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Subsonic Jet Noise from Nonaxisymmetric and Tabbed Nozzles

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Subsonic jet noise from nonaxisymmetric and tabbed nozzles are investigated experimentally and theoretically. It is shown that the noise spectra of these jets are in good agreement with the similarity spectra found empirically earlier by Tam et al. through a detailed analysis of supersonic jet noise data (Tam, C. K. W., Golebiowski, M., and Seiner, J. M., "On the Two Components of Turbulent Mixing Noise from Supersonic Jets," AIAA Paper 96-1716, 1996). Furthermore, the radiated noise fields of the jets under study, including elliptic and large-aspect-ratio rectangular jets, are found to be quite axisymmetric and are practically the same as that of a circular jet with the same exit area. These experimental results strongly suggest that nozzle geometry modification into elliptic or rectangular shapes is not an effective method for jet noise suppression. A lobed nozzle, on the other hand, is found to impact significantly the noise field. Noise from large-scale turbulent structures, radiating principally in the downstream direction, is effectively suppressed. Tabs also impact the noise field, primarily by shifting the spectral peak to a higher frequency. A jetlets model is developed to provide a basic understanding of the noise from tabbed jets. The model predicts that the noise spectrum from a jet with N tabs ($N \geq 2$) can be obtained from that of the original jet (no tab) by a simple frequency shift. The shifted frequency is obtained by multiplying the original frequency by $N^{1/2}$. This result is in fairly good agreement with experimental data.

I. Introduction

THERE are two basic objectives in this investigation. The first objective is to perform a systematic study of the noise characteristics of subsonic jets from nonaxisymmetric nozzles. The nozzles used have rectangular, elliptical, and lobed geometries. Such a study for nonaxisymmetric subsonic jets has never been done before. Second, we will investigate the effect of tabs (inserted into the jet flow) on subsonic jet noise. For application to an aircraft propulsion system, it is essential that the nonaxisymmetric nozzle configuration or the blockage by the tabs be such that there is no large loss of thrust. This will be assumed throughout this investigation.

Recently, Tam et al.[1] performed an in-depth analysis of supersonic jet noise data from circular nozzles. They found that the turbulent mixing noise from these jets was composed of two apparently independent components. One component is highly directional and radiates principally in the downstream direction. The noise spectrum is dominated by a rather sharp peak at relatively low frequency. These characteristics are consistent with Mach wave radiation from the large turbulence structures of the jet flow. The mathematical theory of Mach wave radiation from large turbulence structures/instability waves, first formulated and developed by Tam and Burton,[2] is now well-established.[3,4] The other component has a broad spectral peak and has a relatively uniform directivity. It is the dominant noise component in the sideline and upstream direction. These characteristics suggest that the latter component is the noise from the fine-scale turbulence of the jet flow.[5]

Tam et al.[1] succeeded in deriving empirically two seemingly universal spectrum from the data. They demonstrated that one of the spectrum is a good fit to the noise from the large turbulence structures and the other is a good fit to the noise from the fine-scale turbulence regardless of the jet velocity, temperature, and direction of radiation. These spectra as functions of f/f_p, where f is the frequency and f_p is the frequency at the peak of the spectrum, are shown in Fig. 1. Tam et al. also provided the following analytical formulas (in decibel) for the large turbulence structures noise spectrum $F(f/f_p)$ and the fine-scale turbulence noise spectrum $G(f/f_p)$:

$$10\log F \begin{cases} = 5.64174 - 27.7472\log(f/f_p), & f/f_p \geq 2.5 \\ = \{1.06617 - 45.2994\log(f/f_p) \\ \quad + 21.40972[\log(f/f_p)]^2\}\cdot\log(f/f_p) & 2.5 \geq f/f_p \geq 1 \\ = -38.19338[\log(f/f_p)]^2 - 16.91175[\log(f/f_p)]^3 & 1 \geq f/f_p \geq 0.5 \\ = 2.53895 + 18.4\log(f/f_p), & 0.5 \geq f/f_p \end{cases} \tag{1}$$

$$10\log G \begin{cases} = 29.77786 - 38.16739\log(f/f_p), & f/f_p \geq 30 \\ = -11.8 - \{27.2523 + 0.8091863\cdot\log(f/10f_p) \\ \quad + 14.851964[\log(f/10f_p)]^2\}\cdot\log(f/10f_p) & 30 \geq f/f_p \geq 10 \\ = -[8.1476823 + 3.6523177 \\ \quad \cdot\log(f/f_p)]\cdot[\log(f/f_p)]^2, & 10 \geq f/f_p \geq 1.0 \\ = [-1.0550362 + 4.9774046 \\ \quad \cdot\log(f/f_p)]\cdot[\log(f/f_p)]^2, & 1.0 \geq f/f_p \geq 0.15 \\ = -3.5 + \{11.874876 + 2.1202444\cdot\log(20f/3f_p) \\ \quad + 7.5211814[\log(20f/3f_p)]^2\}\cdot\log(20f/3f_p) & 0.15 \geq f/f_p \geq 0.05 \\ = 9.9 + 14.91126\log(f/f_p), & 0.05 \geq f/f_p \end{cases} \tag{2}$$

Both $F(f/f_p)$ and $G(f/f_p)$ are normalized so that $F(1) = G(1) = 1.0$. During the course of this investigation, it was found that the preceding two spectra were crucial to the analysis of subsonic jet noise as well. For easy reference, these spectra will be designated as TGS-1 and TGS-2, respectively.

