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AERONAUTICAL NOISE: SESSION A: JET NOISE

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NOISE FROM HOT JETS

P.A. Lush, M.J. Fisher, K.K. Ahuja

Institute of Sound and Vibration Research,
University of Southampton.

Introduction

An investigation of the effect of temperature on mixing noise has been recently initiated at the ISVR. For many years it appears to have been commonly accepted that the effect of heating a jet at constant velocity would be to reduce the noise as a result of decreasing the density in the Lighthill source term $\rho u_i u_j$. However, a carefully conducted series of experiments by Cocking[1] and Jamieson at the NGTE contradict this conclusion. They show that the heated jet is quieter only at jet velocities above about $U_J/a_o = 0.7$. Below this velocity the noise levels increase progressively with increasing jet temperature. This effect can be seen quite clearly in Figure 1, which shows their results for the overall intensity at 90° to the jet as a function of velocity and temperature.

Theoretical Considerations

In an attempt to resolve this difficulty, work at ISVR concentrated on producing a scaling law using a more complete version of the Lighthill source term, which may be written as follows,

$$T_{rr} = \rho u_r^2 + p - a_o^2\rho \ , \qquad (1)$$

where u_r is the component of velocity in the direction of the observer. The viscous stresses have been omitted as usual. For a cold, i.e. unheated, flow, the term in $p - a_o^2\rho$ will tend to be zero as is usually assumed since pressure and density fluctuations will be related isentropically and the speed of sound (temperature) will be near ambient throughout. For a heated jet, this may not be so and by considering the thermodynamic properties of the gas, the density fluctuation may be split into two parts, namely a pressure fluctuation at constant entropy (i.e. isentropic) and an entropy fluctuation at constant pressure. The relationship between the fluctuating quantities is,

$$\rho' = \frac{p'}{a^2} - \frac{\bar{\rho}S'}{C_p} \qquad (2)$$

On substituting for ρ' in (1), we obtain for the direction at right angles to the jet, where $\bar{u}_r = 0$,

$$T_{90^o} = \bar{\rho}v'^2 + \left(1 - \frac{a_o^2}{a^2}\right) p' + \frac{\bar{\rho}a_o^2 S'}{C_p} \qquad (3)$$

Terms involving mean quantities only have been dropped since they do not contribute to the rate of change of T_{rr}, which is what is required for the far field radiation. The first term is clearly the usual Reynolds' stress for which the density $\bar{\rho}$ must presumably be evaluated in the dominant source region. Since this is probably in the centre of the shear layer, some value of density between that in the jet core ρ_J and the ambient ρ_o is appropriate. It is convenient to take simply the geometric mean, so that,

$$\bar{\rho} = \sqrt{\rho_J \rho_o} \tag{4}$$

The second term depends upon the temperature difference between the source region and the ambient. For jet temperatures near to the ambient, the contribution of this source term will be small. In the case of heated jets, the coefficient of p' can never be greater than unity and varies rather slowly with temperature. Since p' scales in a similar way to $\bar{\rho}v'^2$, the term can be absorbed into the Reynolds' stress term. Therefore for hot jets, it is reasonable to neglect this contribution completely, although it will become important for jets with temperatures substantially below ambient as discussed by Lighthill.

However, the third term of (3) containing entropy fluctuations does appear to give an additional source of acoustic energy. If it is assumed that the entropy fluctuations are a function of temperature only and independent of jet velocity, it can immediately be seen that the acoustic intensity from this source will scale as U_J^4. In order to estimate how the entropy fluctuations scale with temperature, we assume that the entropy fluctuation is proportional to the entropy difference across the shear layer. For a jet flow in which there are no static pressure gradients, we can use the equation of state for a gas to obtain,

$$S' \sim S_J - S_o = C_p \log_e \frac{T_J}{T_o} \tag{5}$$

At this stage it is not clear whether T_J should refer to the static temperature in the jet or to the stagnation temperature. The balance of evidence is in favour of the stagnation temperature at the present time.

