Towards A Holistic Prediction of Fan Stage Tone Noise Mechanisms

P. Sureshkumar, M. Vahdati
Mechanical Engineering Department, Imperial College London, London, UK
A. Parry, S. Bianchi, M. Doherty
Rolls-Royce plc, Derby, UK

ABSTRACT
A computed prediction of the tonal noise generated in the fan stage of an aero-engine is presented. This paper focuses in particular on unsteady fan stage aerodynamics, which leads to the generation of noise. It is further shown that there are a variety of sources of tonal noise and that, for a more complete analysis of the fan stage tonal noise balance that is due to rotor and stator interaction, these sources should be evaluated simultaneously. The computational model has been validated against steady state aerodynamic measurements and measured sound pressure levels. Some acoustic theory is also presented to explain the in-duct radiation behaviour of fan stage tonal noise towards the external environment.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>rotor blade count</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$P_0$</td>
<td>total temperature</td>
</tr>
<tr>
<td>$T_0$</td>
<td>total pressure</td>
</tr>
<tr>
<td>$V$</td>
<td>stator vane count</td>
</tr>
<tr>
<td>$c$</td>
<td>sound speed</td>
</tr>
<tr>
<td>$k$</td>
<td>wavenumber</td>
</tr>
<tr>
<td>$m$</td>
<td>harmonic index</td>
</tr>
<tr>
<td>$n$</td>
<td>radial mode order</td>
</tr>
<tr>
<td>$p$</td>
<td>static pressure</td>
</tr>
<tr>
<td>$Ω$</td>
<td>rotor speed</td>
</tr>
<tr>
<td>$β$</td>
<td>Prandtl-Glauert factor</td>
</tr>
<tr>
<td>$ν$</td>
<td>circumferential mode order</td>
</tr>
<tr>
<td>$κ$</td>
<td>acoustic wavenumber</td>
</tr>
<tr>
<td>$\Box_1$</td>
<td>axial parameter</td>
</tr>
<tr>
<td>$\Box_θ$</td>
<td>circumferential parameter</td>
</tr>
<tr>
<td>$\Box_τ$</td>
<td>fan parameter</td>
</tr>
<tr>
<td>$\Box_β$</td>
<td>OGV parameter</td>
</tr>
<tr>
<td>$\Box_ν$</td>
<td>ESS parameter</td>
</tr>
</tbody>
</table>

INTRODUCTION
Aircraft engine noise is a major component of aircraft noise emissions at take-off and landing. A number of aircraft engine noise sources originate from within the engine and are capable of radiating to the external environment, either through the fan intake or downstream of the fan and through the engine bypass and exhaust. Mitigating this radiated noise is key to meeting noise regulations. A new set of noise regulatory standards is to be introduced in the near future (Dickson, 2013). Therefore when proposing new engine designs, manufacturers must further account for tougher standards to ‘future-proof’ the final engine.

This paper focuses on the prediction of fan-stage interaction tone noise. Fan stage interaction noise sources are shown to be dependent on features of flow in the fan interstage region. In particular, attention is given to the unsteady aerodynamics that govern the interaction noise generation process. The typically dominant sources of aero-engine fan tone noise, such as buzz-saw and fan-outlet guide vane (OGV) interaction, have been studied extensively (Peake and Parry, 2012; Envia, 2002; Huff, 2004) and, as a result, modern aero-engines tend to be designed for minimisation and mitigation of those noise sources. More recent work on in-duct fan tonal noise is presented in de Laborderie and Moreau (2016). In this work, all
the sources of tone noise in a typical fan stage are considered simultaneously, including rotor-alone tones, fan-OGV interaction tones, fan-engine section stator (ESS) interaction tones and furthermore tones generated by interaction with both stator rows (see Figure 1). Previous experiments and predictions show that, for pretty much any architecture, different sources dominate at different conditions; it is, therefore, appropriate to ensure that all sources of fan-associated tone noise are considered simultaneously and this paper highlights that it may be prudent to do so. Note that other sources of in-duct tonal aero-engine noise, which may arise from other aero-engine structures such as the intake or bifurcations (Holewa et al., 2012; Bonneau et al., 2015) are not currently included in this paper, which focuses only on the rotor and stator interaction in the fan stage.

