to step the sample past the hydrophone, usually in a linear scan in the direction from pith to bark.

The sample was isonified using the weakly focused 2MHz transducer mentioned above, with the sample placed at its focus. The sample was aligned to be perpendicular to the field of the 2MHz probe by connecting the 2MHZ probe in a pulse-echo arrangement and adjusting the orientation of the sample to give a maximum echo.

During the actual scans of the samples the 2MHz transducer was excited with a one cycle sinewave of amplitude 60mV generated by a Hewlett Packard pulse generator (HP3314A) and amplified by a wideband RF amplifier. The short tone burst was used to prevent interference between portions of the start of the toneburst which had been doubly reflected within the samples and the end of the tone burst.

The procedure for making measurements on the sample was as follows. First a 'zero' scan was recorded, with no sample between the isonifying probe and the hydrophone. Next the sample was placed between the sound source and the receiver. The sample was placed about 5mm in front of the hydrophone tip. The scan length and step size were then entered in the microcomputer controlling the stepper motors and a scan commenced. After movement of the sample to the next measurement in the scan.

Figure 8.3 Block Diagram Of Apparatus Used For Measurement Of Within Ring Ultrasonic Velocity Measurement.
position a delay of 10s was incorporated before the next measurement was recorded. This was to ensure that the system had settled after movement.

The temperature of the water at the beginning and the end of each scan was recorded. This was used in conjunction with the water ‘zero’ reference when calculating delay times in the sample. If the temperature of the water deviated by more than 0.1° from the starting temperature during a scan then that scan was rejected.

The acquired data was stored in the form of a series of 1000 point datafiles representing the averaged time trace (128 averages) at each measuring point. It was necessary to record the full trace of the received signal since preliminary analysis showed that there were unexplained jumps in the position of the received signal when recording parameters such as the position of the maximum peak.

The results from a typical scan consisted of 201 such datafiles generated at 250μm intervals. Thus typical scans were 5cm in length and took over two hours. The scan length was limited slightly by the amount of data being generated and the fact that the stepping system sometimes did not perform correctly for longer scans. Since the scanning system had been constructed by a previous worker and the time available for measurements was limited, the simplest compromise was to limit scan size. This data was then combined with the data obtained from the ‘zero’ trace mentioned above to calculate the ultrasonic velocity at each position in a scan.

8.4.2 Determination of Received Signal Features from Acquired Scan Data.

The received waveforms were analysed using a peak finding program written specially to determine the positions and amplitude of the received peaks. The positions and amplitude of the received peaks were stored in a file which was then imported to a spreadsheet to be combined with other data in order to calculate the velocity in the wood as well as the received amplitude.
8.4.2.1 Determining Location of Received Signal Peaks

Determining the received peak position proved problematic. Since there were 201 traces recorded for each scan it was decided to use a software routine to determine the peak positions. The software program developed for this function (barread.pas) is listed in Appendix 3. In essence the following procedure was followed.

Firstly the sample number and number of files in a scan were entered by the user. The program then opened each file in turn and carried out the following processes:

1. A five-point smoothing was carried out on each trace. This involves reading in the first five points (points 1-5) in a time record, calculating the average amplitude of the five points and putting the average into point 3 of the a new time record. Next points 2-6 are read in, the average calculated and placed in point 4 or a new record. This process is repeated until the end of the time record is reached. Dummy average values are used for points 1 and 2. The smoothed trace is effectively a low-pass filtered version of the original (Press et al., 1988).

2. Next the positions of the extrema in the smoothed traces were obtained. A thresholded peak-finding routine (Press et al.:1988) was used for this process. The threshold was created by finding the overall maximum value in the smoothed time record and setting a constant within the programme to 63% of this value (The 63% value was arrived at by trial and error). The peak finding process now simply involved finding all maximum values (greater than their neighbours) above the threshold value and recording these maximum values and their positions within the time record.

3. The maxima and minima were sorted in time order and files were created containing lists of the time of the first occurring maxima, the time of the second occurring maxima, the first minima, and the second minima. Files were also created containing the corresponding amplitude values for these data. As will be discussed later in this section the first maximum peak position and amplitude were used in practice for measurements. The integral of the area under the rectified signal curve was also recorded for each trace.
Where the signal was very weak the automated peak finding routine could be in error, because it missed the first cycle of the received toneburst. This was observable on a plot of peak positions as a sudden jump of 1 cycle in the received signal. Where necessary this was corrected for by hand. In certain cases where the signal was too weak for identification by the software, identification of the correct peak by hand was also used.

The 0.5mm tip hydrophone was the smallest available in the laboratory at the time of measurement. However, the relatively large size of the hydrophone time caused some difficulties. As the sample was scanned at some points the tip of the hydrophone covered both early and late wood in certain positions. At these points two received signals were observed, one from the early wood and one from the late wood. In some cases the received signals were distinct from each other, in other cases, they overlapped and interfered. Thus while the arrival of the first wave was relatively easy to distinguish, the starting point of the second wave could be difficult to determine. For this reason the automated peak finding routine concentrated on measuring the arrival of the first toneburst. This of course caused preferential recording of faster signals around the transition points between the end of latewood and the beginning of earlywood.

Figures 8.4(a)-(d) illustrate this phenomenon. The apparent interference effect was first noticed when some of the early linescans were carried out. Careful observation of the position of the hydrophone in relation to the sample when some of these traces were recorded lead to the conclusion that the phenomenon occurred when the end of an annual ring traversed the position in front of the hydrophone.

Figure 8.4(a) shows a typical trace received through water with no sample present. The signal is clear and well defined. In Figure 8.4(b) a typical signal received through a sample is shown. This signal is similar in shape to the signal received through water. In Figure 8.4(c) some distortion of the received signal is apparent as evidenced by the third peak not being the highest in amplitude, and by some distortion of the first two peaks. In Figure 8.4(d) the signal is much more distorted with much of the signal apparently suffering destructive interference.
Signal Received through Water.

Figure 8.4 (a) Signal Received Through Water Only, No Sample.

Figure 8.4. (b): Typical Received Signal - Influence Of Annual Ring Transition Not Apparent.

Figure 8.4. (c): Received Signal - Onset Of Annual Ring Edge Apparent In Signal Shape

Figure 8.4. (d): Received Signal At Edge Of Annual Ring. Interference Apparent.
8.4.2.2. Calculation of Velocity

The peak finding software generate a file containing the locations in the time record of the peaks and the magnitude of the peaks along a line of scans. The file was inspected to eliminate false identifications as outlined above, and the file of peaks brought into a spreadsheet. The absolute time of reception of the signal was obtained from a knowledge of the time-base and delay for a particular signal. Calculation of velocity in the samples was achieved by the standard relation:

\[ v = \frac{d_s}{t_s} \]  \hspace{1cm} (8.1)

As mentioned above \( d_s \), the thickness of the sample, was obtained by direct measurement of the dry samples using a vernier callipers. Obtaining a value for \( t_s \), the propagation time in the sample, involved subtracting the propagation time in the water path from the overall propagation time.

\[ t_s = t_t - t_w, \]  \hspace{1cm} (8.2)

where \( t_t \) is the total propagation time, \( t_w \) is the propagation time in the water path and \( t_s \) is the propagation time in the sample. The total propagation time was obtainable directly from the peak position in the received trace and a knowledge of the delay setting on the oscilloscope.

The propagation time in the water was obtained from the water path length and the velocity of water (\( v_w \)) at the relevant temperature as given by del Grosso and Mader (1972).

\[ t_w = \frac{d_w}{v_w} \]  \hspace{1cm} (8.3)

The water path length, \( d_w \), was the difference between of the overall path length, \( d_t \), and the thickness of the sample, \( d_s \). The overall path length was found by measuring the 'zero' time, \( t_z \), for pulses to propagate without a sample and again using the velocity at the appropriate temperature obtained from del Grosso and Mader, (1972).
\[ d_w = d_t - d_s, \quad 8.4 \]

\[ d_t = v_w \times t_z. \quad 8.5 \]

This was combined with the thickness of the sample at the point of measurement to give the velocity in the sample. Typical sample thicknesses were of the order of 5mm with typical distances between the source probe and the hydrophone needle being of the order of 125mm.

8.4.2.3 Measurement Errors Associated with Velocity Determination.

Section 8.4.2.2. outlines clearly what has to be measured to arrive at the velocity in the wood samples using the hydrophone scanning technique. Working backwards from equation 8.5 we see that the total distance in water separating the hydrophone and the centre of the source transducer depends on the velocity in water at a particular temperature as given by delGrosso and Mader (1972). Since the temperature in this experiment was determined to 0.1°C, assuming the water in the tank was at a uniform temperature. This would lead to an uncertainty of 0.02% in \( v_w \), the velocity in water.

Equation 8.5 also shows that \( d_t \), the separation of the source and receiver, depends on \( t_z \), the time recorded for a zero scan. The received signals with no sample present were very consistent and the peak positions could be repeatably measured to 10ns giving an error in determining \( t_z \) or the order of 0.011% for a typical propagation time of 85μs. Thus the error in determining \( d_t \) was 0.03%.

The error in \( d_w \), in equation 8.4 depends on the error in \( d_t \) and the error in \( d_s \). The total water path was dealt with in the previous paragraph. \( d_s \), the sample thickness, \( d_s \), presents a different challenge. It was measured using an electronic callipers with a stated accuracy of ±0.005mm. Thus for a 4mm thick sample (the thinnest sample used) this would give an error in thickness of 0.125%. However, as noted in section 8.2 the samples were not necessarily uniform in thickness. The thickness dimension of the samples was measured at 0.5cm intervals. The maximum change in sample dimension between one thickness measurement and the next was 0.2mm. If we consider this to be the maximum change in thickness between readings this gives a potential error in
dimension of 0.1mm or 2.5%. This is much more significant than the error due to the total water path length measurement $d_t$. Given a typical distance in water of 130mm this gives an error of approximately 1% error in $d_t$, the distance travelled by the ultrasound in water when a sample is present.

When the propagation time in water is calculated from the path length in water (equation 8.3) this gives an error in time of 67ns, neglecting the much smaller error due to temperature measurement. The total time $t_t$ can be measured to one position on the timebase giving an associated error of 10ns. The accuracy of this determination would be reduced in the region of peaks where the phase cancellation artefact plays a role. Neglecting the region around the peaks this gives an uncertainty in the propagation time in the samples of the order of 80ns.

For a velocity of the order of 5500m/s in a 4mm sample the propagation time would be 750ns. Thus the maximum measurement error in propagation time in the sample is of the order of 10.7%. When allied to the maximum error in determining the sample thickness this give an uncertainty in determining the velocity in the samples of 13.3% or 660m/s for a 5000m/s pulse.

The relatively large error is mainly due to the uncertainty in the sample thickness. Clearly this can be reduced by the use of specialist saws to prepare samples, although cutting thin samples of green wood as was required for these measurements is not a trivial task. It might be more sensible to use re-wetted dry samples for these measurements. These can be dimensioned very accurately using a high speed spindle saw as was used for the increment core type samples described in section 7.2

8.5 Results of Scans of Velocity in the Longitudinal Direction.

Results of ultrasonic scans in the longitudinal direction are shown in figure 8.5. Velocities in the range 3000m/s to 4500m/s were recorded. The variation of ultrasonic pulse velocity as each annual ring is crossed is clearly observed. The velocity is low at the beginning of each annual ring. The velocity increases as the year progresses reaching a peak at the end of the latewood.

The latewood peaks are wider than those observed on the densitometry scan (figure 8.2) for the same sample. A great deal of this can be explained by the fact that the
hydrophone tip has a 0.5mm diameter compared to the 20µm spot size of the microdensitometry system. It may be recalled that it was necessary to use the first recorded signal as the received signal (section 8.4.2.1) position and that this leads to exaggerated recording of the faster signals through latewood. There may also be a stiffening effect related to microfibril angle (Hiller and Brown, 1967) as the annual ring is traversed but more work would need to be done to ascertain this effect.

