Advanced open rotor noise prediction

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ABSTRACT

The purpose of this paper is to describe the current status of open rotor noise prediction methods and to highlight future challenges in this area. A number of analytic and numerical methods are described which can be used for predicting 'isolated' and 'installed' open rotor tonal noise. Broadband noise prediction methods are also described and it is noted that further development and validation of the current models is required. The paper concludes with a discussion of the analytical methods which are used to assess the acoustic data collected during the high-speed wind-tunnel testing of a model scale advanced open rotor rig.

1.0 INTRODUCTION

The advanced open rotor offers potentially significant reductions in fuel burn relative to current generation turbo-fan engines. Because of this significant benefit, the open rotor is currently being investigated by a number of leading aeronautical companies as a potential aircraft propulsor. A cut-away view of an open rotor concept is shown in Fig. 1 below. The engine consists of two contra-rotating rotors which, in this case, are driven by a gas turbine engine housed within a large centrebody which protrudes both fore and aft of the rotors. In order to be a viable aircraft engine, the open rotor will need to meet stringent noise certification standards and thus, a range of prediction methods are required for assessing the noise produced by various open rotor designs. These range from simple analytical methods, which are useful for design optimisation studies e.g. Parry and Vianello[1], to high-fidelity CFD/CAA methods which are useful for design validation e.g. Colin *et al.*[2]. The purpose of this paper is to describe a range of noise prediction methods and, in particular, to highlight recent developments and to identify further work which is required.

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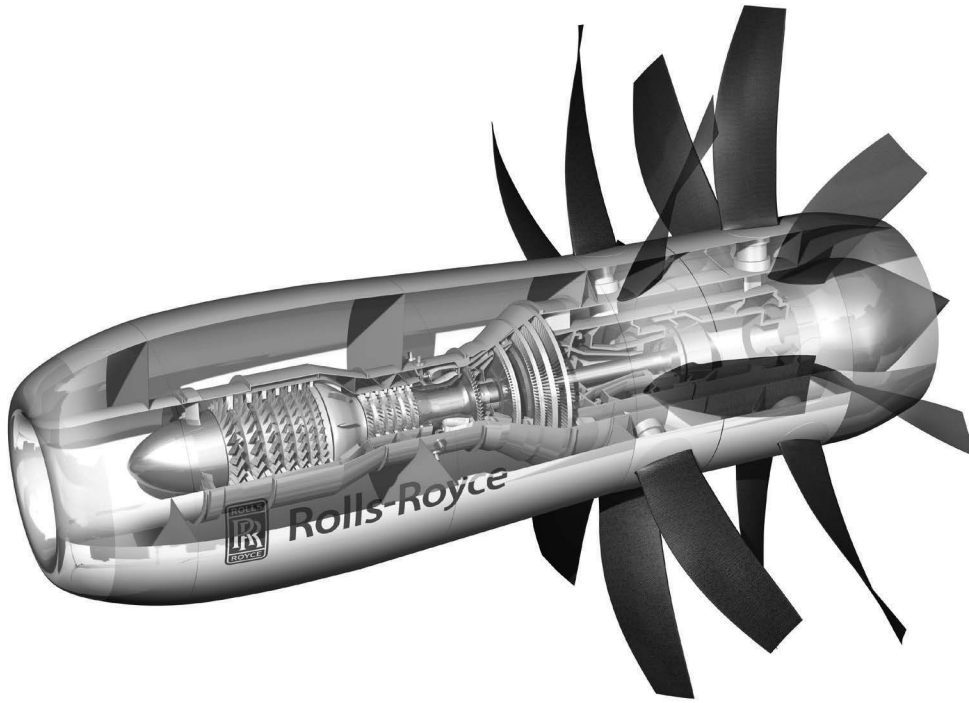


Figure 1. Cut-away view of an advanced open rotor engine. (courtesy of Rolls-Royce)

In Section 2, methods for predicting the tonal noise produced by an isolated open rotor engine are described. The usefulness of simple analytical methods for noise prediction is highlighted including recent work by the author and collaborators on the development of models for predicting the effect of acoustic scattering from the open rotor centrebody. In section 3, methods for predicting broadband noise are described. It is noted that the accuracy of these methods is dependent on obtaining precise information about the turbulence in the boundary layer and wakes of the rotor blades – which is difficult. In section 4, a number of installation effects and methods for predicting them are discussed. Section 5 describes the various analytical methods which are used to analyse the acoustic data collected from high speed wind-tunnel testing of a model-scale advanced open rotor rig. These methods are required because of the need to make measurements in the acoustic near-field of the rotor and also to assess the importance of reverberation on the noise level within the tunnel.

