Acoustic Measurements in High-Speed Subsonic Jets

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Nomenclature

C_{ph} = phase velocity of disturbance
D = diameter of the jet
f = frequency, Hz
k = complex wave number
k_i = imaginary portion of k
k_r = real portion of k
M = Mach number
r = radial distance from the jet centerline
St = Strouhal number, fD/U_0
U_0 = centerline velocity at the exit of the jet
x = downstream distance from the nozzle exit
θ = azimuthal angle
λ = axial wavelength
ϕ = angle from jet axis

Abstract

ACOUSTIC measurements have been made in the "near" ($r/D<60$, $x/D<60$) field of high Reynolds number (184,000-262,000) axisymmetric cold-air jets exhausting at atmospheric pressure. These measurements were in conjunction with an investigation that characterized the large-scale coherent structure in the flowfield of Mach number 0.6-0.8 jets. Natural jets as well as artificially excited jets were studied. Directivity plots were made for all jets at various frequencies. Overall noise radiated by the jets was found to reach a maximum value around 30 deg from the jet axis. However, individual frequencies emitted maximum sound pressure level (SPL) at different angles from the jet axis. As the angle from the jet axis increased, the spectra of the noise shifted to higher frequencies. It was observed that the coherent structure's axial wave speed decreased with decreasing frequency, much in the same way the angle of peak noise emission decreased with decreasing frequency. We propose that it was this slowing of the wave speed that caused the decrease in the peak noise emission angle. The noise production mechanism in the jet was found to be more responsive to midband excitation frequencies. Excitation at these frequencies caused a small increase in SPL at the frequency of excitation, but a much larger increase in full spectrum noise.

Contents

The present research was conducted to determine the Mach number dependence of large-scale coherent structures in high-speed, subsonic jet flowfields.[1] Acoustic measurements were made in conjunction with the flowfield measurements. This synoptic will present the results of these acoustic measurements and investigate relationships between the coherent structure and the noise emitted.

Sound pressure level directivity plots were measured for Mach number 0.6, 0.7, and 0.8 jets at a constant radius of 36 diameters from the nozzle exit. The overall SPL increased with increasing Mach number and, in all three cases, reached a maximum at 30 deg from the jet axis. This was consistent with the findings of Mollo-Christensen et al.[2]

A spark excitation mechanism[1] was used to introduce a repeatable disturbance into the jet in order to stabilize the jet and to provide a phase reference for the characterization of the coherent structure in the flowfield. To determine the effect this artificial excitation had on the acoustic field, the SPL directivity plots were repeated for the excited $M=0.6$ jet. The microphone signal was bandpass filtered from $St=0.063$ to 1.264, while the jet was excited at each of six arbitrarily selected frequencies. As the frequency of excitation was increased from $St=0.158$ to 0.474, the peak SPL increased from 95.2 to 98.5 dB. In addition, at $St=0.316$ the noise became less directional and, hence, the overall SPL increased substantially. Increasing the Strouhal number from 0.474 to 1.264 resulted in the peak SPL decreasing with increasing frequency. This illustrates that the jet's noise production mechanism was more responsive to excitation at the midband frequencies. This also happens to be the frequency range where the majority of the noise was radiated.

Spectra were also obtained for each of the six frequencies at an angle of 50 deg from the jet axis. From these spectra, it was found that artificial excitation did not produce a discernible peak in the spectra, but instead slightly enhanced the amplitude of the higher frequencies. It should be pointed out that the noise generated by the artificial excitation device was measured with the flow off. When corrections were made to the SPL measurements for the amount of noise directly emitted by the exciter mechanism, the SPL amplitude changed less than 0.2 dB. Therefore, any noise produced directly by the excitation device was deemed negligible.

Individual frequencies were studied by one-tenth octave bandpass filtering the microphone signal about the excitation frequency and measuring the directivity of the signal. Comparison of these directivity plots with identical measurements in an unexcited jet show that the largest differences occurred when the jet was excited at $St=0.948$ and 1.264 for 50 deg $\leq \phi \leq$ 80 deg. The increase in SPL was probably due to the exciter slightly enhancing the coherent structure fluctuation amplitude at the frequency of excitation and, hence, increased the noise produced at that frequency. Previous full-band measurements showed that considerably more noise was produced when the jet was excited by midband frequencies. However, this magnitude of increased SPL was not evident in the individual frequency measurements. This indicates that excitation at the midband frequencies increased the broadband noise in addition to the noise produced at that individual frequency.