In a recent work, Tam[6] analyzed a large collection of supersonic jet noise data from rectangular, elliptic, plug, and suppressor

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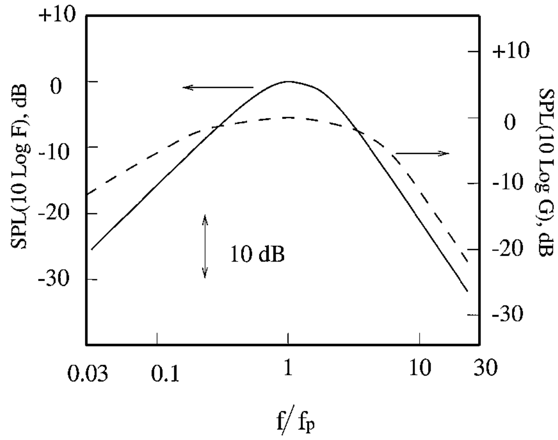

Fig. 1 Similarity spectra for the two components of turbulent mixing noise: ——, large turbulence structures/instability waves noise (TGS-1 spectrum), and – – –, fine-scale turbulence noise (TGS-2 spectrum).

nozzles. It was found that the spectra of these jets in the downstream directions fitted the TGS-1 spectrum well regardless of jet velocity, temperature, and direction of radiation. In the sideline directions, the measured spectra could be well represented by the TGS-2 spectrum, irrespective of the jet velocity and temperature. In addition, even noise spectra from supersonic jets embedded in an open wind tunnel, simulating forward flight effects, were found to have spectral shapes that were the same as the TGS-1 and TGS-2 spectra. Independently, Dahl et al.[7] studied the noise from supersonic coaxial jets. The experimental data involved different velocity and effective temperature ratios between the fan and primary jet streams. They discovered that all of their measured noise spectra had shapes that were in good agreement with the TGS spectra. Evidently, the TGS spectra, although developed originally for circular jets in a static condition, are more universal and less nozzle geometry dependent. Note that for jets in simulated forward flight, no extra length scale is introduced in the core region of the jet flow. That the TGS spectra are also applicable to these jets provide strong support for the validity of the similarity argument that motivated the search for these spectra in the first place.

One reason for using nonaxisymmetric nozzles is the belief that these nozzles would promote mixing of the jet fluid and, hence, reduce the radiated noise. However, there are alternative ways to enhance mixing without modifying the nozzle geometry. One such method is to insert tabs into the jet flow. The tabs generate longitudinal vortices leading to a rapid mixing of the jet fluid. Ahuja and Brown[8] used tabs to suppress jet screech and control mixing. Rogers and Parekh,[9] Surks et al.,[10] and Samimy et al.[11] measured the effect of tabs on mixing noise. Mixing enhancement, of course, has other applications, such as efficient combustion. Recently, there have been a number of experimental investigations on the geometry, size, spacing, and location of tabs for most effective mixing enhancement.[12–14] There are also a number of computational studies on the effect of tabs on the mean and unsteady flowfields of the jet.[15–17] Unfortunately, in spite of these efforts, the effect of tabs on jet noise remains largely unknown.

In Sec. III, measured subsonic jet noise spectra from elliptic and rectangular nozzles are first presented. It is shown that they are in good agreement with the TGS spectra. Further, the sound fields of all of the jets, even for an aspect ratio 8 rectangular jet, are practically axisymmetric. They are the same as that of a circular jet (with same equivalent diameter based on the exit area). In the case of a six-lobe nozzle, the measured data indicate that the convoluted nozzle geometry effectively suppresses the large turbulence structures of the jet flow and their noise. The noise field, even in the downstream direction, is primarily from the fine-scale turbulence. It possesses the same characteristic spectral shape as the TGS-2 spectrum. The noise from the large-scale turbulence in the form of a low-frequency peak, the TGS-1 spectrum, is essentially suppressed. In Sec. IV, the effect of tabs on subsonic jet noise is investigated. A jetlets model is developed to quantify the effect of the tabs on the noise spectrum and intensity. It will be shown that there is good agreement between the predictions of the model and the experimental results. Finally, the effectiveness of nozzle geometry modification and the use of tabs for suppression of subsonic jet noise is discussed in the last section.

II. Experimental Facility and Nozzle Configurations

The experiments were carried out in an open jet facility at NASA John H. Glenn Research Center at Lewis Field. Compressed air passed through a cylindrical (4.3 in. diameter $\times$48 in. long) plenum chamber fitted with flow conditioning units. The flow exhausted through the nozzle into the quiescent ambient of the laboratory. All measurements were carried out for cold flows, that is, the total temperature was approximately a constant throughout and equaled that of the ambient. Further description of the jet facility may be found in Refs. 11 and 12.

All nonaxisymmetric nozzles were machined from solid cylindrical blocks of aluminum. The interior along the major and the minor axes was contoured according to third-order polynomial fits. The rest of the interior was faired smoothly. For all nozzles, the flow always converged and entered and exited the nozzle axially. The equivalent diameter, based on nozzle exit cross-sectional area, was the same for all asymmetric nozzles and was 0.58 in. The circular nozzle was fabricated earlier and had an exit diameter of 0.5 in. All nozzles had end walls, that is, were thick lipped, to facilitate easy installation of the tabs at desired locations. The exit geometries of the various nozzles are shown schematically in Fig. 2. Data were also obtained with the circular nozzle fitted with equally spaced multiple tabs. The tabs used were delta tabs,[12] having triangular shapes with the base on the nozzle wall and the apex leaning downstream with the plane of the tab inclined at an angle of about 45 deg with respect to the flow direction. The geometric area blockage due to each tab was approximately 1.8% of the nozzle exit area.

The jet facility was located in a large, semianechoic test chamber, whose walls and ceiling only were covered with acoustically absorbent material. For the present noise measurements, preliminary diagnostics were performed to alleviate reflection and background noise contamination. The floor and side walls in the immediate vicinity of the jet facility were covered with acoustic absorbent material. Covering all flanges of the jet facility itself and the arms holding the microphones removed some of the ringing in the spectra. Significant further improvement was achieved when the microphone stem itself (especially at the location where the diameter changed) was covered. Two $\frac{1}{4}$-in. (B and K 4135) microphones with standard B and K amplifiers were used. All measurements were carried out with the protection grid removed, and the data are reported as measured without any further correction. The data accuracy is further discussed in Sec. III. One microphone was located at 90 deg relative to the jet axis, another was mounted on a movable stand to carry out measurements at two other angular locations (45 and 25 deg). The

