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JET NOISE MODELLING INSIDE THE CONE OF SILENCE BY GEOMETRIC ACOUSTICS

C.L. MORFEY I.S.V.R., UNIVERSITY OF SOUTHAMPTON

V.M. SZEWCZYK ROLLS-ROYCE LIMITED, DERBY

1. INTRODUCTION

Even outside the cone of silence, substantial improvements in the collapse of jet noise spectra are achieved by allowing for acoustic-mean flow interaction [1,2]. The present study extends our previous work into the cone of silence, using the same models as previously for the source and the mean flow. Radiation through the shear layer occurs via locally evanescent (cut-off) wave motion, for which an approximate high-frequency description has been found. Predictions are compared with jet noise spectra measured inside the cone of silence.

2. THE JET NOISE MODEL

2.1 The Mean Flow Model

The real diverging jet flow is replaced by a steady, infinite, stratified shear flow with a single velocity profile shape (error function) of constant shear layer thickness. However, the choice of velocity profile is allowed to vary with Strouhal number according to axial source location data [1]. In the acoustic source region the flow properties are treated as constant, (U_s, ρ_s, c_s) while outside the flow profile varies, the assumption being that the sound propagates out of the flow according to the laws of geometric acoustics.

2.2 The Source Model

The jet noise source model consists of a combination of dipole-order and quadrupole-order displacement distributions. The displacement source model was adopted from the work of Tester and Morfey [3], who showed that in the shear flow analogy the Lighthill type volume acceleration source was inappropriate. Source region non-compactness, axial convection and inherent directivity are all included.

In the high-frequency limit, source non-compactness and convection are allowed for in a modified Doppler factor [2] defined by

$$D_m^2 = (1 - U_c\cos\theta_o/c_o)^2 + \beta^2(U_J/c_o)^2\cos^2\theta_o + \alpha^2(U_J/c_o)^2(D_s^2c_o^2/c_s^2 - \cos^2\theta_o) \quad \ldots \quad (1)$$

Here α and β represent the transverse and axial non-compactness effects, and U_c is the source axial convection velocity; these influence the convective amplification of the radiated sound. Values of these three turbulence parameters have been estimated [2] from model jet mixing noise data provided by Lockheed Georgia.

The geometric acoustics scaling laws [2] for the 1/3 octave intensity radiated at a given R/d and modified Strouhal number $S_m = fdD_m/U_J$ are

$$I(\text{quadrupole source}) = I_q(S_m)G_q(\theta_o)(U_J/c_o)^8 D_m^{-9} F_q \quad \ldots (2)$$

$$I(\text{dipole source}) = I_d(S_m)G_d(\theta_o)(U_J/c_o)^6 [(T_s-T_o)/T_s]^2 D_m^{-7} F_d \quad \ldots (3)$$

The inherent source directivity is allowed for via the factors G_q, G_d (which contain $\cos^4\theta_o, \cos^2\theta_o$ weighting factors). In order to fit measured data it was necessary to assume that the axial-axial quadrupole component (or axial dipole component) was of different strength from the others [1]. I_q, I_d represent the source strengths and D_m^{-9}, D_m^{-7} the respective convective amplification factors. The effect of acoustic-mean flow interaction is represented by F_q, F_d.

It has been assumed in this study that the source scaling and turbulence parameters estimated from noise measurements <u>outside</u> the cone of silence are relevant for radiation <u>inside</u> the cone of silence; only the modelling of the acoustic-mean flow interaction changes.

2.3 The Acoustic-Mean Flow Radiation Model

Although expressions valid for F_q, F_d outside the cone of silence can be simply derived using Blokhintsev's acoustic energy conservation law, these are not appropriate inside the cone of silence [2]. The starting point for the derivation of a suitable analytical flow factor (defined as ratio of the far field intensity to its value for zero flow with the source strength held constant) is the monopole source flow factor derived by Tester and Morfey [eqn. (68) of ref. 3] from their analyses of the Lilley equation in the high-frequency limit. It is effectively a three-dimensional WKB solution, allowing for the exponential decay of pressure waves crossing the shear layer from the source position to the transition point (where the radial wavenumber q has zero value). The radial gradient of $|q|^2$ evaluated at the transition point is the primary term in the exponential decay; it is evaluated assuming a perfect gas and similarity of velocity and total temperature profiles. The final expressions for F_q, F_d, G_q, G_d (to allow for the stronger axial components) are made up from suitably phased combinations of simple sources.

The flow factors inside the cone of silence reduce to expressions valid outside when $\theta_o = \theta_c$. The approximation to the exact high frequency asymptote is in excellent agreement with Lilley equation solutions by Tester [4] for all $\theta_o > 20^o$. Full details may be found in reference [4].