In order to provide information on the repeatability of the measurements some samples were measured twice (labelled ‘scan1’ and ‘scan2’ respectively). As far as practicable these scans were carried out under identical conditions. There was some difficulty in aligning the start position of the scan on the sample to the exact same location on the sample.

![Longitudinal Axis, Larch, Scan 1](image1)

A: Larch (first scan)

![Longitudinal Axis, Larch, Scan 2](image2)

B: Larch (second scan).
C: 'B' sample of Spruce (first scan).

D: Spruce 'B' Sample. (second scan).

E: Spruce 'A' sample (first scan).
The observation of a higher velocity in latewood than in earlywood agrees with observations made by Bucur et al. (1991) who made measurements in early wood and latewood using a simple two point approach on dry increment core samples of Pine. It also agrees with work by Yiannos and Taylor (1967) who measured the stiffness of isolated specimens of earlywood and latewood using mechanical techniques.
8.5.1 Repeatability of Scans of Velocity in the Longitudinal Direction.

Over the period during which these measurements were carried out several samples were measured twice enabling the repeatability of the measurement technique to be assessed. The results obtained are shown in figure 8.6 below:
For all samples it is clear that there is some deviation in absolute velocity between the two scans, particularly in the region of the peaks. Some of this may be due to the experimental error described in 8.4.2.3. However there is also an indeterminate error due to errors associated with replacing a sample in the tank for measurement in exactly the same position and orientation as it had been measured originally. The pulse echo system used to ensure that the samples were aligned perpendicular to the sound field was sensitive to small angular movements of the sample but the velocity in the longitudinal direction is also sensitive to small changes in orientation of the sample (see section 6.5). The horizontal and vertical positioning of the sample for the start of scans was achieved by visual alignment of the hydrophone tip with a line drawn on the sample. Experience in arranging the data shown in plots 8.6(a)-(c) to align the peaks showed that differences of 2-3mm in positioning in the horizontal axis are typical.

Again if it was desired to make more accurate and repeatable versions of the measurements reported in this chapter it would be a straightforward engineering task to make an improved positioning mechanism for the sample holder.

8.6 Results of Scan of Velocity in the Tangential Direction.

Results of a ultrasonic scan in the tangential direction are shown in figure 8.7. Velocities in the range 1100m/s to 2000m/s were recorded. The variation of ultrasonic pulse velocity as each annual ring is crossed is clearly observed. The velocity is low at the beginning of each annual ring. The velocity increases as the year progresses.
reaching a peak at the end of the latewood. Some minor peaks may be observed in the regions between the annual rings, particularly in the first three years. The wood in this region has a particular nature to help support the young tree and is different to the more regular pattern observed later (Harvald and Olesen:1987). Similar irregularities are observed in the corresponding density trace shown in figure 8.8.

Figure 8.7 Velocity Along Tangential Axis Against Distance From Pith (Spruce).

Figure 8.8 Plot of Density Against Distance from Pith (Spruce)
8.7 Relation between Ultrasound Scans of Velocity in Longitudinal and Tangential Directions and the Corresponding Density Scans.

In this section a comparison is made between the results obtained using the densitometry technique and the results obtained using the ultrasound scanning technique. First the longitudinal direction scans are considered and then the tangential direction scans are considered.

8.7.1 Comparison of Peak Locations using Densitometry and Ultrasonic scanning

The ultrasonic densitometry scans and the longitudinal velocity scans illustrated in figures 8.2(a) and 8.5(a) were carried out on the same sample of Larch. As far as possible the same portion of the sample was scanned. The most clear features in each type of scan, namely the positions of the peaks, were compared to see if each system was finding the same peaks position and separation.

The densitometry measurements and velocity measurements were made on the sample samples but using instruments in different countries. When comparing the positions of the peaks found by the two techniques, the major difficulty was in finding a similar starting point for both scans. This was compounded by the fact that the densitometry scans were made at 20µm intervals and the velocity scans were made at 250µm intervals. A subset of each set of measurements was used to bring the measurements to a common length interval of 500µm. The peak positions determined by both systems were then recorded and the results obtained are presented in table 8.1 below. Also given is the linear regression correlation coefficient ($r^2$) between the peak positions recorded by the two systems.
Comparison of Peak Locations

<table>
<thead>
<tr>
<th>Larch Sample</th>
<th>Spruce 'B' Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Longitudinal</td>
<td>(Tangential</td>
</tr>
<tr>
<td>Velocity Scan)</td>
<td>Velocity Scan)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Velocity scan position mm</th>
<th>Density pos. mm</th>
<th>Correlation coefficient, ( r^2 )</th>
<th>Velocity pos. mm</th>
<th>Density pos. mm</th>
<th>Correlation coefficient, ( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.725</td>
<td>2.698</td>
<td>0.998</td>
<td>0.625</td>
<td>0.618</td>
<td>0.998</td>
</tr>
<tr>
<td>3.2</td>
<td>3.1</td>
<td>1.2</td>
<td>2.075</td>
<td>2.08</td>
<td></td>
</tr>
<tr>
<td>3.65</td>
<td>3.53</td>
<td>2.725</td>
<td>3.325</td>
<td>3.434</td>
<td></td>
</tr>
<tr>
<td>4.25</td>
<td>4.126</td>
<td>3.85</td>
<td>4.125</td>
<td>4.486</td>
<td></td>
</tr>
<tr>
<td>4.75</td>
<td>4.658</td>
<td>5.924</td>
<td>4.625</td>
<td>4.872</td>
<td></td>
</tr>
<tr>
<td>5.375</td>
<td>5.244</td>
<td>6.37</td>
<td>6.788</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.725</td>
<td>5.646</td>
<td>6.85</td>
<td>7.175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.425</td>
<td>6.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.85</td>
<td>6.788</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.175</td>
<td>7.182</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.1. : Table Of Location Of Annual Rings As Measured By X-Ray Densitometry And Ultrasonic Velocity.

It is clear from the table that while there is some offset in terms of absolute peak position, the peak separation correlates extremely well. Correlation between ultrasound velocity values and density values was also measured and plotted. Rings 4, 5 and 6 were chosen for this study. In this case the larger sampling area of the hydrophone combined with the preferential measurement of latewood velocities (section 8.4) combine to yield a less well correlated result. There may also be an effect due to variation in the elastic properties of the cell walls through out the rings. The results obtained for the longitudinal velocity scan illustrated in 8.2(a) and 8.5(a) are shown in figure 8.9.
The correlation between density and velocity obtained from this plot was $r = 0.73$. It should be noted that this result was obtained by omitting the five data points around each peak. This was because slight fluctuations in peak position were observed to have a undue effect on the correlation result obtained.

A similar process was carried out on the tangential velocity scan (Spruce 'B'). The result is plotted below in figure 8.10. For this plot data from rings 4, 5 and 6 was selected as it was felt that these rings were reasonably representative of regular annual rings. As in the longitudinal velocity case a positive relation between velocity and density is observed, with a correlation coefficient $r^2$, of 0.78.
Several points are clear from these results. Firstly there are significant differences in the velocity of ultrasound in earlywood and the velocity of ultrasound in latewood. Secondly there is a positive correlation between the velocity variations and density variations and density. Thirdly the observed velocity difference exists for propagation in both the tangential and longitudinal directions.

8.8 Direct Measurement of Variation of Longitudinal Ultrasound Velocity in the Radial Direction.

As mentioned in section 8.4 the variation of velocity in the radial direction can not be measured in the fashion as that adopted for the longitudinal and tangential direction. While RT plane samples permit measurement of the variation in the longitudinal direction and RL plane samples permit measurement in the tangential direction, the curvature of the annual rings prevents construction of a sample which would permit measurement in the pure radial direction.

This meant that a new approach to measuring the acoustic inhomogeneity in the radial direction had to be adopted. Extraction of thin samples suitable for direct measurement of radial velocity in earlywood or latewood is extremely difficult. It was decided instead to try to quantify the variation of longitudinal ultrasound velocity in the radial direction by measuring average radial velocity in a sample, removing 1mm of material from that sample and then re-measuring the velocity in the sample. Any velocity difference was then attributed to a difference in velocity in the removed layer.

The velocity measurements for this section was carried out using the same coupling system as was described for the measurements on increment core type samples (see section 7.3) except that a digital storage oscilloscope was used for transit time measurements. This means that these measurements were carried out on dry samples. The work was carried out in a mechanical workshop adjacent to a milling machine.

There are several difficulties associated with this technique. Firstly the very fact that the samples had to be removed from the ultrasonic measurement rig so that material could be ground off led to a variability in the measurements. This is because of the
difficulties associated with achieving the identical coupling regime when replacing the sample in the test rig.

Secondly obtaining samples with wide rings and little distortion of the ring pattern over the size of the sample block is quite difficult. Thirdly, the velocity in the removed layer had to be inferred from the difference in velocity between two much larger samples of similar magnitude. Needless to say even small experimental errors are important in such a situation.

The results of one such experiment are shown below in figure 8.11. The plot shows calculated velocities for the removed slice with decreasing sample thickness. In this plot the effect of removing an area of latewood can be observed at around 31mm. The errors associated with this measurement mean that it can only be used as a guide to the actual behaviour of the sample.

![Figure 8.11 Calculated Velocity Of Removed Slice With Distance From Pith.](image)

While direct measurement of the variation in ultrasound velocity in the radial direction as presented by the annual ring structure has proved difficult, it is possible to infer from the variation observed on the longitudinal and tangential directions that significant inhomogeneity is likely to be present also in the radial direction. This is supported by Kahle and Woodhouse (1994) who considered the influence of cell geometry on the elasticity of wood.

**8.9 Summary**

For the measurements reported in this chapter a novel measuring technique for determining the variation of the velocity of ultrasound within annual rings in the
longitudinal and tangential directions was reported. The annual ring structure of the samples was clearly visible in the data obtained. The ultrasonic readings were compared to microdensity density readings made on the same samples. A positive correlation between density and ultrasound velocity was observed. The significance of this is discussed in sections 9.2 and 9.3 along with other implications of these results (sections 9.1).

In respect of the method itself, the experimental error associated with the velocity measurements was high at 13.3%. The main source of error was uncertainty in determining the sample dimensions. This was mainly due to difficulties experienced in preparing regular, well dimensioned samples. This might be overcome by using dry wood samples and a high speed spindle saw. Such samples, if dimensioned to an accuracy of 0.01mm, would reduce the experimental error in the velocity determination to 2%.

As outlined in section 8.4.2.1, using a 0.5mm diameter hydrophone results in exaggerated recording of the latewood section of the ring. Hydrophones with 75 microns diameter are available and would reduce this effect significantly. A smaller diameter hydrophone would also reduce the region where the process of locating the received signal peaks is affected by the presence of signals from both earlywood and latewood.

The repeatability of the measurements would be enhanced by an improved technique for mounting and orienting the samples. In particular alignment of the sample with respect to the sound field and the ability to align the sample and hydrophone are issues which could be improved upon.

An improved measurement system based on the suggestions given here would be, given the time and resources, reasonably straightforward to implement. It could be of significant benefit to wood scientists as is discussed at the end of the next chapter.
9 THE INFLUENCE OF THE INHOMOGENEITY OF WOOD ON THE PROPAGATION OF ULTRASOUND.

In the previous chapter the inhomogeneity of wood in terms of its density and acoustic wavespeeds within an annual ring was measured. Significant variations in both density and the velocity of longitudinal ultrasound were observed. In this chapter the influence of this inhomogeneity on the properties of wood as well as the implications of this inhomogeneity for wood quality measurement using ultrasound are considered.

9.1 The influence of Inhomogeneity on the Propagation of Longitudinal Ultrasound Waves in the Radial Direction in Wood.

In chapter 6 of this work longitudinal ultrasound waves propagated in the radial direction in wood were seen to be severely attenuated. This effect was seen to be particularly strong in softwoods such as Norway spruce. In this section the influence of the inhomogeneity presented by the annual rings is put forward as one explanation for the severe attenuation experienced by longitudinal waves propagating in the radial direction.

