Far Noise Field of a Two-Dimensional Subsonic Jet

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The acoustical radiation characteristics of a high-aspect ratio, cold subsonic, model slot jet have been investigated experimentally. Acoustical measurements were made in both a free-field environment and a reverberation field environment. Mean velocity distribution of the slot jet was determined to provide information on the mixing characteristics of the flow. Free-field results obtained reflected a characteristic asymmetrical directivity pattern of the slot jet noise. The total radiated sound power yielded a typical U^7 dependence on mean jet velocity. The experimental findings are compared with data from similar studies and also with radiation characteristics of circular cold subsonic jets.

Introduction

THE majority of experimental and analytical research conducted on jet noise in the past has been concentrated on turbulent free jets exhibiting circular symmetry. The noise generation and radiation from two-dimensional turbulent jets have not been extensively studied. This is primarily because circular jets have been the engine exhaust configuration of practical interest. Recently, however, with the development of the short takeoff and landing (STOL) aircraft, aerodynamic designers have considered the use of various blown-flap concepts to provide the lift augmentation required for this type of aircraft, where a slot jet may be used above the wing-flap. As a result, there is an apparent need to improve our understanding on the noise radiation from two-dimensional turbulent jets.

Existing research work[1-7] on noise radiation from two-dimensional jets are few and fragmentary, and are mostly concerned with two-dimensional jets at high-subsonic and/or supersonic speeds. Maglieri and Hubbard[1] made directivity measurements of high-speed slot jets of various aspect ratios. Cole[2] examined noise directivities of high-aspect ratio slot jet generated from engine exhaust. Maestrello and McDaid[3] presented some limited power spectrum and intensity spectrum data for slot jets of aspect ratio 5 and 20, operated at high-subsonic velocities. Olsen, Gutierrez, and Dorsch[4] reported directivity data and spectral data for various aspect ratios slot jets over a range of subsonic velocities. Grosche,[5] in his study of noise generation from a simulated jet flap, also carried out some directivity measurements for slot jet at high-subsonic velocities. Gruschka and Schrecker[6] and Schrecker and Maus[7] investigated the radiated power and power spectrum of high-aspect ratio slot jets operated over a range of subsonic velocities.

Note that in most of these studies, only some aspects of the radiation field of a slot jet have been investigated. A systematic and thorough study of the radiation field of a slot jet, in which all aspects of the radiation field were examined, however, is not available. The purpose of this study is to systematically investigate the far field acoustic characteristics of a two-dimensional turbulent air jet operated at low and intermediate subsonic speeds. The experimental results reported in the paper were obtained with a slot jet of aspect ratio 10. The experimental findings are discussed in terms of total radiated power, power spectrum, directivity, and sound intensity spectrum, and their respective dependence of jet velocity.

Experimental Facilities and Procedures

The outdoor test facilities used for obtaining free-field acoustical data is shown schematically in Fig. 1. The nozzle was mounted directly onto a 600-ft^3 air storage tank treated internally with 1-in. thick acoustic foam. The blow-down method was used to generate the jet flow in order to eliminate the upstream acoustical contamination of the jet noise. The test nozzle, designed to provide smooth area contraction, had an exit area of 3.14 in.^{2} and an aspect ratio of 10. The far-field microphone was mounted on a 10-ft radius motorized boom. The azimuth angle θ of the microphone was varied from 15-105° measured from the forward axis of the jet in 15° increments.The circumferential angle ϕ was varied from

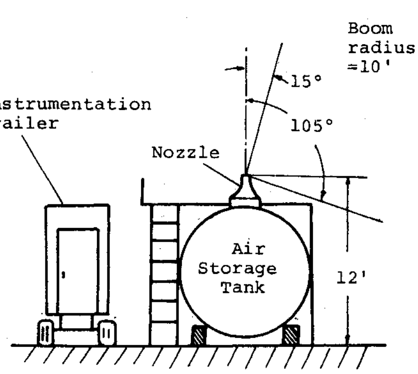
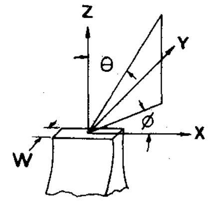


Fig. 1 Sketch showing the outdoor jet noise facility.

Fig. 2 Coordinate system.