Computed predictions are obtained using the solver AU3D (Sayma et al., 2000), and these predictions are validated by comparison with the available data from an experimental campaign, which the computations have been set up to simulate. Acoustic measurements are used for comparison with modal predictions of each of the sources of tone noise. Some acoustic theory is highlighted to compliment the computed predictions and measurements, and is used to provide insight into the character of fan stage interaction noise and the nature of its propagation.

**SUMMARY OF ACOUSTIC THEORY**

The fan is the only rotor present in the fan stage and it follows that all fan stage tones are at the blade passing frequency or one of its harmonics, i.e.

\[ \omega = m_f B_f \Omega_f \]  

(1)

where \( \omega \) is the tone frequency, \( m_f \) and \( B_f \) are the fan harmonic index and blade number and \( \Omega_f \) is the fan speed. Tones generated in the fan stage may be categorised as either rotor only tones or interaction tones. Each of the tones is generated at a particular circumferential mode number, \( \nu \). For rotor only tones, this is given by

\[ \nu = m_f B_f \]  

(2)

whilst for interaction tones \( \nu \) may in general be expressed using
\[ \nu = m_f B_f \pm m_e V_e \pm m_o V_o \] (3)

The subscripts \( e \) and \( o \) correspond respectively to ESS and OGV parameters; \( V \) indicates the vane count of the stator. Interaction tone generate noise at harmonics of the fan blade passing frequency and with a number of spinning azimuthal lobe patterns, usually identified as Tyler-Sofrin modes. To recover the standard expression from Tyler and Sofrin (1962), for a rotor interacting with a single stator row, set either \( m_e \) or \( m_o \) to zero in eq. (3). In these expressions, the harmonic index \( m \) must be a non-negative integer. The mode order for either a sum (+) or difference (−) interaction tone is given but generally for a rotor-stator interaction it is the difference tones that are of interest, since these tones are less likely to be cut-off. The concept of cut-off is fundamental to acoustic propagation in the fan stage and will be explained in more detail in following paragraphs.

Alternatively, setting both \( m_e \) and \( m_o \) as non-zero corresponds to the what is described here as a ‘mixed’ interaction mechanism. The ‘mixed’ interaction tone may be induced by a rotating disturbance generated from one rotor-stator interaction impinging on the remaining stator row; a similar phenomenon (where rotating pressure fields from one rotor-stator interaction impinge on another rotor in the compressor stage of an aero-engine) has been described in Cumpsty (1974).

Due to the presence of the engine nacelle, the sound field in an aero-engine is often theoretically modelled as propagation in a ‘duct’ (see for example Rice (1974); Rienstra and Tester (2008)). The basis of such theory is that the sound field may, under certain assumptions, be decomposed into constituent modes. In a cylindrical annular volume, such as inside an aero-engine fan stage, the mode is characterised by its circumferential and radial mode numbers. A fan stage tone with a specific circumferential mode number will establish a number of radial modes which may or may not propagate through the volume (both upstream and downstream of the source) and thus radiate to the external environment.

A key aspect to predicting mode propagation in a duct is determining if the mode is cut-off. If a mode is cut-off it does not propagate, exhibiting an exponential decay from the source instead. Otherwise the mode may propagate either upstream or downstream from the source axially. The propagation characteristics of a mode can theoretically be defined by a dispersion relation of the following form

\[
\left( \beta^2 k_1 + \left( \kappa - \frac{\nu M_\theta}{r} \right) \right)^2 = M_1^2 \left( \left( \kappa - \frac{\nu M_\theta}{r} \right)^2 - \beta^2 k_r^2 \right) \] (4)

where \( \kappa = \omega / c, \beta = \sqrt{1 - M_1^2}, c \) is the sound speed and \( k_r \) and \( k_1 \) are radial and axial wavenumber components. \( M_1 \) and \( M_\theta \) are axial and circumferential Mach numbers. Eq. (4) is consistent with a similar expression in Kerrebrock (1977). Note that a number of assumptions have been made in arriving at this relationship. The flow is assumed uniform and steady. The flow is assumed to have a constant value of axial Mach number and angular velocity along the span i.e. plug and wheel flow. Realistically, the flow in an aero-engine fan stage is much more complicated. The theory also assumes axially invariant annulus lines - such an assumption is for modelling purposes and practically could only be applied very locally. Despite the assumptions, much insight into mode propagation characteristics may be derived from the analytic model.

