AIAA 80-0167R

Noise Characteristics of Coannular Flows with Conventional and Inverted Velocity Profiles

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The results of the investigation of the noise characteristics of the exhaust jets from coannular nozzles with conventional and inverted velocity profiles are presented. Experiments were carried out on a series of coannular nozzles of equal primary and secondary area. The results of this study show that at high thrust level the coannular flows with inverted velocity profiles are quieter than those with standard velocity profiles at the same thrust and the same mass flow. The acoustic differences are much greater when the velocity ratio is produced by differences in the stagnation temperature rather than by differences in the stagnation pressure.

Nomenclature

A = area
a_0 = ambient speed of sound
D = diameter
I = sound intensity
IL = intensity level
$\dot{m}$ = mass flow rate
P = pressure
R = radial distance
Th = total thrust
U = local mean velocity
u' = turbulence velocity
V = jet-exit velocity
θ = polar angle measured from flow axis
Π = pressure ratio, P_0/P_a
ρ = density

Subscripts

a = atmospheric
c = convection
e = exit
0 = stagnation or ambient
p = primary
s = secondary

Introduction

A MOST successful method for reducing the exhaust noise levels of jet engines is based on the bypass principle, which provides for additional air to bypass the primary gas generator of the turbojet engine, have it energized by a fan, and afterward exhausted into the atmosphere. Initially, it was considered to be essential that the bypass air exhaust into the atmosphere at velocities lower than those of the primary airflow. Since the exhaust velocity of the primary air is reduced by energy transfer from the primary air to the bypass air through the turbofan system, the mean velocity of the engine exhaust is reduced in comparison to straight turbojet engines of equal thrust. Both the reduction of the mean exhaust velocity level and the low velocity of the bypass air combine to produce a large reduction of the exhaust jet noise. The bypass method has been applied, with great success, to most commercial subsonic aircraft of today.

Presented as Paper 80-0167 at the AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 14-16, 1980; submitted Feb. 5, 1980; revision received June 20, 1980.

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Recent experiments[1,2] have shown that the usual method of keeping the exhaust velocity of the bypass air lower than that of the primary air does not produce necessarily the maximum noise attenuation. To the contrary, it was found that considerably greater noise attenuation could be achieved, in some cases, by having the bypass air deliberately exhaust with higher velocities than the primary air. In contrast to the "standard" exhaust velocity profile, that is with the bypass air exhausting with lower velocity than that of the primary air, the new scheme employs an "inverted" exhaust velocity profile.

The purpose of the research reported here was to investigate the noise-reducing potential of bypass engines with inverted velocity profiles by directly comparing with a standard profile exhaust and to attempt to shed light into the physical reasons behind the experimental observations.

In order to explore the relative merits of coannular nozzle systems, employing either the "standard" or the "inverted" velocity profile, a series of experimental studies was conducted in which the velocity profile of the exhaust was changed gradually from one extreme to the other. The experiments were conducted for cold flow and for hot flow conditions up to air temperatures of 1480° R.

Experimental Program and Facilities

The experimental program consisted of the five principal phases that follow: 1) sound power measurements on a 2-in. nominal diameter coannular nozzle under cold flow conditions; 2) free-field tests on a 4-in. nominal diameter coannular nozzle under cold flow conditions; 3) free-field tests on the 4-in.-diam nozzle with either primary or secondary flow heated; 4) free-field tests on an 8-in.-diam coannular nozzle with either primary or secondary flow heated; and 5) Laser Doppler Velocimeter measurements in the exhaust flow from the 4-in. nozzle with conventional and inverted profiles.

The sound power measurements on the 2-in. nozzle were obtained in a small reverberation chamber of heavy plywood. The dimensions of the chamber are 8×7×6.5 ft high with a volume of 360 ft³. During testing, the only opening in the chamber was an 8-in.-diam exhaust port. Air flow to the primary and secondary stilling chambers were controlled by two independent control valves. Two ¼-in. microphones were used to take the data.