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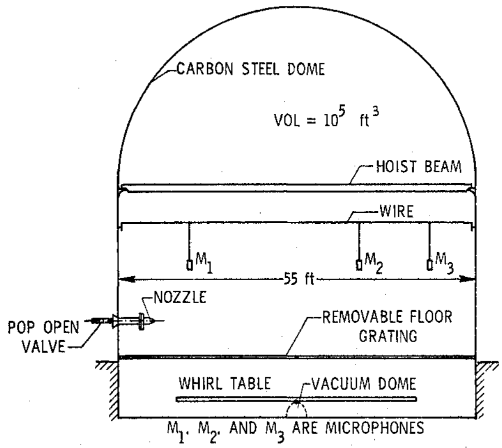

Fig. 3 Sketch showing the vacuum chamber for total power measurement.

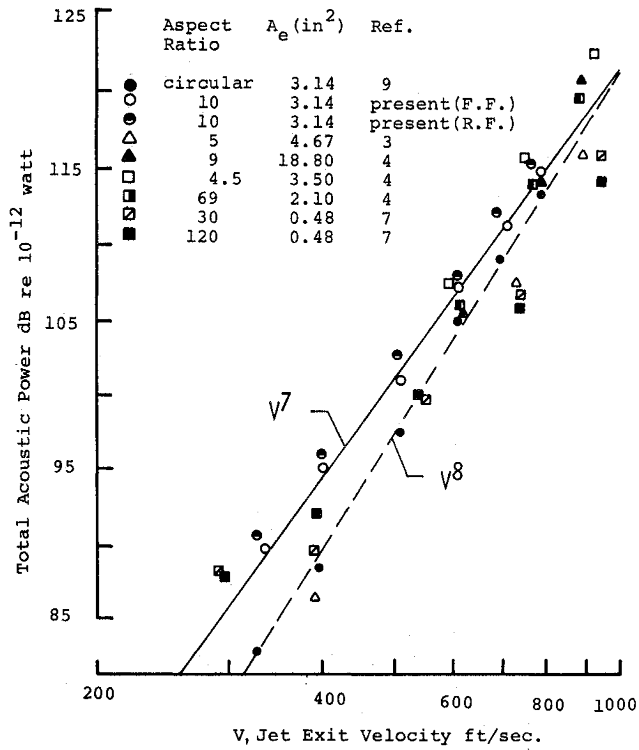

Fig. 4 Acoustic power dependence on jet velocity.

0-90°. A sketch showing the coordinate system used for data presentation is given in Fig. 2.

To minimize the possible influence of ground reflection, the nozzle was placed about 12 ft above the level grassed ground of an open terrain. The maximum ground reflection correction in the 100-Hz 1/3 octave band was found to be less than 1 db and this occurs when the microphone boom is at $\theta = 105°$ position. Therefore, the correction was not incorporated in the data. As a further experimental precaution, the microphone boom was kept in a fixed plane relative to the experimental setup. The ϕ angle variation was accomplished by rotating the nozzle in 22.5° increments with respect to the vertical plane containing the microphone boom. This way, the possible influence of acoustic reflections from ground and the surface of the storage tank would be the same for all the ϕ planes.

The background noise level (including the wind turbulence induced noise) at selected measurement positions was sampled at frequent intervals. The envelope of all the background noise spectra was used for data correction. The background noise level at the 100-Hz 1/3 octave band was about 45 db and decreased at a rate of 3 db/octave.

The acoustical instrumentation for free-field measurement consisted of a 1/2-in. free-field microphone with the matching cathode follower, a microphone amplifier, and a real time 1/3 octave band spectrum analyzer. A high-pass filter having a cutoff at 100 Hz was used to filter out the predominant wind noise components at low frequencies. The integrating time used for spectral analysis was 1/2 sec and the bandwidth was from 100-40 kHz.

In taking the free-field acoustical data, the nozzle was first closed by a rubber plug, and the air storage tank was pumped up to a pressure of 10 psig. The plug was then manually released to generate the jet flow. When the desired pressure was reached the real-time spectrum analyzer was activated. Within the half second of the integrating time for spectral analysis, the velocity variation of the jet was no more than 2% of the averaged value. Sound pressure spectra were recorded for six jet velocities ranging from 330-790 fps at a total 35 microphone locations located on a quarter of the 10 ft radius spherical surface enclosing the jet flow. The total run time for the blow-down lasted approximately 30 sec.