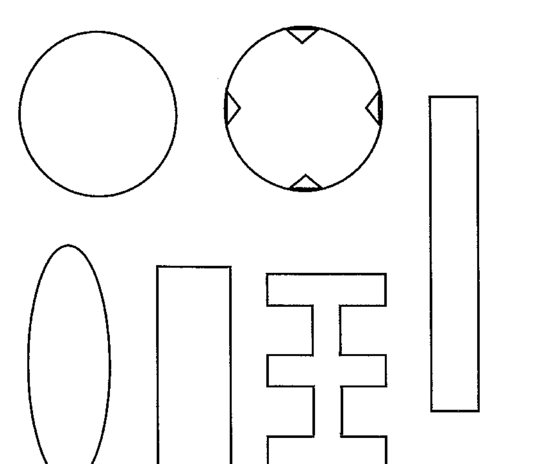

Fig. 2 Schematic of the exit geometry of the nozzles. Clockwise from top left are circular, circular with four tabs, 8:1 rectangular, six-lobe, 3:1 rectangular, and 3:1 elliptic nozzles. Equivalent diameter D for all nonaxisymmetric nozzles is 0.58 in., that of the circular nozzle is 0.5 in.

two microphones were on the same plane containing the jet axis and 35 in. away from the jet exit. The nozzles were rotated to carry out measurement on different azimuthal planes (minor axis and major axis planes). The narrowband spectral analysis was performed using a 400-line analyzer (Nicolet 660B), with a bandwidth of 125 Hz (0–50 kHz).

III. Experimental Results: Noise Spectra and Intensities

Results will now be presented to show, first, that subsonic jet noise exhibits almost identical characteristics as the turbulent mixing noise of supersonic jets. The spectra measured in different directions are in good agreement with the TGS similarity spectra [Eqs. (1) and (2)]. In addition, the sound field is axisymmetric, independent of nozzle geometry. For the six-lobe nozzle with highly convoluted geometry, the measured spectra agree with the TGS-2 spectrum at all angles. This observation can be considered as new evidence that there are indeed two components of turbulent mixing noise. Details of these are given subsequently.

Before comparing the experimental data with the TGS spectra and the predictions of the jetlets model in the next section, it is important to assess the quality and plausible error of the data. The present experiments were conducted, due to logistic constraints, in a quasi-anechoic chamber. As stated in Sec. II, although every effort was made to ensure the absence of reflections from the surroundings, there is no assurance that the quality of the data is not somewhat compromised. Data acquisition and analysis were done with the best equipment available. Long time averages were performed in the spectral analysis to ensure good repeatability. However, the spectrum still exhibits small wiggles (ideally, for a stationary random signal, the spectrum is a smooth curve). Small wiggles in jet noise spectrum appear to be unavoidable and are apparently due to residual reflections and other noise sources in the flow. They are found in all published spectra in the literature. Best quality data have wiggles of a magnitude of 0.5–1.0 dB. The present data, generally, have wiggles of a magnitude of 2.0–2.5 dB.

Jet noise data measured in different facilities are known to differ slightly. Tam and Auriault[5] reported that there was a consistent difference of 1–2 dB between the supersonic jet noise data measured at the NASA Langley Research Center[1] and those measured by Tanna et al.[18] at Lockheed. Taking into account all of the factors that could affect the quality of the measured data, it is our estimate that the present data have a probable error of about 2–3 dB. This is not deemed to be excessive, although less error is desirable. This limitation should, however, be borne in mind by readers of this paper.

A. Comparisons with the TGS Similarity Spectra

In Refs. 1, 6, and 7, it was shown that the two TGS similarity spectra are in good agreement with measured supersonic jet noise spectra regardless of jet velocity, temperature, direction of radiation, nozzle configuration, and whether it is a single or coaxial jet. Here the TGS spectra are compared with the subsonic jet noise measured specifically for this purpose. Figure 3 shows a superposition of the TGS similarity spectra and the noise spectra of a 0.5-in.-diam circular jet at Mach 0.93. In Fig. 3, S is the power spectral density scaled to a distance of 100 jet diameters; U_j and D are the jet exit velocity and diameter, respectively; P_{ref} is the reference pressure for the decibal scale; and f is the frequency. At $\theta = 25$ deg (θ is the angle measured from the jet flow direction), there is good agreement between the experimental measurements and the TGS-1 spectrum. Similarly, there is also good agreement between the data and the TGS-2 spectrum at $\theta = 90$ deg. At $\theta = 45$ deg, both the large turbulence structure noise and the fine-scale turbulence noise are important. As shown in Fig. 3, by using a combination of both spectra, it is again possible to produce a good fit to the measured spectrum.

B. Axisymmetric Property of Jet Noise

In his investigation of supersonic jet noise Tam[6] found that the radiated noise field is quite axisymmetric even though the nozzle geometry is highly nonaxisymmetric. It turns out this is also true for subsonic jets. Figure 4 compares the noise spectra of a Mach 0.82,

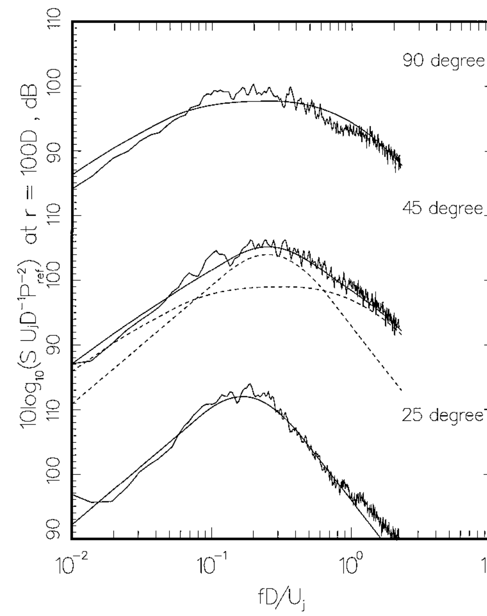

Fig. 3 Comparison of subsonic jet noise spectra with the TGS similarity spectra, $M_j = 0.93, D = 0.50$ in.; smooth curves are the TGS spectra.