The majority of the data taken in this program was obtained in the Acoustic Free-Field Facility shown in Fig. 1 where sound directivity and spectra can be measured. Acoustic data are taken by a ¼-in. microphone mounted on a sweep arm (not shown in Fig. 1), which permits a traverse around a polar angle measured from the jet axis. During the

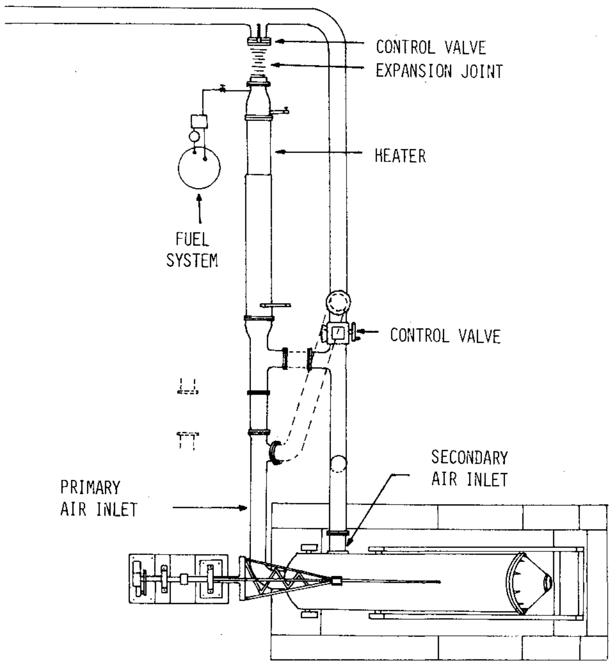


Fig. 1 Plan view of free-field facility (dashed lines show piping for heated secondary flow).

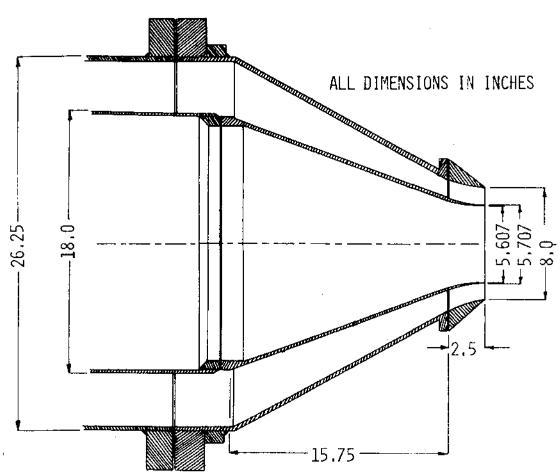
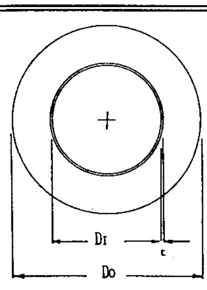


Fig. 2 8-in. nozzle and free-field transition piece.

Table 1 Nozzle parameters

Nozzle, in.	D_O, in.	D_I, in.	t, in.	A_p, A_s, in.^{2}
2	2.220	1.550	.02	1.88
4	4.0	2.778	.05	6.06
8	8.0	5.607	.05	24.69



traverse, the microphone is maintained at a constant radius of 13 ft from the nozzle exit. A kerosene heater is used to provide heated air up to a temperature of 1480° R.

Several modifications to this facility were required to conduct the coannular nozzle tests. An inner stilling chamber with an acoustic liner was installed with additional piping to supply air to the secondary stilling chamber. The experimental program required that tests be conducted for the inner flow heated and the outer cold, and the reverse conditions of the outer flow heated and the inner cold. Since only one stream of the supply air could be heated, some rearrangement of the piping was necessary to produce both of these conditions. The piping layout for both configurations is shown in Fig. 1.