2.0 ISOLATED OPEN ROTOR TONE NOISE PREDICTION METHODS

Ffowcs-Williams and Hawkings[3] show that the noise produced by a moving impermeable surface, such as the blades of an advanced open rotor, can be thought of as being due to surface distributions of 'thickness' and 'loading' sources and a volume distribution of 'quadrupole' sources. Thickness sources effectively generate noise via the periodic volume flow produced by the displacement of air by the rotating impermeable blades of each rotor. Loading sources produce noise via the stresses exerted by the surface of the rotor blades on the fluid. The quadrupole sources are determined by the

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Lighthill stress tensor in the volume of fluid surrounding the blades. Thickness noise and the noise produced by the steady component of the loading and quadrupole 'sources' on and surrounding the blades will produce tones at integer multiples of the blade passage frequency. These tones are commonly referred to as rotor-alone tones. Periodic unsteady loading on the rotor blades due to their interaction with a stationary flow distortion, such as the wake from an upstream pylon, will also produce tones at integer multiples of the blade passage frequency. However, if the distortion is produced by an adjacent counter-rotating rotor, then tones will be produced at integer multiples of the sum and difference of the front and rear rotor blade passage frequencies. These tones will be referred to in this paper as 'rotor-rotor interaction tones'.

A number of standard methods based on extensions of Ffowcs-Williams and Hawkings' acoustic analogy are available for predicting both near- and far-field tonal noise. These methods require 'sources' to be specified on, and in the fluid exterior to, a closed surface which may be permeable or impermeable to the flow. The sound radiation from these 'sources' is then either calculated in the time-domain e.g. Farassat[4,5] and Farassat and Myers[6] or in the frequency domain e.g. Hanson[7] for near-field rotor-alone tones, Hanson[8] for far-field 'rotor-alone' tones and, Hanson[9], Sharma and Chen[10] for far-field tones produced by a contra-rotating open rotor. The near-field frequency domain method of Hanson[7] requires the evaluation of a spatial Fourier transform, which can be computationally expensive. For far-field frequency domain predictions, the spatial Fourier transform can be evaluated using the method of stationary phase, which drastically reduces the computational expense. Further simplifications have been developed by Parry and Crighton[11] and Crighton and Parry[12,13] who used asymptotic techniques to evaluate the radial integral in Hanson's far-field radiation formula for rotor alone tones. Parry[14] describes how these asymptotic methods could be extended to apply to the rotor-rotor interaction tones produced by a contra-rotating advanced open rotor. Peake and Crighton[15] have also developed asymptotic formula for the near-field radiation due to steady loading and thickness sources.

As stated previously, in order to predict the noise produced by an open rotor using either time- or frequency-domain radiation methods, the 'sources' must be determined. Various methods exist for calculating these which range from high fidelity (but time intensive) CFD methods to simple (but quick) analytical methods. Notable recent papers describing the prediction of isolated open rotor tone noise using CFD/CAA methods include a series of excellent papers by Colin *et al.*[2,16,17], who describe the development of a computational strategy for open rotor tone noise prediction at Airbus, Peters and Spakovszky[18] and Sharma and Chen[10], who use a frequency domain, permeable Ffowcs-Williams and Hawkings surface method to predict the far-field tone noise produced by an advanced open rotor.

Parry[14] and Whitfield *et al.*[19], describe analytic methods for predicting the rotor-alone and rotor-rotor interaction tones produced by an advanced open rotor. These methods utilise far-field radiation formula equivalent to those developed by Hanson[8,9], however, the volume quadrupole source is neglected in both methods. The steady-loading and thickness sources are specified by the rotor geometry, operation and aerodynamic performance data. The unsteady loading on the rotor blades at a particular radial location is calculated using the following procedure: the rotor is 'unwrapped' at the radius of interest and an equivalent 2D problem is considered. The flow field in this 'unwrapped' system is then decomposed into a series of Fourier gusts. Finally, simple analytical models, such as those described in Refs 14,20,21, are used to calculate the 'response' or unsteady loading on the blade due to its interaction with each gust. The flow field produced by each rotor is modelled by splitting it into different components; models for the viscous wakes and potential fields are described in Refs 14 and 22, whilst Whitfield *et al.* utilise the tip vortex model developed by Majjigi *et al.*[23]. Kingan and Self[24] and Roger *et al.*[25] have developed alternative methods for predicting the upwash on the downstream blade row due to the tip vortex shed from the blades of the front rotor.

