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Dynamic Soil-Structure Interaction issues in designing offshore wind turbines

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ABSTRACT

Choosing appropriate foundations for supporting offshore wind turbines is one of the uncertainties in the future rounds of offshore wind power development. Offshore wind turbines are dynamically sensitive structures as the global natural frequency of the whole system is very close to the forcing frequencies (due to the environmental loads and the associated frequencies due to the rotor). This particular aspect is important for designing foundations for Round 2 and Round 3 offshore wind farms in the UK. It must be mentioned here that monopile foundations have been commonly used to support offshore wind turbine generators (WTGs), but this type of foundation encounters economic and technical limitations for larger WTGs in water depths exceeding 30m. Therefore offshore wind farm projects are increasingly turning to alternative multipod foundations (for example tetrapod, jacket, tripods) or on shallow foundations to reduce the environmental effects of piling noise. However the characteristics of these foundations under dynamic loading or long term cyclic wind turbine loading are not fully understood. This keynote lecture summarizes the results from a series of scaled model tests of the overall wind turbine system (including the foundations).

1 INTRODUCTION

In an effort to reach environmental CO_2 targets set down both domestically and internationally (Renewable Obligation), the UK has invested significant time and energy in developing offshore wind power sources. So far expansion has occurred in ‘rounds’. Apart from the renewable obligations, there are very strong economic incentives to construct offshore wind farms. Also following the 2011 Tohoku earthquake (the Great East Japan earthquake also known as 311 earthquake) offshore wind turbines is becoming a natural choice for energy generation mainly for two reasons: (a) good performance of most Japanese wind turbines; (b) Low carbon and non-nuclear technology giving members of the public more confidence.

The rate of expansion of offshore wind energy in Europe is soon predicted to outstrip levels even seen during the heyday of the offshore oil and gas industry, and as a result there has been substantial effort put into research and development.

The aim of the keynote lecture is as follows:

(1) Identify the Dynamic Soil-Structure Interaction challenges that need to be addressed while designing the overall system.
(2) Summarise the experimental research carried out so far identify some of the design issues.

The next section of the paper summarizes the loading acting on the wind turbine.

1.1 Loading on offshore wind turbines

Offshore wind turbines are dynamically sensitive structures that are placed in adverse environmental conditions (with strong wind and wave loading). This makes the design of foundations extremely challenging. Figure 1 schematically shows the typical wind and wave pressure distribution along the length of the tower and the foundation for a monopile-supported wind turbine. The tower, above the water, experiences two types of loads:

(a) the bottom part of the tower, unobstructed by the spinning turbine blade experiences a nearly constant value of the wind loading;

(b) the top part of the tower, which is periodically obstructed by the spinning of the blades is subjected to a cyclic loading often called the blade passing effect (2P/3P) or blade shadowing effect or wind shielding effect in the literature.

The total environmental lateral load acting on the offshore wind turbine in Figure 1 can be modelled simplistically as an instantaneous static horizontal load, P acting at a distance y above the foundation level. Thus P represents the resultant lateral load on the tower that must be resisted by the monopile foundation. Figure 1 also shows an equivalent force model for the foundation where the lateral load (P) on the tower is replaced by a force (P) and a moment (M) at the pile head. More details can be found in [1 2].

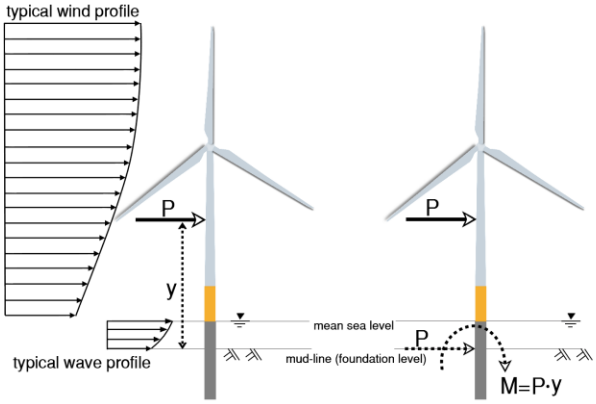

Fig.1 Schematic of the loading on the turbine

Figure 2 shows a simple structural model of a wind turbine currently being used in practice to predict the natural frequency of the system. The lateral vibration of wind turbines is controlled by two foundation springs: K_L (transverse spring) and K_R (rotational spring). However strictly, a cross coupling spring is also necessary, see Figure 3 for more details.

