NUMERICAL STUDIES OF TURBINE RIM SEALING FLOWS ON A CHUTE SEAL CONFIGURATION

Feng Gao\textsuperscript{1}, John W Chew\textsuperscript{1}, Paul F Beard\textsuperscript{2}, Dario Amirante\textsuperscript{1}, Nicholas J Hills\textsuperscript{1}

\textsuperscript{1} Faculty of Engineering & Physical Sciences, University of Surrey, Guildford, GU2 7XH. UK
\textsuperscript{2} Osney Thermo-Fluids Lab., Dept. of Eng. Sci., University of Oxford, Oxford, OX2 0ES. UK
Email: f.gao@surrey.ac.uk, j.chew@surrey.ac.uk, paul.beard@eng.ox.ac.uk, d.amirante@surrey.ac.uk, n.hills@surrey.ac.uk

ABSTRACT
This paper presents CFD (computational fluid dynamics) modelling of a chute type rim seal that has been previously experimentally investigated. The study focuses on inherent large-scale unsteadiness rather than that imposed by vanes and blades or external flow. A large-eddy simulation (LES) solver is validated for a pipe flow test case and then applied to the chute rim seal rotor/stator cavity. LES, Reynolds-averaged Navier-Stokes (RANS) and unsteady RANS (URANS) models all showed reasonable agreement with steady measurements within the disc cavity, but only the LES shows unsteadiness at a similar distinct peak frequency to that found in the experiment, at 23 times the rotational frequency. However, there are some significant differences between unsteadiness predicted and the measurements, and possible causes of these are discussed.

KEYWORDS
TURBINE RIM SEAL, CHUTE SEAL, UNSTEADY FLOW STRUCTURE, LARGE-EDDY SIMULATION

NOMENCLATURE
\begin{align*}
b & \quad \text{rotor disc rim radius} \\
C_p & \quad \text{static pressure coefficient} \\
E_{pp} & \quad \text{power spectral density amplitude} \\
f & \quad \text{frequency} \\
N & \quad \text{number of lobes} \\
p & \quad \text{static pressure} \\
p_1 & \quad \text{static pressure at sensor 1001} \\
r & \quad \text{radius} \\
V_r, V_t & \quad \text{radial, swirl velocity} \\
\alpha & \quad \text{angle between two probes} \\
\beta & \quad \text{angle between two flow structures} \\
\Delta t_\alpha & \quad \text{time for a structure to travel through two probes} \\
\Delta t_\beta & \quad \text{time lag between two adjacent flow structures} \\
\Omega & \quad \text{rotor speed} \\
\omega_s & \quad \text{speed of flow structures} \\
\theta & \quad \text{Azimuthal angle} \\
\langle q \rangle & \quad \text{Ensemble average operator} \\
q' & \quad \text{Fluctuation of quantity } q
\end{align*}

INTRODUCTION
Turbine rim sealing flows are an important aspect of turbomachinery design, affecting both turbine aerodynamic performance and turbine disc temperatures. Seal clearances must accommodate relative movements between rotating and stationary components during engine operation and this requires use of additional cooling air to prevent ingestion of the hot main annulus gas into the turbine disc cavity. In addition, the rim seal design may affect the aerodynamic losses associated with interaction of the cooling air and the main turbine gas flow. Modelling of such flows with CFD has proved difficult and several studies have indicated that the rim seal gap and disc cavity flows can contain large scale unsteady flow structures with frequencies unrelated to those associated with the rotating blades.
The main mechanisms involved in rim seal flow phenomena were clarified in an early literature survey by Johnson et al. [1994]. These are (1) disk pumping, (2) periodic vane/blade pressure fields (3-D and time dependent), (3) 3-D geometry within rim seal region, (4) asymmetries in the rim seal geometry, (5) turbulent transport in the platform overlap region and (6) flow entrainment. In addition to the mechanisms stated above, Smout et al. [2002] and Chew et al. [2003] reported large-scale low-frequency flow structures, even in an axisymmetric geometry without vanes and blades. The URANS simulations on rim seal geometries of Boudet et al. [2005] revealed that those structures are inherently 3-D and unsteady, and that reasonable predictions of those features might improve the estimation of sealing effectiveness. They attributed this phenomenon to the possible Taylor-Couette instability. O’Mahoney et al. [2011] extended the turbine stage URANS study of Boudet et al. to LES, and showed closer agreement of sealing effectiveness with the experiment of Gentilhomme [2004]. Schuepbach et al. [2010] have claimed that the asymmetric pressure field induced by the large-scale flow features can significantly reduce engine performance. Chilla et al. [2013] reported strong unsteady flow interaction between rim seal and main gas path at nominal sealing flow conditions, and periodically vortex shedding from rim seal into the main annulus. Rabs et al. [2009] identified similar vortex structures and conjectured that they could be induced by the Kelvin-Helmholtz instabilities. The latest researches have all experimentally confirmed the existence of rim seal cavity modes which are unattributed to blade passing. Amongst recent experimental studies are papers by Beard et al. [2016], Savov et al. [2016], and Schädler et al. [2016]. The studies of Beard et al. revealed the speed and number of flow structures independently of CFD solutions.