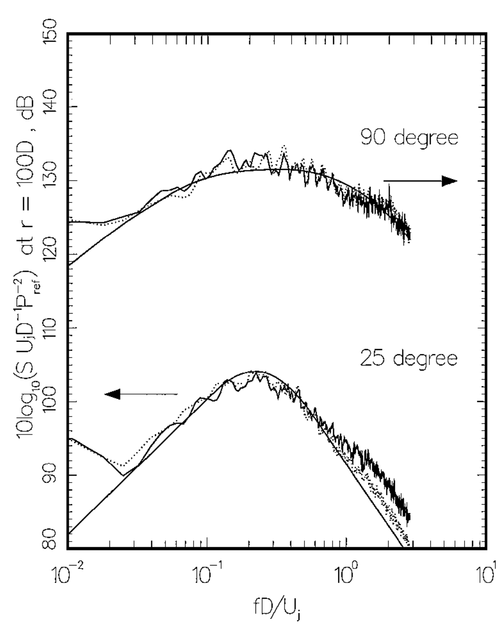

Fig. 4 Noise spectra from aspect ratio 8 rectangular jet, $M_j = 0.82$, $D_{\mathrm{equivalent}} = 0.58$ in.: · · · , major axis plane; ——, minor axis plane; and smooth curves, TGS spectra.

aspect ratio 8 rectangular jet measured in the major and minor axis planes at $\theta = 25$ and 90 deg. It is clear that at each angle the spectra from the two measurement locations are nearly identical so that the sound field is quite axisymmetric. Shown in Fig. 4 also are the TGS similarity spectra. The agreement between the experimental measurements and the empirical spectra is fairly good.

Figure 5 shows a superposition of four jet noise spectra at $\theta = 90$ deg, scaled to a distance of 100 jet diameters, in the major and minor axis planes. The jets are from the circular, the aspect ratio 3 elliptic, and the aspect ratios 3 and 8 rectangular nozzles. It is clear that the four spectra in both the major and minor axis planes are approximately the same. They are also in reasonably good agreement with the TGS-2 spectrum. Figure 6 shows the corresponding spectra measured at $\theta = 25$ deg. Again, irrespective of nozzle geometry, the spectra are nearly identical and are in reasonably good agreement with the TGS-1 spectrum. In Fig. 4, it was shown that the sound field of the aspect ratio 8 rectangular jet is axisymmetric. Taking into account the results of Figs. 4–6, it becomes clear that not only the sound fields are nearly axisymmetric but also they are

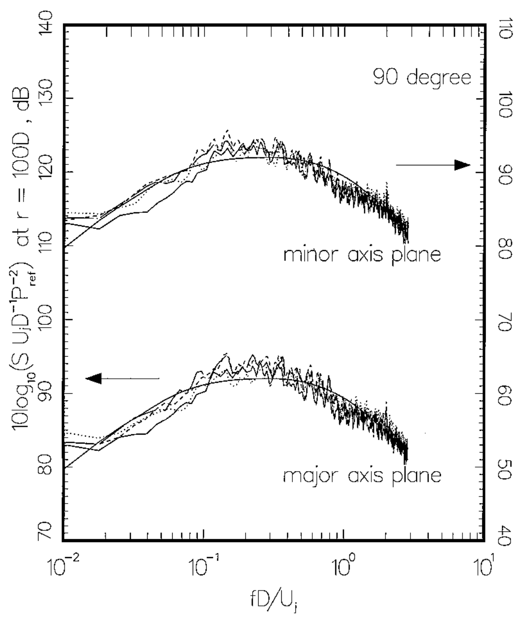

Fig. 5 Comparisons of jet noise spectra from various nozzles, $M_j = 0.82$: ——, axisymmetric; – – –, 3:1 elliptic; – -, 3:1 rectangular; · · ·, 8:1 rectangular; and smooth curves, TGS-2 spectrum.

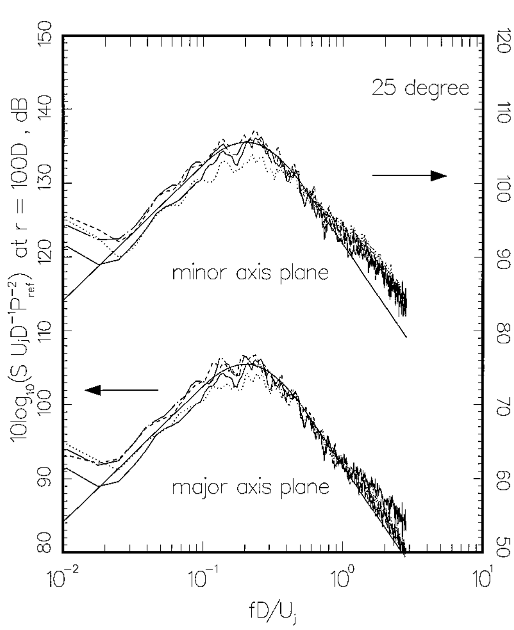

Fig. 6 Comparisons of jet noise spectra from various nozzles, $M_j = 0.82$: ——, axisymmetric; – – –, 3:1 elliptic; – -, 3:1 rectangular; · · ·, 8:1 rectangular; and smooth curves, TGS-1 spectrum.

all nearly the same as that of a circular jet with the same exit area. That is, the radiated noise is quite independent of nozzle geometry, a somewhat unexpected result.

Figure 7 compares the noise spectra of the circular, elliptic, and rectangular jets at Mach 0.93. Here all of the noise spectra at $\theta = 25$ deg are plotted together, and similarly for the spectra at $\theta = 90$ deg. At each angle, they collapse roughly into a single spectrum that is in good agreement with the corresponding TGS spectrum. This set of data provides additional confirmation of the axisymmetric characteristics and the nozzle geometry independence property of the noise field.

In a similar study on supersonic jets, Tam[6] pointed out that, for the noise field to be independent of nozzle geometry, it must be true that all of the jet flows evolve into a more or less identical asymptotic state. Furthermore, the dominant jet noise sources must not be located close to the nozzle exit, but near the end of the potential core, where the flow and turbulence attain the self-similar asymptotic state. In view of the preceding results, this must also be true for subsonic jets. Recently Zaman[19] studied the mass entrainment rates of the jets used in the present investigation. It was found, irrespective of the nozzle geometry, that the jets attained a circular cross section beginning at a few equivalent diameters downstream of the nozzle exit. In the asymptotic region, the mass flow rate was only slightly higher for the nonaxisymmetric jets relative to the axisymmetric case. In other words, the flowfields, as well as the acoustic fields, of these jets were not much different from those of an axisymmetric jet.