Spectra were also recorded at various angular locations from the jet centerline for each of the jets. An obvious trend observed in these spectra was that the frequencies in the jet shifted toward higher values as the angle from the jet centerline ϕ increased. This phenomenon was also observable in

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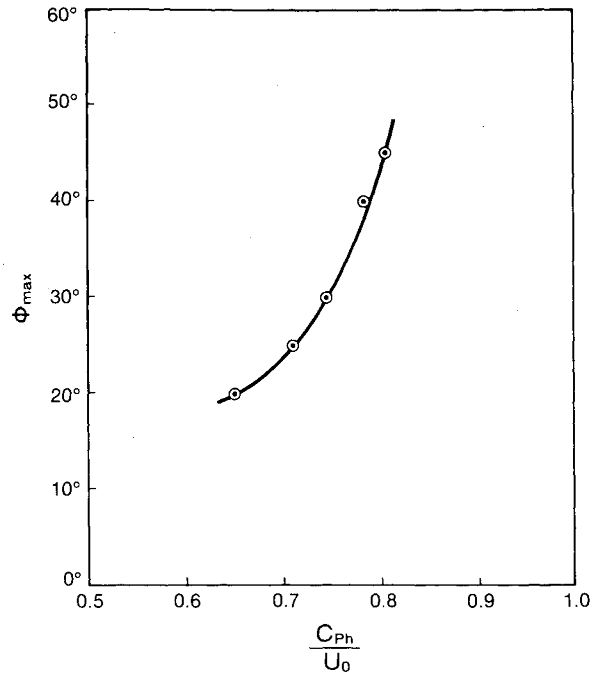

Fig. 1 Peak noise emission angle variation with axial wavespeed for discrete spectral components from $St = 0.32$ to 1.26, $M = 0.6$.

the individual frequency directivity plots. An explanation for this angular dependence of the frequencies in the jet was given by Mollo-Christensen and Narasimha.[3] They postulated that a sound wave traveling in the downstream direction would be moving at the speed of sound with respect to the air in the jet and with a Mach number of $M+1$ with respect to the outside air. The noise transmission would therefore be at an angle given by

$$\phi = \cos^{-1}(1/(1+M)) \tag{1}$$

Sound waves moving obliquely to the jet axis would be transmitted and reflected by the shear layer. This would cause certain long wavelengths to resonate back and forth across the jet. All waves would be radiated according to the equation stated, but by the time the waves that have been bounced back and forth many times and are radiated they have been carried downstream into a region where the Mach number has decreased. Thus, if M has decreased the value of ϕ would be smaller. This would account for the low-frequency maxima near the jet axis and the high-frequency maxima further away from the jet axis.

The above explanation was proposed without detailed information about the characteristics of the coherent structure in the jet that produced the noise. We have measured the axial wave number/frequency relationship for the jets currently being studied and have compared them to results obtained by other investigators.[1] The same relationship between the axial wave number and frequency was found for all jets with Mach numbers greater than 0.3. A linear curve fit of all the data using a least squares method shows that wave number/frequency relationship can be expressed by

$$k_r D = 0.7735 + 7.226\, St \tag{2}$$

This expression can be rearranged further to produce an equation relating the axial wave speed of the disturbance (phase velocity C_{ph}) and frequency. Realizing that $C_{ph} = \lambda f$, $St = fD/U_0$, and $\lambda = 2\pi/k_r$, the following expression can be obtained:

$$C_{ph}/U_0 = (2\pi St)/(0.7735 + 7.226\, St) \tag{3}$$

This reveals that, above a Strouhal number of about 0.4, the phase velocity C_{ph} remains fairly constant at around 80% of the jet exit velocity. Below $St = 0.4$, the phase velocity decreases with decreasing frequency. This phase velocity variation at low frequencies was also noted by Troutt and McLaughlin.[4]

In light of the above sound emission directivity discussion, it is interesting to note that the phase velocity C_{ph} decreased with decreasing frequency in much the same way that Mollo-Christensen and Narasimha[3] suggested convection and refraction carried the lower-frequency sound waves into regions of slower mean flow before being emitted to the surroundings. We propose that there is an interaction between the coherent structure's axial wave speed and the peak sound emission angle ϕ such that lower wave speeds result in lower noise emission angles.

In support of this hypothesis, the angle at which the peak noise level occurred was plotted as a function of frequency. A curve fit of these data resulted in the following functional relationship between the two:

$$\phi = [1772\, St - 210]^{0.5} \tag{4}$$

By calculating the axial wave speed for the frequencies we studied and plotting the measured maximum noise emission angle as a function of the computed axial wave speed, Fig. 1 was obtained. This figure clearly shows that ϕ is dependent upon the axial wave speed of the disturbance. A curve fit of the data shows that

$$\phi = 401 - 1196(C_{ph}/U_0) + 939(C_{ph}/U_0)^2 \tag{5}$$

This result illustrates that there is definite, identifiable relationship between the peak noise emission angle ϕ and the axial wave speed C_{ph}.

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