From recent publications it is clear that the detailed flow physics in rim seals is of considerable interest, with a need for better understanding of the underlying flow mechanisms. The present study focuses on the inherent unsteadiness involved in the rim seal, and considers CFD modellings of the chute rim seal geometry published in [Beard et al., 2016]. Wall resolved URANS and LES solutions are presented and discussed.

EXPERIMENTAL RIG

A sectional view of the Oxford rotor facility (ORF) used by Beard et al. [2016] is illustrated in Fig. 1 (a). In this build turbine vanes and blades were replaced by platform rings, labelled ‘4’ and ‘5’ respectively. The design of the rim seal followed the chute seal of Gentilhomme [2004] is drawn in Fig. 1 (b). The nominal seal gap was 1mm with 2mm axial overlap, and the rim seal angle is 20° to the shaft axis.

![Figure 1](image)

**Figure 1:** (a) Schematic of the ORF working section, (b) Rim seal geometry (dimensions in mm), (c) unsteady pressure sensor instrumentation on vane platform ring (viewed from downstream).

Pressure sensors were embedded in the vane platform ring to record the steady and unsteady
static pressure, and the illustration is shown in Fig. 1 (c). The radial and circumferential locations of the sensors are listed in Tab. 1. Azimuthal angles are defined in a clockwise direction from top-dead-center viewing from downstream. Five pressure sensors were radially installed on the azimuthal location of $0^\circ$. An additional five sensors were circumferentially distributed, having the same radius as the sensor 1002. The radially distributed sensors 1001-1005 were employed for registering steady pressure, while the six sensors of radius 227.5mm were used in unsteady pressure measurements. Further details about the rig, pressure measurement error and test matrix are given by Beard et al. [2016]. As reported by Beard et al., similar unsteady flow features were identified over a range of rotor speeds and sealing flow rates.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Radius (mm)</th>
<th>Angle (°)</th>
<th>Sensor</th>
<th>Radius (mm)</th>
<th>Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>224</td>
<td>0</td>
<td>1006</td>
<td>227.5</td>
<td>10</td>
</tr>
<tr>
<td>1002</td>
<td>227.5</td>
<td>0</td>
<td>1007</td>
<td>227.5</td>
<td>25</td>
</tr>
<tr>
<td>1003</td>
<td>231</td>
<td>0</td>
<td>1008</td>
<td>227.5</td>
<td>30</td>
</tr>
<tr>
<td>1004</td>
<td>234.1</td>
<td>0</td>
<td>1009</td>
<td>227.5</td>
<td>90</td>
</tr>
<tr>
<td>1005</td>
<td>235.9</td>
<td>0</td>
<td>1010</td>
<td>227.5</td>
<td>-40</td>
</tr>
</tbody>
</table>

**CFD MODELLING AND NUMERICAL SETTINGS**

Wall resolved URANS and LES models are reported for the geometry described above at a rotor speed of 7000rpm and without any imposed seal flow. Simulations were carried out using a modified version of the Rolls-Royce plc in-house CFD solver Hydra. This code is an unstructured, node-based finite volume solver for compressible Navier-Stokes equations in Cartesian coordinates, and is parallelised using the OPLUS library (Oxford parallel library for unstructured solver) [Hills, 2007]. The URANS and LES modelling as well as LES code validation for pipe flow will be introduced in this section.