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Recently, Carazo, Roger and Omais[26] have presented a 'hybrid' frequency domain method for predicting wake-interaction noise produced by an open rotor. This method utilises flow-field information from CFD simulations and calculates the unsteady loading on the blade using blade response functions. The sound radiation is calculated via a standard far-field frequency domain method.

Glegg[27] shows that the scattering of sound from the centrebody of a propeller is negligible for rotor-alone tones but can be significant for tones produced by periodic impulsive loading on the propeller blades. Glegg developed a mathematical model for predicting this effect by modelling the propeller blades as rotating point forces and the centrebody as an infinite rigid cylinder. Kingan [28] extended Glegg's analysis to include the effect of distributed sources and an axial flow. They then calculated the effect of centrebody scattering on the rotor-rotor interaction tones produced by an advanced open rotor and were able to show that the effect could be significant. Recent work by the author[29] has yielded further insight into the centrebody scattering effect. Asymptotic expressions equivalent to those of Parry[11], and Crighton and Parry[12] have been developed for estimating the magnitude of the centrebody scattered field. Glegg's observation that centrebody scattering is negligible for rotor-alone tones was investigated and it was shown that this is because the tones produced by a subsonic rotor radiate inefficiently inboard of the rotor tips. However, it was also shown that particular rotor-rotor interaction tones radiate efficiently inboard towards the centrebody. For these tones, the sound pressure field scattered from the centrebody can be of similar amplitude to that of the incident (free-field) pressure. This effect is demonstrated in Fig. 2 which shows the first harmonic of the instantaneous pressure field in the plane of rotation of 12 evenly spaced, rotating, tangential point forces in a quiescent fluid. The plot on the left shows the field produced by the forces rotating at a Mach number of 0·9, whereas the plot on the right-hand side shows the field produced by the forces rotating at a Mach number of 5. The field produced by the subsonic forces is qualitatively similar to the rotor-alone tones produced by an open rotor. For this case, the acoustic field radiates efficiently outboard of the 'sonic radius' (which for this case is located just outboard of the source radius) but very inefficiently in the evanescent region inboard of the sonic radius. However, the field produced by the 'hypersonic' forces is qualitatively similar to that which would be produced by certain interaction tones for which centrebody scattering is important. For these tones, the sound radiates efficiently both inboard and outboard of the source radius and the amplitude of the pressure field scattered from the centrebody surface can be similar in magnitude to that produced by free-field radiation.

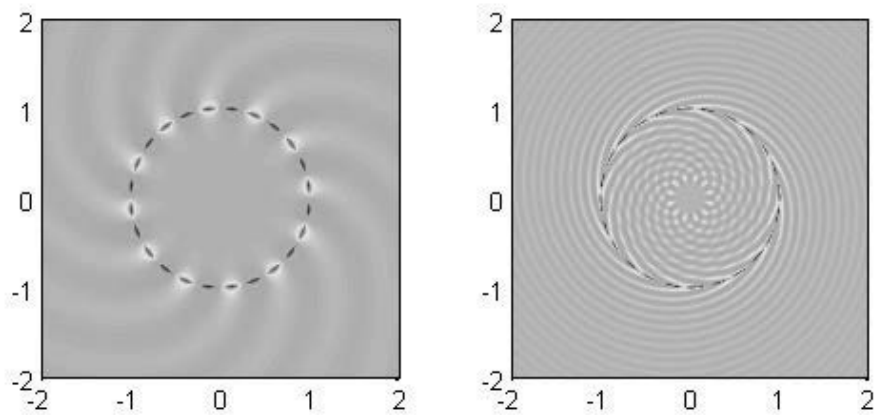


Figure 2. Contours of instantaneous pressure in the plane of rotation for the first harmonic of the field produced by 12 rotating tangential point forces located at radius 1m in a quiescent fluid. The rotational Mach number of the forces is 0·9 (left) and 5 (right). The forces rotate about the origin and the horizontal and vertical axes have units of metres.