The dynamic response of these structures is dependent on the support condition (i.e. the stiffness of the foundation in Figure 2 and Figure 3) which relies on the strength and stiffness of the surrounding soil. Under moderate to high cyclic loading most soils change their properties, which may alter the stiffness of the foundation and this may have an adverse effect on the long-term performance. Therefore the dynamic behaviour and the prediction of the long-term performance of offshore wind turbines require a deeper understanding of various dynamic interactions between the superstructure, foundation, soil and external loads.

Lateral load and the moment at the foundation level can be linked to the corresponding displacement and slope by the following equation. Analytical solutions for this problem can be found in [3 4 5].

$$\begin{bmatrix} P \\ M \end{bmatrix} = \begin{bmatrix} K_L & K_{LR} \\ K_{LR} & K_R \end{bmatrix} \begin{bmatrix} w \\ w' \end{bmatrix} \tag{1}$$

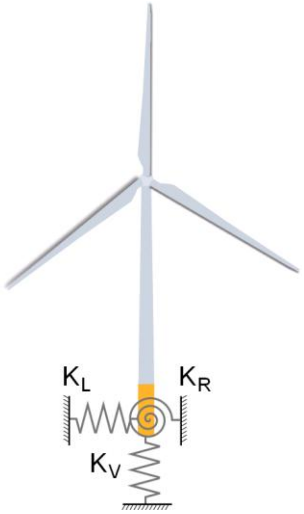

Fig.2 Simplified structural model of a wind turbine

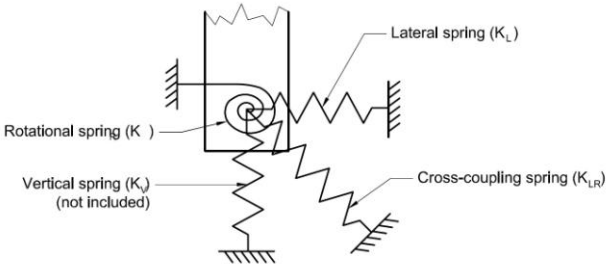

Fig.3 Simplified structural model of support taking into account the cross-coupling spring

1.2 Frequency of the loading on wind turbine foundations

Figure 4 shows the main frequencies for a three-bladed 3MW Vestas V90 Wind turbine with an operational interval of 8.6 to 18.4rpm: the rotor frequency (often termed as 1P) lies in the range 0.14-0.3Hz and the corresponding 'blade passing frequency' for a three-bladed turbine lies in the range 0.42-0.9Hz. The figure also shows a typical frequency distribution for wind and wave loading. The peak frequency of offshore waves is about 0.1Hz. It is clear from the frequency content of the applied loads that the designer of the turbine and foundation has to select a system frequency (the global frequency of the overall wind turbine-foundation system) which lies outside these in order to avoid system resonances. The usual choice would lie between turbine and blade passing frequencies (so-called 'soft-stiff', option 2 in Figure 4). There are two challenges:

(a) The foundation stiffness must be estimated very accurately from the available soil data.
(b) The potential for change in foundation stiffness with time as a result of the cyclic loading must be understood so that the risks of the system frequency coinciding with a loading frequency can be avoided.