**URANS**

The URANS mesh is initially generated in a 2D plane (as shown in Fig. 2 (a)) and extruded into a $30^\circ$ sector, using ICEMCFD. The near wall grid size is set to $\Delta y^+ \approx 1$ with circumferential grid spacing being $0.5^\circ$ (61 nodes), yielding a total of $\sim 1.6$ million mesh nodes. All the inlets and outlet are configured as inviscid wall for the zero flow case considered. Other boundaries are set as isothermal no-slip walls with a fixed static temperature (288K) and the corresponding rotational speed. Circumferential boundaries are linked by a periodic condition. Fluxes are interpolated using a 2nd-order centred scheme with a 2nd-order smoothing for the inviscid components. The RANS equations are closed by the Spalart-Allmaras turbulence model. The URANS simulation is initialised by a steady RANS solution.

A dual-time stepping implicit temporal scheme is employed for URANS. The physical time step is set to 1/7200 rotor revolution time, corresponding to a CFL (Courant-Friedrichs-Lewy) number of 2976 in the smallest grid cells. A five-step Runge-Kutta scheme is used for inner iteration convergence acceleration. As suggested by Jameson [1991], a physical time step at CFL=4000 could converge to a sufficient accuracy within 10-15 multi-grid cycles with an inner CFL number 5-8. This yields a speed-up ratio of 33-80 compared with an explicit temporal scheme. A smaller speed-up ratio is expected in this study as the multi-grid scheme is not

---

1 A slight geometric discrepancy exists between the experiment and CFD geometry. The edge with $45^\circ$ slope connected to the chute rim seal boundary on the stator (as shown in Fig. 1 (b)) moved horizontally toward the rotor by 1mm in the CFD modelling, due to a confusion with a previous rig design. This is expected to have little effect on the results, as confirmed by the comparison of the steady pressure distribution in Fig. 5.
LES

The Rolls-Royce plc in-house CFD code Hydra was initially developed during the Ph.D. thesis of Moinier [1999], and has recently been extended to LES with 2nd-order accuracy by Amirante and Hills [2015] using monotone upwind schemes for conservation laws (MUSCL) with linear reconstructions of the primitive variables. This solver is validated for a pipe flow test case and then applied to a sector model of the disc cavity and chute rim seal.

Validation: Pipe Flow Test Case

A DNS (direct numerical simulation) study of a pipe flow by Khoury et al. [2013], at $Re_\tau = 1000$, is taken as reference test case to validate the LES solver. Non-dimensional parameters provided in the literature and dimensional variables used in this study are listed in Tab 2.

<table>
<thead>
<tr>
<th>Non-dimensional parameters</th>
<th>Dimensional parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>$Re_b$</td>
<td>37700</td>
</tr>
<tr>
<td>$Re_\tau$</td>
<td>1000</td>
</tr>
<tr>
<td>$u_\tau/u_b$</td>
<td>0.053</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The near wall grid size in radial direction is set to be less than 1 wall unit, and the maximum sizes are about 80 and 40 in streamwise and circumferential direction. The Roe scheme is employed for spatial flux discretisation, and its weighting coefficient of numerical viscosity $\varepsilon$ is set to its minimum value possible ($\varepsilon = 0.005$) to minimise the artificial dissipation and to assure numerical stability. Time integration is performed using an explicit 3-step Runge-Kutta scheme. The standard Smagorinsky subgrid-scale (SGS) model with a Van Driest damping function is implemented to predict the subgrid-scale behaviours. Although researchers [Moin and Kim, 1982] suggested a Smagorinsky model coefficient of $C_s = 0.1$, the present authors adopt the value $C_s = 0.08$ suggested by Li [2013] through an a priori analysis of SGS model based on DNS databases.