In the radial direction in wood the annual rings present a quasi-periodic inhomogeneity to material waves. For this section the inhomogeneity is modelled using the layered model described in 3.5 of this work. The layered model predicts the existence of acoustic stopbands in the material, that is frequencies at which it is not possible to transmit a material wave through the layered system. That wood presents periodic density steps in the radial direction is clear from the densitometry trace in figures 8.2(a)-(d). While the existence of a periodic array of infinite extent is not an appropriate representation of a material such as wood, James et al.(1995) have shown that a finite number of layers, as little as five, can give rise to the existence of sonic bandgaps. It is also an assumption, of course, that the annual rings are identical (and thus equally spaced).
In order to use the layered model described in section 3.5 to determine whether the density and acoustic wavespeed variations might cause the appearance of stopbands, a number of physical parameters were required. These were the layer thicknesses, the acoustic impedances and the longitudinal acoustic wavespeeds of the two materials considered to make up the layered system.

Layer thicknesses and typical density variations were obtained from densitometry scans (section 8.2), from the literature (Desch and Dinwoodie, 6th (1981) and 7th (1996) editions; Davidson and Freas, 1987; Evertsen, 1986; Olesen 1977; Harvald and Olesen, 1987) and from consultation with a wood scientist with experience in measuring density variation and other properties of softwoods (Pedini, 1999). Acoustic wave speeds in early wood and latewood were obtained from the data measured in section 8.4. The data obtained from the measurement of radial velocity variations described in section 8.8 of chapter 8 is, however, rather less than satisfactory, in terms of its accuracy.

Thus for velocity data to input to the layered model we turned to the tangential velocity scan. In this direction the acoustic wave speed was seen to present significant variations between earlywood and latewood (figure 8.7). The stiffness of wood in the tangential direction is comparable to that in the radial direction (Bodig and Jayne, 1982). As a first approximation in this work we take the velocity variation between earlywood and latewood in the radial direction to be of the same order, in ratio terms, as that observed in the tangential direction. Given that the velocity scans in reported in chapter 8 show significant variation between earlywood velocity and latewood velocity in both the longitudinal and the tangential directions it is reasonable to hypothesise that the similar velocity variation will be observed in the radial direction.

Table 9.1 shows data used to generate a ‘typical’ dispersion relation of the form developed in equation 3.99 for a ‘typical’ young softwoods and a ‘typical’ mature hard wood. The main differences between hard wood and softwood in this case is taken to be the density variation between early wood and latewood, and the width of the annual rings.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hardwood (Ring Porous)</th>
<th>Softwood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Wood Thickness</td>
<td>0.5 mm</td>
<td>4.5mm</td>
</tr>
<tr>
<td>Early Wood Velocity</td>
<td>2000 m/s</td>
<td>1800 m/s</td>
</tr>
<tr>
<td>Early Wood Density</td>
<td>400 kg/m³</td>
<td>300 kg/m³</td>
</tr>
<tr>
<td>Late Wood Thickness</td>
<td>0.5mm</td>
<td>0.8mm</td>
</tr>
<tr>
<td>Late Wood Velocity</td>
<td>2200 m/s</td>
<td>2400 m/s</td>
</tr>
<tr>
<td>Late Wood Density</td>
<td>700 kg/m³</td>
<td>700 kg/m³</td>
</tr>
</tbody>
</table>

**Table 9.1:** Typical Physical Parameters Used In Evaluating Dispersion Relation For Wood As A Layered Material.

Considering just one such abrupt earlywood / latewood interface as presented in the softwood figures would give an intensity reflection coefficient of 0.38, or 38% of the incident energy (Pain, 1983). The hardwood case has a much lower reflection coefficient of 11% and indeed the transition may not always be abrupt (Bodig and Jayne, 1982). Figure 9.1(a) shows a plot of the dispersion relation for the case of young softwood, while figure 9.1(b) shows a plot of the dispersion relation for the mature hardwood case. Stopbands occur where the dispersion relation for the layered medium has values of greater than ±1, indicated by the horizontal bars in the graphs. (Brillouin, 1946, Gazanhes and Sageloli, 1994).

![Figure 9.1 (a): Plot Of Dispersion Relation Against Frequency For ‘Typical’ Young Softwood. Note stopbands indicated where dispersion relation has values >±1](image-url)
In the young softwood case the influence of the greater inhomogeneity in terms of density and acoustic wavespeeds is immediately clear. Stopbands are apparent at frequencies as low as 300kHz. Tables 9.2(a) and (b) list the stopbands generated by the model using the parameters in table 9.1. The dispersion relation for the more homogenous hardwood shows some evidence of stopbands but only at the higher frequency of 1MHz. This is evidenced in practice by better propagation in the radial direction in more homogeneous woods as observed in chapter 6. It should be noted the measurements made in chapter 8 were all made on softwoods. Thus the data used for table 9.2 in terms of wave velocity in hardwoods is a best estimate based on experience from the measurements in chapter 6.

Of course this analysis takes into account only the inhomogeneity presented by the density and velocity variations present due to the annual rings. At higher frequencies, beyond 1MHz, where wavelengths become of the order of 2 millimetres or less, the structures at a cellular level may become a significant source of scattering based attenuation.
Table 9.2(a) Table Of Stopbands Calculated for Softwood.

<table>
<thead>
<tr>
<th>Stopband Number</th>
<th>Lower Limit of Stopband (kHz)</th>
<th>Upper Limit of Stopband (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>144</td>
<td>190</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>382</td>
</tr>
<tr>
<td>3</td>
<td>470</td>
<td>572</td>
</tr>
<tr>
<td>4</td>
<td>650</td>
<td>758</td>
</tr>
<tr>
<td>5</td>
<td>834</td>
<td>942</td>
</tr>
<tr>
<td>6</td>
<td>1,024</td>
<td>1,116</td>
</tr>
<tr>
<td>7</td>
<td>1,214</td>
<td>1,280</td>
</tr>
<tr>
<td>8</td>
<td>1,406</td>
<td>1,428</td>
</tr>
<tr>
<td>9</td>
<td>1,572</td>
<td>1,594</td>
</tr>
<tr>
<td>10</td>
<td>1,720</td>
<td>1,786</td>
</tr>
<tr>
<td>11</td>
<td>1,884</td>
<td>1,976</td>
</tr>
</tbody>
</table>

Table 9.2(b) Table Of Stopbands Calculated for Hardwood.

<table>
<thead>
<tr>
<th>Stopband Number</th>
<th>Lower Limit of Stopband (kHz)</th>
<th>Upper Limit of Stopband (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>834</td>
<td>1,260</td>
</tr>
</tbody>
</table>

While the calculations above indicate that juvenile wood appears to offer the best conditions for the appearance of sonic bandgaps, in practice this does not appear to be the case. The model requires that the periodicity of the structure through which the wave is passing be very regular in both dimension and properties. The annual rings observed in juvenile wood on the other hand display significant variability in both size and density. Annual rings in juvenile wood are also significantly more curved than in adult wood.

All this can be taken to mean that adult wood samples are more likely to give rise to sonic bandgaps. However even in adult wood samples the necessary conditions are difficult to achieve. While reductions in received signal power at certain frequencies may often be observed, it can be difficult to attribute these reductions to a particular cause. Mode conversion and difficulties in obtaining repeatable coupling also obscure the issue. In figure 9.2 below are two examples of spectra obtained from softwood samples. These were obtained with equipment similar to that described in chapter 6 but the received (broadband) pulse was captured and Fourier transformed. Figure 9.2(a), obtained from Scots Pine with narrow (1mm), uniform annual rings appears to show a stopband just above 1MHz. Figure 9.2(b) obtained from Spruce with wider,
less regular rings does not appear to have a stopband within the range of the probes used.

Spectral Amplitude

![Spectral Amplitude](image)

Spectral Amplitude

![Spectral Amplitude](image)

(A) (B)

Figure 9.2: Spectra Of Signals Propagated Through (A) Scots Pine And (B) Spruce Samples.

9.2 Comparison of Inhomogeneity in the Longitudinal Velocity from Pith to Bark with other work.

The inhomogeneity observed in density terms presented by the annual ring structure of Larch wood was presented in figure 8.2(a). Variations in density from 400kg/m³ to 900kg/m³ are observed. The variation in ultrasonic wavespeed along the longitudinal direction for the corresponding sample was given in figure 8.5(a). Variations in ultrasound velocity from 2800m/s to 4300m/s are observed. Macroscopically the velocity in the longitudinal direction \( V_{\text{L}} \) may be linked to the density of the material by the relation given in Table 2.1:

\[
\rho V^2 = c_{11}
\]  

8.1

From this relation an inverse relationship would be expected between density and the square of velocity, assuming the elastic constant \( c_{11} \) remains constant. However as reported in 8.7 a strong positive correlation between density and velocity is observed.
This implies that there is a significant variation in elastic stiffness of the latewood material in comparison to that of the earlywood material.

This finding does not agree with the assumptions made by Kahle and Woodhouse (1994) when modelling $E_L$ from wood microstructure. Kahle and Woodhouse used the fraction of the cross-sectional area of micrographs covered by wood material to calculate $E_L$ in samples of wood. Effectively this links the relative density of the wood material to $E_L$. Using this measure the relative density model predicts strengths of the order of 9GPa for 400kg/m$^3$ early wood and 23GPa for 100kg/m$^3$ latewood. However the ultrasound velocity in the same sample ranges from 2800m/s to 4400m/s implying an $E_L$ range of 3GPa to 19GPa, more in line with the average figures (3.45GPa and 14GPa) for a laminate growth ring model used by Bodig and Jayne (1982). Thus it appears that the Kahle and Woodhouse model overestimates the contribution of earlywood to the Young’s modulus $E_L$. Taken in conjunction with the finding that velocity in the longitudinal direction correlates positively with density in chapter 8 this implies that a more sophisticated model is needed to explain the dependence of $V_{LL}$ on wood density.

9.3 Comparison of Inhomogeneity in the Tangential Velocity from Pith to Bark with other work.

In section 8.6 the results of a typical scan of velocity of longitudinal waves in the tangential direction were presented. Once again the annual ring structure is clearly visible. The velocities found in this scan were lower than those observed for the longitudinal direction, in agreement with the lower stiffness of wood found in the tangential direction compared to the longitudinal direction (Beery et al., 1983, Bodig and Jayne, 1982). The range of velocities measured was 1100m/s to 2000m/s, and again a positive linear correlation was found between ultrasound velocity and density. Using the simple relation given in 9.1 above for the tangential direction this would imply a range for $E_T$ for this particular sample of 0.7GPa to 4GPa, for earlywood and latewood respectively. These figures are significantly higher than those used by Bodig
and Jayne (1982) in their laminate model (0.207GPa and 0.69GPa) for describing growth ring behaviour.

Kahle and Woodhouse (1994) used a model based on an irregular honeycomb to calculate the value of $E_T$ from the arrangements of cell walls in the tangential direction in softwoods. They noted that the latewood stiffness acts in parallel with the earlywood stiffness when $E_T$ is evaluated on a pieces of timber covering several annual rings. They observed that latewood stiffness can be an order of magnitude greater than earlywood stiffness so that models evaluating its contribution to overall strength should treat latewood stiffness carefully and perhaps this is a factor in the overestimation of the tangential modulus using material waves.

9.4 Summary Regarding the Measurements Reported in Chapters 8 and 9.

The novel experiments reported in chapter 8 give results of some interest not only to workers applying ultrasound to the determination of wood quality and but also to workers interested in assessing wood quality at a microstructural level who may not have considered the application of ultrasound to such problems.

The presence of inhomogeneity in wood due to its annual ring structure has been shown to be of major significance when propagating material waves through wood. Most workers examining wood consider scattering due to air filled cells to be the major source of attenuation in for ultrasound propagating in wood. Most workers also consider that by working at frequencies of the order of a few hundred kHz that attenuation is not a significant factor.

However the layered model applied to the case of wood in this chapter shows that it may be possible to encounter stop-bands at frequencies as low as 150kHz based on propagation on data describing a 'typical' young softwood (Pedini, 1999). Thus it appears that the inhomogeneity presented by the annual rings should not be ignored, particularly when propagating through softwoods. It should be noted that Berndt and Johnson (1995) have also found indications that stopbands might occur in wood using a pulse-echo immersion technique.