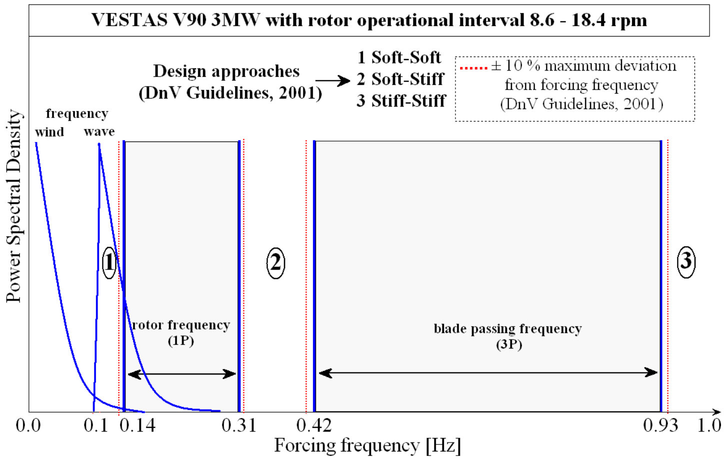

Fig.4: Excitation range for a typical wind turbine

2 WHOLE SYSTEM SCALED MODEL TESTS

Offshore wind turbines are relatively new structures and there is no track record of long term performance (say, 20 to 30 years). Under these circumstances, experimental investigations on physical wind turbine models can provide valuable information for understanding the dynamic behaviour and long-term performance of these relatively new structures.

The design and interpretation of any test carried out on a small scale model require the assessment of a set of laws of similitude that relate the model to the prototype structure.

The section therefore has the following aims:

(a) To summarise the scaling laws necessary to study dynamic-soil-structure interaction and also to identify appropriate controlling dimensionless groups.
(b) To present typical test results from a study in which a 1:100 scale wind turbine model was tested in the Bristol Laboratory for Advanced Dynamics Engineering (BLADE) and then to comment on the usefulness of the dimensionless groups derived in this paper

Derivation of the correct scaling laws constitutes the first step in an experimental study. These are necessary to interpret the model test results in order to scale up the results for prediction of prototype consequences. Every physical process can be expressed in terms of non-dimensional groups and the fundamental aspects of physics must be preserved in the design of model tests. The necessary steps associated with designing such a model, to be implemented either in one-g or a multi-g testing environment, can be stated as follows:

1. To deduce the relevant non-dimensional groups by thinking of the mechanisms that govern the particular behaviour of interest both at model and prototype scale.
2. To ensure that a set of crucial scaling laws are simultaneously conserved between model and prototype through pertinent similitude relationships.
3. To identify scaling laws which are approximately satisfied, and those which are violated and which therefore require especial consideration.

Following [1 2] the physical mechanisms are considered important in order to develop the non-dimensional groups.

1) The strain field in the soil around a laterally loaded pile which will control the degradation of soil stiffness
2) The cyclic stress ratio in the soil in the shear zone
3) The rate of soil loading which will influence the dissipation of pore water pressure
4) The system dynamics, the relative spacing of the system frequency and the loading frequency
5) Bending strain in the monopile foundation for considering the non-linearity in the material of the pile
6) Fatigue in the monopile foundation

The non-dimensional groups are tabulated in Table 1 following [1] and other details can be found in [1].

Table 1: Non-Dimensional group to study wind turbines

Physical mechanism	Non-dimensional group
Strain field in the soil and Cyclic Stress Ratio (*CSR*)	$\left(\dfrac{P}{GD^2}\right)$
Rate of loading*	$\left(\dfrac{k_h}{f_f D}\right)$
System dynamics	$\left(\dfrac{f_f}{f_n}\right)$
Strain in the monopile	$\left(\dfrac{Py}{ED^2 t_w}\right)$
Stress in the monopile	$\left(\dfrac{Py}{\sigma_y D^2 t_w}\right)$

Figure 5 shows the small scale model of a monopile supported wind turbine.

2.1 Experimental procedure

A typical test consists of the application of the cyclic loading for a particular time interval (or certain number of cycles) and then measuring the frequency and damping of the system by a free vibration test. This is carried out using an actuator. In the free vibration test (also known as a "snap back" test in the literature), the actuator was disconnected from the tower and the tower was given a small amplitude vibration and the acceleration of the system recorded. The cyclic lateral loading was applied at three different frequencies (2Hz, 20Hz and 125Hz) and for different lateral load magnitudes. This set of tests created a database of change of frequency and damping of the wind turbine system for different values of: (a) strain field in the soil i.e. various values of (P/GD^2); (b) forcing frequency (f_f); (c) number of cycles of loading (N). The next section of the paper presents typical test results in order to illustrate the usefulness of the non-dimensional groups. Figure 6 shows the results from a monopile supported in clay soil. Other details can be found in [8].