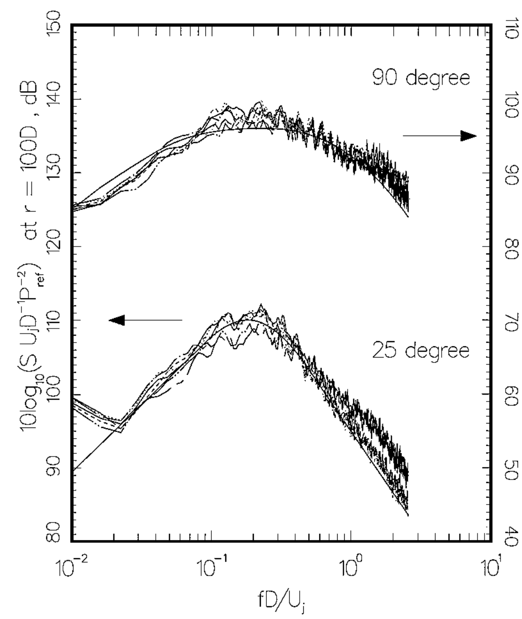

Fig. 7 Data showing axisymmetry of jet noise independent of nozzle geometry, $M_j = 0.93$: ——, 3:1 elliptic nozzle, minor axis plane; – – –, 3:1 elliptic nozzle, major axis plane; – -, 3:1 rectangular nozzle, minor axis plane; · · ·, 3:1 rectangular nozzle, major axis plane; – - –, 8:1 rectangular nozzle, minor axis plane; – · -, 8:1 rectangular nozzle, major axis plane; and smooth curves, TGS spectra.

C. Noise Spectra from the Six-Lobe Nozzle

The six-lobe nozzle was originally designed for mixing enhancement purpose. It represents a highly convoluted nozzle configuration. At the nozzle exit, the jet fluid is discharged in thin sheets into the ambient air. Because of the thin shear layers and the convoluted geometry, the flow apparently does not support large turbulence structures with scales comparable to the equivalent diameter. In other words, the nozzle effectively suppresses the large turbulence structures and their noise.

Figure 8 shows the measured noise spectra of the six-lobe nozzle at Mach 0.93. Shown in Fig. 8 are the spectra at $\theta = 25$, 45, and 90 deg in both the minor and major axis planes. It is clear from the data that the noise field is axisymmetric even though the nozzle is highly nonaxisymmetric. These data suggest that turbulent mixing has the tendency to eliminate azimuthal dependence. This appears to be generally true, at least, for nozzles with two planes of symmetry. Another important new result observed in this set of data is that the noise spectra have the same spectral shape as the TGS-2 spectrum for all angles including those close to the jet axis. For all jets considered so far, including the circular jet, the noise spectrum close to the jet flow direction has the shape of the TGS-1 spectrum. The TGS-1 spectrum is due to noise radiation from the large turbulence structures of the jet flow. The present results not only lend strong evidence that the six-lobe nozzle effectively suppresses the large turbulence structures, but also supports the concept of two independent jet mixing noise sources. When the large-scale structures are suppressed, the noise from the fine-scale turbulence becomes the dominant source of noise in all directions.

Figure 9 gives the noise spectra of the six-lobe nozzle at Mach 0.82. This set of data is included here to provide additional confirmation of the axisymmetry as well as the single mixing noise source characteristics of the sound field of this jet.

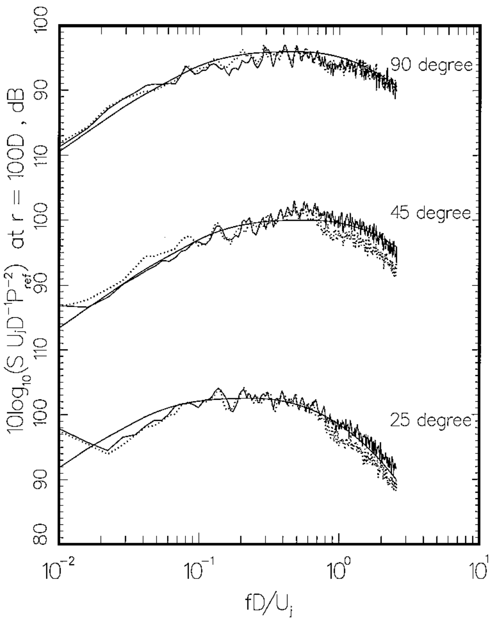

Fig. 8 Noise spectra from the six-lobe nozzle, $M_j = 0.93$: · · · , major axis plane; ——, minor axis plane; and smooth curves, TGS-2 spectrum.

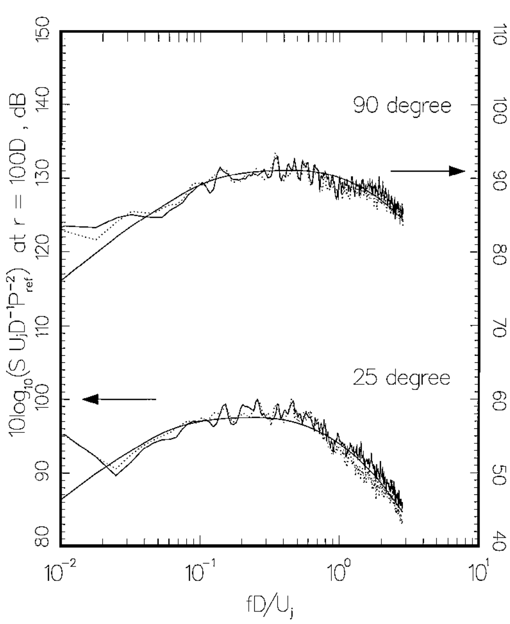

Fig. 9 Noise spectra from the six-lobe nozzle, $M_j = 0.82$: · · · , major axis plane; ——, minor axis plane; and smooth curves, TGS-2 spectrum.

