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# Influence of Nozzle Geometry on the Noise of High-Speed Jets

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**The effectiveness of jet noise reduction by the use of different nozzle exit geometry is examined. Because there will be thrust loss associated with a nozzle of complex geometry, consideration is confined to practical configurations with reasonably small thrust loss. Only jets with a single stream are considered. The nozzle configurations examined are circular, elliptic, and rectangular. Plug nozzles as well as a suppressor nozzle are included. It is shown that the measured turbulent mixing noise of the jets from these nozzles consists of two independent components. The noise spectrum of each component is found to fit the shape of a seemingly universal similarity spectrum. It is also found that the maximum levels of the fitted noise power spectra of the jets are nearly the same. This finding suggests that nozzle geometry modification may not be an effective method for jet noise suppression.**

## I. Introduction

REDUCING high-speed jet noise is currently a high-priority research and development effort of the aircraft industry. Despite many years of jet noise research, noise reduction is a highly empirical endeavor. Since the early work of Westley and Lilley,[1] many attempts have been made to modify the shape of the nozzle exit in the belief that this would reduce the turbulence intensity of the jet, leading to a reduction in the radiated noise. On following this concept, plug nozzles and corrugated nozzles, as well as nozzles with multichute elements, have been introduced for noise suppression purpose.

The objective of this paper is to examine the effectiveness of jet noise reduction by nozzle exit geometry modification. Of course, there will be thrust loss in using a nozzle with complex geometry. Our consideration is, therefore, confined to practical geometries for which the thrust loss is reasonably small. To focus attention on nozzle geometry alone, we will only consider jets formed by a single stream. Multistream jets, invariably, would introduce thermodynamic and other flow parameters as variables. Under this circumstance, a simple statement on the effectiveness of nozzle configuration for noise suppression cannot be easily made.

Recently, Tam et al.[2] performed an in-depth study of the noise spectra from circular supersonic jets. They found that the turbulent mixing noise from these jets consisted of two independent components. One component is generated by the large turbulence structures of the jet flow in the form of Mach wave radiation. This component radiates primarily in the downstream direction. It is the dominant noise component of supersonic jets in the downstream direction. The other component is generated by the fine-scale turbulence of the jet flow. It is the dominant noise component on the sideline and in the upstream direction. Tam et al.[2] discovered empirically that the noise power spectrum of each of these two noise components fitted a self-similar spectrum. In this work, it will be shown that the measured turbulent mixing noise from a variety of nozzles also consists of two components. Further, the noise power spectrum of each component is found to fit the corresponding similarity spectrum developed by Tam et al.[2] This finding is important because it provides a simple way to compare the noise levels of jets issued from nozzles of different configurations. In this way, the effectiveness of nozzle geometry as a method for jet noise suppression can be evaluated.

In Sec. II of this paper, the effect of nozzle geometry on the turbulent mixing processes in jets is discussed. For high-speed jets, the mixing process is influenced only by upstream events. Thus, the normal expectation is that the nozzle exit configuration would exert considerable influence on the development of the large- and fine-scale turbulence of the jet flow and, hence, its noise. In Sec. III, turbulent mixing noise data from a variety of nozzles is examined and analyzed. It is shown that the noise level is, to a large extent, insensitive to the nozzle shape. This is true even for jets embedded in open wind-tunnel flows simulating forward flight effects. This result seems to suggest that modification of a nozzle exit configuration may not be an effective method for noise suppression.

## II. Nozzle Geometry as an Initial Condition

Tam and Chen,[3] based on their observation of the noise directivity and spectrum measurements of Seiner et al.,[4] were the first to clearly suggest that turbulent mixing noise from high-speed jets is made up of two components. One component is in the form of Mach wave radiation generated by the large turbulence structures of the jet flow. This component radiates only in the downstream direction. The other component is generated by the fine-scale turbulence of the jet. The radiated noise has a more uniform directivity. Experimental confirmation of the existence of the two noise components was not available until the recent investigation of Tam et al.[2] By analyzing the entire data bank of axisymmetric jet noise spectra measured in the Jet Noise Laboratory of NASA Langley Research Center, they were able to extract the shapes of two self-similar spectra from the data. They then demonstrated that all of the noise spectra were made up of a combination of the two similarity spectra. Let $S$ be the noise power spectrum ($S$ has the dimensions of pressure squared per unit frequency), then $S$ can be expressed in the following similarity form:

$$S = [AF(f/f_L) + BG(f/f_F)](D_j/r)^2 \quad (1)$$

where $F(f/f_L)$ and $G(f/f_F)$ are the similarity spectra of the large turbulence structure noise and the fine-scale turbulence noise, respectively; $f_L$ is the frequency at the peak of the large turbulence structures noise spectrum; and $f_F$ is the frequency at the peak of the fine-scale turbulence noise spectrum. The spectrum functions are normalized such that $F(1) = G(1) = 1$. Figure 1 shows the shape of these spectrum functions as found by Tam et al.[2] In Eq. (1), $A$ and $B$ are the amplitudes of the independent spectra. They have the same dimensions as $S$. $D_j$ is the fully expanded jet diameter, and $r$ is the distance between the noise measurement point and the nozzle exit. The amplitudes $A$ and $B$ and the peak frequencies $f_L$ and $f_F$ are functions of the jet operating parameters $v_j/a_\infty$, $T_r/T_\infty$, and the direction of radiation $\chi$ (measured from the jet inlet). Also, $v_j$ and $a_\infty$ are the jet velocity and the ambient sound speed and $T_r$ and $T_\infty$ are the reservoir and ambient temperature. One remarkable feature of the similarity spectra is that they fit the data well regardless of jet velocity, jet temperature, direction of radiation, and whether the jet is perfectly or imperfectly expanded (in the case of supersonic jets). These spectra are used extensively in the present investigation.

What motivated Tam et al.[2] to look for the similarity noise spectra was the recognition that at high Reynolds number molecular viscosity is not a relevant parameter. As a result, there is no intrinsic

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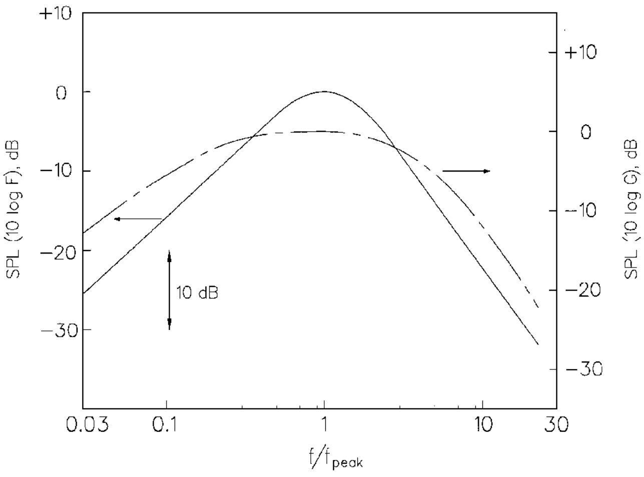


**Fig. 1 Similarity spectra for the two components of turbulent mixing noise: ——, large turbulence structure noise, and —·—, fine scale turbulence noise.**

length and timescales in the mixing layer (in the core region) of high-speed jets. In the absence of length and time scales, in addition to the mean flow profile and the turbulence statistics, the radiate noise spectra also must exhibit self-similarity. Extensive instability wave calculations indicate that the wave amplitudes peak near the end of the potential core of the jet. Thus, one expects the dominant part of the Mach wave radiation is generated there. On the other hand, fine-scale turbulence is produced by the large turbulence structures. It follows, therefore, most of the fine-scale turbulence noise is also generated in the jet mixing layer near the end of the core of the jet. In other words, the dominant sources of high-speed jet noise are located near the end of the potential core of the jet.