If finally it is assumed that the Reynolds' stress term and the entropy term in (3) are independent (i.e. uncorrelated) source terms, the intensity of the total radiation may be estimated from the sum of the squares of the two terms times the fourth power of the typical frequency. This results in an expression of the form,

$$I = A\left(\frac{U_J}{a_o}\right)^8 + B\left(\frac{U_J}{a_o}\right)^4 \quad , \tag{6}$$

where

$$A \propto \left(\frac{\bar{\rho}}{\rho_o}\right)^2 = \frac{\rho_J}{\rho_o} = \left(\frac{T_J}{T_o}\right)^{-1} \quad , \tag{7}$$

and

$$B \propto \left(\frac{\bar{\rho}}{\rho_o}\right)^2 \frac{S'^2}{C_p^2} \propto \left(\frac{T_J}{T_o}\right)^{-1} \left(\log_e \frac{T_J}{T_o}\right)^2 \quad , \tag{8}$$

using both (4) and (5).

Comparison of Theory and Measurement

In order to test these ideas, using (6), the two components are separated by investigating the variation of $I/(U_J/a_o)^4$ with $(U_J/a_o)^4$. If this function is linear then the slope of the line will give the coefficient of $(U_J/a_o)^8$ and the intercept at $U_J/a_o = 0$, assumed positive, will give the coefficient of $(U_J/a_o)^4$. Their variation with temperature can then be investigated.

When this method is applied to the hot jet results*, reasonable linear variations are produced as shown in Figures 2 and 3, which are for a cold case, i.e. $T_J/T_o = 1.0$ and $T_J/T_o = 3.0$ respectively. The variation of the coefficients with temperature ratio are shown in Figure 4. When these are compared with the predicted variations of (7) and (8), it can be seen that there is good agreement except for the coefficient of $(U_J/a_o)^4$ near the temperature ratio of unity. However, in this region the contribution is presumably very weak and the calculated values contain either unwanted noise or result because the Reynolds' stress contribution does not follow U_J^8 exactly but a slightly lower index. Figure 4 also contains some results of hot jet noise due to Lush and Burrin.

Conclusions

Therefore it seems that the Reynolds' stress contribution does decrease with increasing jet temperature in the way commonly accepted, i.e. as $(T_J/T_o)^{-1}$. However, there also appears to be an additional source with a lower velocity dependence, U_J^4 which increases with temperature. The overall effect of this is to reduce the usually observed U_J^8 dependence to approximately U_J^6 over the velocity range usually considered.

At present these results are tentative and more data is being sought to confirm them. Two major difficulties need to be resolved: the first is, which temperature, static or stagnation, is the more important and the second is, what is the nature of the entropy source. The first question is raised by one of the results of Lush and Burrin in which the exit static temperature was maintained equal to the ambient throughout the whole Mach number range up to 2.0. In this case the velocity dependence was considerably below the normally expected eighth power, which was in fact maintained for a cold jet up to the same Mach number. This result suggests that stagnation temperature is the more relevant parameter.

The second question is raised on theoretical grounds by which it may be shown that if heat conduction and viscous dissipation are presumed negligible, the acoustic energy radiated from entropy fluctuations will vary as the sixth power of jet velocity and not the fourth. This result is not compatible with the experimental results and so it seems that the usual assumption of ignoring heat conduction and viscosity is not valid in this case.