The inhomogeneity due to the annual rings also gave rise to the velocity patterns observed in sections 8.5 and 8.6 which are for waves travelling along the longitudinal
and tangential axes. Such velocity variations could lead to erroneous readings of attenuation and greater uncertainty in velocity readings due to a potential phase cancellation artefact as discussed in 4.7. Again the worker should be aware of these possible effects when designing experiments.

The measurements reported in Chapter 8 show that density alone does not explain the variation in stiffness across the annual ring. There is clear potential for further work in this to measure the contributors to stiffness both within an annual ring and from pith to bark. Such a study would involve measuring ultrasound velocity, density, microfibril angle and fibre length. The technique of measuring ultrasound velocity variation within rings has the potential to give stiffness quality information of great benefit to wood scientists working on wood quality improvement studies for growing trees, as well as scientists working on microstructural models of wood.
10 CLASSIFICATION OF WOOD SPECIES BY NEURAL NETWORK ANALYSIS OF ULTRASONIC SIGNALS

Many studies have been carried out on the propagation of ultrasound in wood (see chapter 5). As was seen there, the majority of these studies focus on measuring the group velocity or relative attenuation in the material to estimate a physical parameter such as an elastic constant.

Material waves which have passed through a particular species of wood may be expected to show the influence of the species through which they have travelled. The range of measured values of wave velocity and attenuation for one species often overlaps with the measured values from other species (figure 10.3 below). This implies that identifying the species of wood from an ultrasonic waveform is a difficult task.

In this section it is proposed that the overall shape of the received waveform may be a characteristic of a particular species. Thus the possibility of using this received waveform to identify the species of wood through which a particular signal has passed is investigated. Artificial neural network analysis, as described in the following sections is used to classify the received waveforms in terms of species.

10.1 Introduction to Artificial Neural Networks

Artificial Neural Networks (ANNs) are machine learning algorithms: they can be used to learn a task from examples. In many interesting problems there is some knowledge of the problem and some idea about solutions but not enough is known to write a set of rules or program which will perform well enough on a task. Speech recognition is typical of such a problem. A worker may collect a range of utterances of certain words. In such a case the utterances are input signals and the words uttered may be considered outputs. The task of
linking the utterances to the words can be performed by machine learning algorithms such as ANNs.

The example of speech recognition is not too far away from the application of ANN analysis considered in this chapter. Here we consider ultrasonic signals received through different species of wood as the input signals and the species through which the signal propagated as the desired output.

The direct result aimed for is a system for identifying the species of wood samples from the received signal. A secondary output from successful development of such a system is the knowledge that, under appropriate conditions, the unique microstructure of each species of wood can interact with a material wave passing through it in such a way as to give the material wave a characteristic shape.

10.1.1 Models of Neural Network Behaviour.

ANNs are based on a connectionist model. Connectionism has been described as the study of certain classes of massively parallel architectures composed of a large number of similar and simple processing units (Bengio, 1996).

As the term neural network indicates they have been inspired by biological and psychological models. An untrained ANN consists of a large number of equal processing units with similar connections. When learning a particular task (‘training’) the connections between the inputs and the processing elements of an ANN are changed in weight or strength until such time as the ANN has minimised the error between the ideal output data and the desired output data based on the input signals given to it.

Interesting characteristics of neural networks include a reported ability to generalise - that is to develop rules for dealing with input signals not directly presented in the training set. Applications of neural networks include speech recognition, vision systems, handwriting recognition and other classification problems (Bengio 1996: Davalo and Naim, 1991).
10.1.2 The Perceptron.

The perceptron was one of the first models of the neuron proposed. The perceptron model has three principal elements (Davalo and Naim, 1991). The first is a 'retina' on which the stimulus is input. Generally the cells in the retina react in an all or nothing manner. The next layer in the perceptron is a layer of associative cells. Each of these may be connected to cells of the retina, to other associative cells and to decision cells described below. In general these cells follow an all or nothing law, comparing the effective sum of inputs to a threshold.

The decision cells form the last layer in the perceptron. These represent the output of the perceptron and operate in the same manner as associative cells, receiving their input from associative cells or from other decision cells.

10.1.3 Multi-Layer Architecture.

ANNs are networks of neurons computing a non-linear function of their inputs, which come from other inputs or from external inputs. The typical computation performed by such a unit is a scalar function of the weighted sum of its inputs:

\[ y_i = f \left( \sum_j w_{ij} + b_j \right) \]

where \( y_i \) is a scalar output for unit \( i \). For a multi-layered architecture, unit \( j \) and unit \( i \) above belong respectively to successive layers of units. \( b_i \) is a parameter sometimes called a bias, or its negative is called a threshold. The parameters \( w_{ij} \) (the weights) represent the existence and strength of connections between units. The weights and biases of the ANN are tuned by the learning algorithm to optimise some training criterion. The scalar function \( f(.) \) is usually a non-linear squashing function - quasi-linear near the origin but flat near the extremes.
Figure 10.3 below shows a representation of a typical multi-layer network of the sort used in this study. Units are arranged in layers, with an input layer, an output layer and a certain number of intermediate or hidden layers.

The learning algorithm used in this case was based on the idea of gradient descent. The performance of the network was measured by the mean squared error (MSE) criterion. In this case the objective is to minimise the sum of the squares of the differences between the network output and the desired output. For a certain input pattern x the squared error is:

\[ C = \sum_i (M_i(x,w) - \text{desired}_i)^2, \]

where \( \text{desired}_i \) is an ideal output value for output unit i and \( M_i(x,w) \) is the actual network output for unit i, that is a function of the input x and of parameters w. The principle of gradient descent is that in order to reduce the output error one changes the parameters in the direction given by the derivative of the output error with respect to the gradient, \( \delta C/\delta w \).

10.2 Experimental Arrangement for Acquisition of Signals for Neural Network Classification Study.

A pair of 0.5MHz nominal frequency, 20mm diameter broadband longitudinal wave probes were employed as transmitter and receiver in a through-transmission technique. The probes were excited using a broadband pulse from a Panametrics pulser/ receiver. Coupling was achieved by the means of the torque wrench system described in 7.3. The probes had 10mm thick hard rubber delay lines applied to the face to improve coupling. The measurements were carried out on waves propagating along the longitudinal axis of symmetry. The ultrasonic pulse velocity and received signal amplitude were calculated for each sample based on the time position and amplitude of the received peak compared to the time position with no sample in place. (This velocity information was used to draw figure 10.2 but was not used for the neural network study.)
Neural networks train better if knowledge about a task is used to introduce structure and meaningful representation into the design of the system (Bengio, 1996). The longitudinal direction was chosen for this study since it is the direction least influenced by structures in the wood. As pointed out in the work on inhomogeneity (chapters 8 and 9) in the radial direction the periodicity of the annual rings has a strong influence on wave motion in this direction. The curvature of the rings influences propagation in the tangential direction. Both of these effects tend to obscure the species to species variation.

In a pilot study on artificial neural networks, longitudinal waves, classified in the time domain, were also found to give better classification results than either shear waves or classification in the frequency domain. It is supposed that inhomogeneities, particularly due the annual ring structure, had an influence on the signal which masked species to variation in the shear waves.

10.3 Preprocessing of Ultrasonic Waveforms

The ultrasonic waveforms were processed prior to input to the neural network. The amplitude data was scaled to a maximum of one. This has the effect of masking the variation of received signal amplitude from sample to sample and species to species. Time data was adjusted so that the first minimum of each signal occurred at the same point in each waveform before being used in the neural network. Thus direct velocity information was unavailable to the neural network.

10.4 Numbers of Species/Samples

The four different species of wood used were Oak, Alder, Maple and Pine. The wood samples were selected at random from the stocks of a wood processing factory and were high quality joinery wood. Ten samples of each species of wood were chosen. From each of these samples three 30mm lengths were cut. The samples were 25mm in each of the
tangential and radial directions. This gave a total of one hundred and twenty samples, thirty samples from each of the four species.

Twenty of the thirty samples from each species were randomly chosen to provide data for training the neural network. The other ten samples from each species of wood were kept aside for testing the ability of the system to classify the different species, after training of the network (figure 10.1).

![Experimental Design used for Training and Testing Neural Network](image)

Figure 10.1: Experimental Design used for Training and Testing Neural Network

10.5 Ultrasonic Velocity Measurements

Ultrasonic velocity measurements were carried out on the samples for the purpose of illustrating the overlap in velocities between the different species. Values obtained ranged from 3800m/s to 4850 m/s. As is evident from figure 10.2 below, velocity values for each species did indeed overlap. Received signal amplitudes also overlapped prior to scaling for
input into the network. Clearly this precludes the use of velocity or received signal amplitudes for species classification.

![Plot Of Mean, Maximum And Minimum Velocity For Samples Used In Neural Network Species Classification Study.](image)

**Figure 10.2** Plot Of Mean, Maximum And Minimum Velocity For Samples Used In Neural Network Species Classification Study.

### 10.6 Design of the Neural Network

The ANN was designed using the Neural Network Toolbox for the MATLAB software package. A multi-layer perceptron (MLP) model was used for the neural network classifier (Davalo and Naim, 1991). The most successful neural network was found to be an MLP with 700 nodes in the input layer, 8 nodes in the hidden layer and 4 output nodes, as shown in figure 10.2. Log-sigmoidal functions were used in the perceptrons and a backpropagation algorithm was used for learning.

The 700 input nodes were the time record of the digitised waveform. The first positive peak was been brought to point 50 in the time record and amplitudes normalised to give a maximum value of 1. This was an effort to remove time and amplitude information from the signal to see if it could classify based on the remaining information in the signal.. The network was trained using a standard back propagation algorithm.
10.7 Artificial Neural Network Classification Results

The neural network was trained using eighty waveforms (twenty of each species) obtained from different samples. These waveforms were pre-processed as described in section 10.3. The training set was re-introduced to the network. All eighty of the training waveforms were correctly classified. The test data was then input into the network. Thirty nine of the
forty previously unseen samples were correctly classified by species. The fortieth sample was not associated strongly with any particular species.

Thus artificial neural network analysis of ultrasonic signals has been shown to be successful in classifying ultrasonic signals by species. The success rate when compared with other neural networks applied to biological classification problems is high [Kilmartin et al, 1993, Hughes et al., 1979]. The former authors for example, gave a figure of 63% in the diagnosis of liver disorders.

This result leads to several conclusions. Clearly the proposal that each species can affect a material wave travelling though it in a characteristic fashion has been shown to be credible. It is interesting that species were still identifiable even though groups of samples were chosen which overlapped both in terms of velocity and received signal amplitude.

Identifying the species of a sample of wood from the visual and even microscopic inspection of wood alone can be a notoriously difficult task. The technique reported here is potentially of assistance to workers in the field of species identification.

The next task in relation to this type of work is to identify the characteristics of the received signals which the neural network used for the classification process. After identifying the characteristics of the received signals, the next, more challenging, task would be to gain an understanding of the physical processes which give rise to the characteristic wave forms: in other words to find those elements of the microstructure of the wood which contribute to the characteristic waveforms.

Such further work as described in the previous paragraph could best be undertaken in the context of a larger study over a wide range of samples both in terms of numbers and species. Some success has been achieved in another context of using neural networks to analyse CT images of wood for the automatic detection of knots (Javadpour et al., 1996).
11. CONCLUSION AND DISCUSSION

In the opening chapter of this thesis wood was described as a strong, light and flexible material with many engineering applications. However it was noted that its natural origin and consequent variability mean that each individual piece of wood must be subject to some form of quality assessment before use. In chapter 5, the application of typical non-destructive strength and elastic quality assessment techniques was shown to be problematic when applied to such a variable anisotropic and inhomogeneous material such as wood. The stated aim of this thesis was to advance the knowledge of the interaction of material waves with wood and thereby to assist in the task of assessing the quality of wood.