Table 2 Acoustic results for 2-in. nozzle constant mass flow series

V_s/V_p	P_{0p}/P_a	P_{0s}/P_a	Th/A, lb/in.^{2}	$\dot{m}/A$, lb/s in.^{2}	PWL, dB
2.07	1.149	1.871	11.83	0.46	120.86
1.58	1.228	1.710	11.20		119.21
1.24	1.328	1.555	10.87		115.93
1.01	1.425	1.439	10.74		114.81
0.82	1.540	1.328	10.87		115.09
0.64	1.710	1.228	11.22		117.92
0.50	1.871	1.156	11.89		120.13
1.35	1.387	1.849	14.46	0.52	120.42
1.23	1.452	1.767	14.31		119.66
1.01	1.587	1.604	14.22		119.43
0.90	1.691	1.509	14.25		119.12
0.81	1.787	1.425	14.31		120.17

Acoustic tests were carried out on three different coannular, coplanar nozzles. Each nozzle is of the same basic design, differing only by a scale factor. In this paper, the nozzles are referred to by the nominal diameter of the larger circular nozzle. The inner and outer diameters were fixed so that the exit area for the inner (primary) and outer (secondary) streams were the same. Figure 2 shows the dimensions of the 8-in. nozzle and the manner in which it was mounted on the free-field facility stilling chamber. Table 1 gives the pertinent dimensions for the nozzles used in this test program.

The 2-in. nozzle was tested only in the reverberation chamber and only under cold flow conditions. The 4-in. and 8-in. nozzles were tested in the free-field facility with cold and hot flow.

The majority of the acoustic tests were carried out holding either the total thrust or the total mass flow of the jet exhaust constant while varying the velocity ratio V_s/V_p. In the cold flow tests, the change in the velocity ratio was accomplished by changing the stagnation pressure ratio of the primary and secondary stilling chambers. In the heated flow tests, the velocity ratio was varied mainly by changing the stagnation temperature of either the primary or secondary flow.

Presentation of Results

Acoustic Data for Cold Flow

Initial tests with the coannular nozzles were made in the reverberation chamber on the 2-in. nozzle with both primary and secondary streams unheated. Several test series were carried out varying the velocity ratio of the secondary to primary stream while maintaining either constant total thrust or constant total mass flow. In these test series, the velocity ratio was changed by varying the pressure ratio; that is, the exit Mach number of the primary and secondary streams. The test conditions and acoustic results for two constant mass flow series are given in Table 2. Complete data from these tests are contained in Ref. 3. The sound power level (PWL) values in this table were obtained from microphone measurements in the chamber and have been corrected for the chamber's reverberation time.

The sound power values given in Table 2 show that the minimum sound power occurs at or near a velocity ratio of one. This minimum should be viewed with care, however, since the thrust is also a minimum at this condition. The most meaningful comparisons from these tests are for those points

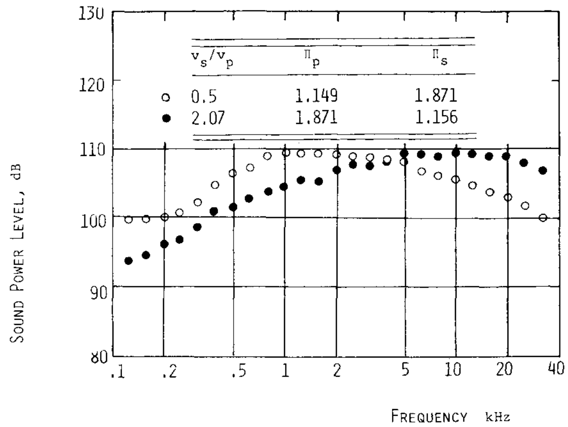


Fig. 3 Comparison of sound power spectra for 2-in. nozzle: $\dot{m}/A = 0.46$ lb/s in.^{2}, $Th/A = 11.8$ lb/in.^{2}.