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3.0 BROADBAND NOISE PREDICTION

Whilst the sound pressure level spectrum produced by an open rotor contains a significant number of tones, Parry *et al.*[30] show that broadband noise can be a significant contributor to the total noise field produced by a modern, acoustically optimised open rotor. Their conclusions were based on an analysis of the one-third octave band sound power levels produced by a 1/6th scale open rotor rig running in the large open-jet wind tunnel at DNW. During these tests, noise levels were measured using microphones mounted on the large 'C-shaped' traverser shown to the right of the open rotor rig in Fig. 3. The measured narrowband and one-third octave band sound pressure spectra at a particular observer location are shown in Fig. 4. A broadband spectrum was calculated by fitting a moving median curve through the narrow-band data and it was observed that at medium to high frequencies the broadband noise was the dominant contributor to the one-third octave band levels. Thus, although most of the work on open rotor noise prediction has focussed on developing methods for tones, there is a need for methods to be developed which can accurately calculate the broadband noise produced by an open rotor. For modelling purposes, broadband noise can be divided up into a number of separate sources:

Self-noise is produced by the diffraction of turbulence in the boundary layers and near-wake of the rotor blades by the trailing edge. A number of different methods exist for calculating the self-noise produced by an open rotor, although most of these were developed for helicopter rotors or wind turbines. One such model was developed by Schlinker and Amiet[31]. In this model, the rotor is divided up into a number of segments or 'strips' and at any instant in time it is assumed that the self-noise produced by any strip is equivalent to that which would be produced by the same strip in rectilinear motion. The time-averaged spectrum for each strip is then calculated by averaging over one blade rotation. The total rotor noise is then calculated by summing the contribution from each strip incoherently. Note that the exact form of the method proposed by Schlinker and Amiet appears to be somewhat controversial. Similar methods have been used by Pagano *et al.*[32], Rozenberg *et al.*[33] and Sinayoko *et al.*[34]. Alternative methods for predicting rotor self-noise, based on the exact solution for a rotating point force, have also been proposed by Kim and George[35], Chou and George[36], Zhou and Joseph[37] and finally Sinayoko *et al.*[34] who show that both approaches to self-noise prediction are comparable. One of the main difficulties of predicting rotor self-noise is obtaining an accurate estimate of the characteristics of the turbulent boundary layer on the open rotor blades.

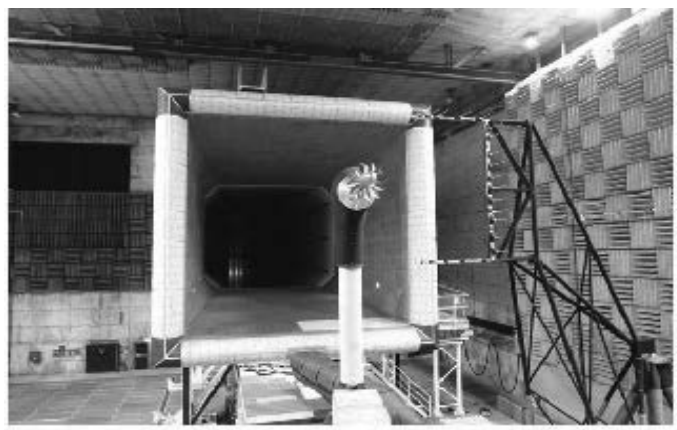


Figure 3. Testing of a 1/6th scale open rotor rig in the DNW wind tunnel[30].

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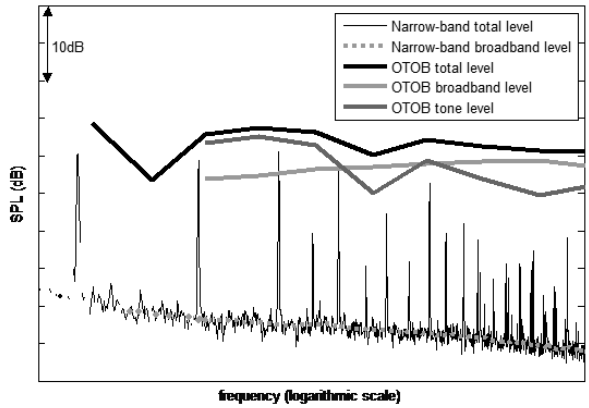


Figure 4. Narrowband and 1/3 octave band SPL produced by an open rotor[63].

