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Strouhal Number Influence on Flight Effects on Jet Noise Radiated from Convecting Quadrupoles

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Nomenclature

c_f = speed of sound in the simulated flow inducing flight effects
c_0 = speed of sound in the ambient quiescent fluid
I = relative intensity amplification
k_0 = wave number, ω_0/c_0
M_c = convection Mach number, 0.65 M_j
M_f = flight Mach number, U_f/c_0
M_j = jet Mach number, U_j/c_0
r_0 = radius of the jet
St = Strouhal number, $\omega_0 r_0/U_j$
θ = angle between the directions of convection and emission at the retarded time
ρ_f = density of the simulated flow inducing flight effects ($\sim\rho_0$)
ρ_j = density of the jet
ω_0 = source frequency

Introduction

THIS work is a complementary extension of our recent work[1,2] which discovers several interesting features recognizable in experimental jet noise fields as well as in actual flyovers. However, those predictions are descriptive of a low frequency situation and, consequently, we report here a complementary extension to include the high frequency features which will be reflected in our discussion on the higher Strouhal number influence on the flight effects. From our knowledge of the distant pressure field, developed in Eq. (13) of Ref. 2, one can easily write an expression for relative intensity amplification factor, I, as

$$I = \left|\frac{\psi(M_f)}{\psi(M_f=0)}\right|^2 \left[\frac{1-(c_o/c_f)M_c\cos\theta}{1-(c_o/c_f)(M_c-M_f)\cos\theta}\right]^6 \tag{1}$$

This, however, is the ratio of the intensity of noise in flight to that without flight. As the dependency of ψ rests on M_f, M_j, St, and θ, it will be interesting to plot graphs in Figs. 1-3 for 10 $\log_{10} I$ against θ as the independent variable, with M_f, M_j, and St as the fixed variables; it has to be pointed out that while handling the above equation, $(kr)_o$ in ψ is replaced by $St\, M_j$, to which it is directly related.

The Strouhal number values chosen are St = 0.5, 1.0, and 3.0, respectively in Figs. 1-3. The computation is facilitated by expressing the Bessel functions through their equivalent Chebyshev series.[3]

Discussion of Graphs

Figures 1-3 describe the change in directional distribution of relative intensity amplification which arises as a result of radiation from an axial point quadrupole convecting along the jet centerline at Mach number M_c by a jet flow of Mach number M_j under the influence of flight at Mach number M_f, the values of which are indicated against the curves. The angle θ is measured from the direction of convection to the direction of emission at the retarded time.

Like the low frequency case reported in our earlier work, the high frequency case of our present work shows many of the important features of the flight effects on noise which are in common agreement in both the situations. As is obvious from the plots in Figs. 1-3, these common features are:

1) Forward arc amplification is caused as a result of forward speed.

2) Flight effects steadily amplify noise in the forward quadrant ($\pi/2<\theta\leq\pi$) and diminish noise in the aft quadrant ($0\leq\theta<\pi/2$).

3) Amplification in the forward quadrant decreases when jet velocity is increased (up to its critical vlaue) with, however, a weaker attenuation in the aft quadrant.

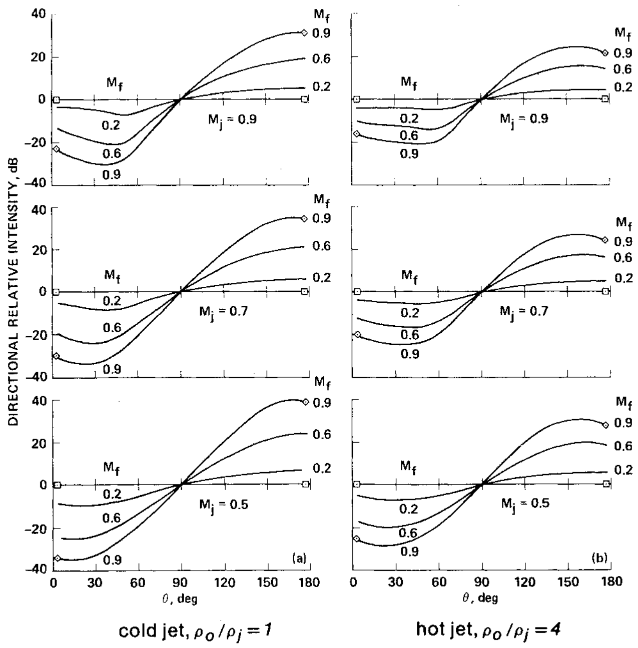

Fig. 1 Variation in directional distribution of relative intensity I showing the forward arc amplification cum rear arc attenuation, $St = 0.5$.