Power spectrum, total radiated power, and mean flow characteristics of the slot jet were also obtained in a 55-ft-diam semispherical vacuum chamber. The vacuum capability of the chamber made it possible to generate a "clean" jet flow by using blow-down through the nozzle mounted inside the partially evacuated chamber. The reverberation time of the chamber in 1/3 octave band was determined by standard methods; 12 sec at 100-Hz band and decreased nearly linearly to 0.5 sec at 10-kHz band. The chamber was considered appropriate for power measurement in 1/3 octave band for frequencies of 100 Hz and above. A schematic view of the chamber is shown in Fig. 3.

Acoustical instrumentation used for reverberant field measurement were similar to those used in free field except that three 1/2 in. pressure microphones were used for spatial averaging. The variation in spectral level among the three microphones was about 1 1/2 db in 1 kHz band and decreases with increasing frequency. Relative larger variation was found at lower frequency bands. Averaging time used for spectral analysis was 1 sec and the variation of jet velocity over the same period is less than 1% of the mean value. Other details on facility, instrumentation, and procedures are available elsewhere.[8]

Mean velocity measurement sof the jet flow were obtained to establish the nozzle performance and jet mixing characteristics. The measurements were carried out by surveying the pitot-static pressure of the jet flow. It was found[8] that the initial mixing region extends from nozzle exit to six nozzle heights downstream. the fully developed turbulent region starts at ten nozzle heights downstream of the nozzle exit and the centerline velocity decay in this region follows the usual inverse square-root dependence of downstream distance. The boundary-layer thickness at the nozzle exit plane is 1% of the nozzle width and 6% of the nozzle height along the x-axis and the y-axis respectively (see Fig. 2).

Results and Discussion

Total Acoustic Power

The total acoustic power radiated from the slot jet over a range of subsonic velocities is plotted in Fig. 4. Acoustic power obtained in a related study for an equivalent circular jet and acoustic power data for slot jets reported by other investigators were also included in the same figure for comparison. All data have been normalized to the same exit area of 3.14 in.[2] by assuming that the total acoustic power scales linearly with nozzle exit area.

It is noted that the acoustic power dependence on jet velocity for the slot jet studied follows a V^7 relation as opposed to the well-established V^8 relation for a circular jet over subsonic velocities. Moreover, it is seen that the total power radiated by the slot jet exceeds that of an equivalent circular jet and the difference diminishes with the increasing jet velocity. The average acoustic efficiency (defined as the ratio between acoustic power and mechanical power) for slot jet over the velocity range investigated is $5.5 \times 10^{-5} M_e^4$, where M_e is the ratio of the jet velocity and the ambient speed of sound. For an equivalent circular jet over the same velocity range, the acoustic efficiency is given by $5 \times 10^{-5} M_e^5$. The difference in acoustic power between free-field measurement and the reverberant field measurement in Fig. 4 is due to the difference in surface area used for integration.

It is pertinent to point out, as is shown in Fig. 4, that experimental findings on the acoustic power dependence on velocity for slot jets differs among various investigators. Maestrello and McDaid[3] reported a V^8 dependence for an aspect ratio 5 slot jet and they also found that the slot jet radiates less acoustic power than an equivalent circular jet over the high-subsonic velocity range. Olsen, Gutierrez, and Dorsch[4] investigated the far-field noise of slot jets of aspect ratios 3.5, 4.5, 9, and 69 for jet velocities above 600 fps. They estimated acoustic power by integrating the sound intensity measured in one plane of symmetry of the nozzle over an enclosing sphere assuming that the sound field was axisymmetric. Their results indicated a $V^{8\text{-}9}$ dependence of acoustic power for slot jets which radiated nearly the same acoustic power as the equivalent circular jets. Grushka and Schrecker[6] and Schrecker and Maus[7] obtained acoustic power radiated by slot jets with aspect ratios of 30, 60, and 120 in a reverberation chamber. The acoustic power dependence on jet velocity was found to vary with aspect ratio of the jet as well as the jet velocity. By fitting this data, we found that for aspect ratio of 30, a nearly V^7 relation is obtained. For aspect ratio of 120, however, the dependence of acoustic power on jet velocity is nearly V^6. The results reported in Refs. 6 and 7 also indicate that the relative radiation efficiency of slot jets as compared to equivalent circular jets varies with jet velocity; for jet Mach number less than 0.5 the slot jets radiate more acoustic power, while for jet Mach number greater than 0.5 the trend is reversed.