Atmospheric turbulence ingestion noise is produced by atmospheric turbulence being ingested by the rotor and 'chopped' by the rotor blades. A number of different models exist for predicting this noise source. Amiet[38] and Paterson and Amiet[39] present and validate a model for predicting this noise source. Amiet[40] extended this work to include the effect of turbulent stretching as the turbulence passes through the rotor plane using rapid distortion theory. Majumdar and Peake[41] developed an alternative model for calculating turbulence ingestion noise which also includes the effect of turbulent stretching using rapid distortion theory.

Rotor-rotor interaction noise is produced by the turbulence in the wake of the front rotor interacting with the contra-rotating blades on the downstream rotor. Blandeau and Joseph[42] developed the first model for this particular noise source. Kingan[43] extended this model to include the effect of an axial flow and also corrected a number of minor errors in the original formulation of Ref. (42). Kingan also describes a simple extension of the model which allows it to be used to predict the broadband noise produced by the interaction of a pylon wake with a rotor. Both formulations model the turbulent wake from the front rotor or pylon using simple empirical formulae calculated from wind-tunnel experiments on 2D aerofoils. Work on validating these models is currently underway.

4.0 INSTALLATION EFFECTS

A number of analytic methods are available for predicting various 'installation effects'. In particular, the sound pressure on the surface of the fuselage can be predicted using the method proposed by Hanson and Magliozzi[44]. This method models the 'incident' tone noise produced by a propeller using the Hanson's frequency domain radiation formulae. Refraction through the boundary layer and scattering from the fuselage surface are then calculated using straightforward analytical and numerical techniques. Alternative methods have also been developed by Spence[45] and Lu[46] who also investigated the far-field radiation scattered from the aircraft fuselage. Simple analytical models for calculating the far-field noise due to scattering by the aircraft surfaces have also been proposed by Amiet[47] who models the wing as a semi-infinite half-plane and McAlpine and Kingan[48] who model the fuselage as an infinite cylinder. However, given the gross simplifications of the aircraft geometry used in these models, their accuracy is somewhat questionable. Fortunately, it is possible to accurately calculate scattering numerically using schemes such as those described by Le Garrec and Reboul[49] and also Lummer *et al.*[50].

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A number of methods have been proposed for calculating the effect of angle-of-attack on the tonal noise produced by an open rotor. Kresja[51] and Hanson[52] present equivalent analytical expressions for calculating the far-field tone noise produced by an open rotor at an angle-of-attack to the direction of motion. Note that the formulae presented by Kresja includes an extra infinite summation, which is absent from Hanson's formulation. According to Hanson[53] it can be shown that this infinite summation can be evaluated analytically to yield identical results to those presented in Ref. 52. Hanson and Parzych[54] extend the work presented in Ref. 52 to include a near-field calculation method and also a more accurate representation of the rotor geometry which places the noise 'sources' on the blade surface rather than the mean camber or chordal surface. Recently Brandvik, Hall and Parry[55] have presented a promising method for performing CFD analysis of an open rotor at an angle-of-attack, which should allow high fidelity CFD/CAA analysis of an advanced open rotor at angle-of-attack.

Much recent work has focussed on the installation of an open rotor in a 'pusher' configuration where the engine is mounted towards the rear of the aircraft on the fuselage using a pylon upstream of the front rotor. An obvious way to model the noise produced by the interaction of the pylon wake with the open rotor is to use the standard radiation formulae of Hanson[9] and Parry[14] for rotor-rotor interaction tones and model the upstream pylon as a one-bladed stationary upstream rotor. However, a recent experimental study conducted by Rolls-Royce and Airbus and reported in Ref. 56 has shown that trailing-edge blowing to fill out the pylon wake can be used to significantly reduce this noise source.