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

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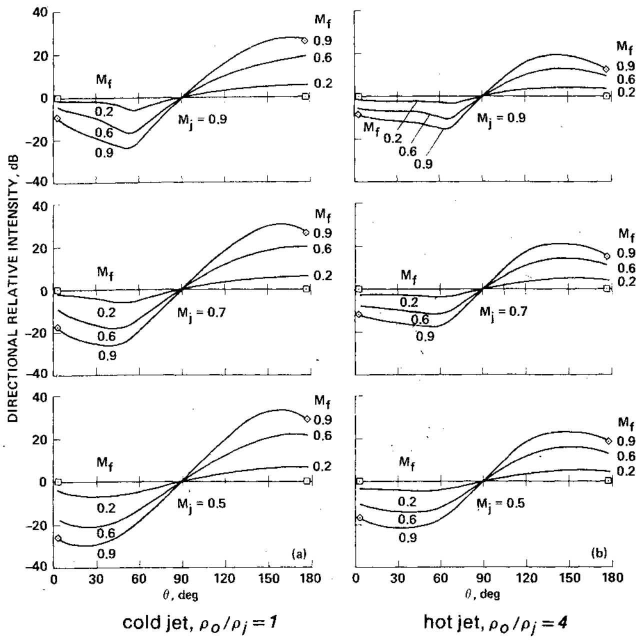

Fig. 2 Variation in directional distribution of relative intensity I showing the forward arc amplification cum rear arc attenuation, $St = 1.0$.

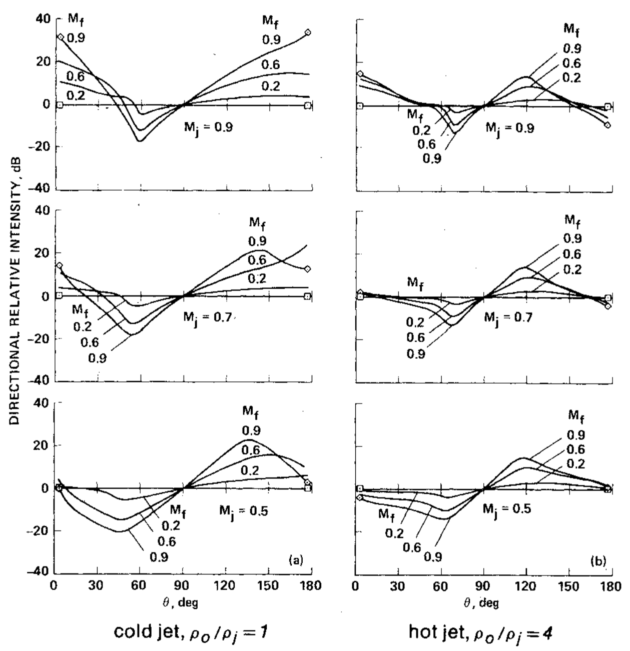

Fig. 3 Variation in directional distribution of relative intensity I showing the forward arc amplification cum rear arc attenuation, $St = 3.0$.

4) Forward arc amplification at $\theta = 90$ deg to the jet axis is virtually absent.

However, unlike the low frequency case, flight effects on high frequency radiation show some interesting additional features deducible from the qualitative trends of these plots. As the Strouhal number, St increases from 0.5 (Fig. 1) to 1 (Fig. 2) to 3 (Fig. 3), the forward arc amplification and the rear arc attenuation steadily diminish. Also, in each of these figures, on comparing both the cold and the hot jets simultaneously at a specific Strouhal number, $St = 0.5$ (1 or 3), we find that the amount of amplification/reduction is noticeably much less in the case of hot jets than in the case of cold jets.

