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THE EFFECT OF NOZZLE GEOMETRY ON THE NOISE OF HIGH-SPEED JETS

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ABSTRACT

This paper examines the effectiveness of jet noise reduction by the use of different nozzle exit geometry. Since there will be thrust loss associated with a nozzle of complex geometry, consideration is confined to practical configurations with reasonably small thrust loss. In this study, only jets with a single stream are considered. The nozzle configurations examined are circular, elliptic and rectangular. Included also are plug nozzles as well as a suppressor nozzle. 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.

1. 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 Westly 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, corrugated nozzles as well as nozzles with multi-chute 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. In order to focus attention on nozzle geometry alone, we will only consider jets formed by a single stream. Multi-stream 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.

In Section 2 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 Section 3, turbulent mixing noise data from a variety of nozzles will be examined and analyzed. It will be 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.

2. 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, Golebiowski and Seiner[2]. By analyzing the entire data bank of axisymmetric jet noise spectra measured in the Jet Noise Laboratory of the NASA Langley Research Center, they were able to extract the shapes of two self-similar spectra from the data. They then demonstrated that all 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,

$$S = \left[AF\left(\frac{f}{f_L}\right) + BG\left(\frac{f}{f_F}\right)\right]\left(\frac{D_j}{r}\right)^2 \tag{1}$$

where $F\left(\frac{f}{f_L}\right)$ and $G\left(\frac{f}{f_F}\right)$ 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 $F(1) = G(1) = 1$. In equation (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 $\frac{v_j}{a_\infty}$, $\frac{T_r}{T_\infty}$ and the direction of radiation χ (measured from the jet inlet). v_j and a_∞ are the jet velocity and the ambient sound speed. T_r and T_∞ 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.

In high-speed jet flows, there is practically very little upstream influence. Thus the turbulence level near the end of the core region, where most of the jet noise is generated, 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 is affected. However, turbulent mixing is a highly nonlinear process. It is known, 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. In the next section, it will be shown that this appears to be the case.

3. EVALUATION AND COMPARISONS OF DATA

Supersonic jet noise data from two sources are used in the present study. The first set of data is taken from the data bank of the Jet Noise Laboratory of the 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, Golebiowski and Seiner[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 include 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.

3.1 COMPARISONS WITH SIMILARITY NOISE SPECTRA

Figure 1 shows direct comparisons between the measured elliptic and rectangular jet noise spectra at Mach 2 and $\frac{T_r}{T_\infty} = 1.8$ 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 degrees to the minor axis plane and the third on the major axis plane. They are the top three curves in the figure. 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 $F(\frac{f}{f_L})$ function of equation (1)). This is so despite the fact that the nozzle geometries are very different.

Comparisons between the measured spectra at $\chi = 90$ deg. and the similarity noise spectrum or the fine scale turbulence noise (the $G(\frac{f}{f_F})$ function of equation (1)) for the elliptic and rectangular jets are given in Figure 2. 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 Figure 1. It is evident that there is good agreement overall regardless of nozzle shapes.

Figure 3 shows the noise spectrum shapes of the Yamamoto *et al.* data[6] at $\chi = 150$ deg. The jet velocity in each case is very close to 2420 ft/sec and the total temperature is approximately 1715 deg. Rankine. 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 is nearly the same as the C-D round nozzle and is, therefore, not displayed. The full curves are the similarity noise spectrum (the $F(\frac{f}{f_L})$ 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 the cases.

Figure 4 shows similar comparisons as in Figure 3 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 $G(\frac{f}{f_F})$ function. Overall, there is again good fit between the data and the similarity spectrum.

3.2 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 dB/Hz at $r = 100D_j$ from the various jets with the level of the simple circular C-D nozzle. The results are shown in Tables 1 to 4.

Table 1 compares the $SPL_{\max}$ of the elliptic jet at temperature ratio $(\frac{T_r}{T_\infty})$ 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 $\chi = 150$ 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 degrees to the minor 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 the table 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 and 4 show the $SPL_{\max}$ data at $\chi = 150$ and 90 deg. for the various nozzles of the Yamamoto *et al.* experiments. It is worthwhile to remind the readers that the data are converted from $\frac{1}{3}$ octave band measurements and possibly slightly contaminated by shock and facility noise. The experimental uncertainty could be as large as 2 to 3 dB by our estimate. By comparing all 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 are 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.

4. 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 the jets is comprised 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 that the shapes of the spectra of the two noise components are nearly the same as those of the similarity spectra of Tam, Golebiowski and Seiner[2]. 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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Table 1. Elliptic jet (aspect ratio 3, $M_j = 1.98$)

	$\chi = 90$ deg.				$\chi = 141$ deg.				
T_r/T_∞	1.00	1.37	1.80	2.27	1.00	1.37	1.80	2.27	measurement plane
$SPL_{\max}$	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, $M_j = 2.0$)