Isothermal no-slip wall conditions are applied to the pipe surface, and streamwise boundaries are connected by a periodic condition. A variable body force is applied to the flow field
to maintain a constant mass flow rate, following the procedures of Lenormand et al. [2000]. The simulation is initialised with a laminar parabolic Poiseuille velocity profile with a random velocity fluctuation up to 30% of its mean value. Five flow passing periods through the pipe are used to reach the transition and steady state, and ten periods are simulated to converge the statistics.

The comparison of velocity profile and Reynolds stresses with the DNS data is plot in Fig 3. Very good agreement of the mean streamwise velocity profile with the DNS results is achieved by the present LES, and the LES Reynolds stresses also agree reasonably well with DNS.

![Figure 3: (a) Mean velocity profile. (b) Reynolds stresses. Dashed line: DNS of Khoury et al. [2013]; solid line: present LES. In subfigure (b), blue, green, red and black lines represent streamwise, radial, tangential velocity RMS and Reynolds shear stress.](image)

**Chute Rim Seal Case**

The LES of chute rim seal flow has the same geometry as for the RANS modelling presented above, but without the inner cavity beneath the inner seal. The mesh is refined to reach the LES requirement: wall normal distance $\Delta y^+ \approx 1$ at near wall grids, streamwise grid size $\Delta x^+ < 40$ in meridional plane, circumferential grid size $\Delta (r\theta)^+ \leq 100$ on the rotor rim. In this study, the LES mesh is coarsened in circumferential direction ($\Delta (r\theta)^+ \leq 160$) to reduce computing costs. This yields a total of $\sim 6.2$ million mesh nodes. As about 27 lobed flow perturbation cells were observed in the experiment, the sector angle is set to $13.33^\circ$ to contain at least one lobe in the computational zone. The Smagorinsky and the artificial viscosity coefficients are the same as for the pipe flow test case. Five rotor revolution periods are simulated to reach a steady state, and eight rotor rotational periods are used to converge the statistics.

The statistical convergence of static pressure on the five radial sensors is plotted in Fig. 4. The mean pressures are well converged, and high order statistics reach a satisfactory convergence.

![Figure 4: Statistical convergence of static pressure on the five radial distributed sensors.](image)
for further analysis and discussion of the results, which are presented in the next section.

RESULTS AND DISCUSSIONS

In this section, the RANS and LES solutions are further validated against the mean pressure measurements. Then the unsteady flow characteristics are deduced and discussed in detail. The instantaneous LES flow field is also examined.

Mean Pressure Distribution

While the aim of this study is to investigate the unsteady flow structures involved in the rim seal, the mean pressure distribution is also of interest. The mean pressure is presented here as the pressure difference to the sensor 1001 normalised by the dynamic head at disc rim speed \( (C_p = (\langle p \rangle - \langle p_1 \rangle)/(0.5 \rho \Omega^2 b^2)) \). In the experiment, the pressure differences were less than 1% of the atmospheric pressure and the variation of temperature is also relatively small, so fluid density and viscosity are assumed to be constant and their values were computed from the atmospheric pressure and the coolant flow temperature which is close to atmospheric conditions. In the simulations, fluid density and viscosity are nearly constant as well. The reference density is taken as the averaged value at the five radial sensor locations.

The mean static pressure distributions from the experiment, steady RANS, LES and URANS are plotted in Fig. 5. The radii of the pressure sensors are normalised by the disc rim radius. The main flow path is open to the atmosphere in the experiment, so the experimental outer annulus pressure will be approximately uniform. This and the CFD annulus pressure are plotted at \( r/b = 1.01 \). In the sealed CFD system, annulus pressures near the casing and hub are different, therefore both of them are plotted to compare with the experiment. A forced vortex pressure distribution at 55% rotor speed is also plotted in the figure. In the cavity all of the results follow the forced vortex distribution, indicating that the pressure is dominated by the disc rotation. All the CFD results show good agreement with experiment at the inner three sensor position in the cavity, while a significant improvement of the prediction near the chute seal has been achieved by LES. The RANS and LES pressure at rotor hub are close to the experimental atmospheric pressure. The URANS mean pressure follows the RANS one in the cavity at the four inner sensor position, and appears a slight improvement over RANS at outer radii in the cavity.