In the present study, a consistent V^7 dependence of acoustic power for the slot jet was obtained from both the outdoor free-field measurement and the reverberant field measurement. Comparison made with data obtained for an equivalent circular jet where identical experimental procedures were used indicated that a slot jet is invariably a more efficient noise radiator at least over the low and intermediate subsonic jet velocities.

Little theoretical analysis is available at present to resolve the apparent experimental disagreements discussed. Based on the hypothesis that the flow similarities in a two-dimensional turbulent jet are the same as those found in a circular turbulent jet, Cole[2] deduced that the quadrupole sound emitted by a slot jet should be only half that of one emitted by an equivalent circular jet. This deduction, however, can not be considered conclusive. Firstly, the turbulent structure in a two-dimensional jet flow differs from that of an axisymmetric jet flow at least in the main noise producing initial mixing region of the jet flow. Secondly, the mean flow environment within which the noise sources radiate also differs in these two types of jet flow. Ffowcs-Williams[9] has pointed out that nozzle exit geometry affects the noise generation from jets by the possible addition of "lip noise" source, in the form of a fluctuating force with axis perpendicular to the jet centerline. For slot nozzle, the nozzle exit geometry would seem to favor the existence of lip dipole source as compared to a circular nozzle. A fluctuating force source, if compact, gives a V^6 dependence of acoustic power on typical flow velocity with a higher acoustic efficiency than a quadrupole at subsonic Mach numbers. The experimental observations made in the present study thus imply the existence of lip dipole source which when combined with the turbulent mixing noise yields a typical V^7 dependence of the radiated power. The variation of acoustic power dependence on slot jet velocity reported in Refs. 6 and 7, as has been discussed earlier, also seems to support the lip noise argument made here.

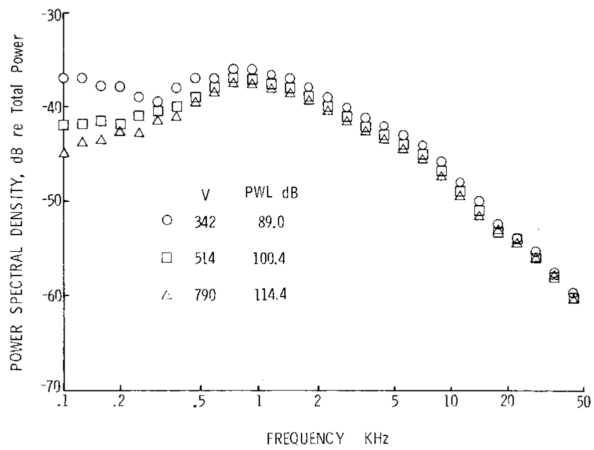

Fig. 5 Acoustic power spectral density.

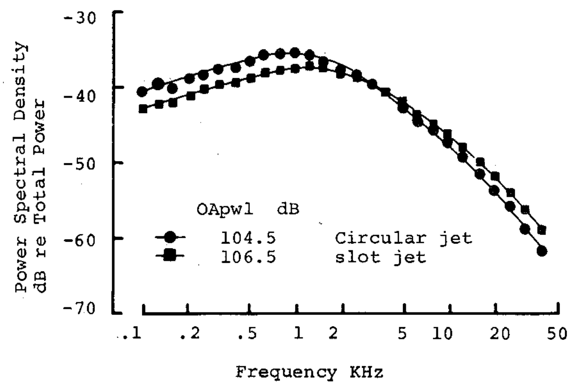

Fig. 6 Comparison of acoustic power spectral density between the slot jet and an equivalent circular jet, $V = 616$ fps.