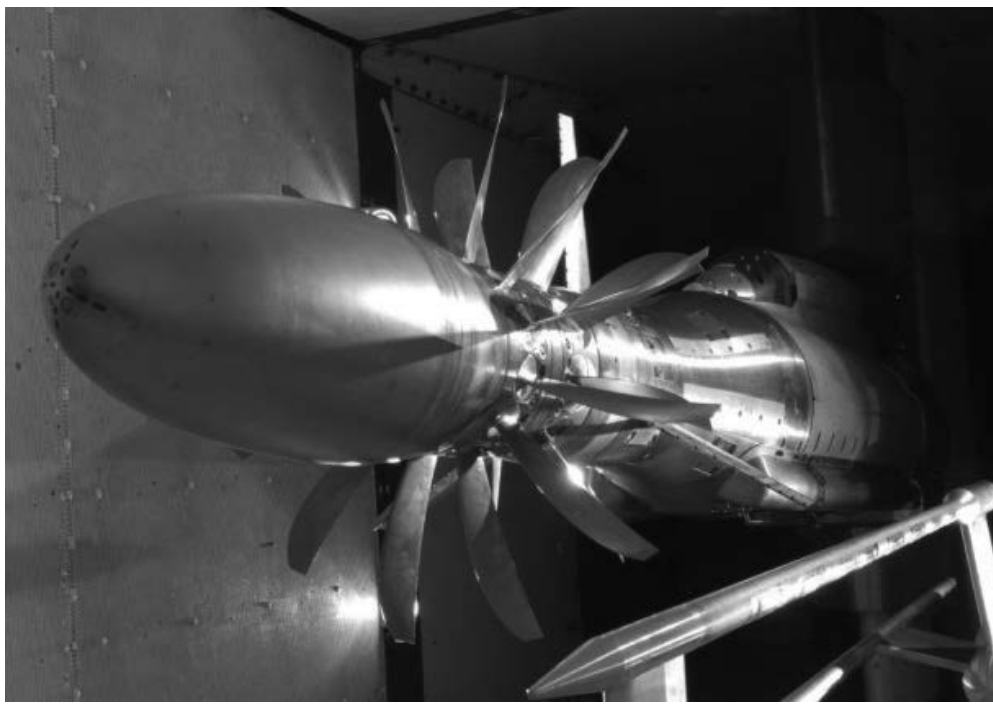


Figure 5. Rolls-Royce's 1/6th scale open rotor rig installed in the ARA wind tunnel in Bedford, UK. (courtesy of Rolls-Royce)

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5.0 HIGH SPEED WIND-TUNNEL TESTING OF A 1/6TH SCALE ADVANCED OPEN ROTOR RIG

A number of tests campaigns have recently been conducted in the ARA transonic wind tunnel in Bedford, UK, using Rolls-Royce's 1/6th scale open rotor rig. The primary purpose of these tests was to assess the aerodynamic performance of the open rotor at conditions representative of cruise. However, the walls of the wind-tunnel test section are acoustically lined and thus noise measurements are also possible (see Ref. 57). The results of these tests are reported in Ref. 58. A photograph of the open rotor rig installed within the tunnel is shown in Fig. 5 below. Measurements of the sound pressure level are made by microphones mounted within the rail visible in the foreground of the photograph. Because the microphones are located well within the acoustic near-field of the open rotor, in order to calculate the far-field tone noise levels, the approximate method of Peake and Boyd[59] is used to 'project' measurements to the acoustic far-field where the sound pressure level decays in a predictable manner. It is worth noting that for rotor-alone tones, near-field effects can be very significant. Differences of 20dB are typical between a sound pressure level prediction at a measurement point close to the rotor tips using the near-field prediction method described in Ref. 7 and the far-field prediction method described in Ref. 8.

Despite the fact that the walls of the ARA transonic wind tunnel are lined, the experimental results reported in Ref. 58 indicate that away from the plane of the rotor, reverberation may be an issue. In order to assess the possible effect of reverberation within the ARA wind tunnel, Sureshkumar, Kingan and Parry[60] developed an analytical method for calculating the noise within a rectangular wind tunnel with rigid walls. A comparison of an experimental measurement of the sound pressure level for a rotor-alone tone with both a free-field prediction and a prediction made using the new method suggested that measurements within the tunnel away from the plane of the rotor may have been affected by reverberation. Work is currently underway to improve the model so that it includes the effect of the wall liner in order to further assess the significance of reverberation within this tunnel. The reader should note that Eversman[61] and Mosher[62] have also presented alternative methods for predicting the sound produced by a propeller and a helicopter rotor in a wind tunnel.

6.0 CONCLUSIONS

This paper has presented a review of the methods available for predicting the noise produced by an advanced open rotor. A number of well-developed methods currently exist for calculating the tonal noise produced by an isolated open rotor. The computational power which is available for numerical simulations also means that high-fidelity CFD simulations can be used as input to these methods although analytic methods are also available and are useful for preliminary design studies. It has been noted that further development and validation of methods for predicting open rotor broadband noise are also required. A number of methods are also available for predicting various installation effects. Finally, analytic models were described which are used for analysing and appraising the acoustic data collected during tests of a scale open rotor in a high-speed wind tunnel.

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