![Figure 5: Mean static pressure distribution.](image)

Both the LES and RANS results agree with measurements within the cavity. Considering the pressure difference across the rim seal, LES gives the best agreement with the measurements. This may be associated with the unsteady flow in the rim seal, as discussed below.
Unsteady Pressure Results

In order to detect large-scale unsteady flow structures, high resolution pressure measurements were recorded from 6 fast response sensors (see Fig. 1 (c)) during 1 second, corresponding to about 116 rotor revolutions. High spectral frequencies at 30 and 60 disc speed observed in the experiment that related to the 30 bolts beneath the inner seal have been filtered out for results presented in this paper. LES results are stored over 8 rotor revolutions using the probes at the same radial positions with 5° circumferential spacing. For URANS, unsteady pressure data have been registered over 4 rotor revolutions using the probes with 20° spacing at the same radial locations as in the experiment and LES.

The deduction of unsteady flow structures is performed with the help of frequency spectra and cross correlation analyses, and is presented in the next two sub-sections.

Frequency spectra

The power spectral density (PSD) is selected for calculating the frequency spectra. The unsteady pressure signals are separated into 25 windows for the experiment and 2 segments for the LES and URANS (corresponding to about 4 rotor revolutions per window for LES, and 2 rotations per segment for URANS), with the segmented signal being zero padded to twice its original length and 50% overlapping between segments.

The PSD results are plotted in Fig. 6 for the radially distributed pressure sensor positions. Distinct peaks of frequency \( f/\Omega = 23.4 \) are observed in the experimental results for the sensors 1001 to 1004, while high amplitude with a wider frequency range is detected at the sensor 1005 within the chute seal clearance. In the LES, only the sensors 1004 and 1005 show distinct peaks. Comparing the LES results with those of the experiment, one should notice that an excellent agreement of distinct peak frequency \( (f/\Omega \approx 23.5) \) has been achieved. This suggests that about 23.5 periodic flow structures have been captured during a rotor revolution time, by both the experiment and LES. Some discrepancies are observed as well. Within the seal clearance (sensor 1005) more pronounced unsteadiness with a wide range of frequencies is indicated by the experiment. This broadband unsteadiness is not observed in the LES results. Another two distinct peaks are found at \( f/\Omega = 36.5 \) and 47 in the LES results, but were not observed in the experiment. The PSD of URANS results shows two peaks at \( f/\Omega = 16.2 \) and 21.7 for the two uppermost sensor positions. Thus the LES gives closer agreement with experiment than URANS in terms of the main unsteadiness frequency.

A number of factors may contribute to differences between the LES and experimental results, and these are to be investigated in further studies. As reported by Beard et al. [2016] the unsteady pressure measurements showed effects of boltheads in the inner cavity on the rig (shown in Fig. 1(b)). The experiments were also subject to a small eccentricity giving deriations in the seal gap of up to 8%. Neither of these effects were included in the LES which also imposed periodicity on a 13.3\(^\circ\) sector. A further consideration is that the outer annulus was open to the laboratory environment, while a sealed annulus was assumed for the LES. Rotating flows are known to be susceptible to waves and the LES results indicate that the chute seal can give rise to such flows. In contrast to the LES, the experiments show the amplitude of the distinct frequency reducing as the chute seal region is approached. However, the measured broadband unsteadiness in the chute region shows more fluctuating energy than observed at lower radii. The broadband energy could, for example, be due to eccentricity while the growth of distinct frequency signal moving away from the seal might be associated with resonance involving interaction with the inner seal, inner disc cavity and/or outer annulus flow. Further research is needed to clarify such effects.
Unsteady flow structures