In high-speed jet flows, there is practically very little upstream influence. Thus, the turbulence level near the end of the core region is affected primarily by the mixing processes upstream and the conditions at the nozzle exit. From this point of view, the nozzle geometry may be regarded as an initial condition on the spatial evolution of the jet velocity profile and the turbulence intensity and spectral content downstream. For noise suppression purposes, the crucial question to ask is how sensitive the turbulence level of the jet flow near the end of the potential core is to the initial condition at the nozzle exit. There is no question that, by changing nozzle geometry, the entrainment flow and, hence, jet turbulence in the region immediately downstream of the nozzle exit are affected. However, turbulent mixing is a highly nonlinear process. As is known, a nonlinear process can lead to the same asymptotic state regardless of initial conditions. (For a discussion of the lack of influence of initial conditions on self-similar turbulent flows, see the work of Tam and Chen.[5]) For high Reynolds number jet flows, it is possible that a jet issued from a noncircular nozzle evolves quickly into a more or less axisymmetric jet before the end of the core is reached. In such a case, the radiated noise would be similar to that of a circular jet both in intensity and spectral content. Now, one can design a nozzle of unusual shape to alter the turbulence level at the noise-producing region. But such a jet would probably incur significant thrust loss and is, therefore, not practical. The point here is that nozzle geometry of limited thrust loss may only exert very limited influence on the state of turbulence near the end of the potential core. When this is true, nozzle geometry modification would not be an effective method for noise suppression. In the next section, it will be shown that this appears to be the case.

## III. Evaluation and Comparisons of Data

Supersonic jet noise data from two sources are used. The first set of data is taken from the data bank of the Jet Noise Laboratory of NASA Langley Research Center. This set of data consists of noise spectra from a Mach 2, aspect ratio 3, elliptic jet and a Mach 2, aspect ratio 7.6, rectangular jet. These are high-quality data, comparable to those used in the work of Tam et al.[2]

The second set of data is taken from the published measurements of Yamamoto et al.[6] In this series of experiments, six nozzles are used. They are a conical nozzle, a convergent–divergent (C–D) round nozzle, a convergent annular plug nozzle, a C–D annular plug nozzle, a 20-chute annular plug suppressor nozzle with convergent flow segment terminations, and a 20-chute annular plug suppressor nozzle with C–D flow element terminations. The noise spectra of the jet from the fifth nozzle, however, are strongly different from the same configuration suppressor nozzle but with C–D flow element terminations and the other nozzles. Without knowing the cause of the difference, it is decided to ignore the data associated with this nozzle.

The Yamamoto et al.[6] data are recorded in one-third octave band at a 40-ft arc. During the present investigation, they are all converted to narrow band (decibel per hertz) and rescaled to a distance of $100D_j$. The data contain screech tones and broadband shock associated noise.[7] In our data analysis, the screech tones are ignored. The broadband shock-associated noise is unimportant in the downstream direction. Around the 90-deg direction it forms a relatively easy to recognize spectral peak. The presence of such a peak has not caused any difficulty in our data evaluation effort. More problematic about this set of data is that they appear to be contaminated by facility noise below a frequency of 400 Hz. Accordingly, we place no significance on the data in this low-frequency range. It is also found that the microphone data at inlet angle $\chi = 160$ deg might have been affected by instrumentation blockage. To assure that the data analyzed are of reasonable quality, we use the measurements at $\chi = 150$ deg for evaluating the noise from the large turbulence structures of the jets.

### A. Comparisons with Similarity Noise Spectra

Figure 2 shows direct comparisons between the measured elliptic and rectangular jet noise spectra at Mach 2 and $T_r/T_\infty = 1.8$ from the NASA Langley Research Center and the similarity spectrum for the large turbulence structures noise of Tam et al.[2] at $\chi = 150$ deg. The elliptic jet noise data are measured on three planes containing the jet axis. One is on the minor axis plane, one on a plane at 58 deg to the minor axis plane, and the third on the major axis plane. They

