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Suppression of Jet Noise Peak by Velocity Profile Reshaping

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Proposed here is an efficient noise-abating system having the potential for application to a broad spectrum of turbofan engines. An exhaust system with the core nozzle reshaped into an elliptic exit section from the conventional circular nozzle is recommended. The comparison of the scale-model tests revealed that a 5 dB decrease in peak noise levels was realized with a slight increase of the sound pressure at large emission angles. A laser Doppler velocimeter was used to quantify the high-temperature flow turbulence. With the elliptic core nozzle, the jet flow was more diffused axially and spread radially along the major axis. The noise reduction was attributed to the enhancement of the sound refraction and to the lower sound generation, due to the turbulence suppression as well as the lowered mean density gradients at the noise source.

Nomenclature

a	= speed of sound
D	= outer nozzle diameter (the reference diameter of the elliptic nozzle was taken as its equivalent circle of $D=45$ mm)
f	= frequency of sound waves
r	= radius
S_t	= Strouhal number, fD/U_c
T	= mean static temperature
U	= axial mean velocity
(u,v)	= turbulence velocity in axial and radial direction
u'	$=(\overline{u^2})^{1/2}$
v'	$=(\overline{v^2})^{1/2}$
z	= axial distance from the nozzle exit
θ	= angle from the jet axis
ρ	= density
$(\bar{\ })$	= time average

Subscripts

c	= core
f	= fan
i,j	= tensor representation $(u_i u_j)$
j	= exit, core, or fan
0	= reference

Introduction

IN the search for a jet noise suppressor using something other than a variety of multitube and multilobe nozzles, there exist a few concepts that include the use of swirl,[1] the introduction of a second jet,[2] or the flow shielding of a rectangular jet.[3] This paper is concerned with another means of reducing peak jet noise in the coaxial flow arrangement.

Noise reduction for turbofan engines should be achieved with minimal thrust loss, external drag, and weight penalties. With this end in mind, numerous investigations of jet noise, both experimental and theoretical, have been made over the years. However, it is still the least understood process relevant to the convection, refraction, and source modification of sound, particularly in the heated coaxial jet that resembles practical situations in turbofan engines. Most of the results quoted in the available literature were obtained under isothermal conditions and some were extended to cover the hot jet.[4-11]

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The main objective of this paper is to propose a possible system for reducing the noise of turbofan engines, one that requires little alteration of the engine exhaust system. The proposed configuration reshapes the core nozzle into an elliptic exit section from the conventional circular nozzle. There is no appreciable thrust loss and no interference between the noise suppressor and the thrust reversal system.

In order to support the proposed concept, a comparison of the conventional round jet with the noncircular nozzle combinations is experimentally demonstrated in scale-model tests. Details of the acoustic and aerodynamic data on the selected configurations are described. The high-temperature flow was successfully approached by a laser Doppler velocimeter. Hence, a better understanding of the suppression mechanism is also emphasized, which is necessary for designing a practical suppression device.

Test Description

Facility

The tests were performed in a vented anechoic environment. A 6×4.2×3.5 m anechoic chamber, once used for turbomachinery noise research, was modified for exhaust testing. A 1×1 m opening was made in the roof (see Ref. 12 for the detailed dimensions of the chamber). The nozzle axis was vertically placed at the floor. This structure had an anechoic enclosure down to 250 Hz. A schematic diagram of the test setup is shown in Fig. 1. Both the core and fan jets were supplied with two separate air compressors and controlled by their respective valves. An electric heater of 60 kW was installed outside of the chamber to heat the core air, and the air temperature was maintained within ±1 deg during each test run by a thermostatically feedback mechanism.

Nozzle Hardware and Test Conditions

The baseline circular nozzles were well convergent down to inner diameters of 20 mm (core) and 45 mm (fan) at the exhaust section. The contraction ratio was 14 and 30, respectively. With the exit areas kept the same as the corresponding round nozzles, two types of elliptic nozzles having major/minor axes of 40/10 mm (core) and 80/25 mm (fan) were fabricated for comparison purposes. Within the permissible range of the facility, most of the tests were carried out in heated high-speed flow to cover the thermodynamic conditions of interest in typical turbofan engines. The experimental conditions, together with the nozzle combinations tested, are summarized in Table 1. Besides the flow area, the temperature, velocity, and thrust were kept common for the configurations considered in each group of core/fan velocity ratios.