11.1 The Nature of the Problem

The original impetus that lead to this work was the impression that elastic wave propagation techniques were not being exploited to their potential in application to wood. From the review of the literature in chapter 5 it is clear that may workers have made significant efforts to apply ultrasonic techniques to solve technical measurement problems associated with determining the quality of wood. Thus efforts have been made to assess the elastic behaviour of samples, to determine the presence of rot, to locate and size flaws, and to determine the moisture content in samples. Practically all of these studies have been successful in the sense that that ultrasonic wave propagation has been shown to be sensitive to the parameter under investigation. However only in a limited number of cases has the measurement technique “taken off” in terms of commercial application.

For example Ross et al (1997) report that the principle application of elastic waves to non-destructive evaluation in lumber is stress waves grading of veneers used to form laminated veneer material (Ross et al. 1997). Sandoz, 1989, has had some success in having ultrasonic measurement of $E_L$, the Young’s modulus in the longitudinal direction accepted for the grading of lumber in Switzerland. Ross and Pellerin, (1994), have also reported that elastic wave propagation techniques have been successfully applied to problems of non-destructive evaluation of wood members in structures. These tend to have been
exercises in the determination of rot in one-off timber structures. There is a clear role for ultrasonic techniques in this area as part of a ‘preventative maintenance’ regime. The technique tends to be expensive to apply and so may be of interest only in special cases. What is clearly needed is a reliable and effective technique that can be applied economically on a much broader basis. A broader basis can be taken to include both broader in terms of the proportion of timber on which tests are actually made, and broader in terms of the range of stages in the process of timber production and use at which testing is applied. The need for a rapid and effective technique requires that it be easy to use but does not necessarily imply that it must have a simple scientific basis. With the power of modern electronics signal processing techniques the quest is rather to understand the basic science at whatever level of complexity is appropriate, and then to look for ways of instrumenting it.

11.2 The Role of Inhomogeneity in Ultrasound Transmission in Wood.

One hypothesis which might explain the lack of exploitation of non-destructive techniques applied to wood is that when non-destructive testing techniques are applied to wood, it is necessary to take into account its unique structure, severe anisotropy, natural origin, and indeed the fact that wood is a general term which covers a class of materials with quite disparate elastic properties rather than a single material.

A review of the literature shows widespread acceptance the orthotropic elastic model as a basis for describing the elastic behaviour of wood. This model is generally accepted as a good model when dealing with mechanical testing of structural lumber (Desch and Dinwoodie, 1996; Bodig and Jayne, 1982). However the orthotropic model ignores the quasi-periodic inhomogeneity presented by the annual rings in wood. Most of the work reviewed in Chapter 5 accepts the premise that it is the scattering of elastic waves from the air filled voids in the cells of wood dry wood which place an upper limit on the frequencies which can propagate through wood.

With the exception of some empirical work presented by Berndt and Johnson (1995), the validity of the assumption as to whether it is safe to ignore the inhomogeneity presented
by annual rings has not been examined experimentally. Indeed the extent and influence of the inhomogeneity of wood in elastic wave terms has not been the subject of serious investigation.

11.3 The Contributions of This Thesis.

There is a considerable body of literature on attempts at using ultrasonics techniques to characterise wood. However before the status of this literature can be properly assessed it is necessary to have some understanding of three distinct areas of knowledge. The first of these is the structure of wood, the process of its growth, and the dimensional scales of its microstructure. This is briefly discussed in chapter 2. The second fundamental area is the theoretical basis of elastic wave propagation in solids. The usual model for wood - of an (homogeneous) orthotropic material - is discussed in detail in chapter 3, together with two extensions. The first of these briefly notes the effect of specimen size, and the conditions under which the waves being measured cannot be considered to be bulk plane waves. The second extension considers the effect of microstructural inhomogeneity - namely the annual growth rings. The analysis of waves travelling (in a radial direction) through a periodic structure is presented and the relevant formula for the existence of stop-bands and pass-bands are derived.

The third major area of importance for critical assessment of the literature is that of ultrasonic measurement science. Rather than attempt a comprehensive review of this area, chapter 4 catalogues the key areas of difficulty associated with measurements of ultrasonic velocity and attenuation on wood. This includes the identification of two potential sources of error that do not appear to have been mentioned before.

With this basis chapter 5 reviews the literature on the use of ultrasonic techniques for quality assurance in the timber industry. It is probably the only succinct review available which ranges from grading techniques to sophisticated science and thus permits the main work of the thesis to be seen in context.

Of particular interest is the fact that, in spite of (or indeed perhaps because of!) the very many potential variables involved, the author has failed to find a single example of any
attempt by one author to confirm the results of previous workers by repeating their experiments. The simple orthotropic model for propagation in wood mentioned above implicitly assumes no losses. Thus the elastic constants derived from measurements of ultrasonic velocity based on the model are essentially independent of frequency. In fact there are significant losses. Before the work of this thesis the evidence of their frequency dependence was uncertain. However the evidence suggested that the attenuation would depend on frequency, and this would of necessity imply velocity dispersion. As was shown in chapter 3, one of the measurement compromises that has to be made involves the choice of specimen size. It is limited by the intrinsic nature of the material. If the specimen is too big, it will attenuate higher frequencies beyond the possibility of measurement, but if lower frequencies are used the possibilities of guided waves enter the discussion. If the prime objective is determination of the elastic constants, the velocity dispersion is a key piece of information since if it is small the frequency of the measurements will not matter. There appeared to be no definitive statement on this subject in the literature.

As a result the main part of this thesis is devoted to a systematic attempt to measure velocity and attenuation in some woods. Three species were carefully chosen as being characteristic of the main types of microstructure observed. Measurements were made at five frequencies between 100kHz and 1.5MHz of longitudinal and shear waves (two polarisations), along the principal axes and at angles stepped at 15° to these axes. Although not quite comprehensive the study involved over 1000 measurements each of which required separate location and adjustment of the specimens.

It was found that there is clear evidence of velocity dispersion in several cases - and probably evidence of dispersion in many others, for waves propagating along the principal axes. The Horse chestnut specimens displayed the most significant detectable dispersion for longitudinal waves in all propagation directions. Horse chestnut has a ring porous structure which makes it the wood with the largest consistent bands of voids of the three measured in this study. Maple, the most uniform wood in the study, with small pores distributed throughout the specimen also displayed some dispersion albeit not as consistently as Horse chestnut. Norway spruce also displayed some dispersion for those directions in which it was possible to measure.
Furthermore, as seen in chapter 6, there is clear evidence that in all cases the attenuation depends strongly on frequency. The attenuation results appear to present a less monotonic response with frequency with severe attenuation being observed after certain frequencies for both Horse chestnut and Maple. Norway spruce was also seen to display increasing attenuation with frequency, with attenuation so severe in some cases that only the 100kHz signals were detectable.

The possibility that the annual ring structure might play a role in ultrasound propagation is given some credibility by the results from the attenuation measurements in Chapter 5. These measurements showed that waves propagating in the Norway spruce samples in particular experienced more attenuation than the other two species. Horse chestnut is a ring porous wood with large pores. The pores in Horse chestnut are typically an order of magnitude larger than the cell diameter of tracheids observed in softwoods such as Norway spruce (Desch and Dinwoodie, 6th Edition, 1981). Thus if scattering was the only basis for the observed attenuation one would expect the Horse chestnut to display attenuation at a lower frequency than Norway spruce. However the reverse occurs in practice. This is of interest since of the three species used Norway spruce was the only species with particularly distinct annual rings.

The orthotropic model of elasticity has been used to generate slowness curves for various types of timber based on static data. In chapter 5 the form of these slowness curves was seen to follow the form of the experimental slowness curves in general. However some of the features present in the experimental results are not predicted by the theoretically developed slowness curves. A ‘pinching’ of the slowness curves for longitudinal waves as the longitudinal axis is approached indicated that the change in elasticity with propagation angle may be different than that assumed by the model as the longitudinal axis is approached. Also a potential asymmetry was observed for shear wave velocities between the TL wave and the LT wave. Indeed when considering shear wave attenuation results a marked asymmetry was observed.

In order to investigate the question of the dependence of ultrasonic wave propagation on some of many variables, a study was constructed on the variation of ultrasonic velocity
with position in a tree (chapter 7). Measurements were made along increment cores from bark to pith at three heights in the tree from seven trees. This study reveals the variation of ultrasound properties that may be observed within a tree and indicate how much care should be taken when one is selecting samples for measurement. Even adjacent regions in a tree can have significant variations between them. The pattern of velocity variation observed was seen to differ from the typical density variation pattern observed giving rise to the possibility of enhanced understanding of microstructural variations within trees.

The critical problem of the importance of the obvious inhomogeneity of the wood structure for ultrasonic wave propagation was investigated by a novel set of measurements described in chapter 8. Measurements were made of velocity with sufficiently high resolution to resolve the annual ring structure, using a miniature hydrophone in a scanning tank. The data was compared with density measurements made using X-ray densitometry. 

The results showed that there was significant variations in velocity depending on whether a wave was propagating through the earlywood or the latewood part of the annual ring. This inhomogeneity was measured directly in the tangential and longitudinal directions and inferred for the radial direction. The ultrasonic measurements made on samples in chapter 8 were also correlated with density measurements on the same samples and a positive correlation found.

The implications of the inhomogeneity measured in Chapter 8 was discussed in Chapter 9. It was shown, using data based on a ‘typical’ young softwood, that stopbands can appear for frequencies as low as 150kHz for elastic waves propagating in the radial direction. Data used to describe a ‘mature hardwood’ showed that it may be possible to observe a stopband at frequencies around 1MHz, although it would be necessary to carry out elastic wave measurements of inhomogeneity in hardwoods in the same fashion as was determined for softwoods to be more definite about this. Thus when making measurements in the radial direction attenuation is likely to become severe for particular combinations of propagation frequency and annual ring spacing. Attenuation measurements made without an awareness of this phenomenon may well cause ‘sound’ samples to be classified as lower grade ‘unsound’ samples. One way to circumvent, or at
least identify, this problem would be to use broadband techniques for measurement in the radial direction.

The annual ring structure of wood also gives rise to interesting effects for waves propagating in the longitudinal and tangential directions. A classic phase cancellation artefact can arise where a wave which has travelled through slower early wood may arrive at a receiving transducer out of phase with a wave which has propagated through faster latewood. The net effect of the two waves arriving at different points on the transducer may be to cancel later parts of the faster wave with early parts of the slower wave. Indeed many different possibilities exist depending on the dimensions of the earlywood, the dimensions of the latewood, the elastic wave velocities in each, the dimensions of the samples and the dimensions of the receiver. Again workers in the field need to be aware of this phenomenon.

The particular patterns of measurement using the conventional basis of plane wave propagation in a material as complex as wood were discussed in chapter 3 and emphasised by the experimental results of chapter 6. It is probable that the mechanisms which confound this approach - most probably those of mode conversion-produce wave packets that are characteristic of the microstructure that produces them. In order to begin to assess this idea an artificial neural network analysis was applied to the received waveforms (chapter 10). It is shown that it is possible to classify received signals by the species of wood through which they have travelled. This despite the fact that the velocities of the waves overlapped in the different species. The artificial neural network technique approach adopted in this work represents a first application of neural network classification to ultrasonic signals in wood. It represents one potential approach to the engineering problems such as flaw detection in wood. While the artificial neural network approach is a black box approach to problem solving, it works best when the problem presented to it is well posed.

It is clear from the previous sections that there is no shortage of avenues which could be profitably explored in future work. What is perhaps important is that each study be carefully designed and aimed at testing a specific hypothesis.

While pursuing the measurement of inhomogeneity in wood in elastic wave terms it became clear that the measurement technique under development might have more relevance than to estimate inhomogeneity for the purposes of modelling ultrasound propagation in large samples. In particular the within ring measurements of elastic wave propagation, in conjunction with density measurements, were able to test hypotheses put forward by Kahle and Woodhouse, 1984, in regard to the origin of the elastic stiffness of wood. Given a full scientific study of density, microfibril angle, tracheid length as well as elastic wave velocity it should be possible to gain a fuller understanding of the basis of the elastic properties of wood.