	$\chi = 90$ deg.			$\chi = 150$ deg.			
T_r/T_∞	1.10	1.82	2.26	1.10	1.82	2.26	measurement plane
$SPL_{\max}$	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.* data
($v_j \simeq 2420$ ft/sec, $T_r \simeq 1715$ deg. R)

nozzle type	conical nozzle	C-D nozzle $M_d = 1.4$	convergent plug nozzle	C-D plug nozzle	suppressor nozzle	inlet angle χ, degree
$SPL_{\max}$ 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.* data
($v_j \simeq 1720$ ft/sec, $T_r \simeq 870$ deg. R)

nozzle type	C-D nozzle $M_d = 1.4$	convergent plug nozzle	C-D plug nozzle	suppressor nozzle	inlet angle χ, degree
$SPL_{\max}$ at	95.0	96.2	97.1	92.5	150
$r = 100D_j$ (dB/Hz)	70.3	73.0	74.0	70.0	90

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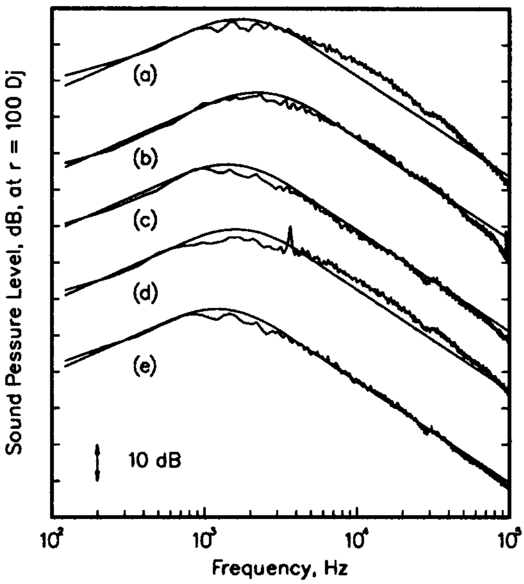
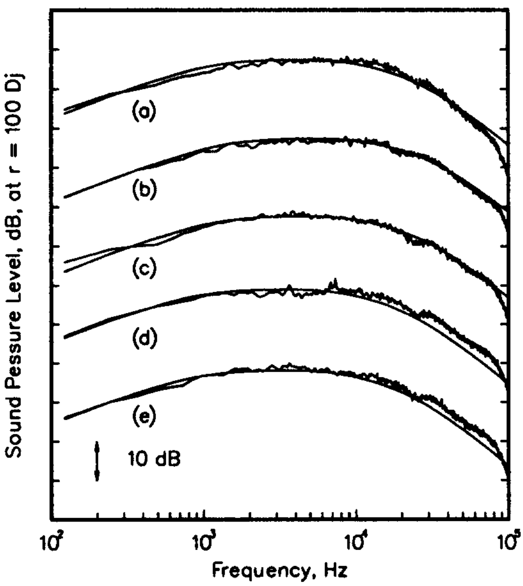


Figure 1. Comparisons between elliptic and rectangular jet noise data and the similarity spectrum at $\chi = 150$ deg., $\frac{T_r}{T_\infty} = 1.8$

Aspect ratio 3 elliptic jet: (a) minor axis plane, (b) 58 degree plane, (c) major axis plane.

Aspect ratio 7.6 rectangular jet: (d) minor, (e) major axis plane.



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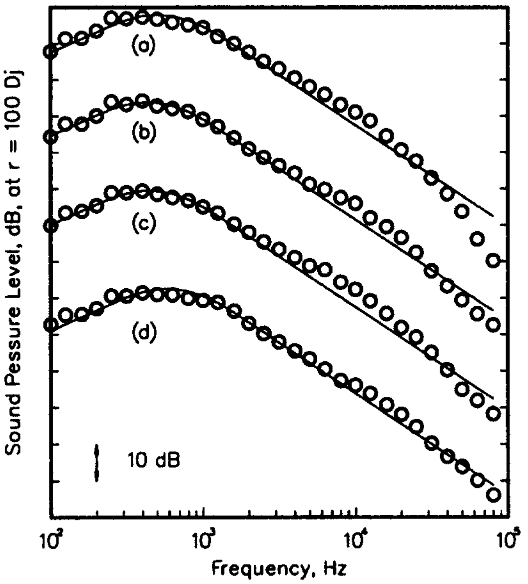
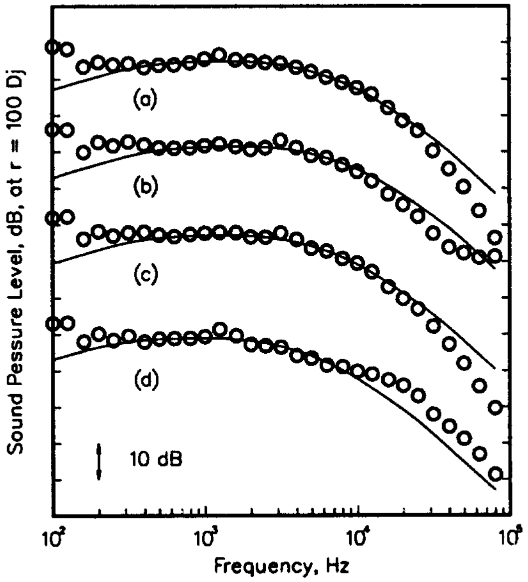


Figure 3. Comparisons between Yamamoto *et al.* data and the similarity spectrum. $V_j \simeq 2420$ ft/sec, $T_r \simeq 1715$ deg R, $\chi = 150$ deg; o data, ——— similarity spectrum. (a) C-D nozzle, (b) convergent plug nozzle, (c) C-D plug nozzle, (d) 20-chute C-D suppressor nozzle.



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