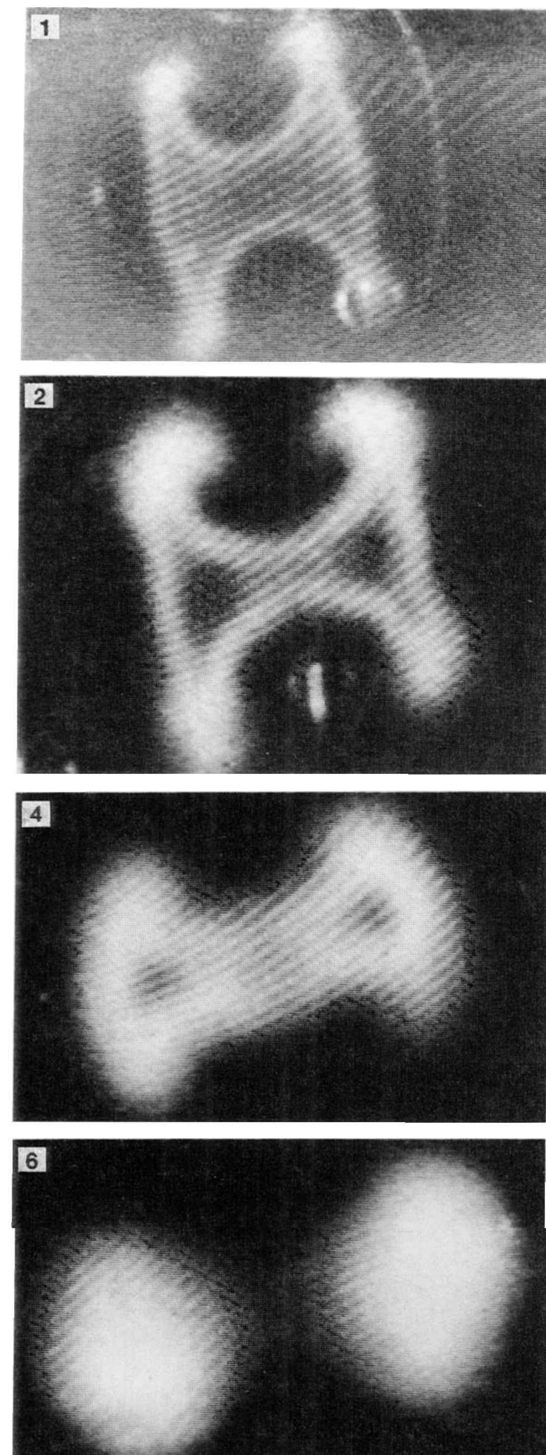

Fig. 10 Laser sheet illuminated cross section of the circular jet with two tabs, at indicated *x/D* locations; $M_j = 1.63$.

IV. Effect of Tabs on Subsonic Jet Noise

The original motivation for inserting tabs into a jet was to promote mixing and reduce noise. Since then, a good deal of understanding on how tabs induce longitudinal vortices, which lead to faster mixing of the jet and ambient fluid, has been obtained. However, little progress has been made in terms of understanding the tabs' effects on jet noise. In the past, most noise studies were carried out on a trial and error basis. They provided no coherent results or insight.

Recent experimental investigations[12–14] have shown that a tab can generate longitudinal vortices on its two sides. For maximum vorticity strength, it has been found experimentally that the optimum shape of the tab is triangular with its base on the nozzle wall and apex tilted downstream. Such tabs have been called delta tabs. The shed vortices of a delta tab usually form a vortex pair by themselves or with the vortices of the adjacent tabs. Depending on the direction of rotation of the vortex pair, fluid may be sucked from the outside into the jet or ejected from the jet into the ambient air.

One important consequence of the longitudinal vortices is that they shear the jet into smaller jets. Figure 10, taken from Ref. 12, illustrates the effect of inserting two tabs into a circular jet on the opposite sides of the diameter. The pictures represent a laser sheet illuminated cross section of the jet at various measurement stations. Close to the nozzle exit, the tabs introduce enormous distortions on the cross section of the jet. As the jet flow evolves downstream, these distortions slowly pinch the jet off into two small jets. When multiple tabs are inserted, similar visual observations indicate that the jet is sheared off into a corresponding number of jetlets.

The delta tabs used in Refs. 12–14 were fairly large. If smaller tabs are used, flow visualizations by Zaman, as well as by others, reveal that a row of jetlets are formed encircling a primary jet. This

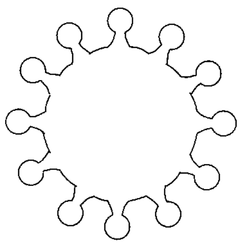

Fig. 11 Cross section of a jet showing the formation of jetlets enclosing a primary jet.

is illustrated schematically in Fig. 11. For each tab, there is a corresponding jetlet; that is, the number of jetlets is the same as the number of tabs. The jetlets, of course, eventually merge downstream. However, the merged jet has low velocity and is not a significant source of noise. The size and shape of the jetlets obviously would depend on the size of the tab. However, at the present time, there are not enough data to develop such a relationship. Generally speaking, as the size of the tabs becomes larger, the jetlets are larger at the expense of the primary jet. When the tabs are larger than a certain size, there is no primary jet. This is the case in Fig. 10.

A. Jetlets Model

In this section, a jetlets model is developed to explain and correlate the measured noise spectra from tabbed jets. The model assumes that the jet is broken up into small jets by the tabs. For each tab (two or more) there is a jetlet, as shown in Figs. 10 and 11. The two principal assumptions of the model are that 1) the velocity of the jetlets as well as the primary jet is the same as the original jet and 2) the jetlets and the primary jet radiate noise as independent jets. There is negligible interference.

These are reasonable assumptions. As an independent jet, each jetlet emits two components of turbulent mixing noise with spectral shapes given by the TGS spectra. The maximum level of the noise spectrum is the same as that of an equivalent circular jet. Note that the cross section of the jetlets may not be circular. However, based on the results of the preceding section, they can be regarded as circular as far as noise characteristics are concerned.