The measurements made on dry increment core type samples in Chapter 6 show the variation of longitudinal velocity within the tree. These measurements are more accessible than the water tank based measurements. While not offering the same level of detailed information as the inhomogeneity measurements they might be of interest to wood scientists concerned with how a particular stand of trees is developing. It would be an interesting study to measure ultrasonic pulse velocity, as was measured in this case, in conjunction with microfibril angle and density. It is possible that the ultrasound technique can provide a relatively straightforward assessment of elastic variation with in a tree or stand of trees. It may even be possible, when taken in conjunction with density measurements, to have a more convenient technique for the assessment of variation of microfibril angle than currently exists.

At present it would appear that the theoretical models available are adequate, the problem appears to be the lack of sufficient quality of experimental work to test them effectively. A relatively large study would be one carried out to determine elastic constants on the same
species of wood measured in chapter 6. It should be possible to carry out measurements on a more representative selection of samples at fewer angles. Measurements along the principal axes, at 45°, and at angles near the longitudinal axis (to examine the ‘pinching’ effect) might be sufficient. Clearly it would be of interest to measure a complementary set of samples tested by alternative techniques such as MOE/MOR testing or resonance testing. However it might be more profitable to concentrate on resolving the reported difficulties in the ultrasonic techniques for determining elastic properties (Bucur and Archer, 1984) before undertaking a comparison study which would have to be on a very large scale to overcome variations due to the different samples sizes and shapes required by each technique.

Since the measurements reported in chapter 6 were carried out improved signal processing techniques (including simple averaging techniques) and improved transducers have become available. This should permit improved signal to noise ratios for the weaker signals and thus the selection of larger specimens. It should also be possible to examine the phenomenon of dispersion using a broadband pulse technique, provided it is possible to resolve the received modes in the time domain.

A preliminary study might be carried out to examine the possibility of using an immersion tank measurement techniques on varnished or wax coated samples for the determination of elastic coefficients. Such a technique has the advantage of reducing coupling uncertainties.

A study could also be carried out to determine the difference in reflection and transmission coefficients which might be observed for shear waves impinging on a wood surface with different polarisation angles. It might be possible to get a first approximations to the variation in reflection coefficients by measuring the reflections from a buffer-wood surface for a buffer inserted between normal shear wave probes and wood samples.

Advances in air coupled transducer technology point to one possible development route for the application of ultrasonics in the sawmill. Such technology, appropriately applied has potential benefits for both flaw detection and grading problems, particularly if used in conjunction with other non-destructive testing techniques such as vision systems.
Clearly there is no shortage of possibilities for further work in the application of ultrasonic techniques to wood quality determination. In terms of the work reported in this thesis probably the simplest next steps would be to consider a study on microfibril angle, density and ultrasound velocity based on the method reported in chapter 7. Improved sample dimensioning and using a smaller hydrophone could lead to a study of within ring ultrastructure variations as reported in chapter 8. Using a broadband pulse technique to study dispersion in solid wood samples would also represent a straightforward development of the work reported in chapter 6.

The artificial neural network study reported in Chapter 10 also offers possible interesting developments. Firstly one could further analyse the existing signals and neural network to find which elements in the input signals are most important for successful classification. Thus one would try to define the characteristics in the received signals used by the neural network for classification. A natural extension of this would be to relate the signal characteristics used for classification to the microstructure of the species being studied.

Secondly one could carry out a wider study on a larger number of samples to determine how good the system is at generalisation. It is worth remarking that identification of the species of wood samples by examining the wood alone can be a difficult task so that using ultrasound to identify the species of wood may prove of benefit in itself.

Thus it is that while some questions have been answered, a new set of questions open up. It seems like a good point to draw this particular work to a close and draw breath before tackling the many challenges which lie ahead in this complex but rewarding field.
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Appendices

Appendix 1 Velocity and Attenuation Data Discussed in Chapter 6 A-2
Appendix 2 Velocity Data Discussed in Chapter 7 A-15
Appendix 3 Signal Analysis Program used in Chapter 8 A-20
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Appendix 1

**Velocity and Attenuation Data Discussed in Chapter 6.**

<table>
<thead>
<tr>
<th>Wave type, species.</th>
<th>Table Number</th>
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<td>A3-A4</td>
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<td>A13-A14</td>
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Table A.1 Velocity of longitudinal waves measured at specified angles and frequencies in the LR plane of a Horse Chestnut sample.

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<th>Frequency Angle</th>
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<th>250kHz Velocity m/s</th>
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Table A.2 Attenuation of longitudinal waves measured at specified angles and frequencies in the LR plane of a Horse Chestnut sample.

<table>
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<th>Frequency Angle</th>
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<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
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<td>19.6</td>
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Table A.3 Velocity of longitudinal waves measured at specified angles and frequencies in the LT plane of a Horse Chestnut sample.

<table>
<thead>
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<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>4249</td>
<td>4568</td>
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<td>3657</td>
<td>3680</td>
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<td>2268</td>
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<td>2014</td>
<td>2327</td>
</tr>
<tr>
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<td>1808</td>
<td>1768</td>
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<td>1623</td>
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<td>1271</td>
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### Table A.4 Attenuation of longitudinal waves measured at specified angles and frequencies in the LT plane of a Horse Chestnut sample.

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>14.0</td>
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<td>19.5</td>
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<td>24.6</td>
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<td>28.5</td>
<td>26.4</td>
</tr>
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<td>21.3</td>
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<td>26.5</td>
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<tr>
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<td>22.8</td>
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<td>23.4</td>
<td>25.1</td>
<td>26.5</td>
</tr>
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<td>24.1</td>
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### Table A.5 Velocity of longitudinal waves measured at specified angles and frequencies in the RT plane of a Horse Chestnut sample.

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2119</td>
<td>2153</td>
<td>2188</td>
</tr>
<tr>
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<td>1767</td>
<td>1648</td>
<td>1868</td>
<td>1925</td>
<td>1945</td>
</tr>
<tr>
<td>30</td>
<td>1566</td>
<td>1449</td>
<td>1566</td>
<td>1602</td>
<td>1539</td>
</tr>
<tr>
<td>45</td>
<td>1372</td>
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<td>60</td>
<td>1284</td>
<td>1256</td>
<td>1284</td>
<td>1302</td>
<td>1313</td>
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<td>1234</td>
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<td>1270</td>
<td>1284</td>
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</table>

### Table A.6 Attenuation of longitudinal waves measured at specified angles and frequencies in the RT plane of a Horse Chestnut sample.

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>17.2</td>
<td>21.5</td>
<td>20.9</td>
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<tr>
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<td>21.0</td>
<td>20.7</td>
<td>25.0</td>
<td>26.8</td>
<td>26.5</td>
</tr>
<tr>
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<td>22.2</td>
<td>20.7</td>
<td>24.0</td>
<td>no signal</td>
<td>26.5</td>
</tr>
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<td>22.2</td>
<td>20.7</td>
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<td>no signal</td>
<td>26.5</td>
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<td>20.7</td>
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<td>26.5</td>
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<td>21.0</td>
<td>24.1</td>
<td>26.8</td>
<td>26.5</td>
</tr>
<tr>
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<td>23.4</td>
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</tbody>
</table>
**Table A.7 Velocity of shear waves measured at specified angles and frequencies in the LR plane of a Horse Chestnut sample.**

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
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<td>1794</td>
<td>1796</td>
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<td>1610</td>
<td>1617</td>
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**Table A.8 Attenuation of shear waves measured at specified angles and frequencies in the LR plane of a Horse Chestnut sample.**

<table>
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<tr>
<th>Frequency Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
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<td>23.0</td>
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<td>19.6</td>
<td>23.1</td>
<td>24.8</td>
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<td>20.0</td>
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<td>23.1</td>
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<td>19.8</td>
<td>22.1</td>
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**Table A.9 Velocity of shear waves measured at specified angles and frequencies in the LT plane of a Horse Chestnut sample.**

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<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
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<td>1381</td>
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<td>1519</td>
<td>1519</td>
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### Table A.10 Attenuation of shear waves measured at specified angles and frequencies in the LT plane of a Horse Chestnut sample.

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<th>Frequency Angle</th>
<th>100kHz Attenuation (dB/cm)</th>
<th>250kHz Attenuation (dB/cm)</th>
<th>500kHz Attenuation (dB/cm)</th>
<th>1MHz Attenuation (dB/cm)</th>
<th>1.5MHz Attenuation (dB/cm)</th>
</tr>
</thead>
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<td>24.8</td>
<td>25.5</td>
</tr>
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<td>21.5</td>
<td>21.7</td>
<td>23.1</td>
<td>24.8</td>
<td>26.5</td>
</tr>
<tr>
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<td>16.8</td>
<td>17.3</td>
<td>20.2</td>
<td>24.8</td>
<td>26.5</td>
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<td>18.6</td>
<td>17.0</td>
<td>20.5</td>
<td>21.4</td>
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<td>19.6</td>
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<td>18.3</td>
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### Table A.11 Velocity of shear waves measured at specified angles and frequencies in the RT plane of a Horse Chestnut sample.

<table>
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<th>Frequency Angle</th>
<th>100kHz Velocity (m/s)</th>
<th>250kHz Velocity (m/s)</th>
<th>500kHz Velocity (m/s)</th>
<th>1MHz Velocity (m/s)</th>
<th>1.5MHz Velocity (m/s)</th>
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</thead>
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<tr>
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<td>573</td>
<td>523</td>
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<td>714</td>
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<tr>
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<td>804</td>
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<td>674</td>
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<td>510</td>
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<td>625</td>
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### Table A.12 Attenuation of shear waves measured at specified angles and frequencies in the RT plane of a Horse Chestnut sample.

<table>
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<th>Frequency Angle</th>
<th>100kHz Attenuation (dB/cm)</th>
<th>250kHz Attenuation (dB/cm)</th>
<th>500kHz Attenuation (dB/cm)</th>
<th>1MHz Attenuation (dB/cm)</th>
<th>1.5MHz Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
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<td>28.3</td>
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<td>24.9</td>
<td>28.3</td>
<td>no signal</td>
<td>no signal</td>
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<td>15.7</td>
<td>20.3</td>
<td>20.9</td>
<td>22.6</td>
<td>22.6</td>
</tr>
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<td>16.4</td>
<td>19.2</td>
<td>20.9</td>
<td>21.5</td>
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<tr>
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<td>19.2</td>
<td>22.2</td>
<td>25.6</td>
<td>28.4</td>
</tr>
<tr>
<td>75</td>
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<td>19.5</td>
<td>20.9</td>
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<td>24.9</td>
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<td>25.0</td>
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</tbody>
</table>
### Table A.13 Velocity of longitudinal waves measured at specified angles and frequencies in the LR plane of a Maple sample.

<table>
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<th>Angle</th>
<th>Frequency</th>
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<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
<th>90</th>
</tr>
</thead>
<tbody>
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<td>3375</td>
<td>2908</td>
<td>2350</td>
<td>2152</td>
<td>1852</td>
<td>1833</td>
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<td>3789</td>
<td>3285</td>
<td>2552</td>
<td>2161</td>
<td>1939</td>
<td>1804</td>
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<td>4234</td>
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<td>2966</td>
<td>2250</td>
<td>2014</td>
<td>1844</td>
</tr>
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<td>4472</td>
<td>4035</td>
<td>2811</td>
<td>2290</td>
<td>2051</td>
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</tr>
<tr>
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<td>3913</td>
<td>2725</td>
<td>2322</td>
<td>2024</td>
<td>1838</td>
</tr>
</tbody>
</table>

### Table A.14 Attenuation of longitudinal waves measured at specified angles and frequencies in the LR plane of a Maple sample.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Frequency</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
<th>90</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>100kHz</td>
<td>20.2</td>
<td>19.0</td>
<td>20.1</td>
<td>20.7</td>
<td>22.5</td>
<td>24.7</td>
<td>24.8</td>
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<tr>
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</table>

### Table A.15 Velocity of longitudinal waves measured at specified angles and frequencies in the LT plane of a Maple sample.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Frequency</th>
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<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
<th>90</th>
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<tbody>
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<td>2901</td>
<td>2721</td>
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<td>2302</td>
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<td>3620</td>
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<td>2997</td>
<td>2484</td>
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<td>2279</td>
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<td>3814</td>
<td>3082</td>
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<td>2403</td>
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</table>
### Maple - Longitudinal-Tangential Disc

<table>
<thead>
<tr>
<th>Frequency</th>
</tr>
</thead>
<tbody>
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<td>Angle</td>
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<tr>
<td>75</td>
</tr>
<tr>
<td>90</td>
</tr>
</tbody>
</table>

Table A.16 Attenuation of longitudinal waves measured at specified angles and frequencies in the LT plane of a Maple sample.