3. COMPARISONS WITH SUBSONIC VELOCITY JET NOISE MEASUREMENTS

The exponential decay is proportional to a shear layer thickness parameter $\omega_m\delta_s/U_J = k_o\delta_s D_m/(U_J/c_o)$. The unknown shear layer thickness δ_s can be estimated from acoustic data. The method adopted is detailed in reference [4]. Figure 1 shows the variation with jet static temperature of the optimum shear layer parameter obtained from subsonic jet noise data. The increase in shear layer thickness at a given axial location is consistent with the idea of a more rapidly spreading flow when a jet is heated [5]. In fact the parameter values can be converted to δ_s/d; this was done for $T_J/T_o = 1$ and compared with values of δ_s estimated from flow and source location measurements. Good agreement occurs except far downstream (S_m < 0.5), where the error-function profile used is strictly inappropriate. Spectral levels predicted inside the cone of silence using these $\omega_m\delta_s/U_J$ values compare well with measurements; a selection is shown in Figure 2. In the estimation of the shear layer parameter, only subsonic jet noise measurements have been used. This limitation became obvious when an implied flow factor was extracted from measurements by application of equations (2) and (3). Results showed that while the subsonic flow factor was well behaved, increasingly linearly (in dB) with increasing jet velocity, the supersonic velocity values did not continue the trend and were always less than would be predicted [4].

4. COMPARISON WITH SUPERSONIC VELOCITY JET NOISE MEASUREMENTS

Measured levels at supersonic velocities are underpredicted, the discrepancy increasing as the velocity is increased and the angle is reduced. The poor prediction is not due to the high-frequency approximations; Lilley equation solutions by Tester and Morfey also underpredict this data. The onset of this difficulty appears to be closely associated with the occurrence of distinctly positively skewed acoustic signatures in the far field [6]. Possible explanations are as follows:

(a) finite radial extent of the equivalent source distribution;

(b) interaction of the sound field with the unsteady jet velocity field, i.e. scattering of sound into the cone of silence;

(c) the emergence at supersonic efflux velocities of unstable disturbances in the jet flow which constitute an additional noise source;

(d) breakdown of the simplified elliptical cross-power spectral density contour (in this and all previous work to date) for the convected source, particularly in the Mach wave region [4]).

Further work, both experimental and theoretical, to establish the cause of this difficulty in the cone of silence is required to complete what otherwise is a firmly based successful model of jet noise radiation.

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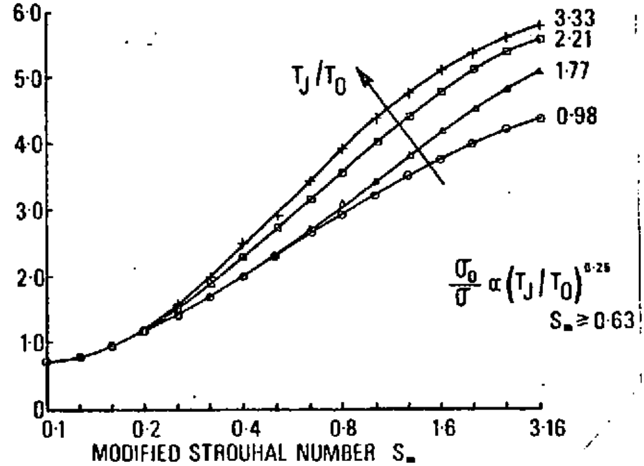

Figure 1: The Variation of the Optimum Shear Layer Parameter $\frac{\omega_m \delta_s}{U_J}$ with Jet Static Temperature Ratio.

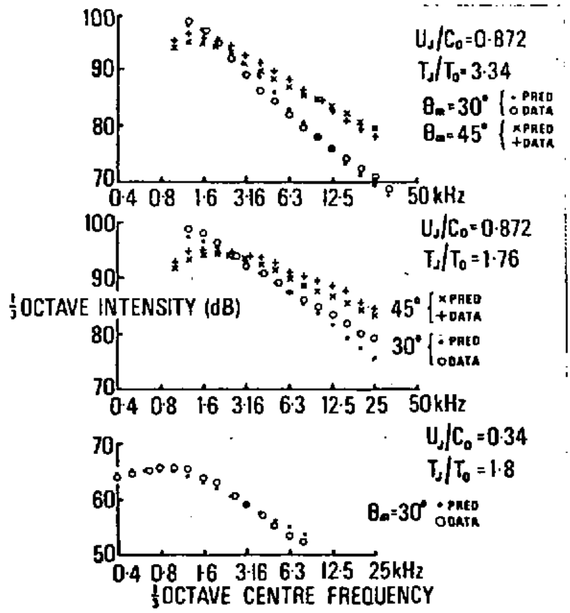

Figure 2: Comparison of Predicted and Measured 1/3 Octave Spectra. R/d = 72, d = 0.1667 ft.