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AERONAUTICAL NOISE: SESSION A: JET NOISE

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SHOCK ASSOCIATED NOISE

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1. Introduction

The shock waves in an incorrectly expanded supersonic jet will interact with the jet turbulence to produce a source of noise in addition to that due to the turbulent mixing. This source has two components, one of which consists of discrete tones harmonically related, often termed screech, and the other more broadband but strongly peaked, often termed shock associated noise. The former, which involves an acoustic feedback from the source region to the nozzle, was studied in some detail by Powell (1), but the latter, which is essentially from the same source but without the acoustic feedback is very poorly documented. This more broadband component has been studied extensively at the ISVR in recent years. The study has comprised two separate but complementary facets, namely using an optical method, the crossed beam schlieren technique (2), to probe the nature of flow field near the shocks and also obtaining a comprehensive set of measurements of the sound field.

The influence of shock associated noise on the variation of noise levels with jet efflux velocity is shown in Fig. 1. It can be seen that at an angle of observation of $\theta = 30^o$ to the jet axis no significant change in the general dependency observed at sub-critical pressure ratios occurs when the nozzle chokes. (i.e., $M_J > 1$). By contrast at $\theta = 90^o$ and 143^o an extremely rapid increase of noise levels ensues once shock waves appear in the flow field. Furthermore, over this range of angles the noise field becomes progressively less directional as the pressure ratio is increased. It is to be emphasised however that the results presented here are for an unheated jet flow. For high stagnation temperature jets these changes are far less dramatic than observed here due, as we shall show below, to the increased contribution of mixing noise.

On the other hand it is to be emphasised that the levels presented in Fig. 1 are not due to a significant contribution from the discrete tones or screech as a result of the precautions taken to eliminate this source. These comprised covering all acoustically reflecting surfaces in the vicinity of the nozzle exit plane with acoustic foam and the use of a small projection on the nozzle lip. These precautions reduced the screech to levels which were undetectable on 6% bandwidth spectral analysis.

2. Dependence of Overall Levels

A more informative manner of presenting the data of Fig. 1 for pressure ratios above the critical value is shown in Fig. 2. Here the overall sound pressure level at 90°, appropriately normalised for nozzle diameter and distance of observation, is plotted against the parameter β where

$$\beta \equiv \sqrt{M_J^2 - 1} \quad (1)$$

and M_J is the fully expanded local jet Mach number, a function of the pressure ratio only.

It can be seen that apart from the smaller β values the measured levels are directly proportional to the fourth power of β. Also shown is an estimate for the mixing noise based on an extrapolation of the lower speed data shown in Fig. 1. It can be seen that as this 'estimated mixing noise' contribution falls progressively below the measured levels so the β^4 law is more accurately obeyed. This suggests therefore that the broad band shock associated noise itself follows a β^4 law, but that at the lower β values the total noise follows a rather slower dependence due to the presence of mixing noise. Further evidence for this is presented in Fig. 3, showing data for the upstream arc, $\theta = 143^{o}$. Here it is seen that the 'estimated mixing noise' is negligible at all but the lowest pressure ratios and the straight line relationship is obeyed over the entire range of measurement. Comparison of the lines drawn on Figs. 2 and 3 indicate furthermore that they differ by only 2 dB, indicating again that the shock associated noise is relatively omnidirectional. Also shown in Figure 3 is the noise from jets at several stagnation temperatures in the region of 1100^{o}K. It can be seen that at a sufficiently high value of β, i.e. pressure ratio, the points coincide with the cold jet line thus indicating that the shock noise is virtually independent of jet temperature.

The β^4 dependence observed above suggests that the amplitude of the 'sources' producing this noise varies as β^2. Consideration of the normal shock relationships, furthermore, shows that this is precisely the dependence of the pressure difference across a shock of upstream number M_J. Thus it appears that the source strength associated with the shock associated noise is proportional to the pressure difference across the shock waves.

In summary, therefore, it appears that the overall level of shock associated noise is principally a function of jet pressure ratio and is relatively independent of either angle of observation or jet stagnation temperature. Whether or not it is the dominant noise source for a given pressure ratio however depends on these parameters since they set the mixing noise levels.

3. Spectral Characteristics

A model, for the prediction of the spectral characteristics of shock associated noise, has been evolved by extending Powell's original model for the discrete components. In this model the end of each shock cell is taken as a source of acoustic energy and the relative phasing between the sources is set by the convection of turbulent eddies between them. The model employed therefore consists of an array of sources in line with the nozzle lip, separated by a distance L which is assumed approximately constant and given by

$$L = \text{const.}\,\beta\, D, \quad (2)$$

where the constant strictly varies with cell position but a good average value is 1.1.

