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Sound Power Spectrum of Shock-Free Jets

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Nomenclature

A = nozzle area
d = nozzle exit diameter
k_D = radiated sound power $\div (U_J/c_0)^6 d^2 \rho_0 c_0^3$
k_Q = radiated sound power $\div (U_J/c_0)^8 d^2 \rho_0 c_0^3$
S = Strouhal number

Subscripts

J = jet efflux condition
0 = ambient condition

Abstract

AIR jet mixing noise data from model tests have been used to study the sound power spectrum of shock-free turbulent jets exhausting into a stationary atmosphere at both subsonic and supersonic velocities. Normalized plots demonstrate the temperature and velocity dependence of the radiated power. Also considered is the influence of upstream radiated sound on the boundary condition at the nozzle exit.

Contents

The present study has three objectives: 1) to present normalized sound power data for jet mixing noise, in ⅓-octave form suitable for predicting spectra; 2) to assess the likely role of amplifying jet-column waves in generating supersonic jet noise around the peak noise angle; and 3) to estimate the sound power trapped within the jet by internal reflection, and in particular to assess whether the power entering the nozzle can provide significant forcing of the jet shear layer. This synoptic summarizes results obtained for 1 and 3.

The model jet data were produced at the Lockheed-Georgia Co. as part of a comprehensive series of jet noise measurements.[1] They cover the range $T_0 \leq T_J \leq 3.3\ T_0$ and $0.35\ c_0 \leq U_J \leq 2.4\ c_0$. The jet and ambient fluids were air in all cases; convergent-divergent nozzles were used to produce supercritical jets ($M_J > 1$).

Figure 1 shows the velocity dependence of the sound power radiated from isothermal air jets ($T_J = T_0$). The power in ⅓-octave frequency bands has been normalized by $(U_J/c_0)^8 d^2 \rho_0 c_0^3$, to remove the U_J^8 dependence predicted for low jet velocities.[2] The frequency bands are defined in terms of the nondimensional frequency $fd/U_J = S$; center frequencies range in Fig. 1 from $S = 0.1$ to $S = 2.5$, covering the peak region of the sound power spectrum.

For small values of U_J/c_0, the coefficient k_Q plotted in Fig. 1 should approach a constant. The corresponding asymptotic sound power spectrum is plotted in Fig. 2. The proportional-band (⅓-octave) spectrum peaks at $S = 0.8$. Figure 2 is valid for any combination of jet and ambient fluids provided $\rho_J = \rho_0$ and $c_J = c_0$.

For jets whose density differs from that of the ambient fluid, a U_J^6 dependence is predicted at low velocities (assuming perfect-gas behavior).[3,4] It is therefore convenient to normalize the measured sound power by $(U_J/c_0)^6 d^2 \rho_0 c_0^3$; the resulting coefficient k_D should approach a constant for small values of U_J/c_0.

Detailed results, which show the effect of temperature ratio on the sound power of air jets at velocities up to 2.2 c_0 (shock-free), are presented in the full paper. By way of illustration, Fig. 3 shows the temperature effect for the ⅓-octave band centered on $S = 0.2$ (which is approximately the peak of the proportional-bandwidth sound power spectrum, at an exhaust velocity of c_0). For a given *subsonic* velocity, the sound power increases with jet temperature, in contrast to the temperature independence predicted in Ref. 5. At *supersonic* velocities ($U_J > c_0$), the trend is reversed.

The sound power plotted in Figs. 1-3 is the power radiated into the *far field*; it does not include the power which is radiated into the exhaust nozzle. The latter may be as much as 5-10% of the far-field radiated power (according to ray-acoustic estimates given in the full paper), even for sources 5 or more diameters downstream of the nozzle exit (corresponding to $S \lesssim 1$). The reason is that the jet acts as a waveguide for sound wavelengths less than about $2d$ (note $d/\lambda = SU_J/c_0$); part of the upstream-directed radiation is then trapped by internal reflection from the shear layer.

Because of the waveguide effect—which has been studied in detail by Neuwerth[6]—the power passing through the nozzle

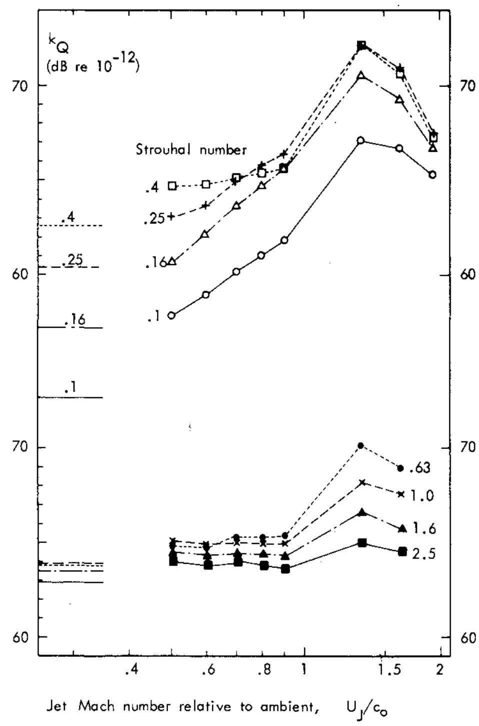

Fig. 1 Sound power coefficient k_Q for isothermal air jets ($T_J = T_0$), based on Lockheed-Georgia measurements.[1] Low-velocity asymptotes shown on left for each Strouhal number.