On further investigation of these plots, especially Fig. 3, one finds that the peak amplification angle in the forward quadrant and the peak suppression angle in the aft quadrant move toward 90 deg and get closer as a result of increasing Strouhal number influence in flight. Furthermore, the tendency on the part of the flight curves to make abrupt steady descent immediately after these weak peaks suggests that in addition to the adverse effects being milder, their area of exposure remains confined to a constricted angular region. This is no doubt a soothing effect at higher Strouhal numbers of the flows. However, with high flight Mach numbers/high Strouhal numbers, the forward arc amplification for a hot jet has a tendency to peak near $\theta = 120$ deg, whereas at lower flight Mach numbers, e.g., $M_f = 0.2$, it peaks somewhere around $\theta = 135$ deg.

Of special interest in Fig. 3 is the phenomenon of double and triple crossings of the flight curves with the static, zero-flight curves for both cold and hot jets. The flight curves in the aft quadrant are above the static line and imply that the zone of silence at high Strouhal number cum high subcritical jet flows ($St = 3$, $0.6 \leq M_j \leq 0.9$) disappears in the close proximity of the jet and, instead, gives rise to actual amplification of noise in the aft quadrant. This amplification prevails in at least half of the aft quadrant adjacent to the jet. Further, the lower the flight Mach number, the milder is this unusual rise in the aft quadrant noise. However, it should be cautioned that this abnormal feature which is toned down in a hot jet (compare in Fig. 3 hot jet with cold jet) does not show up at lower Mach number flows, $0 < M_j < 0.6$. On the other hand, the forward arc amplification begins to slow down and shows actual reduction at higher angles close to the jet axis. This feature is evident only in the case of hot jets at high Strouhal number cum high subcritical jet flows ($St = 3$, $0.6 < M_j < 0.9$), see Fig. 3 (hot jet). Thus as it turns out, multiple crossings indicate that the zone of silence is disturbed and that there are some unusual occurrences in the immediate neighborhood of the jet at both ends upstream and downstream of the jet.

Conclusion

As a result of our investigation we find that, in addition to the usual features of flight effects on noise from ordinary flows, the high Strouhal number flows exhibit some more interesting features which are uniquely characteristic to them. The additional features are as follows:

1) Flight effects are more favorable to hot jets than to cold jets.

2) The higher the Strouhal number of the jet flow, the lesser is the forward arc amplification due to flight.

3) As the Strouhal number increases, the peak amplification angle in the forward quadrant and the peak suppression angle in the aft quadrant move toward 90 deg and get closer, thus reducing the amplification exposure to a constricted angular region.

4) Furthermore, the zone of silence is disturbed and displaced from its normal position parallel to the jet flow to give rise to multiple crossings of flight curves with the static line.

5) The occurrence of multiple crossings is a queer phenomenon solely characteristic of high Strouhal number cum high subcritical jet flows ($St = 3, 0.6 \leq M_j \leq 0.9$) in flight.

Acknowledgment

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Effect of Temperature on Surface Noise

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Introduction

IT has generally been assumed (e.g., Refs. 1 and 2) that the noise from large scale surfaces immersed in a hot turbulent flow can be accurately determined from a simple scale-up of cold flow model data, where the model is geometrically and aerodynamically similar. With such a simple scale-up of data, the effect of temperature on surface noise is considered to be small. This assumption may be in error for two reasons. First, it is well known that temperature and temperature fluctuations have a measureable effect upon jet noise.[3] Second, turbulence measurements[4] have shown that the intensity of the temperature fluctuations in a jet are of the same order of magnitude as the velocity fluctuations; and velocity fluctuations near the edge of a surface are the source of surface noise at ambient temperature.[5,6] Therefore, temperature fluctuations may also be a source of additional surface noise.

Apparently, the effect of temperature on surface noise has not been investigated either by careful experiment or by analysis. The object of the experimental work discussed in this Note was to obtain data that show the effect of temperature and temperature fluctuations on surface noise. This was accomplished experimentally by immersing a small chord airfoil in the turbulent airstream of a hot jet. This experiment was an extension of the experiment reported in Ref. 6, where the fundamental theory of Ref. 5 was shown to be in almost perfect agreement with the data. The theory and experiment discussed in Ref. 6 were limited to ambient temperature jets; nevertheless, they provided a guide for designing and validating the hot jet experiment and for interpreting the data.