Power Spectra

Power spectra for slot jets obtained from free-field measurements at different velocities are given in Fig. 5. The results shown were obtained by normalizing the 1/3 octave band power spectra with respect to the individual bandwidth and the total power. It is noted that the spectral peak frequency shows only a weak dependence on jet velocity; over the velocity range of the slot jet tested, from 340-790 fps, the frequency of power spectral peak varied only slightly, from 800-1250 Hz. Observations similar to this have also been reported for circular jets.[4,6,7] The shape of the power spectra remained essentially similar for different jet velocities. The low-frequency components, however, indicated a relative increase as the jet velocity was lowered. The slope of the power spectra at frequencies above the spectral peak frequency followed an average 5-db/octave roll-off as compared with the typical 6-db/octave roll-off for subsonic circular jets.[6,7] This indicates that the relative contents of high-frequency components for slot jets are higher than those for the circular jets.

Power spectra obtained from the reverberant chamber measurement[8] were essentially similar to those given in Fig. 5. Except that the location of power spectral peak was shifted to higher frequencies by 1/3 of an octave. Large scattering were also found at low frequencies. The results, therefore, are not included here.

A typical comparison of power spectra for a slot jet and that for an equivalent circular jet is given in Fig. 6. It is seen that the spectral shapes at low frequencies for the two types of jets are quite similar. The peak frequency for the slot jet is about 1/3 of an octave higher than that for the circular jet.

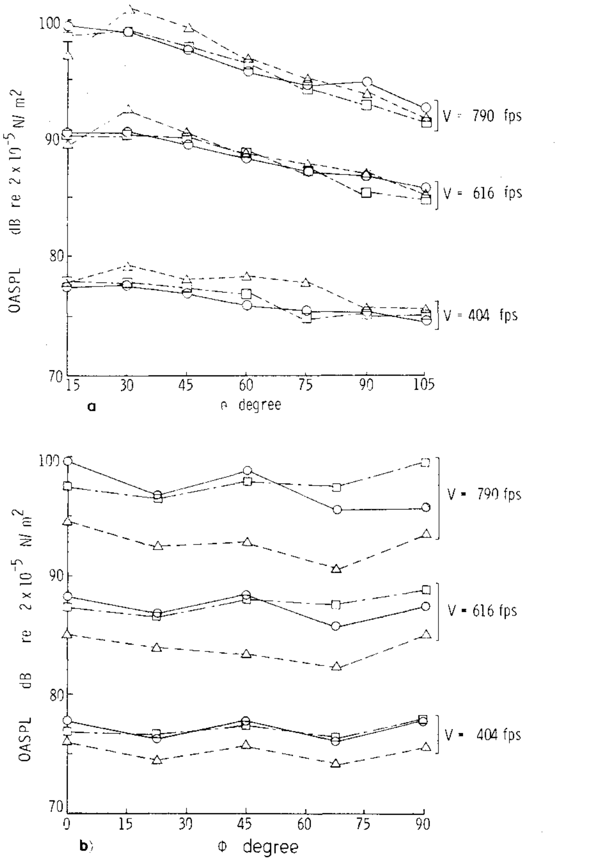

Fig. 7 Overall directional pattern of slot jet noise: a) $-\circ-\phi=0°$, $-\square-\phi=45°$, $-\Delta-\phi=90°$; b) $-\circ-\theta=15°$, $-\square-\theta=45°$, $-\Delta-\theta=90°$.

The slot jet also emits relatively higher levels of high-frequency contents as has been discussed earlier. The similarity in power spectrum at low frequencies between the two cases is not surprising. For both slot jets and circular jets, the low-frequency components are radiated from sources located farther downstream from the nozzle exit. For a slot jet, the two-dimensionality breaks down at about twice the nozzle width downstream[10] which corresponds roughly to the onset of turbulent decay region for an equivalent circular jet in the present study. Thus, it may be expected that the turbulence structure for both types of jets become similar at downstream regions hence the radiated low-frequency sound.

One interesting feature on the power spectra for slot jets is the scaling of the frequency for power spectral peak. For circular jet, it is known[4] that the nozzle diameter is the scaling parameter for power spectral peak, i.e., the peak frequency varies inversely with the nozzle diameter. For slot jets, the extent of the initial mixing region scales with the nozzle height. Therefore, one would expect that the nozzle height should be the scaling parameter for the power spectral peak frequency. Experimental observations,[6,7] however, do not bear out this deduction. It was found that the spectral peak frequencies correlated only weakly with the height of the slot nozzle. It is felt that additional analytical and experimental studies on the source mechanism as well as the characteristics of the fluctuating flow in slot jets are required to resolve this apparent paradox.