The analytic model is essentially an acoustic eigenmode expansion over the cross-section of the (annular) duct. Details of solving this type of problem for duct geometries of arbitrary cross-section and with flow are provided in Goldstein (1976); for a more thorough analysis geared to the application of aero-engines see Rienstra and Tester (2008). Obtaining the theoretic (and infinite number of) modal solutions is dependent on determining the radial wavenumbers \( k_r \) of each mode, which is in turn dependent on
boundary conditions on the duct cross-section. For now, the engine’s inner and outer casings are assumed rigid and impermeable.

Analysis of the dispersion relation leads to the following, theoretical cut-off condition

\[
\left( \kappa - \frac{\nu M_\theta}{r} \right)^2 < \beta^2 k_r^2
\]

(5)

For each tone there are a finite (possibly zero) number of radial modes which do not meet the cut-off criteria in eq. (5), sometimes referred to as cut-on modes. The remainder of the modes in the infinite set are cut-off. Whether a mode is cut-off will depend on the flow, duct geometry and also the circumferential mode number.

Steady state computations show that the radial profile of axial Mach number is generally well approximated as uniform, except near the boundaries. The radial profile of circumferential Mach number is consistent with constant circulation, more representative of free vortex flow, rather than the wheel flow assumed in the theory. This swirling flow causes a coupling between acoustic and vortical disturbances (the extent of which is frequency dependent); see for example Golubev and Atassi (1998) or Kerrebrock (1977). Nevertheless the effect of swirling flow may be significant and has been summarised as such in Peake and Parry (2012). Recent work by Posson and Peake (2013) presents an analytic model which can predict the effect of swirl on acoustic propagation. Note that swirling flow also has a significant impact on the convection and skew of the fan wakes, which in turn affects the generation of interaction noise (Cooper and Peake, 2006). The effect of rotating flow is most readily seen in the interstage of the fan (between the rotor row and two stator rows (see Figure 1)). The circumferential component of the flow in the bypass duct is mostly reduced by well designed OGVs. For the experimental campaign a non-rotating flow was passed into the fan inlet, therefore all rotation in the interstage is induced by the fan.

There are also a number of other significant challenges in predicting the far-field noise of fan stage tones, because of the multiple and complex propagation paths from where the noise is generated to either the engine inlet or exit. For example, interaction noise is likely to be altered by reflection from and transmission through the fan blades, OGVs and ESSs, and also acoustic diffraction by the splitter. The noise may also be altered by varying hub and casing annulus lines. Propagation by a splitter has previously been modelled by Nijboer (2003) A seminal study on this mechanism is presented in Kaji and Okazaki (1970). Scattering from the rotor or stators would also introduce frequency and modal scattering.

THE COMPUTATION SCHEME

The computation domain replicates a scaled fan test-rig, which is representative of the type of fan used on modern large aero-engines (Vahdati and Cumpsty, 2016). The domain consists of five separable regions: an intake, the fan blade row, the fan interstage and finally two stator bladerows, each preceding the aero-engine bypass and core, which represent the outlet guide vanes (OGVs) and engine section stators (ESSs) respectively. There is a one to one node mapping at any adjacent boundaries in these separate domains in order to minimise interpolation error. In the fan domain, there are roughly 200 radial mesh layers and 100 circumferential mesh layers per blade-to-blade passage. The mesh in this region also accounts for the fan blade tip gap and is evaluated in a rotating frame of reference - all other domains are stationary. The mesh is further refined in the fan wake region and in the interstage so that convection of the wake is not sensitive to mesh resolution; the final setup used is the result of a mesh sensitivity analysis. Generally mesh density in the entire computation domain is quantified so that there is enough spatial resolution
to prevent dissipation of noise up the 3rd blade passing frequency, and to definitively capture acoustic modes up to a circumferential mode order of 50 and a radial mode number of 10. The numerical scheme uses dual time stepping and is second order accurate in time and space. As a guideline, the corresponding wavenumbers are approximated in each domain by use of eq. (4), the dispersion relation that includes the effect of wheel and axial flow.

With the proposed computational domain it is not necessary to condition the inflow and outflow boundaries with pre-determined profiles of the flow variables. The intake mesh is extended to the farfield, where ambient flow properties are uniformly prescribed at the boundary. A nozzle is attached downstream of both the bypass and core stators. The static pressure at the nozzle outflow is set sufficiently low to ensure the nozzles are choked, so that information cannot propagate through the shock at the nozzle throat (Vahdati et al., 2005). The operating point on the speed line is then controlled by adjusting the throat area of the nozzle in the engine bypass. Flow into the core has relatively little impact on the operating point but is adjusted to ensure the overall flow is appropriate, guided by an expected value for the bypass ratio.