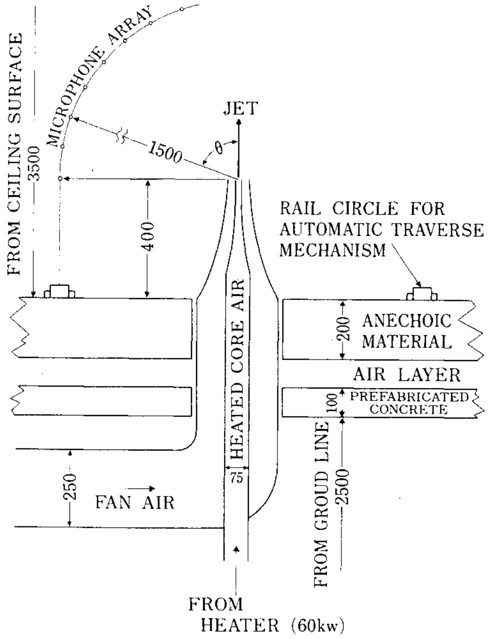


Fig. 1 Test setup and the floor of anechoic room (units in mm).

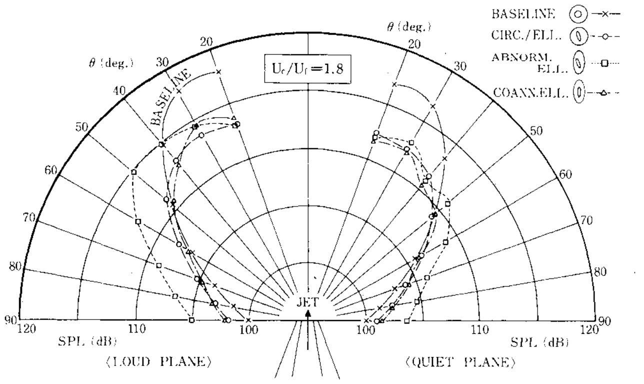


Fig. 2 Overall sound pressure directivities of four-nozzle configurations.

Acoustic and Flow Measurements

Acoustic measurements were made with a 1.5 m polar, far field microphone array (B & K Model 4133, 12 mm diam) that was rotated around the jet axis by a small electric motor moving on a rail circle. All data were processed making use of the NAL on-line noise reduction system. The runs were about 80 s long to permit satisfactory recording of the noise data and the frequency analysis was performed in the 20 Hz bandwidth. Experimental uncertainty of the measured pressure levels was estimated to be within ±0.5 dB.

The flowfield was quantified by a combined use of pitot tubes, thermocouples, and a laser Doppler velocimeter (LDV). To determine the thrust, a fine traverse of rake probes was made at a section 20 mm downstream from the nozzle exit. The total and static pressures thus obtained were put into an equation of the thrust per small area and then integrated over the measuring section. The LDV data reduction system used was the same as that in Ref. 13 except for the countertype signal processor (TSI-Kanomax Model 8001) that replaced the tracker in order to meet the requirements of high-speed flow measurement. However, the photomultiplier used in the system did not permit measurement of flow with a velocity higher than 200 m/s due to the frequency limit (100 MHz). A 2 W argon-ion laser with a 600 mm focal lens was focused to make up a sensing volume by use of the dual-beam method.