### Maple - Radial-Tangential Disc

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<thead>
<tr>
<th>Frequency</th>
</tr>
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<td>75</td>
</tr>
<tr>
<td>90</td>
</tr>
</tbody>
</table>

Table A.17 Velocity of longitudinal waves measured at specified angles and frequencies in the RT plane of a Maple sample.

### Maple - Radial-Tangential Disc

<table>
<thead>
<tr>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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<td>30</td>
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<tr>
<td>60</td>
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<tr>
<td>75</td>
</tr>
<tr>
<td>90</td>
</tr>
</tbody>
</table>

Table A.18 Attenuation of longitudinal waves measured at specified angles and frequencies in the RT plane of a Maple sample.
### Maple - Longitudinal-Radial Disc

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>1573</td>
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<td>1539</td>
<td>1581</td>
<td>1602</td>
<td>1602</td>
</tr>
<tr>
<td>30</td>
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<td>60</td>
<td>1459</td>
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<td>75</td>
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<td>1571</td>
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<td>1607</td>
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<td>1597</td>
<td>1576</td>
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</table>

Table A.19 Velocity of shear waves measured at specified angles and frequencies in the LR plane of a Maple sample.

### Maple - Longitudinal-Radial Disc

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>15.5</td>
<td>16.9</td>
<td>17.9</td>
<td>19.8</td>
<td>20.4</td>
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<tr>
<td>15</td>
<td>15.8</td>
<td>17.6</td>
<td>18.4</td>
<td>21.3</td>
<td>21.3</td>
</tr>
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<td>14.5</td>
<td>15.8</td>
<td>17.0</td>
<td>19.4</td>
<td>19.9</td>
</tr>
<tr>
<td>45</td>
<td>16.7</td>
<td>18.8</td>
<td>19.9</td>
<td>21.3</td>
<td>23.0</td>
</tr>
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<td>18.9</td>
<td>19.1</td>
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<td>16.0</td>
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<td>17.8</td>
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<td>16.3</td>
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</table>

Table A.20 Attenuation of shear waves measured at specified angles and frequencies in the LR plane of a Maple sample.

### Maple - Longitudinal-Tangential Disc

<table>
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<tr>
<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
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<td>1448</td>
<td>1454</td>
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<tr>
<td>30</td>
<td>1232</td>
<td>1342</td>
<td>1368</td>
<td>1396</td>
<td>1407</td>
</tr>
<tr>
<td>45</td>
<td>993</td>
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Table A.21 Velocity of shear waves measured at specified angles and frequencies in the LT plane of a Maple sample.
### Table A.22 Attenuation of shear waves measured at specified angles and frequencies in the LT plane of a Maple sample.

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
<tbody>
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<td>18.4</td>
<td>21.6</td>
<td>21.0</td>
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<td>17.0</td>
<td>18.7</td>
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<td>23.7</td>
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<tr>
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<td>16.1</td>
<td>17.6</td>
<td>20.7</td>
<td>22.0</td>
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<td>14.5</td>
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<td>18.4</td>
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<tr>
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<td>17.3</td>
<td>18.0</td>
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<td>13.6</td>
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### Table A.23 Velocity of shear waves measured at specified angles and frequencies in the RT plane of a Maple sample.

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<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
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</thead>
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<td>926</td>
<td>926</td>
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<td>873</td>
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<td>934</td>
<td>934</td>
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<td>953</td>
<td>972</td>
<td>980</td>
<td>983</td>
</tr>
<tr>
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<td>908</td>
<td>974</td>
<td>988</td>
<td>997</td>
<td>997</td>
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<td>60</td>
<td>882</td>
<td>952</td>
<td>974</td>
<td>979</td>
<td>982</td>
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<td>75</td>
<td>865</td>
<td>904</td>
<td>935</td>
<td>913</td>
<td>953</td>
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<td>932</td>
<td>910</td>
<td>922</td>
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</table>

### Table A.24 Attenuation of shear waves measured at specified angles and frequencies in the RT plane of a Maple sample.

<table>
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<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
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<td>16.2</td>
<td>20.2</td>
<td>21.6</td>
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<tr>
<td>15</td>
<td>14.4</td>
<td>16.3</td>
<td>18.5</td>
<td>20.3</td>
<td>22.0</td>
</tr>
<tr>
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<td>14.5</td>
<td>17.0</td>
<td>17.8</td>
<td>20.1</td>
<td>21.3</td>
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<td>14.0</td>
<td>15.4</td>
<td>17.6</td>
<td>19.3</td>
<td>20.1</td>
</tr>
<tr>
<td>60</td>
<td>13.8</td>
<td>16.3</td>
<td>18.2</td>
<td>19.9</td>
<td>20.8</td>
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<tr>
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<td>14.2</td>
<td>17.6</td>
<td>19.7</td>
<td>21.3</td>
<td>22.0</td>
</tr>
<tr>
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<td>16.3</td>
<td>18.7</td>
<td>20.7</td>
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</table>
### Table A.25 Velocity of longitudinal waves measured at specified angles and frequencies in the LR plane of a Norway Spruce sample.

<table>
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<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
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<td>5399</td>
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<td>4536</td>
<td>4701</td>
<td>4969</td>
<td>5019</td>
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<tr>
<td>30</td>
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<td>2952</td>
<td>2935</td>
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</table>

### Table A.26 Attenuation of longitudinal waves measured at specified angles and frequencies in the LR plane of a Norway Spruce sample.

<table>
<thead>
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<th>Frequency Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
<tbody>
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<td>19.8</td>
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<tr>
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<td>18.3</td>
<td>18.7</td>
<td>19.6</td>
<td>21.7</td>
<td>22.7</td>
</tr>
<tr>
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<td>22.7</td>
<td>22.7</td>
<td>24.5</td>
<td>26.2</td>
<td>27.9</td>
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<td>22.8</td>
<td>23.5</td>
<td>23.5</td>
<td>26.2</td>
<td>28.0</td>
</tr>
<tr>
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<td>24.6</td>
<td>24.6</td>
<td>26.3</td>
<td>28.0</td>
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</tr>
<tr>
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<td>24.9</td>
<td>26.6</td>
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<td>no signal</td>
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<tr>
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<td>no signal</td>
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</table>

### Table A.27 Velocity of longitudinal waves measured at specified angles and frequencies in the LT plane of a Norway Spruce sample.

<table>
<thead>
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<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
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<td>no signal</td>
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<td>no signal</td>
<td>no signal</td>
</tr>
<tr>
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<td>250kHz Attenuation dB/cm</td>
<td>500kHz Attenuation dB/cm</td>
<td>1MHz Attenuation dB/cm</td>
<td>1.5MHz Attenuation dB/cm</td>
</tr>
<tr>
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<td>--------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
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<td>22.5</td>
<td>24.3</td>
<td>25.3</td>
<td>27.1</td>
</tr>
<tr>
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<td>25.4</td>
<td>27.1</td>
<td>28.9</td>
<td>28.9</td>
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<tr>
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<td>27.1</td>
<td>27.1</td>
<td>28.9</td>
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<td>no signal</td>
</tr>
<tr>
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<td>29.2</td>
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</tr>
<tr>
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</tr>
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<td>no signal</td>
<td>no signal</td>
</tr>
<tr>
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<td>29.6</td>
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<td>no signal</td>
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</tr>
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</table>

Table A.28 Attenuation of longitudinal waves measured at specified angles and frequencies in the LT plane of a Norway Spruce sample.

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Velocity m/s</th>
<th>250kHz Velocity m/s</th>
<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1776</td>
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<td>1986</td>
<td>2025</td>
<td>2058</td>
</tr>
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<td>1582</td>
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<td>1729</td>
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Table A.29 Velocity of longitudinal waves measured at specified angles and frequencies in the RT plane of a Norway Spruce sample.

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
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</thead>
<tbody>
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<td>0</td>
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<td>27.8</td>
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Table A.30 Attenuation of longitudinal waves measured at specified angles and frequencies in the RT plane of a Norway Spruce sample.
### Table A.31 Velocity of shear waves measured at specified angles and frequencies in the LR plane of a Norway Spruce sample.

<table>
<thead>
<tr>
<th>Frequency Angle</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
</tr>
</thead>
<tbody>
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<td>1381</td>
<td>1819</td>
<td>1836</td>
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<td>1270</td>
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<td>1528</td>
<td>1541</td>
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<tr>
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<td>1347</td>
<td>1388</td>
<td>1384</td>
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<tr>
<td>60</td>
<td>1237</td>
<td>1591</td>
<td>1667</td>
<td>1667</td>
<td>1659</td>
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<td>1311</td>
<td>1342</td>
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### Table A.32 Attenuation of shear waves measured at specified angles and frequencies in the LR plane of a Norway Spruce sample.

<table>
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<th>Attenuation dB/cm</th>
<th>Attenuation dB/cm</th>
<th>Attenuation dB/cm</th>
<th>Attenuation dB/cm</th>
<th>Attenuation dB/cm</th>
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</thead>
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<td>14.3</td>
<td>17.1</td>
<td>19.7</td>
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<td>13.8</td>
<td>16.3</td>
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### Table A.33 Velocity of shear waves measured at specified angles and frequencies in the LT plane of a Norway Spruce sample.

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<th>Frequency Angle</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
<th>Velocity m/s</th>
</tr>
</thead>
<tbody>
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<td>1294</td>
<td>1309</td>
<td>1194</td>
<td>1198</td>
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<td>30</td>
<td>1146</td>
<td>1084</td>
<td>1158</td>
<td>1174</td>
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<tr>
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<td>850</td>
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<td>1062</td>
<td>1073</td>
</tr>
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<td>1319</td>
<td>1426</td>
<td>1414</td>
<td>1414</td>
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<td>1077</td>
<td>1140</td>
<td>1242</td>
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<td>1133</td>
<td>1199</td>
<td>1182</td>
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</table>
### Table A.34 Attenuation of shear waves measured at specified angles and frequencies in the LT plane of a Norway Spruce sample.

<table>
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<th>Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
<tbody>
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<td>15.5</td>
<td>14.8</td>
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<td>19.4</td>
</tr>
</tbody>
</table>

### Table A.35 Velocity of shear waves measured at specified angles and frequencies in the RT plane of a Norway Spruce sample.

<table>
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<th>Angle</th>
<th>100kHz Velocity m/s</th>
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<th>500kHz Velocity m/s</th>
<th>1MHz Velocity m/s</th>
<th>1.5MHz Velocity m/s</th>
</tr>
</thead>
<tbody>
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<td>1088</td>
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<td>no signal</td>
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### Table A.36 Attenuation of shear waves measured at specified angles and frequencies in the RT plane of a Norway Spruce sample.

<table>
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<tr>
<th>Angle</th>
<th>100kHz Attenuation dB/cm</th>
<th>250kHz Attenuation dB/cm</th>
<th>500kHz Attenuation dB/cm</th>
<th>1MHz Attenuation dB/cm</th>
<th>1.5MHz Attenuation dB/cm</th>
</tr>
</thead>
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</tr>
<tr>
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<td>22.0</td>
<td>24.8</td>
<td>no signal</td>
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</tr>
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<td>24.8</td>
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Appendix 2

Velocity Data Discussed in Chapter 7.
Table of ultrasonic pulse velocity measurements made on increment core type samples of Sitka spruce. PLI samples were measured using 2mm tip probes. CLI samples were measured using 4mm tip probes.