It is assumed that the convection of a turbulent eddy along this line of sources causes each to emit an acoustic signature at the time of arrival of the eddy. In the simplest case where the eddy is assumed to produce an identically shaped acoustic signature at each shock, the amplitude variation of the n^{th} source for a particular frequency, ω, can be written

$$A_n(\omega) \cos \omega(t - \frac{nL}{U_c}) \qquad (3)$$

where the phase term nL/U_c merely allows for the transport time of the eddy along the shock structure.

Consideration of the interference pattern created by such a line of discrete sources indicates that a maximum of constructive interference and hence maximum sound level will occur with a combination of frequency, eddy convection velocity, shock cell spacing and angle of observation given by

$$f_p = \frac{U_c}{L(1 - M_c \cos \theta)} \qquad (4)$$

At 90^o to the jet axis the peak frequency is given by the ratio of eddy convection speed to shock cell spacing. At other angles it varies in the manner of an apparent Doppler shift. At frequencies on either side of f_p the constructive interference is less complete and hence lower sound pressure levels will result.

Confirmation of these ideas is presented in Fig. 4 where the spectrum of noise radiated from a shock free convergent-divergent nozzle is compared with that from a convergent nozzle operated at the same pressure ratio. It is clear that the extra noise radiated by the convergent nozzle is contained in a spectral region centred on the frequency given by (4) above.

The variation of this peak frequency with both angle, velocity and shock spacing is found to follow the prediction of (4) closely.

While the considerations above are adequate for the prediction of the peak frequency of shock associated noise, more information is required to calculate the complete spectrum. This includes, for example, the spectra of the individual sources. The degree of coherence maintained by an eddy convecting between the shocks is also importance since this controls the degree of source coherence and hence the interference. Work to obtain the required information is currently underway using the crossed beam schlieren system. It is currently incomplete and will be reported subsequently.

In the meantime an empirical method providing a satisfactory degree of collapse of the measured spectra has been evolved and is shown in Fig. 5, for a range of pressure ratios for an unheated jet flow. It is based on the joint observations that the spectra are similar if plotted as a function of (f/f_p) while in addition the overall levels vary as the fourth power of β. Fig. 6 shows a similar range of data but for a stagnation temperature of 1100^oK*. Again, a useful degree of collapse is observed while comparison of the two sets of data also demonstrates the utility of this method for a range of stagnation temperatures.

References

1. A. Powell. On the mechanism of choked jet noise. Proc. Phys. Soc. B. (1953), Vol. 66, 1039-1056.
2. M.J. Fisher and F.R. Krause. The crossed beam correlation technique. J. Fluid Mech. (1967) Vol. 28, 705-717.

* We are indebted to Rolls Royce Ltd. for this data.

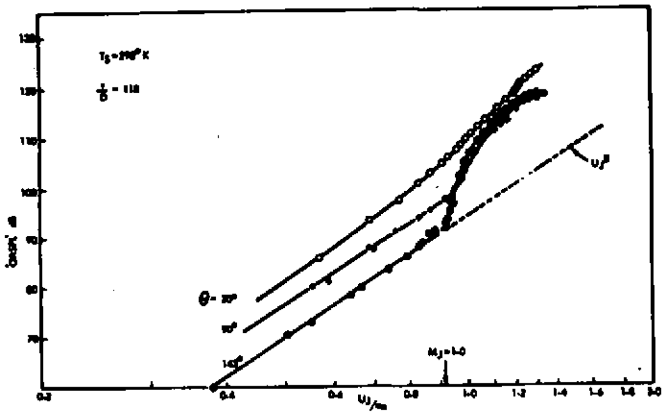

FIG 1 VELOCITY DEPENDENCE OF OVERALL INTENSITY OF JET NOISE AT SEVERAL ANGLES TO THE JET SHOWING SHOCK ASSOCIATED NOISE

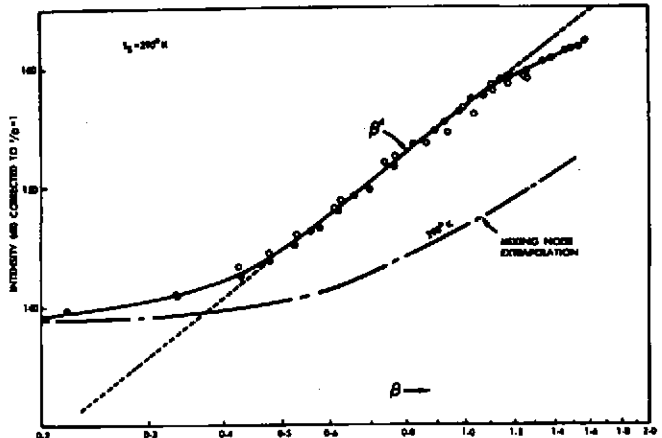

FIG 2 VARIATION OF OVERALL INTENSITY AT 90° TO JET WITH $\sqrt{M^2-1}$ FOR TWO NOZZLES ○25mm ●36mm DIA.