Directivity

Overall noise directivity for slot jets at three selected velocities are given in Fig. 7. As a result of the nonaxisymmetry of the sound field, results are presented in terms of directivity variations with respect to the azimuth angle θ and circumferential angle ϕ, respectively. The variation of noise intensity with azimuth angle θ, Fig. 7a, revealed that the directivity patterns between $\phi=0°$ and $\phi=45°$ planes were grossly similar; a rather flat directional peak occurred near $\theta=15°$ location and decreases more or less uniformly with increasing θ. In $\phi=90°$ plane, perpendicular to the nozzle width, a distinct directional peak at $\theta=30°$ was noted over the entire velocity range tested. Between $\theta=30°$ and $\theta=60°$, the noise intensity in $\phi=90°$ plane was found to be greater than that in $\phi=0°$ plane. It is suspected that the distinct directivity peak in $\phi=90°$ plane is probably attributable to the basic source directivity in a slot jet rather than a refraction effect, since the thin shear layer along the short length of the nozzle does not seem to favor a large refraction over the dominant frequency

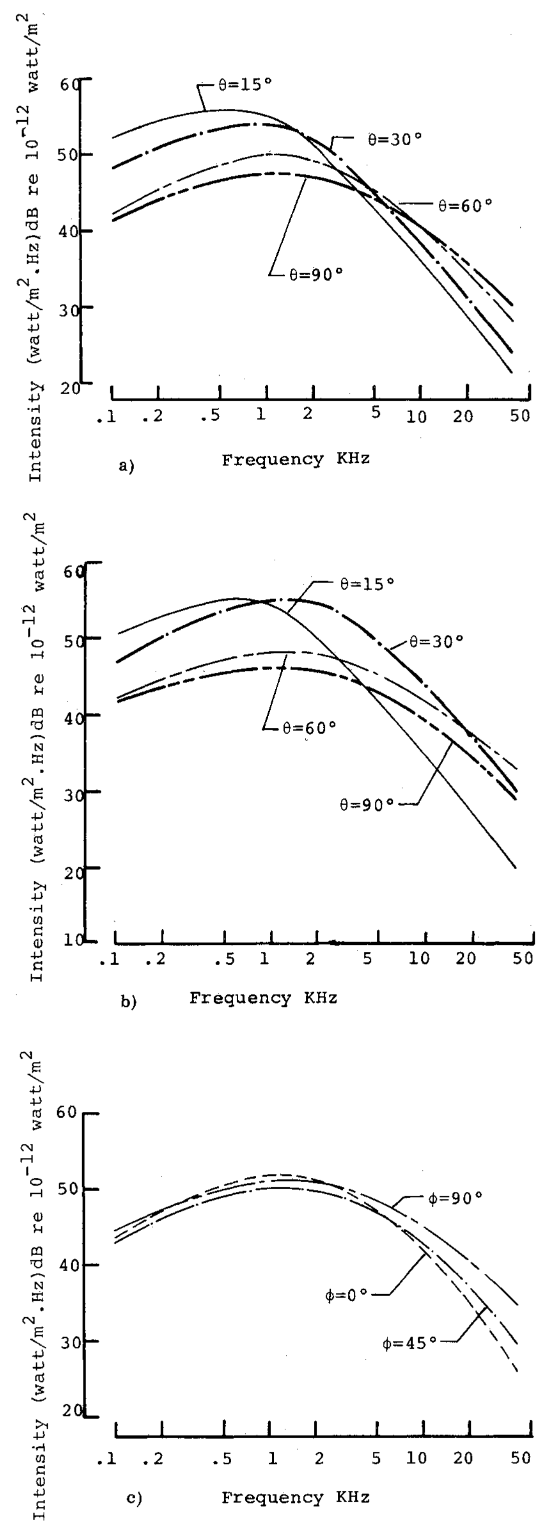

Fig. 8 Intensity spectra of slot jet noise, $V=616$ fps: a) $\phi=0°$; b) $\phi=90°$; c) $\theta=45°$.