Table 1 Test conditions and nozzle configurations

ILLUSTRATIONS											
COMMENTS		BASELINE		CIRCULAR/ ELLIPTIC		ABNORMAL ELLIPTIC		COANNULAR ELLIPTIC		ELLIPTIC/ CIRCULAR	
U_c/U_f		CORE	FAN	CORE	FAN	CORE	FAN	CORE	FAN	CORE	FAN
1.8	RUN NO.	153		252		452		552			
	EXIT MACH	.906	.731	.908	.726	.888	.755	.889	.732		
	T_j (°K)	671	302	668	302	668	305	667	304		
	U_j (m/s)	436	242	436	240	427	250	428	243		
	U_c/U_f	1.80		1.81		1.71		1.76			
	BYPASS RATIO	4.68		4.63		4.94		4.77			
	THRUST (kg)	13.03		12.98		13.00		13.10			
	PWL (dB)	122.5		120.2		121.6		120.1			
1.5	RUN NO.	119		211		411		511		312	
	EXIT MACH	.765	.794	.786	.791	.789	.807	.772	.801	.753	.783
	T_j (°K)	724	295	740	298	727	301	723	296	735	297
	U_j (m/s)	390	257	404	258	402	264	393	260	388	255
	U_c/U_f	1.52		1.57		1.53		1.51		1.52	
	BYPASS RATIO	6.53		6.35		6.37		6.51		6.58	
	THRUST (kg)	13.79		14.11		13.93		14.03		14.11	
	PWL (dB)	120.2		118.9		121.6		119.6		120.1	
1.0	RUN NO.	132		231							
	EXIT MACH	.576	.820	.580	.837						
	T_j (°K)	586	287	576	290						
	U_j (m/s)	271	262	270	266						
	U_c/U_f	1.04		1.01							
	BYPASS RATIO	8.39		8.41							
	THRUST (kg)	13.93		14.08							
	PWL (dB)	115.6		116.1							
0.9	RUN NO.	143		241							
	EXIT MACH	.525	.829	.523	.841						
	T_j (°K)	551	286	512	290						
	U_j (m/s)	240	264	231	269						
	U_c/U_f	0.91		0.86							
	BYPASS RATIO	9.11		8.89							
	THRUST (kg)	13.96		13.95							
	PWL (dB)	115.4		115.8							

Experimental Observations

Noise Data

Figure 2 compares the overall sound pressure levels (SPL) and directivities with four types of nozzle combinations, where the maximum and minimum levels around the axis were plotted and denoted as "loud" and "quiet" planes, respectively. A decrease of about 5 dB in the overall SPL was obtained at shallow angles in the elliptic nozzle combinations. At large angles, however, the SPL of two configurations became slightly higher than the baseline SPL. A great increase in noise was observed in the abnormal elliptic case, where the major axis of the outer nozzle made an angle of 30 deg with the inner minor axis. The quiet and loud planes were detected at major and minor axes of the elliptic cross section, as illustrated in Figs. 3a and 3b. This phenomenon was already predicted by Crighton[14] and Balsa[15] for a simple cold jet, and thereafter confirmed in Kantola's testing[3] of a hot, single rectangular jet. It was found that the location of two planes was completely changed and reversed in the elliptic/circular case (Fig. 3c), probably due to the promotion of jet mixing at the minor axis. A remarkable nonaxisymmetric pattern of sound signature was detected in Fig. 3d, with the maximum/minimum lobe being 90 deg apart.

The results of the frequency analysis in 20 Hz bandwidth are shown in Fig. 4. At small angles up to $\theta=50$ deg, the coannular/elliptic configuration exhibited the smallest SPL in the full range of $0.1 \leq S_t \leq 2.0$, while the circular/elliptic combination gave rise to a decrease of the SPL in a limited range of $0.1 \leq S_t \leq 1.0$ until $\theta=40$ deg. These phenomena were reversed at $\theta=60$ deg and the baseline nozzle became quietest at large angles, 60 deg $\leq \theta \leq$ 90 deg.

Figure 5 indicates the variations in the location of the intensity peak with frequency in comparison of the single cold jet.[16] The variations of the baseline nozzle were closer to the curve of the single-jet data. Although there was scatter in the measured data, the sound waves having short wavelength were much deflected away from the jet axis in the elliptic jets, with a limit angle of $\theta=50$ deg.