<table>
<thead>
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<th>Velocities determined for Increment Core Samples - Sitka Spruce</th>
</tr>
</thead>
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<tr>
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<td>5.62</td>
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</table>

<table>
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A- 17
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Appendix 3

Signal Analysis Program Used in Chapter 8.
PROGRAM mmnts; {filename: barread.pas}
{Written by Barry Feeney 29-06-95}
{This program is for reading stored data files from the tds320. }
{It is intended for the finding the positions and amplitudes of peaks.}
{Recording the top three in amplitude}
{And storing these in order of occurrence}
**********************************************************************
{Set up all global types, constants and variables.}
USES Crt,Dos;

TYPE darr = ARRAY [1..1024] OF real;
datr = ARRAY [1..201] OF real;
int = integer;

VAR 1  : char;
xin,maxval,averval,ndatsum,threshold : real;
minval,integ,a : real;
dat,n_dat,s_dat,abs_dat : darr;
max1amp,max2amp,max3amp : datr;
max1pos,max2pos,max3pos,mxamp : datr;
min1amp,min2amp,min3amp,mnamp : datr;
min1pos,min2pos,min3pos,intg : datr;
i,u,k,j,r,s,sns,Code,st,fl,x,b,c : int;
ns,fnsh,srt : string;
maxdat,realmax,mxpos : array [1..1024] of int;
mindat,realmin,mnpos : array [1..1024] of int;
name,us : string;
datfile : text;
iostatus,phm : word;
arm : boolean;
ampfile : text;
preamble : string;

**********************************************************************
Procedure ReadFile;
Begin
str(u,us);
assign(datfile,concat(name,us,'.txt'));
reset(datfile);
for k:=1 to 1000 do
begin
 Readln(datfile,dat[k]);
end;
close(datfile);
End;

Procedure ResultsArray; {puts results from a scan into an array}
Begin
max1pos[u]:=mxpos[1];
max1amp[u]:=mxamp[1];
max2pos[u]:=mxpos[2];
max2amp[u]:=mxamp[2];
max3pos[u]:=mxpos[3];
max3amp[u]:=mxamp[3];
min1pos[u]:=mnpos[1];
min1amp[u]:=mnamp[1];
min2pos[u]:=mnpos[2];
min2amp[u]:=mnamp[2];
\[
\text{min3pos[u]} := \text{mnpos}[3]; \\
\text{min3amp[u]} := \text{mnamp}[3]; \\
\text{intg[u]} := \text{integ};
\]
End;
{*******************************************************************************}

\text{Procedure StoreRes; \{send results out to files\}}
\text{Begin}
\begin{align*}
\text{assign(datfile,concat(name,'p1mx.txt'));} \\
\text{rewrite(datfile);} \\
\text{for } x:=1 \text{ to } fh-st \text{ do begin} \\
\text{writeln(datfile,\text{max1pos}[x]); \{write position of first max\}} \\
\text{end; \{to file\}}
\end{align*}

\begin{align*}
\text{assign(datfile,concat(name,'p2mx.txt'));} \\
\text{rewrite(datfile);} \\
\text{for } x:=1 \text{ to } fh-st \text{ do begin} \\
\text{writeln(datfile,\text{max2pos}[x]); \{write position of first max\}} \\
\text{end; \{to file\}}
\end{align*}

\begin{align*}
\text{assign(datfile,concat(name,'a1mx.txt'));} \\
\text{rewrite(datfile);} \\
\text{for } x:=1 \text{ to } fh-st \text{ do begin} \\
\text{writeln(datfile,\text{max1amp}[x]); \{write position of first max\}} \\
\text{end; \{to file\}}
\end{align*}

\begin{align*}
\text{assign(datfile,concat(name,'a2mx.txt'));} \\
\text{rewrite(datfile);} \\
\text{for } x:=1 \text{ to } fh-st \text{ do begin} \\
\text{writeln(datfile,\text{max2amp}[x]); \{write position of first max\}} \\
\text{end; \{to file\}}
\end{align*}

\begin{align*}
\text{assign(datfile,concat(name,'p1mn.txt'));} \\
\text{rewrite(datfile);} \\
\text{for } x:=1 \text{ to } fh-st \text{ do begin} \\
\text{writeln(datfile,\text{min1pos}[x]); \{write position of first min\}} \\
\text{end; \{to file\}}
\end{align*}

\begin{align*}
\text{assign(datfile,concat(name,'p2mn.txt'));} \\
\text{rewrite(datfile);} \\
\text{for } x:=1 \text{ to } fh-st \text{ do begin} \\
\text{writeln(datfile,\text{min2pos}[x]); \{write position of first min\}} \\
\text{end; \{to file\}}
\end{align*}

\begin{align*}
\text{assign(datfile,concat(name,'intg.txt'));} \\
\text{rewrite(datfile);} \\
\text{for } x:=1 \text{ to } fh-st \text{ do begin} \\
\text{writeln(datfile,\text{intg}[x]); \{write integral of signal\}} \\
\text{writeln('integ is ',\text{intg}[x],\text{for number ',x);} \\
\text{end; \{to file\}}
\end{align*}

\text{close(datfile);} \\
\text{End;
Procedure SmoothData; {This procedure removes d.c. offset & does a } { smoothing of the data }

Begin
  for k:=1 to 5 do begin {reset garbage values at start of} 
    dat[k]:=32768; {data to ground value}
  end;
  for k:=6 to 1000 do begin {good data now in dat[k]}
    dat[k]:=dat[k];
  end;
  ndatsum:= 0;
  for k:= 1 to 1000 do begin 
    ndatsum:=ndatsum+dat[k]; {calculate d.c. offset}
  end;
  averval:=ndatsum/1000;
  for k:= 1 to 1000 do begin
    dat[k]:=dat[k]-averval; {now data varies around zero}
  end;
  for k:= 1 to 1000 do begin
    val(ns,sns,Code); {converts smoothing string to value}
    for s:=1 to sns do begin
      sdat[k]:=sdat[k]+dat[k+s]; {smooths data}
    end;
    sdat[k] :=sdat[k]/sns;
  end;
  integ:=0;
  for k:=1 to 1000 do begin
    absdat[k]:=abs(sdat[k]);
    integ:=integ+absdat[k];
  end;
End;

Procedure SFile;

Begin
  str(u5 us);
  assign(datfile,concat(name,us,'.txt'));
  rewrite(datfile);
  for k:=1 to 1000 do begin
    writeln(datfile,dat[k]);
  end;
  close(datfile);
End;

Procedure FindMaxima;

Begin
  j:=1;
  maxval:=0;
End.
for k:= 2 to 1000 do
  begin
    if sdat[k] > maxval
      then maxval:=sdat[k]  {find maxval for scaling peak choices}
    end;
  writeln(maxval);
write('Max is ',maxval);
for k:=2 to 1000 do
  begin
    if sdat[k-1] <= sdat[k]
      then if sdat[k] >= sdat[k+1]
          then  {pick peaks greater than neighbours}
            begin
              maxdat[j]:=k;
              j:=j+1;
            end;
  end;
  r:=1;
for k:= 1 to j do
  begin
    threshold:=maxval/1.65;  {set threshold for identifying maxima}
    if sdat[maxdat[k]] > threshold
      then
        begin
          realmax[r]:=maxdat[k];  {record max's over threshold}
          r:=r+1;
        end;
  end;
for k:=1 to r-1 do
  begin
    writeln(k,' ',realmax[k],' ',sdat[realmax[k]]);
    mxpos[k]:=realmax[k];  {Create array for sorting}
    mxamp[k]:=sdat[realmax[k]];
  end;
End;
******************************
Procedure MaxSort;

Begin
for j:=2 to r-1 do
  begin
    a:=mxamp[j];
    b:=mxpos[j];
    i:=j-1;
    while (i>0) and (mxamp[i]>a) do
      begin
        mxamp[i+1]:=mxamp[i];
        mxpos[i+1]:=mxpos[i];
        i:=i-1;
      end;
    mxamp[i+1]:=a;
    mxpos[i+1]:=b;
  end;
  if r-1 >= 3
    then c:=4
  else c:= r;
  for j:=2 to c do

begin
a:=mxamp[j];
b:=mxpos[j];
i:=j-1;
while (i>0) and (mxpos[i]>b) do
begin
mxamp[i+1]:=mxamp[i];
mxpos[i+1]:=mxpos[i];
i:=i-1;
end;
mxamp[i+1]:=a;
mxpos[i+1]:=b;
end;

for k:=1 to c-1 do
begin
writeln(k,'sorted data ',mxpos[k],' ',mxamp[k]);
end;
End;

{************************************************************************************}

Procedure FindMinima;
Begin
j:=l;
minval:=0;
for k:=2 to 1000 do
begin
if sdat[k] < minval
then minval:=sdat[k]  {find minval for scaling peak choices}
end;
writeln('minval is ',minval);
for k:=2 to 1000 do
begin
if sdat[k-1] >= sdat[k]
then if sdat[k] <= sdat[k+1]
    then begin
        mindat[j]:=k;
        j:=j+1;
    end;
end;
r:=1;
for k:=1 to j do
begin
threshold:=minval/1.65;  {set threshold for identifying minima}
if sdat[mindat[k]] < threshold
then begin
    realmin[r]:=mindat[k];  {record min's over threshold}
    r:=r+1;
end;
end;
for k:=1 to r-1 do
begin
writeln(k,'minpos ',realmin[k],' minval ',sdat[realmin[k]]);
mnpos[k]:=realmin[k];
mnamp[k]:=sdat[realmin[k]];

A- 25
procedure MinSort;

begin
  for j:=2 to r-1 do
  begin
    a:=mnamp[j];
    b:=mnpos[j];
    i:=j-1;
    while (i>0) and (mnamp[i]>a) do
    begin
      mnamp[i+1]:=mnamp[i];  {first Sort into the }
      mnpos[i+1]:=mnpos[i];  {Largest minima }
      i:=i-1;
    end;
    mnamp[i+1]:=a;
    mnpos[i+1]:=b;
  end;
  if r-1 >= 3
  then c:=4
  else c:=r;
  for j:=2 to c do
  begin
    a:=mnamp[j];
    b:=mnpos[j];
    i:=j-1;
    while (i>0) and (mnpos[i]>b) do
    begin
      mnpos[i+1]:=mnpos[i];  {Now sort the first three}
      mnamp[i+1]:=mnamp[i];  {into order of occurance }
      i:=i-1;
    end;
    mnpos[i+1]:=b;
    mnamp[i+1]:=a;
  end;
  for k:=1 to c-1 do
  begin
    writeln(k,'sorted data ',mnpos[k],' ',mnamp[k]);
  end;
end;

begin  {main program}
clrscr;
for i:=1 to 1024 do dat[i]:=0;

writeLn(' Choose operation: ');
writeLn(' a: read data for analysis');
writeLn(' c: acquire function data');
writeLn(' x: exit');
write('=>');
1:=readkey;
WRITELN(' ',I);
crsr;

CASE 1 OF

'a','A': BEGIN
  write('Read data from ? (Directory & Root name )

  readln(name);
  write('read starting at file no ?

  readln(srt);
  val(srt,st,Code);
  write('until file number ?

  readln(fhsh);
  val(fhsh,fh,Code);
  writeln(' Enter timebase setting ');
  readln(tbs);
  val(tbs,tb,Code);
  writeln(' Enter delay setting ');
  readln(dls);
  val(dls,dl,Code);
  writeln(' Enter number of points for Smoothing');
  readln(ns); {reads string of no. of points}
    for u:= st to fh do
    begin
      ReadFile;
      SmoothData;
      SFile;
      FindMaxima;
      MaxSort;
      FindMinima;
      MinSort;
      ResultsArray;
    end;
    StoreRes;
  END;

'c','C': BEGIN
  write('save data to? ');
  readln(name);

  END;

ELSE IF NOT (I='x') OR (I='X') THEN WRITELN('wrong letter, try again');
END;
WRITELN;

END.
{SN-}
Appendix 4

PUBLICATIONS ARISING FROM THE WORK PRESENTED IN THIS THESIS.
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MATERIAL REDACTED AT REQUEST OF UNIVERSITY