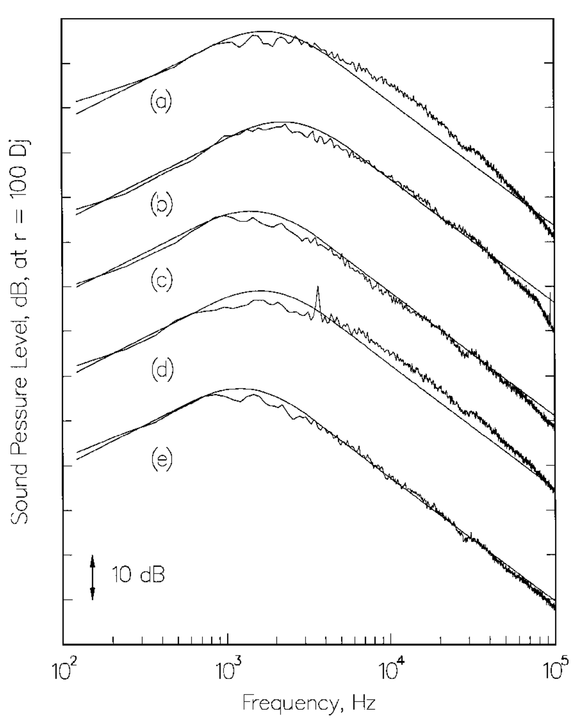


**Fig. 2 Comparisons between elliptic and rectangular jet noise data and the similarity spectrum at $\chi = 150$ deg, $T_r/T_\infty = 1.8$, $M_{jet} = 2.0$: a) minor axis plane, aspect ratio 3 elliptic jet; b) 58-deg plane, aspect ratio 3 elliptic jet; c) major axis plane, aspect ratio 3 elliptic jet; d) minor axis plane, aspect ratio 7.6 rectangular jet; and e) major axis plane, aspect ratio 7.6 rectangular jet.**

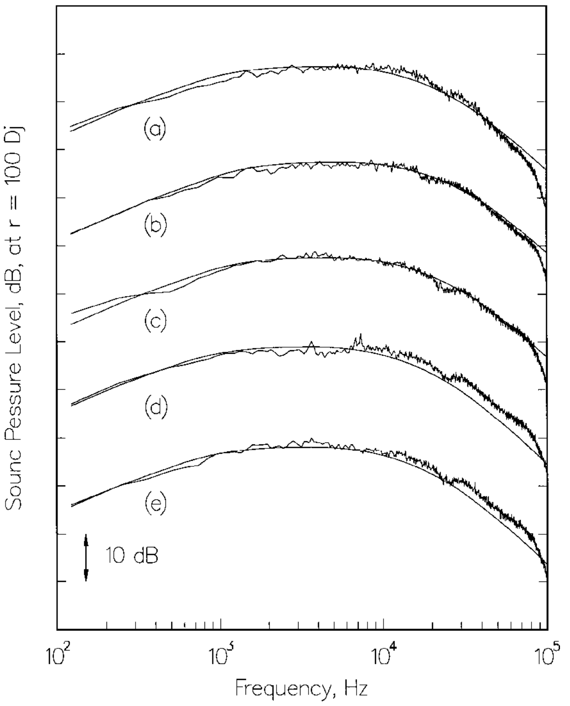


**Fig. 3 Comparisons between elliptic and rectangular jet noise data and the similarity spectrum at $\chi$ = 90 deg, $T_r/T_\infty$ = 1.8, $M_{\text{jet}}$ = 2.0: a) minor axis plane, aspect ratio 3 elliptic jet; b) 58-deg plane, aspect ratio 3 elliptic jet; c) major axis plane, aspect ratio 3 elliptic jet; d) minor axis plane, aspect ratio 7.6 rectangular jet; and e) major axis plane, aspect ratio 7.6 rectangular jet.**