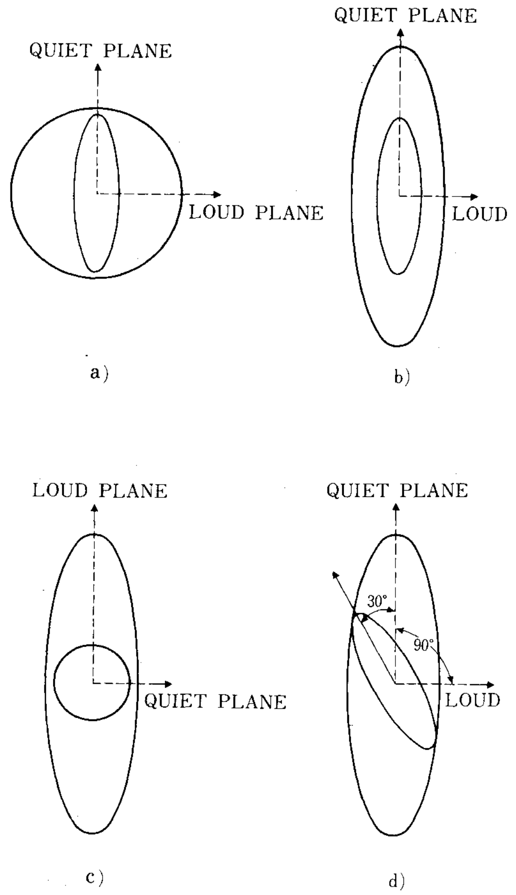


Fig. 3 Locations of quiet and loud planes observed in respective configurations.

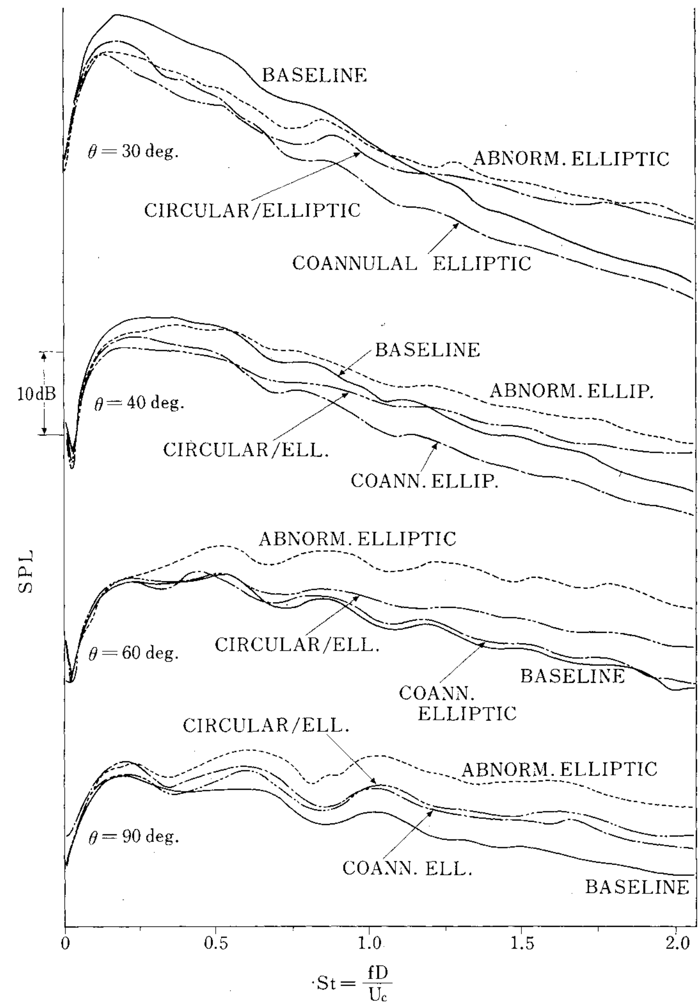


Fig. 4 Comparison of SPL with frequencies, $U_c/U_f = 1.8$, quiet plane.

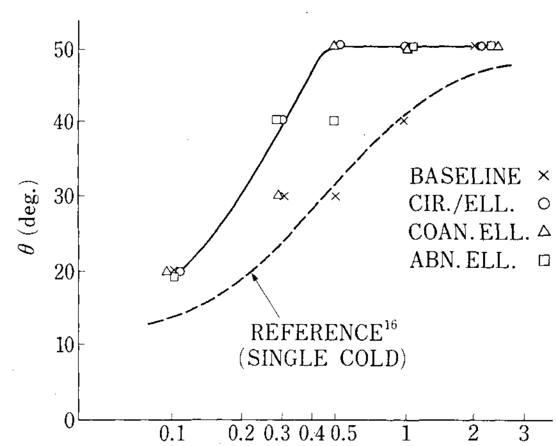


Fig. 5 Locations of peak noise angles with frequencies, $U_c/U_f = 1.8$, quiet plane.