Figure 7 (a) illustrates how a periodic flow structure rotating at angular velocity $\omega_s$ will affect a pressure measurement at two stationary sensors at the same radius but at circumferential locations differing by a known angle $\alpha$. If the flow structure has $N$ periodic pairs of perturbation cells, the angle between each flow structure is $\beta = 2\pi/N$ radians. The sensors 1 and 2 will both record the same frequency ($f$) with a phase lag $\Delta t_\alpha$, corresponding to the time it takes for flow structure to travel between the two sensors. The angular frequency (peak frequency by PSD) detected by each sensor is $f = 2\pi/\Delta t_\beta$, where $\Delta t_\beta = \beta/\omega_s$ is the time taken for a flow feature to pass through an angle $\beta$. These relations give four equations with the six unknown parameters: $f$, $N$, $\omega_s$, $\beta$, $\Delta t_\alpha$, and $\Delta t_\beta$. The measured frequency $f$ and the phase between the pressure signals detected at the two sensors are required to determine the number of lobes $N$ and angular velocity $\omega_s$ of the unsteady flow structure. Generally, the angle $\alpha$ between the two sensors is not always smaller than the angle $\beta$ between two pairs of perturbation cells (as plotted in Fig. 7 (a)). The determination of the phase difference is further complicated since cross correlation of the two pressure signals will show multiple peaks for the phase lag $\Delta t_\alpha$ corresponding to the $N$ lobes, such that $\Delta t_\alpha = \alpha/\omega_s + n\Delta t_\beta$ where $n$ is any integer.

Prior to cross correlations of signals, the measured unsteady pressure data were further filtered to remove components outside the area of interest around $f = 23.4\Omega$ by a 3rd-order Butterworth bandpass filter. The same filter was applied to the LES results to only keep the signals with frequencies around $f = 23.5\Omega$ or $f = 36.5\Omega$. Cross correlation was performed on each pair of sensor combination for the experimental results, while it was only applied to two sensors with a circumferential spacing of $5^\circ$ for the LES results. An example, illustrated in Fig. 7 (b), shows the cross correlation of the pressure data between the sensors 1006 and 1002 (10^9 spacing) over one rotor rotation. The phase lag (time lag) between the two signals is non-dimensionalised by one rotor revolution time. Evenly distributed peaks of the cross correlation coefficient are clearly seen in the figure, indicating a periodic rotating flow structure. If, for a flow structure spinning at the same direction as the rotor, the angle between perturbation cells ($\beta$) is greater than the angle between two pressure sensors ($\alpha = 10^9$) then the time difference from the origin (0) to the first positive peak with positive time lag is expected to correspond to the time taken for a perturbation cell to travel through angle $\alpha$ (between the two probes). The interval between two adjacent positive peaks corresponds to the time lag between two probes.
neighbouring flow structures.

Figure 7: (a) Illustration of cavity flow structures, (b) cross correlation of pressure between sensors 1006 and 1002 over one rotor revolution, (c) summary plot of the cross correlation results.

Cross correlations of pressure data, for each combination of the 6 sensors (15 pairs in total), have been repeated for each of the 116 rotor revolutions. A summary plot of all the cross correlation results is shown in Fig. 7 (c). The angle between the sensor pairs (α, shown on the vertical axis) is plotted against the peak time lag (ΔtαΩ/2π) collected from each rotor revolution. The peak time lag can also be denoted as the angle turned by rotor in Δtα, shown on upper horizontal axis. On the map, symbols are plotted in partial transparency. That means that the more samples drop in the same region, the darker they will appear, and vice versa. Beginning from the origin, a straight line must link as many symbols as possible to signify a periodically rotating flow structure. If, for a lobed flow structure spinning at the same direction as the rotor, the angle between flow features (β) is greater than the angle between two sensors (e.g., α = 5°) then a straight line should traverse the origin and the first group of symbols at α = 5° and pass through symbol groups at other sensor spacing angles as well. This gives the straight line in red in Fig. 7 (c). Its slope indicates the speed of the flow structure (ωs ≈ 0.80Ω), and the flow structure has 29 lobes. It is also observed that nearly all of the symbols lie on straight lines parallel to the red one with a constant interval, which shows the flow structure at different phases. The vertical interval suggests the angle between two flow features (β = 12.3°), and the horizontal interval described the lag time between two adjacent flow structures (Δtβ = 1/f). Another possibility is plotted by the blue dashed line: the angle interval between two perturbation cells are smaller than the angle between the sensors at 5° spacing, i.e., the straight line must connect the origin and the second positive symbol group at α = 5° and pass thought as more groups of symbol at other sensor spacings as possible. This gives a flow structure with 102 lobes rotating at 23% of the rotor speed. As fewer symbols are found on the blue dashed line, this possibility is less likely to the one with 29 lobes and rotating at 80% disc speed. The characteristic parameters of the flow structure are also listed in Tab. 3 for further comparison.