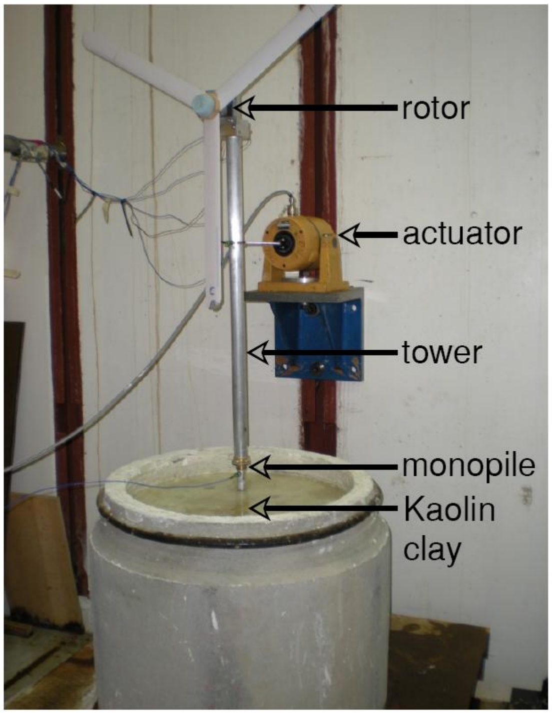

Fig.5: Scaled model of a monopile supported wind turbine

Figure 6 shows the variation of the normalised frequency of the system with respect to the number of cycles of loading for two strain levels in the soil. Please note that P/GD^2 corresponds to strain in the soil next to the foundation. As expected, higher strain levels lead to higher reduction in natural frequency of the model. It is interesting to note that for a low value of (P/GD^2) there is practically no degradation in the natural frequency. For more details of the monopile tests in clay, the readers are referred to [2 8]. However for monopiles in sandy soil, there is an increase in natural frequency possibly due to densification of the soil around the pile. More details can be found in [2 5].

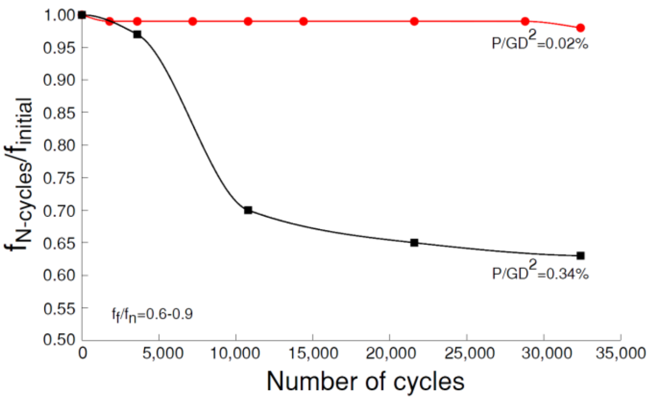

Fig.6: Change in frequency with number of cycles in clay

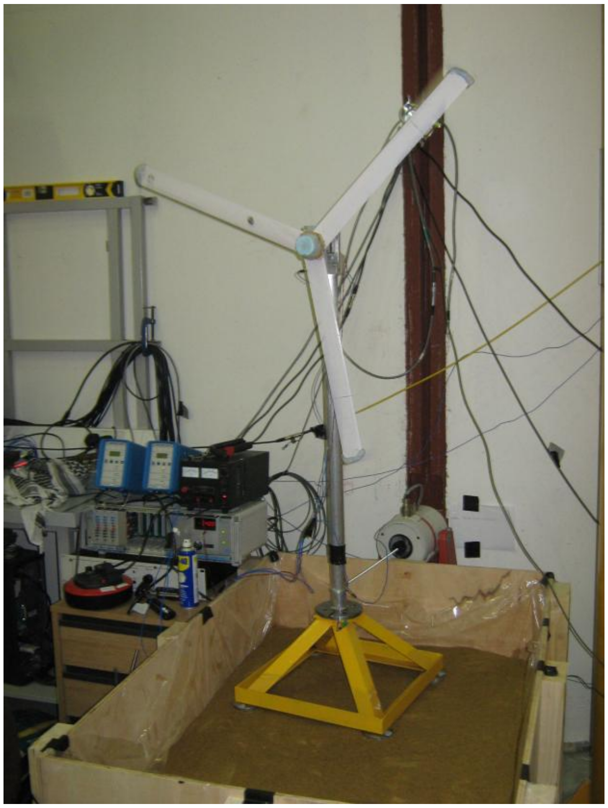

Fig.7: Scaled model of a tetrapod foundation [6]

Scaled model tests were also carried out on other types of foundations, see Figure 7 and 8. Figure 7 shows the test setup for a tetrapod foundation whereas Figure 8 shows that of a asymmetric tripod arrangement. The test bed used consists of either kaolin clay or sand and up to 5 million loading cycles were applied.