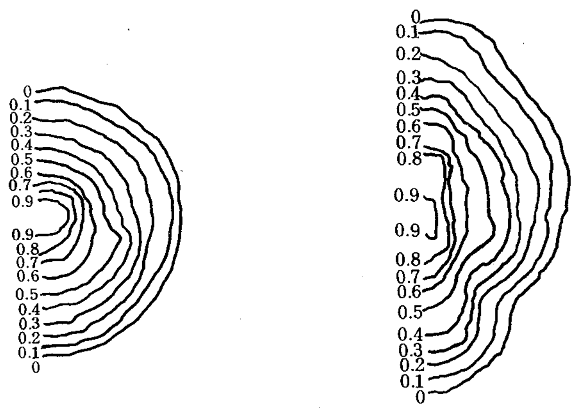
As Table 1 shows, the comparison of the two configurations selected was made in the range of $U_c/U_f = 1.8 \sim 0.9$. As a result, a 3.5 dB decrease in the peak SPL was still recognized at $U_c/U_f = 1.5$, but any appreciable reduction was no longer detectable at $U_c/U_f = 1.0$ or 0.9.

Flow Data

A close look at the acoustic data indicates that there exist only minor differences, at least in the overall SPL, between the circular/elliptic and coannular/elliptic combinations. It is thus tentatively concluded that the circular/elliptic configuration would be potentially better for application to the broad spectrum of turbofan engines, because of the simplicity of its fabrication and its noninterference with the thrust reversal. Therefore, the flow data are focused on only the comparison of the baseline and circular/elliptic configurations in the following discussion.

The contour of the mean axial velocities was obtained using the total pressure and temperature data, together with the assumption that the static pressure between the jet and the surroundings was equal. Typical results are shown in Fig. 6. It is evident that the flow was more rapidly diffused with axial distance and spread outward at both ends of the major axis as a result of the elliptic jet located in the center.

As stated before, a frequency limit of the photomultiplier confirmed the LDV measurement to lower velocity conditions of the potential core than those presented in Fig. 6. The following comparison of the experimental data was carried out at the conditions of $U_c = 180$ m/s, $U_f = 100$ m/s, and of $T_c = 700$ K. Figure 7 shows the axial turbulence velocity correlations. The effect of two separate potential cores emerging from the coannular nozzle on the radial profiles of u'/U_c still remained in the stations close to the nozzle exit. This is in qualitative agreement with Ko and Kwan's observations[17] made on a coaxial cold jet. However, in the quiet plane the peaks rapidly merged into a flat distribution with distance downstream. The maximum of turbulence intensity was of the order of 15% at $Z/D = 5.3$ for the baseline nozzle, which compares closely with other cold-flow measurements.[17-19] It may be then remarked that temperatures up to 700 K cause negligible disturbances in the turbulent intensity. The distributions of the covariance, expressed in $(\overline{uv})^{1/2}/U_c$, are plotted in Fig. 8, which again shows a trend similar to the distributions of u'/U_c. Axial variations of the maximum of u'/U_c, v'/U_c, and $(\overline{uv})^{1/2}/U_c$ are displayed in Fig. 9. The turbulence in the baseline jet increased progressively with the axial distance, while it rapidly decreased in the quiet plane.



a) Baseline. b) Circular/elliptic.

Fig. 6 Contour of nondimensionalized axial velocities by U_c at $z/D = 3$, $U_c/U_f = 1.8$.

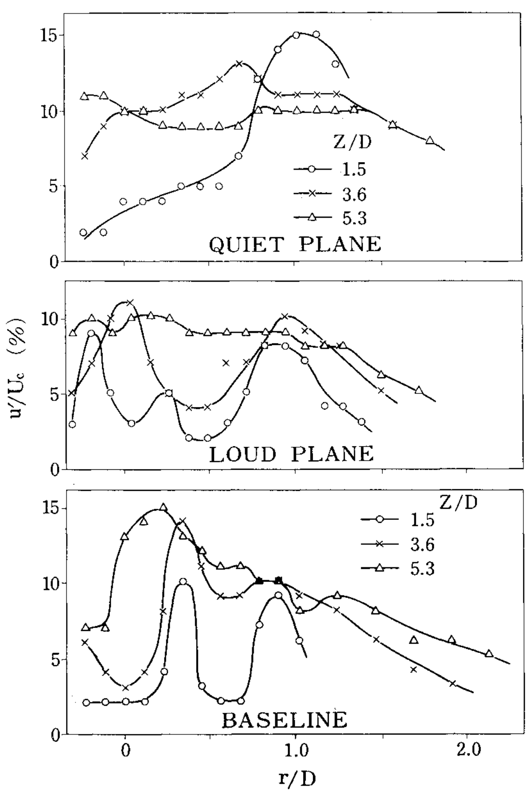


Fig. 7 Radial profiles of axial turbulence intensity with axial distance.