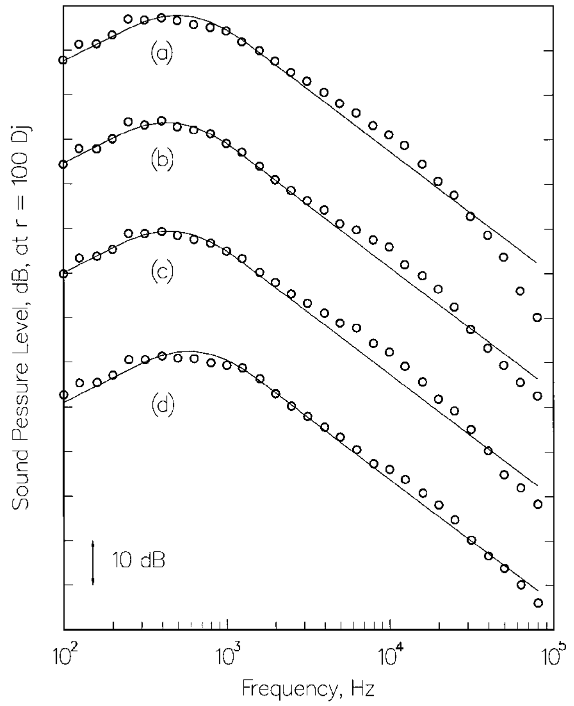


**Fig. 4 Comparisons between Yamamoto et al.[6] data and the similarity spectrum, $V_j \simeq$ 2420 ft/s, $T_r \simeq$ 1715°R, $\chi$ = 150 deg; ○, data, and ——, similarity spectrum: a) C–D nozzle, b) convergent plug nozzle, c) C–D plug nozzle, and d) 20-chute C–D suppressor nozzle.**

are the top three curves in Fig. 2. The bottom two curves are from the rectangular jet noise data measured on the minor and major axis planes. As can be seen, there is good agreement between the measured spectrum shapes and the similarity noise spectrum [the $F(f/f_L)$ function of Eq. (1)]. This is so despite the very different nozzle geometries.

Comparisons between the measured spectra at $\chi = 90$ deg and the similarity noise spectrum or the fine-scale turbulence noise [the $G(f/f_F)$ function of Eq. (1)] for the elliptic and rectangular jets are given in Fig. 3. Again, the top three curves are those of the elliptic jet, and the bottom two curves are of the rectangular jet measured on the same azimuthal planes as in Fig. 2. It is evident that there is good agreement overall, regardless of nozzle shapes.

Figure 4 shows the noise spectrum shapes of the Yamamoto et al.[6] data at $\chi = 150$ deg. The jet velocity in each case is very close to 2420 ft/s, and the total temperature is approximately 1715°R. The four spectra are (from the top down) from the C–D round nozzle, the convergent annular plug nozzle, the C–D annular plug nozzle, and the 20-chute annular suppressor nozzle. The data from the conical nozzle are nearly the same as the C–D round nozzle and are, therefore, not displayed. The full curves are the similarity noise spectrum [the $F(f/f_L)$ function] of Tam et al.[2] On ignoring the very low-frequency part of the noise spectrum, it is clear that the agreement between the measured data and the similarity spectrum is good for all of the cases.

Figure 5 shows similar comparisons as in Fig. 4 but at $\chi = 90$ deg. By comparing the several spectra shown, the facility noise contamination at low frequencies can be readily detected. The full curves are the similarity spectrum given by the $G(f/f_F)$ function. Overall, there is again good fit between the data and the similarity spectrum.

In the Yamamoto et al.[6] experiments, forward flight effects are simulated by embedding the jet in an open wind tunnel. With forward flight, the noise level in the aft quadrant is reduced. Figure 6 shows the measured spectra at $\chi = 140$ deg and wind-tunnel speed of 400 ft/s. The jet operating conditions are the same as in Fig. 4. The full curves are again the similarity spectrum for the large turbulence structures noise. Clearly, there is good agreement between the full curves and the data, even though there is simulated forward flight. Comparisons at $\chi = 90$ deg are given in Fig. 7. The agreement