References

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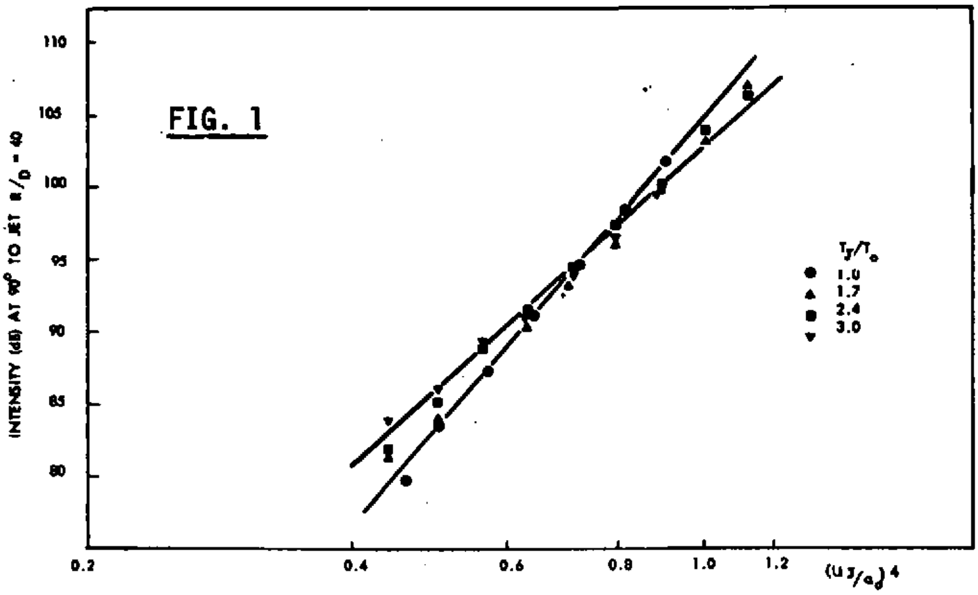

FIG. 1

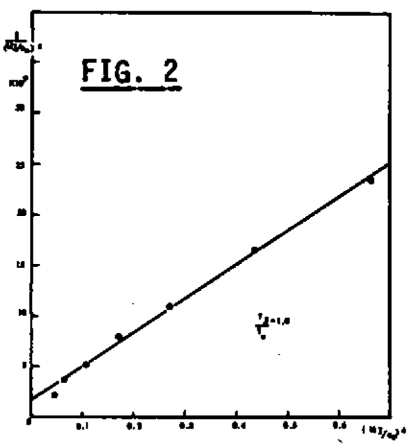

FIG. 2

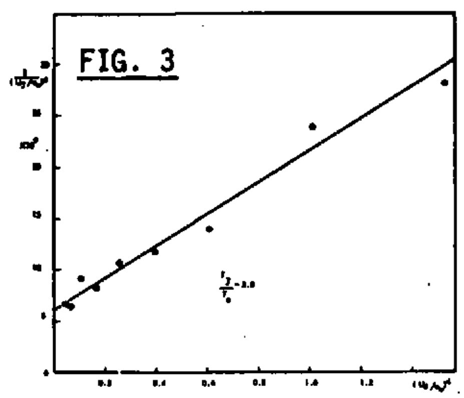

FIG. 3

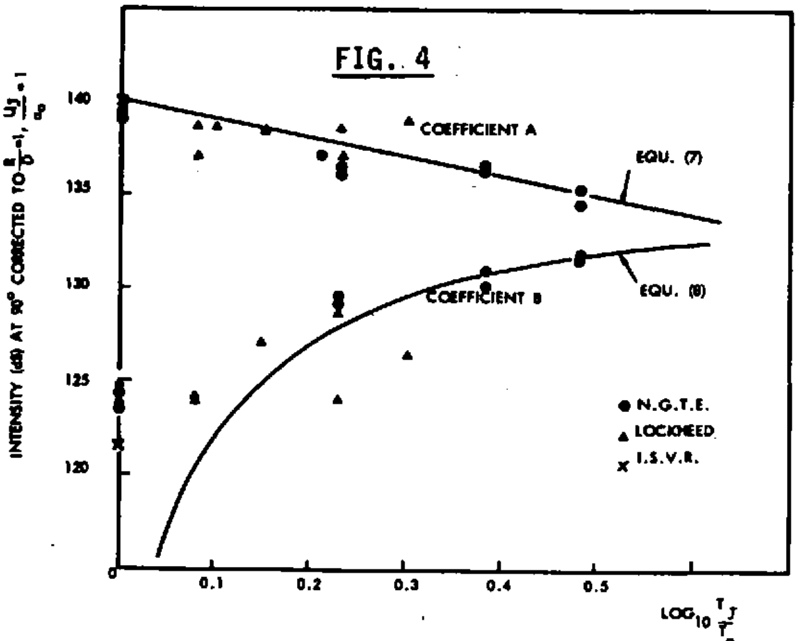

FIG. 4