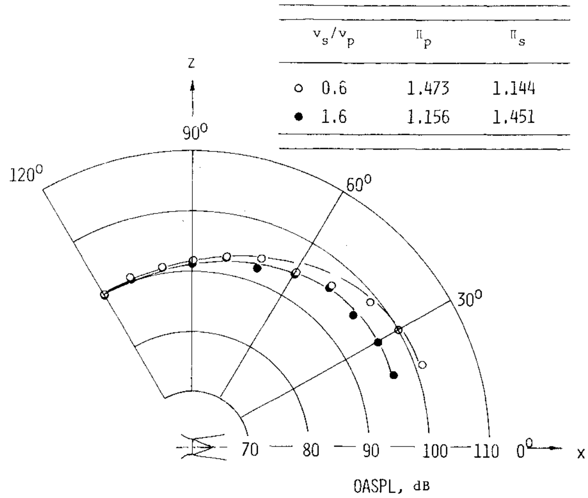


Fig. 4 Comparison of directivities for 4-in. nozzle with standard and inverted profiles: $\dot{m}/A = 0.37$ lb/s in.^{2}, $Th/A = 7.75$ lb/in.^{2}.

where both thrust and mass flow are constant and

$$V_s/V_p|_{\text{inv}} = V_p/V_s|_{\text{std}}$$

The data in Table 2 shows that there is very little difference in the overall sound power produced by the standard and inverted profiles when compared on this basis.

Comparative sound power spectra for two such points are shown in Fig. 3. This comparison shows that the high frequency noise generated by the inverted profile is greater than that produced by the standard profile and that the low frequency noise is correspondingly reduced.

A comparison of the directivities of the noise generated by the standard and inverted profiles at the same thrust and mass flow is shown in Fig. 4. These data were taken in the free field on a 4-in. nozzle with both streams cold. The figure shows a moderate reduction (~5 dB) in the sound intensity in the direction of maximum noise radiation for the inverted profile. The sound pressure level (SPL) at 90 deg to the jet axis is only slightly different for the conventional and inverted profiles.

A comparison of the sound pressure spectra at 30 deg to the jet axis for a standard and inverted profile is shown in Fig. 5. The inverted profile has a much flatter spectrum with less low frequency noise and more high frequency noise radiated.

Acoustic Data for Heated Flow

Acoustic tests on the 4-in. coannular nozzle were carried out in the free-field test stand where either the primary or secondary air flow stream could be heated. As in the cold flow tests, the noise characteristics of the coannular flows were measured for different velocity ratios while maintaining either the total thrust or total mass flow constant. Tables 3 and 4 summarize the flow conditions and acoustic results for two constant mass flow series and two constant thrust series. The sound power values given in these tables were computed by integrating the measured intensity with respect to polar angle from $\phi = 20$ to 120 deg, assuming an axially symmetric sound field.

In these tests, the velocity ratio was varied primarily by changing the stagnation temperature ratio. For consistency, the tests for $V_s/V_p = 1$ were performed with both streams unheated. This resulted in the equal velocity condition yielding a minimum noise level, due to the very low energy input.

Since the primary and secondary exit areas were the same for the nozzles tested, inverse run conditions, where the stagnation pressures and temperatures of the primary and secondary streams were interchanged, resulted in comparable conventional and inverted profiles with the same thrust and the same mass flow at equal energy input. Most of the comparisons cited in this paper are made between these types of profiles where $V_s/V_p|_{\text{inv}} = V_p/V_s|_{\text{std}}$.

Table 3 Acoustic results for 4-in. nozzle constant mass flow series

V_s/V_p	P_{0p}/P_a	P_{0s}/P_a	T_{0s}/T_{0p}	Th/A, lb/in.^{2}	$\dot{m}/A$, lb/s in.^{2}	PWL, dB
0.57	1.587	1.425	0.42	12.34	0.36	135.52
0.65	1.480	1.480	0.42	11.70		133.25
0.75	1.412	1.412	0.55	10.29		125.92
0.84	1.375	1.375	0.70	9.38		120.39
1.02	1.286	1.307	1.00	7.69		114.18
1.21	1.339	1.363	1.39	8.88		118.03
1.39	1.387	1.412	1.82	10.04		123.62
1.58	1.452	1.480	2.36	11.42		128.71
1.70	1.412	1.540	2.32	11.69		129.92
2.22	1.286	1.787	2.34	12.71		133.88
0.65	2.008	2.033	0.42	21.34	0.52	144.28
0.74	1.849	1.871	0.55	19.54		137.91
0.87	1.729	1.767	0.74	17.17		131.65
1.02	1.587	1.638	1.00	14.55		124.49
1.22	1.673	1.748	1.38	16.64		127.81
1.41	1.787	1.893	1.84	19.00		131.87
1.52	1.893	2.008	2.31	20.65		135.65