For convenience, in the rest of this section, subscripts J and p will be used to denote physical quantities associated with the jetlets and the primary jet. Quantities without subscripts are used to denote those of the original jet without tabs. Suppose there are N tabs ($N \geq 2$); then the tabbed jet has N jetlets and a primary jet, as shown in Fig. 11. (Note that the case of $N = 1$ is the same as the no-tab case as there is only one jet.) Because the velocity of all of the jets is assumed to be the same, by conservation of mass flux, the areas A, A_J, and A_p are related by

$$A = NA_J + A_p \tag{3}$$

The diameters of the original jet, jetlets, and the primary jet are given, in terms of A and A_p, by

$$D = 2(A/\pi)^{\frac{1}{2}}, \qquad D_p = 2(A_p/\pi)^{\frac{1}{2}}$$

$$D_J = 2[(A - A_p)/N\pi]^{\frac{1}{2}} \tag{4}$$

Now for all independent jets of the same velocity, the Strouhal number at the peak of the noise spectrum is the same. Thus, if f, f_J, and f_p are the frequencies at the peak of the noise spectrum of the original jet, the jetlets, and the primary jet, respectively, they are related by

$$fD/U_j = f_p D_p/U_j = f_J D_J/U_j \tag{5}$$

On combining with Eq. (4), the following relationship can easily be found:

$$f_p/f = (A/A_p)^{\frac{1}{2}} \tag{6}$$

$$\frac{f_J}{f} = \left(\frac{N}{1 - A_p/A}\right)^{\frac{1}{2}} \tag{7}$$

Because $A_p < A$, frequencies f_p and f_J are, therefore, larger than f. In other words, the noise spectrum of the tabbed jet consists of two peaks, one at f_p and the other at f_J, and both are higher than that of the original peak frequency f. That is, the tabs generate high-frequency noise.

Now consider the noise intensity of the tabbed jet. For independent jets, the spectrum level is inversely proportional to the square of the ratio of the observation distance (distance from the jet exit to the measurement point) to the jet diameter. If the observation distance is fixed, the noise level is lower for a jet with smaller diameter. Let S, S_J, and S_p be the peak level of the noise spectrum of the original jet, a jetlet, and the primary jet measured at a fixed observation point in the far field. By the inversed square law, these quantities are related by

$$S_p = S(D_p/D)^2 = S(A_p/A) \tag{8}$$

$$S_J = S(D_J/D)^2 = (S/N)(1 - A_p/A) \tag{9}$$

In the far field, the noise of the tabbed jet is a direct sum of the noise from the primary jet and the N jetlets. Therefore, on assuming that the two peaks are well separated, the peak level at f_p is given by Eq. (8); whereas at f_J, the peak level is given by N times S_J of Eq. (9), or

$$NS_J = S(1 - A_p/A) \tag{10}$$

Because $A_p < A$, both peak levels are lower than the peak level of the original jet.

In summary, if a primary jet exists, the noise spectrum of a tabbed jet will consist of two peaks, one at f_p and the other at f_J. These frequencies are higher than the frequency at the peak level of the original jet without tabs. Furthermore, the peak levels are given by formulas (8) and (10). Both levels are lower than the original peak level S. However, all of the peaks would have the same shape as the corresponding TGS spectrum.

When large delta tabs are used, there will be no primary jet; that is, $A_p \to 0$. In this case $f_p \to \infty$ and the noise spectrum of the tabbed jet has a single peak. The frequency at the spectrum peak is given by setting $A_p = 0$ in Eq. (7). This gives

$$f_J = N^{\frac{1}{2}} f, \qquad N = 2, 3, \ldots, 6 \tag{11}$$

In other words, the peak frequency and, hence, the entire spectrum shifts up by a factor of $N^{1/2}$. Similarly, the level at the spectrum peak is obtained by setting $A_p = 0$ in Eq. (10). This gives

$$NS_J = S \tag{12}$$

Thus, the peak level remains the same irrespective of the number of tabs.

B. Comparisons with Experiments

Formulas (11) and (12) are for jets with large delta tabs. These formulas can be easily verified experimentally. Figure 12 provides a direct comparison between the noise spectra of a 0.5-in.-diam jet at Mach 0.92 and that of a similar jet fitted with four delta tabs. According to formulas (11) and (12), the two sets of noise spectra should collapse together if the data are plotted as functions of $f_p/(N^{1/2}U_j)$. (The no-tab case is given by $N = 1$.) As can be seen, there is a good collapse of the noise spectra at both $\theta = 90$ and 45 deg. At these angles, the two spectra are nearly on top of each other. At $\theta = 25$ deg, the peaks of the spectra are almost aligned vertically indicating that the frequency shift formula (11) is correct. The peak level is, however, lower for the tabbed jet. The exact cause of this deviation is not known. One possible contributing factor is that the tabs somehow suppress the intensity of the large turbulence structures of the jetlets. This leads to a reduction in the noise radiated in the downstream direction. Further investigation is required to check whether this is indeed the reason.

Figure 13 contains six jet noise spectra at $\theta = 90$ deg. The jets are of 0.5-in. diameter operating at Mach 0.92. The jets have two to six tabs. The spectrum of the jet without tabs is also included. The spectra are plotted as functions of $fD/(N^{1/2}U_j)$. According

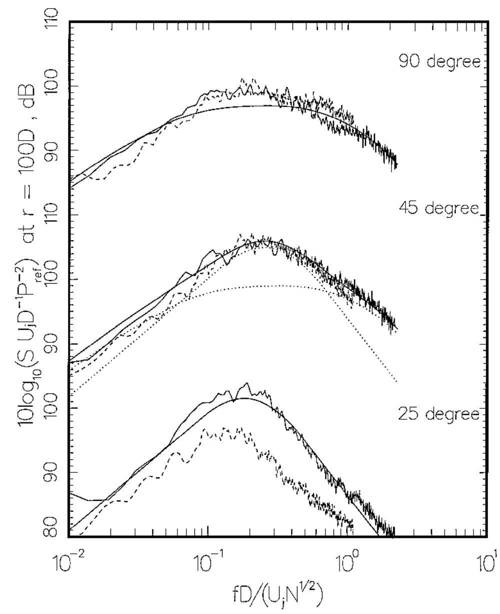

Fig. 12 Noise spectra from tabbed circular nozzles, $M_j = 0.92$, N = number of tabs: ——, no tab (same as $N = 1$); – – –, $N = 4$; and smooth curves, TGS spectra.