Apparatus and Procedure

The apparatus, instrumentation, and data reduction system were essentially the same as those described in Ref. 6, except for changes required for the hot jet. The flow system consisted of, in order: a flow control valve, a muffler, a combustor, a hot flow muffler, and a nozzle. The mufflers removed valve and combustor noise down to a velocity of about 100 m/s, as evidenced by the excellent agreement between the jet noise data of this experiment and published hot jet data.[7]

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Index categories: Aeroacoustics; Noise.

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Figure 1 is a schematic showing the airfoil in the center of the mixing region of the jet. The thin airfoil was made of stainless steel; it was 1-m long, and had a chord of 2.54 cm. The airfoil was attached to a rigid structure; the bottom end of the airfoil was weighted and permitted unobstructed spanwise thermal expansion to avoid buckling. To establish the desired impingement velocity V_i and temperature T_i the nozzle was calibrated to the corresponding nozzle stagnation conditions P_N, T_N. This was accomplished with a temperature and pressure rake attached to the airfoil. The rake was then removed for the acoustic data run, where the nozzle stagnation conditions corresponding to the desired impingement conditions were set.

The noise emission was measured with eleven 0.63-cm diameter microphones at different angles θ_i on a horizontal semicircle of 4.57-m radius. Panels of open-pore urethane foam were placed on the ground in the test area. This arrangement resulted in far-field data that were not subject to ground reflections (i.e., were free field) above about 250 Hz. Furthermore, neither the nozzle nor the airfoil supports caused measureable reflections or shielding.

The noise signals were analyzed by an automated spectrum analyzer which yielded 1/3 octave band sound pressure levels (SPL) at each microphone. These data were corrected subsequently to remove the small losses due to atmospheric attenuation of the sound. Jet noise, which was measured separately with only the airfoil support in place, also was removed subsequently so that the data reported, SPL_c, are corrected and represent pure surface noise. None of the data reported required more than a 2-dB correction. These corrected data were summed spectrally to produce the overall sound pressure level, $OASPL_c$.

Discussion of Existing Theory

There is no theory for the effects of temperature, temperature gradients, or temperature fluctuations on surface noise. However, there is a theory for a small chord airfoil immersed in an ambient temperature turbulent airstream that is small and surrounded by a uniform environment at rest. The noise emission is described by Eq. (1) of Ref. 5. This equation is rewritten here in a summary form that shows only the terms that are appropriate for this study.

$$\mathrm{SPL}_c = 10\log_{10}\left\{\left[\left(\frac{bc}{R^2}\right)\left(\frac{\rho_0}{c_0}\right)^2 V_i^6\left(\frac{\tilde{v}}{V_i}\right)^2\right](\sin^2\theta_i)\right.$$

$$\left.(\text{shape of spectrum, defined in Ref. 6})\right\} + K \qquad (1)$$

The experimental data in Ref. 6 showed that this equation was very accurate.

Equation (1) involves three factors and a term K that is constant for a given spanwise distribution of the turbulent flow. The first factor is the relative amplitude of the noise at $\theta_i = 90$ deg; it is a function of the airfoil chord c, scrubbed span b, microphone arc radius R, the peak impingement velocity V_i, transverse turbulence intensity $\tilde{v}/V_i$, the ambient

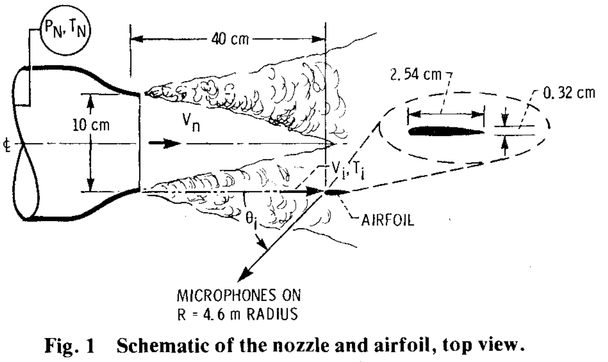

Fig. 1 Schematic of the nozzle and airfoil, top view.