The CFD code used in this body of work, AU3D, is a time-marching, Reynolds-averaged Navier-Stokes (RANS) solver which operates on unstructured/hybrid meshes (Sayma et al., 2000) and uses a one equation Spalart-Almaras turbulence model (Spalart and Allmaras, 1992). Solutions are three dimensional and may also be evaluated such that they are time accurate, viscous and compressible. Over the last 20 years, AU3D has typically and successfully been used to compute flows at off-design conditions; AU3D has been consistently used as a fan stage aerodynamics prediction tool to determine the onset of fan-stage flutter (Sayma et al., 2000; Vahdati and Cumpsty, 2016; Zhao et al., 2016). Further information on the solver and more details on the experimental research fan geometry can be found in Vahdati and Cumpsty (2016).

Steady calculations are solved on a grid with approximately 9.5 million nodes. In a steady calculation, each domain is connected to an adjacent domain using mixing planes. Mixing planes transfer data by circumferentially averaging the solution variables and passing the relevant averaged value onto the new domain by interpolation - therefore, only radial variation of the solution is propagated. The steady calculation domains are also limited to a single blade-to-blade passage (or equivalently narrow sector for mesh domains with no bladerow) to save computation cost. The solution is assumed periodic across this sector and so a periodic boundary condition is employed at the azimuthal boundaries. The mesh used for unsteady calculations is approximately 200 million points in total. A full annulus mesh might be required if the unsteady disturbances would no longer satisfy the periodic boundary condition used on the single blade-to-blade passage meshes as in in the steady state calculations. However, if all unsteady disturbances have an even circumferential mode number the mesh could for example be reduced to a half annulus, with periodic boundaries employed. Data is transferred across adjacent mesh boundaries in the unsteady calculations by the use of sliding planes. Sliding planes are necessary at the boundary between rotating and stationary mesh domains, as they allow for time accurate adjustment of the solution before data is propagated into the next domain. The unsteady calculations presented in this paper are calculated on a half annulus with a periodic boundary condition.

FLOW SOLUTIONS

Figure 3 compares steady CFD predictions of fan mass flow and pressure ratio with a similar set of measurements from the experimental campaign. Solutions are computed at three fan speeds. These speedlines correspond to the fan design speed (speed line C) and two part speed settings associated to plausible cutback (speed line B) and approach (speed line A) conditions, which are relevant to engine noise regulations. Full unsteady calculations, conducted for the purposes of generating radiated noise
field predictions, were run at operating points on a single working line. For speed lines B and C, where there was equivalent data from the experimental campaigns available, the steady predictions are well matched with measurements.

Figure 3 also compares predicted and measured radial profiles of the ratio of stagnation pressure at fan inlet and fan exit for an operating point on speed line B. These profiles show good agreement with each other across the span. The kink in the curve at around 5% span might be present because of generation of a vortex like feature in the fan wake. The vortex stems from the secondary flow generated by corner stall in the fan. Corroborating the existence of such a feature is challenging without validation with an appropriate experimental measurement, and it should be noted that the geometry used for prediction belongs to a research fan design. Typically, much effort is put into reducing these features on real engine fans by the use of hub contouring and advanced fan blade design in the hub region. Nevertheless, for our computed results the ‘hub vortex’ is a persistent feature and is shown to have a significant impact on the computed radiated noise results. The impact of this vortex will be discussed further in a later section. The fan inlet and exit planes used for the measured and predicted profiles are not consistent with each other, which could explain the slight offset in the predicted span of this feature.
Fan wake prediction

The characteristics of the wake are a significant factor in the level of radiated interaction noise. One source of fan stage interaction noise is due to the unsteady loading generated on the surface of the stator vanes, created as wakes from the fan blade wash past them.