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Index categories: Aeroacoustics; Noise; Jets, Wakes and Viscid-Inviscid Flow Interactions.

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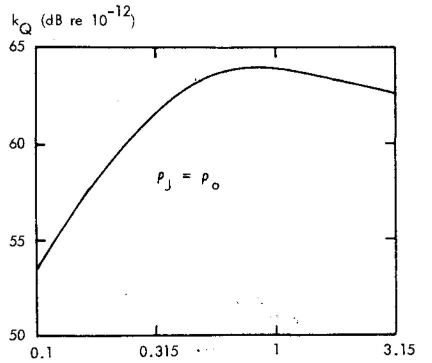

Fig. 2 ⅓-octave spectrum of k_Q in the limit of low jet velocities, for jets with $\rho_J = \rho_0$.

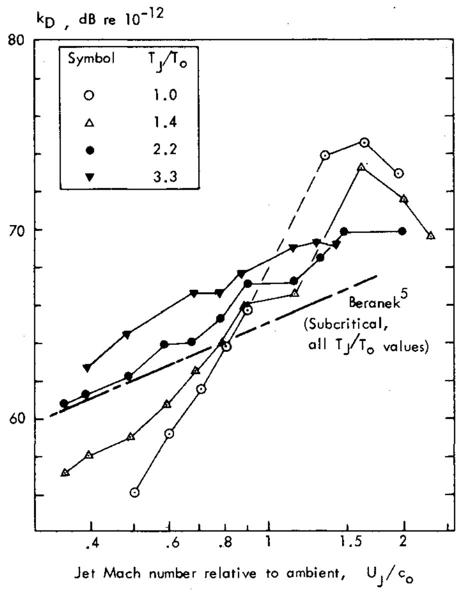

Fig. 3 Variation of k_D with jet velocity, as measured for hot air jets at different temperature ratios.[1] Prediction from Beranek[5] is shown for comparison. $S = 0.2$ ⅓-octave band data.

may be large enough to have a significant influence on the jet itself. Turbulent jets are known to exhibit amplification of exit-plane disturbances, provided these are circumferentially coherent.[7] Moreover, if the disturbance is sufficiently strong, the jet response becomes nonlinear and the *broadband* sound radiation begins to increase.[8-10]

The circumferentially-coherent pressure fluctuations at the nozzle exit may be estimated from the trapped power as follows. All the trapped power is assumed to enter the nozzle, and to have wavenormal directions close to the upstream axis. Then in a particular frequency band

$$W_{\text{trapped}} \doteq \frac{A}{\rho_J c_J} (1 - M_J)^2 \overline{p^2} \tag{1}$$

relates the power to the mean square exit-plane pressure.

To obtain the circumferentially-coherent component of $\overline{p^2}$, we regard the jet as a waveguide, and note that whereas, say, N acoustic modes are trapped in the jet, only N_0 of those will be of zero circumferential order. Thus we estimate finally

$$\overline{p^2}(m=0) \simeq (N_0/N) \cdot \overline{p^2} \tag{2}$$

The value of N_0/N is derived in Appendix 3 of the full paper.

Figure 4 shows the result of translating the trapped-power estimates into values of coherent pressure incident on the

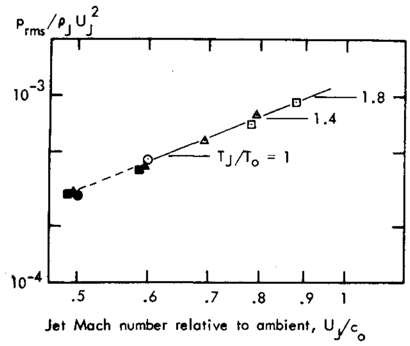

Fig. 4 Coherent exit-plane pressure fluctuations implied by propagation of trapped power upstream through nozzle, for the $S = 0.8$ ⅓-octave band. Code for T_J/T_0: ○, 1.0; △, 1.4; □, 1.8. The upper limits marked for each temperature ratio indicate the point beyond which trapped power is partially swept downstream.

nozzle lip. The $S = 0.8$ band was chosen as having the lowest threshold level for the onset of additional broadband radiation in Moore's experiments.[8] It is interesting to note that values of $p_{\text{rms}}/\rho_J U_J^2$ around Moore's threshold‡ of $0.4.10^{-3}$ are predicted, for jet velocities in the range $U_J/c_0 = 0.6$ to 0.9.

The present estimates suggest that jets at high subsonic velocities are significantly "pre-excited" by their own sound field. This could account for the observation that broadband jet noise loses its sensitivity to upstream forcing as the jet velocity is increased to high subsonic values.

Acknowledgments

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‡Moore used single-frequency forcing in most of his experiments, but also demonstrated the equivalence of tones and bands of noise (of order ⅓-octave wide); see Fig. 41 of Ref. 8.