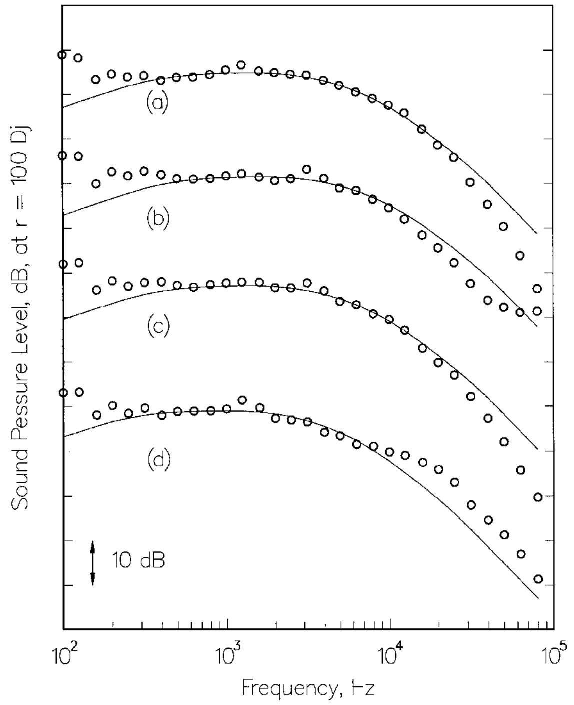


**Fig. 5 Comparisons between Yamamoto et al.[6] data and the similarity spectrum, $V_j \simeq$ 2420 ft/s, $T_r \simeq$ 1715°R, $\chi$ = 90 deg; ○, data, and ——, similarity spectrum: a) C–D nozzle, b) convergent plug nozzle, c) C–D plug nozzle, and d) 20-chute C–D suppressor nozzle.**

between the shapes of the measured spectra and the $G(f/f_F)$ function is about as good as in the case without simulated forward flight.

In addition to the data shown in Figs. 2–7, the noise spectra from the various nozzles at a lower jet velocity and temperature with and without simulated forward flight effects have also been found to fit the similarity noise spectra well. That good agreements are found strongly suggests that the turbulent mixing noise from all these jets must consist of two components: one from the large turbulence

Table 1 Elliptic jet (aspect ratio 3, $M_j = 1.98$)

| Value at indicated $T_r/T_\infty$ | $\chi = 90$ deg | | | | $\chi = 141$ deg | | | | Measurement plane |
|---|---|---|---|---|---|---|---|---|---|
| | 1.00 | 1.37 | 1.80 | 2.27 | 1.00 | 1.37 | 1.80 | 2.27 | |
| $SPL_{max}$ | 74.3 | 75.5 | 77.0 | —— | 96.8 | 99.5 | 101.7 | —— | Minor axis plane |
| at $r = 100D_j$, | 74.3 | 75.7 | 76.8 | 78.3 | 96.1 | 98.8 | 100.3 | 101.3 | 58-deg plane |
| dB/Hz | 74.5 | 75.5 | 77.0 | 78.6 | 94.4 | 97.5 | 101.7 | 101.7 | Major axis plane |
| | 75.5 | 76.2 | 77.3 | 78.5 | 97.3 | 99.3 | 100.7 | 102.1 | Circular jet |

Table 2 Rectangular jet (aspect ratio 7.6, $M_j = 2.0$)

| Value at indicated $T_r/T_\infty$ | $\chi = 90$ deg | | | $\chi = 150$ deg | | | Measurement plane |
|---|---|---|---|---|---|---|---|
| | 1.10 | 1.82 | 2.26 | 1.10 | 1.82 | 2.26 | |
| $SPL_{max}$ | 74.9 | 76.9 | 77.5 | 98.5 | 102.1 | 102.4 | Minor axis plane |
| at $r = 100D_j$, | 74.9 | 75.9 | 77.0 | 98.1 | 100.2 | 100.6 | Major axis plane |
| dB/Hz | 76.0 | 77.7 | 78.8 | 98.4 | 101.5 | 102.6 | Circular jet |

Table 3 Yamamoto et al.[6] data: $v_j \simeq 2420$ ft/s, $T_r \simeq 1715°R$

| Nozzle type | Conical nozzle | C–D nozzle $M_d = 1.4$ | Convergent plug nozzle | C–D plug nozzle | Suppressor nozzle | Inlet angle $\chi$, deg |
|---|---|---|---|---|---|---|
| $SPL_{max}$ at | 98.8 | 97.7 | 98.7 | 99.0 | 97.4 | 150 |
| $r = 100D_j$, dB/Hz | 77.6 | 75.0 | 76.6 | 77.2 | 74.5 | 90 |

Table 4 Yamamoto et al.[6] data: $v_j \simeq 1720$ ft/s, $T_r \simeq 870°R$

| Nozzle type | C–D nozzle $M_d = 1.4$ | Convergent plug nozzle | C–D plug nozzle | Suppressor nozzle | Inlet angle $\chi$, deg |
|---|---|---|---|---|---|
| $SPL_{max}$ at | 95.0 | 96.2 | 97.1 | 92.5 | 150 |
| $r = 100D_j$, dB/Hz | 70.3 | 73.0 | 74.0 | 70.0 | 90 |