The contours of entropy in Figure 4 visualise the fan wake just downstream of the fan trailing edge at different fan speeds (on a single working line). It has already been demonstrated in, for example, Parry (1988) that parameters such as the maximum wake deficit velocity and wake width can be key indicators of the level of noise generated by the wake-blade interaction. As seen in Figure 4 the strength of the wake clearly diminishes with fan speed. Perhaps more interesting, however, is the variation in the wake along the span. Towards the outer casing, a reduction in fan speed causes separated flow which results in a very different wake profile. The strength of the wake is mostly conserved but the wake covers a larger proportion of the annulus with decreasing speed. The vortex at the lower end of the span meanwhile, seems to be strengthened with increasing speed (also seen in Figure 3. The vortex is also more pronounced in shape with increasing speed.

![Figure 4: Contours of entropy on an axially perpendicular plane just downstream of the fan trailing edge. From left to right the contours visualise the fan blade wake generated at fan speed A, B and C respectively.](image)

The impact that convection through the swirling flow in the interstage has on the fan wakes is shown in Figure 5. Figure 5 (a) shows contours of entropy on an axially perpendicular plane which is just downstream of the fan trailing edge whilst Figure 5 (b) shows contours of entropy on an axially perpendicular plane in the interstage. Figure 5 (c) shows similar contours just upstream of and aligned to the leading edge of the OGVs and ESSs. The contours visualise the entropy present in the fan blade wake, tip clearance leakage flow and in the casing boundary layers. These contours are obtained from the computed solution at fan speed C.

![Figure 5: Contours of entropy on an axially perpendicular plane in the interstage.](image)

The most prominent effect seen in this figure is the leaning of the wake. Wake lean is caused in part by the twist and lean of the fan blade itself, as made apparent in the contour just downstream of the fan trailing edge. The wake is further leant by the swirling flow and the swirling flow radial profile would cause a varying amount of lean along the span - the effect of the swirling flow is presented in Figure 5 (b). The lean of the wake is still more pronounced in Figure 5 (c) because this contour is aligned to the leading edge of the OGVs and ESSs, which are swept. Fan stage stator vanes are designed with sweep and lean to prevent wake and blade interaction occurring along the whole span simultaneously (Cooper and Peake, 2006). The speed at which the wake-blade interaction moves along the blade span has an impact on the radiated noise level and is often referred to as the trace velocity.
As the fan wakes convect through the interstage the wakes also mix out, meaning that the peak deficit velocity is reduced and the wake widens. The rotor stator spacing varies with span, which means the convection path does as well, increasing from the inner to the outer casing. A longer convection path means that the wake is mixed out to a further extent. The vortex in the hub region of the wake has mostly retained its strength at the core and its shape, particularly since it has a relatively short convection path.

**Unsteady loading of stator vanes**

To demonstrate the impact of the fan wake on the unsteady loading of the stator vanes, particular focus is given to the interaction with the ESS; in part because the effect of the hub vortex on the magnitude of unsteady loading is interesting. Figure 6 again shows contours of entropy depicting the wake profile just upstream of the leading edge of the ESS, and from left to right solutions at fan speeds A, B and C.

The strength of the wake and vortex at the leading edge of the ESS and indeed the formation of the vortex itself (refer to Figure 4) is clearly dependent on fan speed. The wake-blade interaction is known to generate noise because of the periodic perturbation in blade loading that is created as the wake washes...
past the blade. The unsteady loading of the ESS is dominated by interaction at the stator leading edge. Note that the three dimensional geometry of the ESS will induce radial migration of the flow on the stator vane surface. To quantify the effect that the vortex might play in altering the unsteady loading of the stator, the unsteady lift per span is calculated by integrating the chordwise normal aerodynamic force around the blade section at each span. The resulting spanwise variation is shown in Figure 7. From left to right the figure shows the spanwise variation of loading at \( m_f = \{1, 2, 3\} \). Each plot contains the relative amplitude of loading at each of the three fan speeds.

![Figure 7: Spanwise variation of unsteady loading at harmonics (\( m_f = \{1, 2, 3\} \)) of the blade passing frequency. The amplitude of forcing is given for the three different fan speeds (A, B and C).](image)

Referring to Figure 7 it is clear that the vortex, which impacts the ESS at approximately 33% span, has had a significant impact on the total level and harmonic distribution of the unsteady loading. The \( m_f = 1 \) loading harmonic shows a peak amplitude at this span, whilst the other higher harmonics, in particular \( m_f = 2 \) show a reduction in loading at this span - at other spans the loading is significantly higher. This may be due to the migration of the flow on the blade surface as the interaction takes place or simply because the vortex has altered the wake profile at this span to create a more gust like interaction. In either case it is evident that the unsteady loading sees a significant increase with fan speed which would translate to a higher level of noise. Although the forcing amplitude of the \( m_f = 1 \) harmonic is the highest, it is not likely to translate into radiated noise, through the conventional rotor-stator interaction. This is because a common mode of fan noise reduction in aero-engines is to cut-off interaction noise up to at least the first harmonic by design, by use of a sufficiently high stator count.