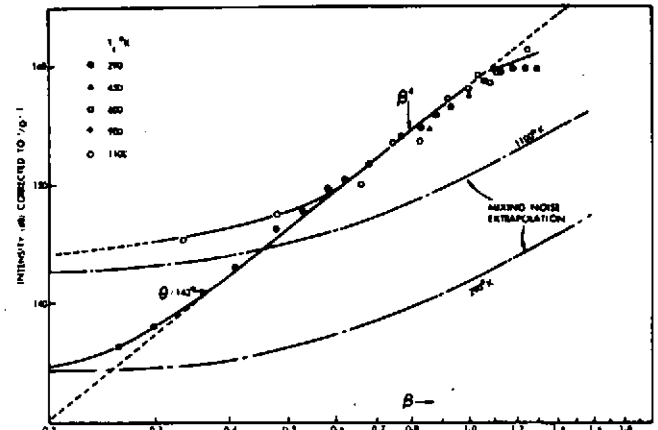

FIG 3 VARIATION OF OVERALL INTENSITY AT 130° WITH $\sqrt{M^2-1}$ FOR A RANGE OF TEMPERATURES FROM COLD TO 1100°K

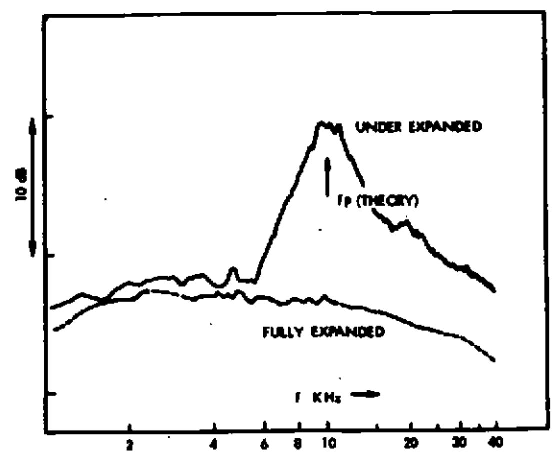

FIG 4 COMPARISON OF SUPERSONIC JET NOISE SPECTRA FOR A FULLY EXPANDED AND UNDER EXPANDED FLOW ($\theta = 90°$, $\beta = 1.0$)

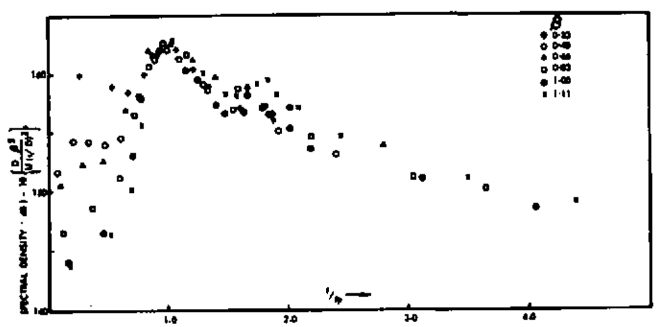

FIG 5 SPECTRAL COLLAPSE OF DATA AT 135° AND AT VARIOUS PRESSURE RATIOS FOR A COLD JET

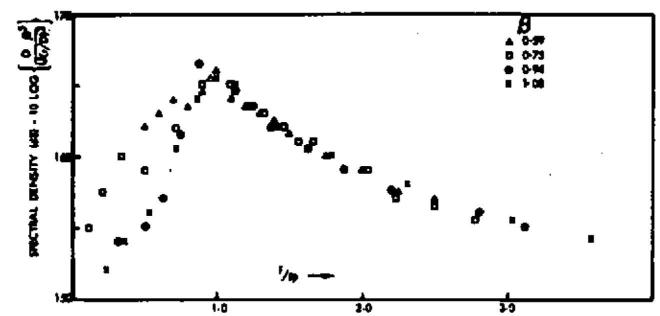

FIG 6 SPECTRAL COLLAPSE OF DATA AT 120° AND AT VARIOUS PRESSURE RATIOS FOR A JET AT 1100°K