In the LES results, two distinct peaks are found at f/Ω = 23.5 and 36.5. The same filtering and cross-correlation procedures are applied respectively to these two peak frequencies to obtain their rotating speed and number of flow structures. As noise is less pronounced in the LES than in the experiment, cross correlations are applied to each of the 8 rotor revolutions. The averaged cross correlation reveals ΔtαΩ/2π = 3.19×10^{-2} for f/Ω = 23.5, and ΔtαΩ/2π = 3.09×10^{-2} for f/Ω = 36.5. Using the formula (ωs = α/Δtα, β = ωsΔtβ = ωs/f, N = 2π/β), one can compute the speed of the flow structure and the number of lobes. The results are listed in Tab 3. 54 and 81 lobes, spinning at 43.5% and 44.9% of the disc speed, are identified for the two
peak frequencies \( f/\Omega = 23.5 \) and 36.5, respectively. These correspond to 2 and 3 lobed flow structures within the 13.33\(^\circ\) computational sector. The results reveal that there are sometimes 54 and sometimes 81 lobed perturbation cells rotating at a speed close to 44\(\%\Omega\) for the entire annulus. This will be discussed further in the next section.

<table>
<thead>
<tr>
<th>Case</th>
<th>Peak frequency ((f/\Omega))</th>
<th>Speed ( (\omega_s) )</th>
<th>N. of lobes ((N))</th>
<th>Extent of lobe ((\beta))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td>23.4</td>
<td>80.0(%\Omega)</td>
<td>29</td>
<td>12.41(^\circ)</td>
</tr>
<tr>
<td>LES</td>
<td>23.5</td>
<td>43.5(%\Omega)</td>
<td>54</td>
<td>6.67(^\circ)</td>
</tr>
<tr>
<td></td>
<td>36.5</td>
<td>44.9(%\Omega)</td>
<td>81</td>
<td>4.44(^\circ)</td>
</tr>
<tr>
<td><strong>URANS</strong></td>
<td>16.2</td>
<td>45.0(%\Omega)</td>
<td>36</td>
<td>10.0(^\circ)</td>
</tr>
<tr>
<td></td>
<td>21.7</td>
<td>45.2(%\Omega)</td>
<td>48</td>
<td>7.5(^\circ)</td>
</tr>
</tbody>
</table>

The results for URANS unsteady flow structure have been calculated following the same procedures. Verification of PSD and cross correlation is made with flow visualisation as URANS results show very clear periodicities. The parameters of the RANS flow structure are shown in Tab. 3. The flow structures associated with the two peak frequencies rotate at the speeds \( \omega_s = 45.0\%\Omega \) and \( \omega_s = 45.2\%\Omega \), respectively. Finally, 48 and 36 lobes have been identified for the two peak frequencies. Another two URANS simulations were conducted with larger inner time step of dual-time stepping scheme but are not presented due to the page limit. However some sensitivity of the URANS results should be noted. With larger inner time steps which lead bigger speed-up ratio, the sub convergence level reduces, and peak frequency changes as well. Furthermore, unsteadiness was found to initialise later for the case with worse sub convergence level. This suggests the URANS prediction of rim seal flows depends on the sub convergence. A possible explanation is that for a time dependent simulation with dual-time stepping, the physical time step CFL number applies to the smallest grid cells which corresponds to a even smaller CFL number for large grid cells. Using the same inner CFL number to accelerate the inner convergence as a steady simulation, large grid cells converge earlier than the small grid cells, unfortunately the region where rim seal phenomenon occurs is generally occupied by numbers of small grid cells.

**Instantaneous Flow Fields**

In order to investigate the relation between the nonaxisymmetric pressure distribution and injection/ejection of the rim seal flows and further confirm the lobe number and rotational speed obtained from PSD and cross correlation, the LES instantaneous flow field is presented and discussed in this section.