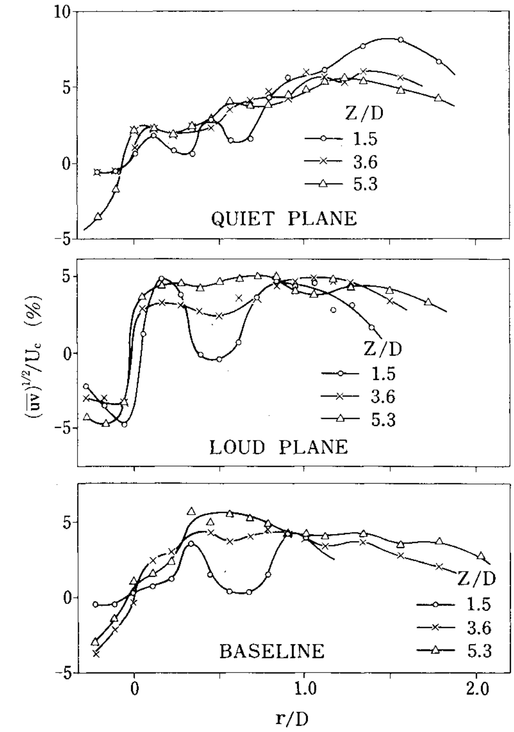


Fig. 8 Radial profiles of turbulence covariance with axial distance.

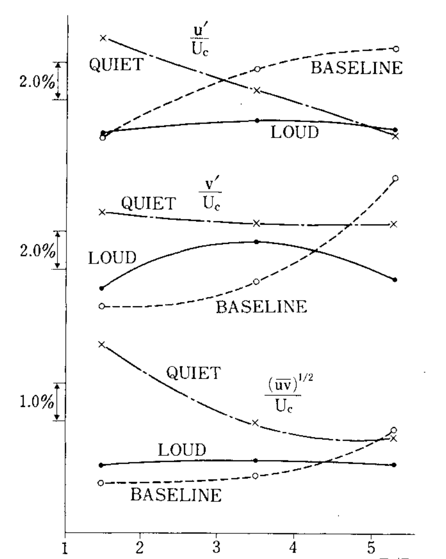


Fig. 9 Axial variations of maximum turbulence intensities and covariance.

The turbulence level in the loud plane remained almost constant.

The radial profiles of density are made dimensionless by the ambient density and compared in Fig. 10. The decrease of mean density gradients suggests that there was a significant entrainment of cold air from the surroundings into the hot jet as a result of the greater diffusion in the elliptic flow.

Discussion

The peak noise reduction at small angles in the present experiment closely resembles the trend of the experimental data of Morris et al.,[2] who used a second hot jet near the main jet. It is evident from this agreement that the refraction of the flow shielding (mean shear) played a major role in the noise reduction of the coaxial nozzles. The elliptic jet with a considerable spread into three-dimensional directions had bent the sound rays away from the axis of the jet much more than the baseline jet did. Another observation that probably has a close connection with refraction is the peak SPL locations shown in Fig. 5. This feature goes some way toward supporting the idea that sound waves have a common limit angle of emission for all jets regardless of flow configurations, although noncircular nozzles enhance the flow shielding at low frequencies.