range of the slot jet (spectral peak occurred at around 1 kHz). The higher noise intensity observed in $\phi = 90°$ plane may be explained if the slot jet is conceptually replaced by a linear array of uncorrelated compact sources, parallel to the nozzle width and with maximum source strength located at the center of the array. This crude physical model is more or less in line with the turbulence structure found in a slot jet.[7]

The preceding observations on the directivity variation with azimuth angle θ are in qualitative agreements with those reported in Refs. 1, 4, and 5 for slot jets of aspect ratio 10 and greater. At higher aspect ratios, however, the $\theta = 30°$ peak occurred in $\phi = 90°$ plane become more pronounced.[4,5]

The variation of directivity with circumferential angle ϕ for slot jets at different velocities are given in Fig. 7b. At velocities less than 500 fps, a characteristic variation of directivity with ϕ was noted at all θ = constant planes; the noise peaked along $\phi = 0°$, 45°, and 90°, which means that the slot jet noise possesses a characteristic 8-lobe pattern around the circumference of the nozzle. At higher jet velocities, this characteristic pattern, though not as distinct, is still detectable. The consistence of this directivity pattern throughout the velocity range tested tends to rule out the possibility of data scattering. Data obtained by Maglieri and Hubbard[1] for slot jet of aspect ratio 10 indicated, however, that the noise intensity around ϕ was nearly uniform. Directional patterns were observed only for slot jets of higher aspect ratios 50 and 100, where peaks occurred at $\phi = 0°$ and 90°. The cause for the occurrence of this observed characteristic directivity pattern, other than the nozzle geometry, is not clear at the present. However, it was speculated that the lip dipole source, whose existence has been implied by the V^7 dependence on the total radiated power, may play an important role.

Intensity Spectra

Typical noise intensity spectra for the slot jet and their variation with measurement position are given in Fig. 8. The results presented were obtained by first smoothing the 1/3-octave-band intensity spectra taken from measurement then normalizing the levels with respect to individual bandwidth. Figures 8a and 8b show the variations of intensity spectrum with azimuth angle θ in $\phi = 0°$ plane and $\phi = 90°$ plane respectively. Figure 8c illustrates the dependence of the intensity spectrum on ϕ at $\theta = 45°$.

The shape and the peak frequency of the intensity spectra were found to depend strongly on the azimuth angle of measurement (see Figs. 8a and 8b). The low-frequency noise radiates primarily in the direction close to the jet axis while the high-frequency radiation takes place perpendicular to the jet axis. The frequency of the spectral peak increased by an octave as θ was increased from 15-90°. The bandwidth, measured by the 10 db down points from the peak level, also increased with θ. The variation of intensity spectra with θ in the planes between $\phi = 0°$ and $\phi = 90°$ (results not shown) followed the same general trends.

The variation of intensity spectra with ϕ, however, is not as pronounced as that with θ (see Fig. 8c). The peak of the spectra occurred at nearly the same frequency for all values of ϕ in a θ = constant plane. For frequencies above the peak, the noise radiated in the direction perpendicular to the nozzle width ($\phi = 90°$) was higher than that along the nozzle width ($\phi = 0°$). The general dependence of intensity spectrum of slot jets on the measurement location discussed in this section have also been reported by other investigators.[2-5]

Conclusions

Far-noise field of a two-dimensional subsonic turbulent air jet of aspect ratio 10 has been experimentally investigated. From the experimental findings, the following conclusions may be drawn. 1) The total acoustic power radiated from a slot jet has a 7th power dependence on jet velocity. Over the subsonic velocity range studied, a slot jet is a more efficient noise radiator than a circular jet of equal exit area operated at the same velocity. 2) Acoustic power spectra for the slot jet at different subsonic velocities are similar. The frequency of spectral peak shows only weak dependence on jet velocity. The low-frequency radiations from a slot jet are similar to those from an equivalent circular jet. For high-frequency radiations, a slot jet is a more efficient radiator than an equivalent circular jet. 3) The overall directivity of a slot jet peaked at an azimuth angle of 30°. The directional distribution of noise around the circumference of the jet exhibits a characteristic 8 lobe pattern. 4) The variation of the intensity spectrum of slot jet noise depends strongly on the azimuth angle. The frequency of spectral peak increases and the bandwidth of the spectrum broadens with increasing azimuth angle. High levels of high-frequency radiation occurred in the plane perpendicular to the nozzle width.

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