**ACOUSTIC PREDICTIONS**

The unsteady solutions were further processed to extract predictions for the radiation behaviour of fan stage tones. Here, the analysis is focussed on fan speed C (the design speed) and furthermore on radiation into the bypass duct. Fan stage noise that propagates into the bypass duct may, without attenuation, radiate into the external environment as rear-arc fan noise.

Figure 8 presents predicted and measured sound pressure levels (SPLs) for distinct and prevalent tones from the experimental data. These sound pressures are observed in the bypass duct, downstream of the OGVs. Sound pressure is extracted from the acoustic simulation by use of a wavesplit technique as outlined in Moinier and Giles (2005). Further details on the acoustic measurement campaign and processing methods for noise can be found in Tapken et al. (2011). Note that in that paper, data is obtained from radial mode detection (RMD) rings, whereas for this work only data from circumferential mode detection (CMD) rings were available. Only sound pressure measurements were available for comparison here as well, meaning the acoustic power analysis presented in that paper may not be replicated here.
Figure 8: Predictions and measurements of sound pressure level (SPL) of a number of fan associated tones, as measured in the bypass duct. The sound pressure levels are in reference to the pressure measured \( (p_m) \) during experiments.

Uncertainty of the measurement of sound pressure is limited to 1dB, however limits on the dynamic range of the measurement transducers mean that results which are more than 15dB below the peak level of measured noise may not be trusted. None of the presented data is below this floor. For sanitization, the sound pressure levels are evaluated with the reference pressure set as the measured values of pressure; the purpose of the figure is to validate the computation method as a tool for predicting fan stage noise. From left to right the figure contains rotor-only tones, fan-ogv interaction tones, fan-ess interaction tones and ‘mixed’ interaction tones. The tones are labelled by the relevant rotor and stator harmonic indices. Note that all azimuthal mode orders for these tones are below 50, the limit by which the computation mesh was designed. For a more involved analysis of the acoustic data collected during the measurement campaign, the reader may refer to Tapken et al. (2011) which presents a larger set of noise results in a more pragmatic format. In essence, the results presented here in Figure 8 correspond Figures 27 and 28 of Tapken et al. (2011). The purpose here is simply a validation and instead focus is turned to the mechanisms of tone noise.

The figure shows that prediction and measurement are generally in agreement across this particular set of tones, despite the presence of a number of modelling differences between the computations and experiments. Clearly there are a significant number of alternate tones that may be generated as well; only tones that were well clear of the noise floor have been shown here. The noise floor refers to the level of noise at which one may ascertain the tone is free from contamination by background, flow or measurement noise. The noise floor was seen at all harmonic frequencies and circumferential mode numbers and could theoretically be explained by various phenomena, such as broadband noise or limitations to the post-processing methods used for the measurement data. Many of the expected fan stage tones were masked by this floor and thus unfeasible choices for comparisons.

It is possible to deduce that the prevailing tones shown in Figure 8 are either well cut-on in the bypass duct (refer to Figure 9 (b)) or originate from the OGV, which is the closest noise generating ‘source’ to the measurement position. The proximity of the OGV means that even though noise might not propagate to the external environment (due to cut off), it may still be picked up at the measurement position.

Four tones (highlighted in red on Figure 9 are analysed further to demonstrate the varying sources of noise, the importance of modal cut-off in radiation to the external environment, and perhaps the necessity to predict fan stage noise in a holistic fashion. Figure 10 shows contours of unsteady pressure in a meridional plane, for these four tones. The unsteady solution has been deconstructed into temporal and spatial circumferential Fourier series in order to isolate the relevant tone.

Figures 10 (a) and (b) correspond to the cut-on \( \{2, -1\} \) fan-ogv and \( \{2, -1\} \) fan-ess interaction tones.
Figure 9: Predicted cut-off frequency curves for duct modes in (a) the bypass duct and (b) the fan interstage. A number of fan stage tones are also presented, identified by tone type and corresponding harmonic indices. + and − are indicative of a sum and difference type interaction respectively. Referring to Figure 9 shows how both these tones would have a number of radial modes cut-on, explaining the reverberant structure of the sound field in the interstage and bypass duct. At this operating condition, both tones would radiate as rear-arc fan noise if allowed to propagate through the bypass duct unattenuated.