Table 5 Yamamoto et al.[6] data: $v_j \simeq 2420$ ft/s, $T_r \simeq 1715°R$, $v_f = 400$ ft/s

| Nozzle type | Conical nozzle | C–D nozzle $M_d = 1.4$ | Convergent plug nozzle | C–D plug nozzle | Suppressor nozzle | Inlet angle $\chi$, deg |
|---|---|---|---|---|---|---|
| $SPL_{max}$ at | 95.5 | 95.0 | 96.6 | 97.0 | 93.5 | 150 |
| $r = 100D_j$, dB/Hz | 72.5 | 72.6 | 73.6 | 74.0 | 70.0 | 90 |

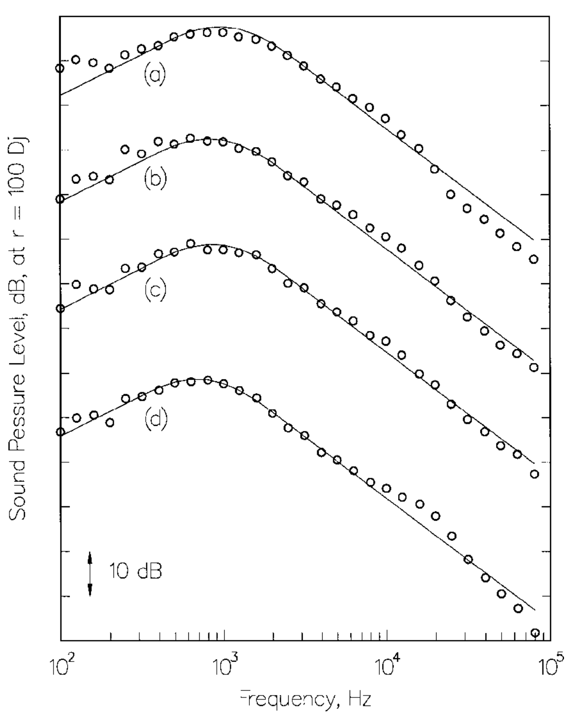


**Fig. 6 Comparisons between Yamamoto et al.[6] data with simulated forward flight and the similarity spectrum, $V_j \simeq 2420$ ft/s, $T_r \simeq 1715°R$, $V_f = 400$ ft/s, $\chi = 140$ deg; ○, data, and ——, similarity spectrum: a) C–D nozzle, b) convergent plug nozzle, c) C–D plug nozzle, and d) 20-chute C–D suppressor nozzle.**

Table 6 Yamamoto et al.[6] data: $v_j \simeq 1720$ ft/s, $T_r \simeq 870°R$, $v_f = 400$ ft/s

| Nozzle type | C–D nozzle $M_d = 1.4$ | Convergent plug nozzle | C–D plug nozzle | Inlet angle $\chi$, deg |
|---|---|---|---|---|
| $SPL_{max}$ at | 89.0 | 88.8 | 90.5 | 150 |
| $r = 100D_j$, dB/Hz | 65.0 | 68.5 | 68.4 | 90 |

structures and the other from the fine-scale turbulence. It may not be surprising that the noise generation mechanisms of all of the jets are the same. However, what is remarkable is that the shapes of their noise spectra are not much different from those of a simple circular jet and that the similarity noise spectra of Tam et al.[2] are far more universal than one would first believe.

### B. Comparisons of Maximum Sound Pressure Levels

To assess whether nozzle geometry has significant influence on high-speed jet noise, we compare the sound pressure levels at the peaks of the fitted noise spectra, ($SPL_{max}$), in decibels per hertz at $r = 100D_j$ from the various jets with the level of the simple circular C–D nozzle (same equivalent diameter $D_j$). The results are shown in Tables 1–6.