Fig.8: Scaled model of a asymmetric tripod

Figure 9 shows the free vibration data from a typical snap back test performed on a wind turbine with monopile foundation in sand (for set-up see Figure 5(a)). The test results are plotted in the frequency domain using the Welch [7] method. The system has a single dominant frequency of about 3.3Hz: the foundation provides significant flexibility to the wind turbine system which has a fixed base frequency of 10.27Hz. A second peak can be observed at about 17Hz which is 5.15 times the first peak and corresponds to the second cantilever mode of the tower.

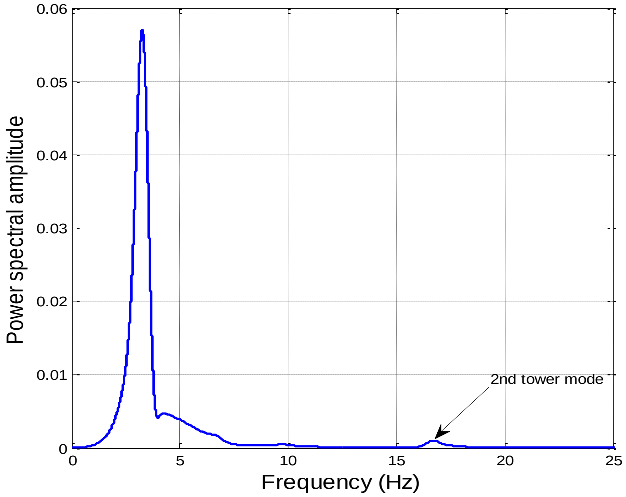

Fig.9: Free vibration of a scaled monopile-supported turbine

Figure 10 shows a free vibration of a wind turbine supported on a tetrapod on sand (Figure 7). Three peaks can be seen in the test results plotted in the frequency domain. These data were recorded just after installation. In contrast to the monopile, there are two very closely spaced peaks at 6.385Hz and 7.754Hz and third peak is observed at 18.5Hz. The third peak is similar to the second peak in Figure 9 suggesting the second cantilever mode of the tower. Similar results were also obtained for the tripod structure shown in Figure 8.

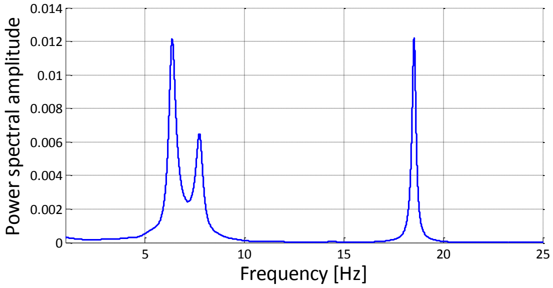

Fig. 10: Free vibration of tetrapod supported wind turbine model on sand.

Discussion, Conclusions and Implications in Design

This section of the paper summarises the conclusions reached following the tests:

(a) The results showed that the multipod foundations (symmetric or asymmetric) exhibit two closely spaced natural frequencies corresponding to the rocking modes of vibration in two principle axes (see the first two peaks in Figure 10).

(b) Furthermore, the corresponding two spectral peaks change with repeated cycles of loading and they converge for symmetric tetrapods but not for asymmetric tripods. These results are not shown in this paper.

From the fatigue design point of view, the two peaks for multipod foundations broaden the range of frequencies that can be excited by the broadband nature of the environmental loading (wind and wave) thereby impacting the fatigue. The system life (number of cycles to failure) may effectively increase for symmetric foundations as the two peaks will tend to converge. However, for asymmetric foundations the system life may continue to be affected adversely as the two peaks will not converge. In this sense, designers should prefer symmetric foundations to asymmetric foundations.

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