The physical mechanism of noise generation is different for the high-frequency "self-noise" and low-frequency "shear noise" and therefore a parameter of fD/a was proposed to characterize the ratio of the jet diameter to the sound wave.[16,23] When it exceeds unity, the geometrical acoustical approximation becomes reasonable. In the present experiment, $fD/a = 1$ which is roughly equivalent to $S_t = 1$. In this light, Fig. 4 indicates that the circular/elliptic nozzle exceeded the baseline in the SPL beyond the point of $S_t \simeq 1$ in the range of 20 deg$\leq \theta \leq$40 deg. As for the coannular/elliptic, the appearance of this phenomenon was not clear, but the gradual increase of the SPL in a whole range of S_t was

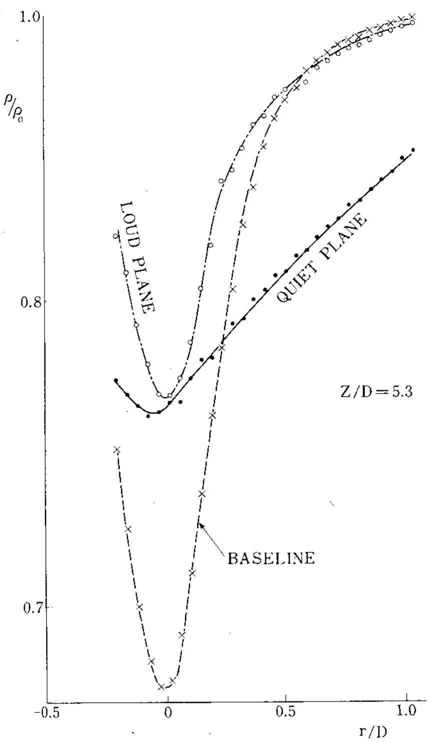


Fig. 10 Comparison of mean density at $Z/D = 5.3$, $U_c = 180$ m/s, and $T_c = 700$ K.

observed. The abnormal elliptic configuration enhanced the phenomenon. Accordingly, it can be remarked that most of the turbulence were transferred into small scales characteristic of efficient radiation of high-frequency noise in the circular/elliptic or abnormal elliptic nozzles. On the other hand, the noise abatement of the coannular elliptic configuration might be attributed primarily to the flow shielding. A similar trend has been reported in other configurations.[2,3]

The present results, interpreted in the light of the theoretical conclusions,[20-26] suggest that the apparent suppression of downstream turbulence (Fig. 9) might make a contribution to the reduction of the shear noise and that a significant increase of the turbulent velocities along the quiet plane near to the nozzle exit could be considered a major cause of the increase of high-frequency noise at small angles in the circular/elliptic nozzle. Most of the sound sources were moved upstream near the nozzle exit as a result of rapid spread in the elliptic flow and then the efficient radiation of self-noise was considered to be observed at a right angle to the jet axis.

The entropy fluctuation term[10] is one of contributors to noise generation in heated jets. In the regime of subsonic jet efflux velocities, the decreased contribution of $\rho u_i u_j$ due to low density is largely compensated for by increased temperature fluctuation noise.[5] The transmission of low-frequency sound across density gradients (refraction), and the generation of new dipole and a source-like term due to the traverse gradients of the mean density,[8] are all features governing the noise of heated jets. Entropy or temperature fluctuation depends strongly on the mean density gradient if the same analogy between the Reynolds stress and the mean shear is assumed in the heat transport. It is apparent that the lowered levels of mean density gradients (Fig. 10) contribute to the lower generation of noise at its source.

Conclusions

An experimental comparison of axisymmetric and nonaxisymmetric coaxial jets was performed acoustically and aerodynamically on the basis of scale-model tests in a vented anechoic chamber. A 5 dB decrease in the peak noise was obtained in nozzle configurations incorporating an elliptic section. This reduction was attributed to the enhancement of the sound refraction and the lower generation of sound due to turbulence suppression as well as lowered mean density gradients.

It is considered that an upstream shift of the noise sources by a greater diffusion of the flow resulted in a slight increase in the sound at large angles in the elliptic jets. It is also clear from LDV measurements that with the circular/elliptic nozzle combination the turbulence levels were reduced much more at the downstream sections in comparison with the baseline nozzle, and that a significant increase in turbulence was observed along the quiet plane very close to the exit. The latter might increase the high-frequency noise at small angles. As for the elliptic/elliptic combination, such an acoustic signature was not detected.

The present results suggest the potential application to turbofan engines. Proposed here is an exhaust system having only a reshaped core nozzle in the elliptic exit. There is no conflict with the thrust reversal mechanism and only a slight loss of thrust. An experimental program evaluating the flight effect on such system is in progress at the Japanese NAL.

Acknowledgments

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