The radial \((V_r)\), circumferential \((V_\theta)\) velocities and static pressure coefficient \(C_p\) on a cylindrical slice at the radial position of sensor 1005 \((r/b = 99.7\%)\), illustrated in Fig. 2 (b)), at two different instants of time, are shown in Fig. 8. The sub-figures on the top, middle and bottom row depict \(V_r\), \(V_\theta\) and \(C_p\), respectively. In each sub-figure, the top edge is on the stator and the bottom edge lies on the rotor. The horizontal axis is the azimuthal angle \(\theta\), and \(\theta\) increases from right to left following the rotor’s rotational direction.

Figure 8 (a) shows the results at the instant of normalised time 0.20456 (by rotor’s spinning period). Ingestion and egress are clearly observed through the negative and positive radial velocities with two lobes. The boundary layers on both the stator and rotor are seen through the tangential velocity map, and the high \(V_\theta\) streaks cover the region between the two boundary layers. A slight shift can be seen between \(V_r\) and \(V_\theta\), and the high \(V_\theta\) region is found to lie around the interface between ingress and egress. The interface between high and low tangential velocity regions reveal high strain effect. Two distinct low pressure streaks are observed covering the
Figure 8: Contour maps of $V_r$, $V_\theta$ and $C_p$ on a cylindrical slice at the radius of sensor 1005 ($r/b = 99.7\%$), at two different instants of time.

gap between the stator and rotor. Savov et al. [2016], citing Phadke and Owen [1988] proposed that where the pressure is lower than the cavity mean egress takes place, and vice versa. This is broadly consistent with the observation here, but a slight shift can be seen between the low pressure streak and egress region. The high $V_\theta$ region seems to match the low pressure streak, suggesting that the asymmetric pressure distribution is dominated by the asymmetry of tangential velocity. The flow structure with two lobes within the sector further confirms the results obtained from the PSD and cross correlation. The maps at a later instant of time 0.43516 rev are plotted in Fig. 8 (b). Three low/high pressure regions are evident in the bottom-row figure, and the corresponding high/small swirl and positive/negative radial velocity zones are shown in the figure, with a slight circumferential phase difference in the rotor’s rotational direction for the radial velocity. These results confirm the perturbation cells of three lobes determined by PSD and cross correlation within the sector.

The results and discussions in this section also provide confidence of the post-processing procedures used in the experiment, in terms of the determinations of the lobe number and their speed.

CONCLUSIONS

The modified Hydra LES code has been validated against a DNS database on pipe flow, and utilised for simulating a chute rim seal flow of a sealed rotor/stator cavity. All the simulation results of the chute rim seal cavity are validated against the mean pressure distribution. LES achieved a best agreement with the experiment, while URANS appears to slightly improve the RANS prediction.

Regarding the large-scale unsteadiness flow structure, the distinct peak frequency at $f/\Omega = 23.4$ observed in the experiment has been accurately captured by LES. This encourages use of LES for rim seal flow investigations. However there are some significant discrepancies between the experiment and LES (29 lobed structures rotating at 80%$\Omega$ in the measurement, 54 or 81 features spinning at about 44%$\Omega$ for LES), which may be caused by the limited sector angle or other approximations. The analysis of instantaneous flow fields provides further confidence in results deduced from PSD and cross correlation procedures for both CFD and experiment. It also reveals a high strain region at the interface of high and low tangential velocity streaks, and that pressure non-axisymmetry may be dominated by the asymmetries of $V_\theta$.

URANS using a dual-time stepping scheme captures some unsteadiness but the peak fre-
frequency did not match experiment. This approach shows dependency of the solutions on the sub convergence level though good periodicity is observed by numerical probes.

ACKNOWLEDGEMENTS

Funding for this research from Rolls-Royce plc and support from colleagues is gratefully acknowledged. In particular, we thank Matthew Miller and Peter Smout of Rolls-Royce.

REFERENCES

A. Jameson. Time dependent calculations using multigrid, with applications to unsteady flows past airfoils and wings. In *10th Computational Fluid Dynamics Conference*, Honolulu, HI, June 1991. AIAA.
C. Li. *A-priori analysis of LES subgrid scale models applied to wall turbulence with pressure gradients*. phdthesis, Ecole Centrale de Lille, November 2013.