Figure 10 (c) depicts the unsteady pressure amplitude of the \{1, −1\} fan-ess interaction tone, which is cut-off in the bypass duct (this result is consistent with the theoretical cut-off for this tone presented in Figure 9 (b)). As discussed earlier, this is consistent with the typical design constraint of selecting stator vane counts high enough such that cut-off is achieved, and note that this tone is not one of the prevailing tones presented in the comparison to measurements in Figure 8. However this tone is cut-on in the interstage, largely due to the rotating flow, which allow the first few radial modes to propagate (see Figure 10 (a)). This result is significant because of the result presented in the unsteady pressure contours for the \{0, −1, +1\} ‘mixed’ interaction tone, in Figure 10 (d). Referring to Figure 9, this tone is theoretically just cut-off in the interstage but just cut-on in the bypass duct, which is consistent with the computed prediction. However it becomes apparent that the source of this ‘mixed’ interaction tone could be due to the \{1, −1\} fan-ess interaction tone further interacting with the OGV. That tone is shown to be cut-on in the interstage, and further interaction with the OGV would allow sound energy to scatter into a new circumferential mode number which is then cut-on in the bypass duct. Thus, even though the \{1, −1\} fan-ess interaction tone is cut-off by design, it could still be contributing to the radiated noise field through this scattering mechanism, creating the presently discussed ‘mixed’ interaction tone.

CONCLUSIONS

A method has been presented for computing aerodynamic and acoustic solutions for the fan stage of an aero-engine, and the solutions have been validated against measurement data from an experimental campaign for a model research fan. The complexity of noise generation and propagation in the fan stage has been briefly highlighted and the impact of the unsteady aerodynamics on fan wake and stator interaction noise has been analysed specifically. The analysis has shown that there are a number of mechanisms to consider. It has also been shown that there is benefit in developing the fan stage so that it attenuates noise by design. A holistic prediction of the fan stage is useful since it further predicts other
sources of noises, such as the mixed interaction by both stators presented here, which may be overlooked in an individual component or noise source analysis. The next step in this work is to incorporate other aero-engine structures, notably bypass duct bifurcations and the fan intake, which will allow for the inclusion of more source of noise and complexity in acoustic propagation still.

This paper is focussed on a specific aspect of fan stage noise however there are a number of other interesting and associated problems to consider. Upstream radiated noise would contribute to fan forward-arc noise and could also further be complicated by interaction with the fan. This study has assumed purely rigid, impermeable walls, however in a real setting this assumption is invalid, due to the presence of acoustic liners for attenuation. A similar analysis and validation but with the additional modelling of liners and forward arc noise is in progress.

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank Rolls-Royce plc and the Rolls-Royce Vibration University Technology Centre (VUTC) at Imperial College London for their funding, provision of technical data and general support for this project.

References

Bonneau, V., C. Polacsek, R. Barrier, S. Lewy, J.-M. Roux, and Y. Gervais
Cooper, A. J. and N. Peake
Cumpsty, N. A.
de Laborderie, J. and S. Moreau
Dickson, N.
2013. ICAO Noise Standards.
Envia, E.
Goldstein, M. E.
Golubev, V. V. and H. M. Atassi

Holewa, A., C. Weckmuller, and S. Guerin

Huff, D. L.

Kaji, S. and T. Okazaki

Kerrebrock, J. L. K.

Moinier, P. and M. B. Giles

Nijboer, R.

Parry, A. B.

Peake, N. and A. B. Parry

Posson, H. and N. Peake

Rice, E. J.

Rienstra, S. W. and B. J. Tester

Sayma, A. I., M. Vahdati, L. Sbardella, and M. Imregun

Spalart, P. and S. Allmaras

Tapken, U., R. Bauers, L. Neuhaus, N. Humphreys, A. Wilson, C. Stoehr, and M. Beutke

Tyler, J. and T. Sofrin

Vahdati, M. and N. Cumpsty

Vahdati, M., a. I. Sayma, C. Freeman, and M. Imregun

Zhao, F., N. Smith, and M. Vahdati