Table 1 compares the $SPL_{max}$ of the elliptic jet at temperature ratio ($T_r/T_\infty$) of 1.0, 1.37, 1.80, and 2.27 at jet Mach number 1.98 with the corresponding values of a circular jet. We have chosen the microphone measurements at $\chi = 141$ deg to characterize the large turbulence structures noise component and the microphone measurements at $\chi = 90$ deg to characterize the fine-scale turbulence noise component. The first row of data is measured in the minor axis plane. The second row is measured in a plane at 58 deg to the minor

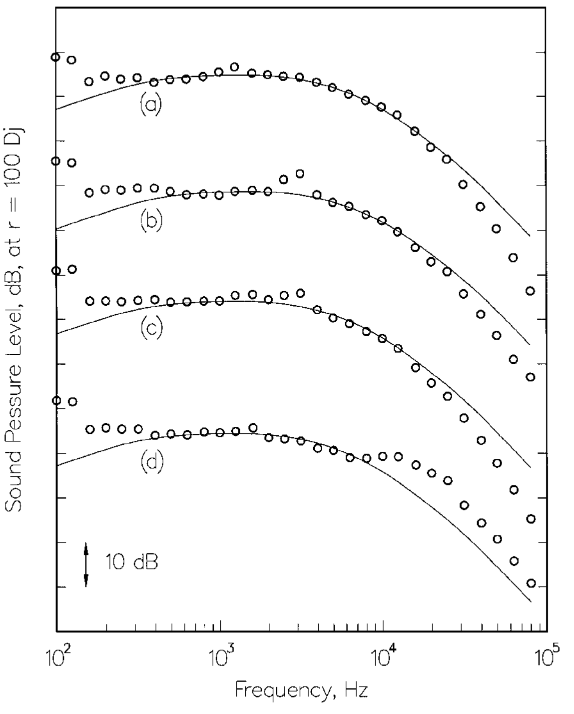


**Fig. 7 Comparisons between Yamamoto et al.[6] data with simulated forward flight and the similarity spectrum, $V_j \simeq$ 2420 ft/s, $T_r \simeq$ 1715°R, $V_f$ = 400 ft/s, $\chi$ = 90 deg; ○, data, and ——, similarity spectrum: a) C–D nozzle, b) convergent plug nozzle, c) C–D plug nozzle, and d) 20-chute C–D suppressor nozzle.**

axis plane. The third row is measured in the major axis plane. The last row is the data from a circular jet at the same jet velocity and total temperature. Within experimental uncertainty, it is clear from Table 1 that the noise from the elliptic jet is, first of all, quite axisymmetric. Further, it is nearly the same as the circular jet. Table 2 provides direct comparisons between the $SPL_{max}$ of the rectangular jet and a circular jet. Again, within experimental uncertainty, there is very little difference in the noise levels.

Tables 3–6 show the $SPL_{max}$ data at $\chi = 150$ and 90 deg for the various nozzles of the Yamamoto et al.[6] experiments. The jet operating conditions with and without simulated forward flight are listed. The data are converted from one-third octave band measurements and possibly slightly contaminated by shock and facility noise. The experimental uncertainty could be as large as 2–3 dB by our estimate. By comparing all of the data with those of the C–D nozzle, it is evident that the differences are well within the experimental uncertainty. Thus, in spite of the large differences in nozzle geometry, the noise from supersonic jets is remarkably the same. Based on these results, it is possible to surmise that nozzle exit geometry may not have significant control over the noise of high-speed jets.

## IV. Conclusion

Extensive comparisons between the noise radiated by supersonic jets operating at various temperatures and velocities with and without simulated forward flight and the noise from a circular jet at the same conditions have been carried out. Seven nozzles of practical geometries are included in the study. It is found that, regardless of nozzle geometry, turbulent mixing noise of all of the jets is composed of two components. One component is the noise from the large turbulence structures and the other is noise from the fine-scale turbulence of the jet flow. Further, the radiated sound is largely axisymmetric, and the shapes of the spectra of the two noise components are nearly the same as those of previously studied spectra. In addition, the noise levels are essentially independent of nozzle configuration. Based on these results, it is concluded (bearing in mind the limited scope of this study) that nozzle geometry modification may not be an effective method for jet noise suppression.

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