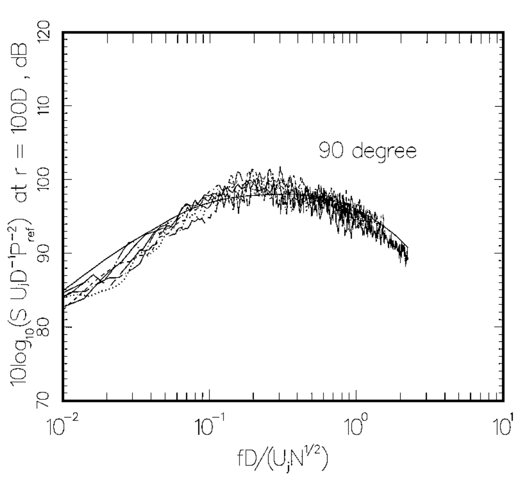

Fig. 13 Noise spectra from tabbed circular nozzles, $M_j = 0.92$, N = number of tabs: ——, no tab (same as $N = 1$); – – –, $N = 2$; – –, $N = 3$; · · · , $N = 4$; – – –, $N = 5$; – · –, $N = 6$; and smooth curve, TGS-2 spectrum.

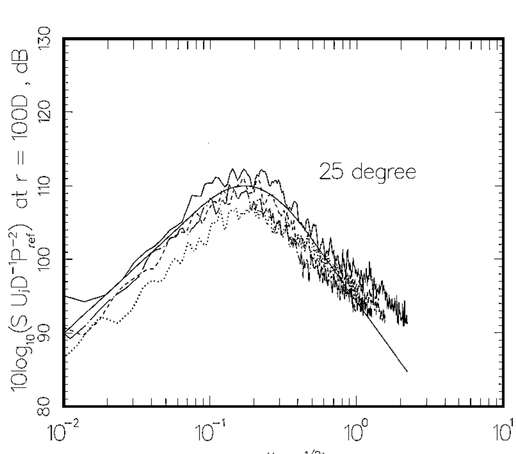

Fig. 14 Noise spectra from tabbed circular nozzle, $M_j = 0.92$, N = number of tabs: ——, no tab (same as $N = 1$); – – –, $N = 2$; – –, $N = 3$; · · · , $N = 4$; and smooth curve, TGS-1 spectrum.

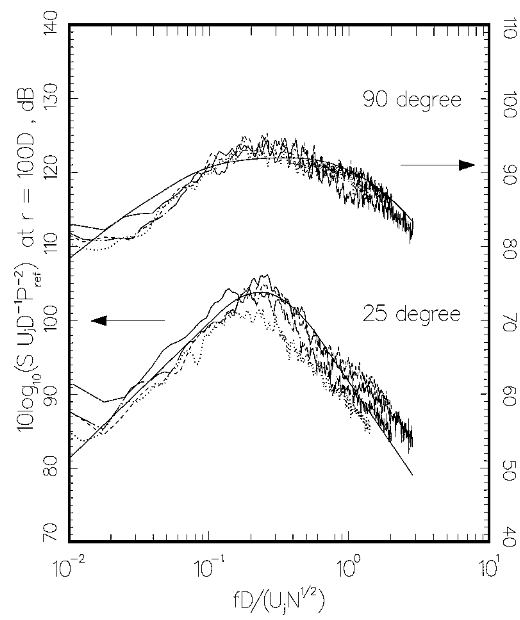

Fig. 15 Noise spectra from tabbed circular nozzles, $M_j = 0.82$, N = number of tabs: ——, no tab (same as $N = 1$); – – –, $N = 2$ (minor axis plane); – –, $N = 2$ (major axis plane); · · · , $N = 4$; and smooth curves, TGS spectra.

to formulas (11) and (12) all of the spectra should collapse into the TGS-2 spectrum. As can be seen, there is indeed a fairly good collapse and reasonably good agreement with the TGS-2 spectrum. Figure 14 is a similar plot at $\theta = 25$ deg. It appears that the data follow the frequency shift formula (11). However, the level is reduced as the number of tabs is increased. The reason for the reduction in the noise level is again not fully understood at this time.

Figure 15 contains additional data on the effect of tabs. The spectra from the no-tab, two-tab and four-tab jets at $\theta = 90$ deg nearly collapse into a single curve as in Fig. 13. At $\theta = 25$ deg, again the frequency shift is in fair agreement with formula (11), but the noise level does reduce somewhat by the tabs, as observed in Fig. 14.

V. Conclusions

Experimental data are presented to show that the noise spectra from subsonic jets are in good agreement with the TGS similarity spectra. Furthermore, for jets from nonaxisymmetric nozzles with two planes of symmetry and small thrust loss, the radiated sound field is axisymmetric. The sound intensity is the same as that of an equivalent circular jet (same nozzle exit area). In other words, nozzle geometry modification into simple elliptic or rectangular shape is not an effective way to suppress jet noise. These conclusions are consistent with those found for supersonic jets.

The noise spectra from a six-lobe nozzle reveal that the spectrum of noise radiated to all directions has the shape of the TGS-2 spectrum. This suggests that the large-scale turbulence structures are suppressed in this flow. This also supports the original proposal of Tam et al.[1] that there are two seemingly independent components of jet mixing noise. In the absence of noise radiation from the large turbulence structures of the jet flow, the observed noise must come from the fine-scale turbulence and has the same shape as the TGS-2 spectrum.

In this study, a jetlets model is developed to correlate the jet noise data from tabbed nozzles. The model predicts that for nozzles with large tabs the radiated noise spectrum can be obtained from that of the original jet without tab by a simple frequency shift involving a multiplication factor of $N^{1/2}$, where N ($N \geq 2$) is the number of tabs. This prediction is in good agreement with experiments for the fine-scale turbulence noise. The frequency shift is also in good agreement with measured noise data for noise from the large turbulence structures. The observed level for the noise from the large turbulence structures, however, is slightly reduced; the reduction is larger for a larger number of tabs. The reason for this reduction is not fully understood. One clear result is that the tabs increase the frequency of jet noise. Thus, by choosing the size, geometry, and the number of tabs appropriately, it may be possible to tailor the noise spectrum of a tabbed jet. In this way, one could influence the perceived noise level of the jet (in PNdB). For actual aircraft engine exhaust jets, this result seems to suggest that tabs could increase the A-weighted noise level of jet engines on moderate-size aircrafts. However, for small jet engines, the spectra may be displaced to the point where atmospheric absorption helps significantly to reduce the perceived noise level.

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