Table 4 Acoustic results for 4-in. nozzle constant thrust series

V_s/V_p	P_{0p}/P_a	P_{0s}/P_a	T_{0s}/T_{0p}	Th/A, lb/in.^{2}	$\dot{m}/A$, lb/s in.^{2}	PWL, dB
0.61	1.452	1.466	0.37	11.20	0.36	134.90
0.65	1.452	1.466	0.41		0.37	131.68
0.69	1.452	1.466	0.45		0.38	131.29
0.74	1.452	1.466	0.53		0.39	129.11
0.85	1.452	1.466	0.69		0.41	124.65
1.03	1.452	1.466	1.00		0.45	120.30
1.22	1.452	1.466	1.44		0.41	122.05
1.41	1.452	1.466	1.92		0.39	125.06
1.59	1.452	1.466	2.43		0.37	127.91
1.87	1.339	1.571	2.33		0.35	128.28
0.51	1.767	1.466	0.39	14.30	0.40	140.00
0.63	1.604	1.555	0.42		0.41	137.16
0.72	1.604	1.571	0.55		0.43	132.38
0.84	1.604	1.571	0.73		0.46	127.38
1.00	1.604	1.604	1.00		0.51	123.81
1.21	1.604	1.604	1.45		0.47	125.41
1.36	1.604	1.604	1.86		0.44	128.55
1.53	1.604	1.604	2.34		0.41	131.15
1.68	1.524	1.691	2.32		0.40	131.19
1.95	1.439	1.787	2.45		0.39	133.39

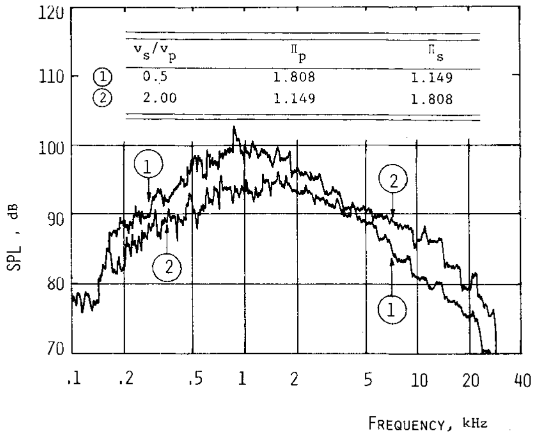


Fig. 5 Comparison of sound pressure spectra at 30 deg for 4-in. nozzle at ambient temperature: $\dot{m}/A = 0.43$ lb/s in.^{2}, $Th/A = 11.1$ lb/in.^{2}.

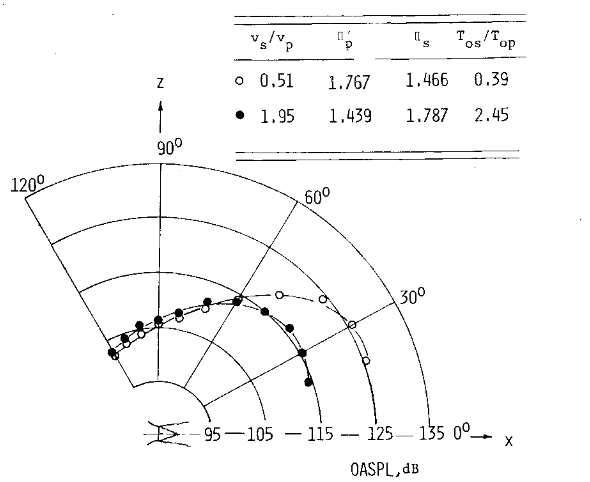


Fig. 6 Comparison of directivities of 4-in. nozzle with one stream heated: $\dot{m}/A = 0.4$ lb/s in.^{2}, $Th/A = 14.3$ lb/in.^{2}.

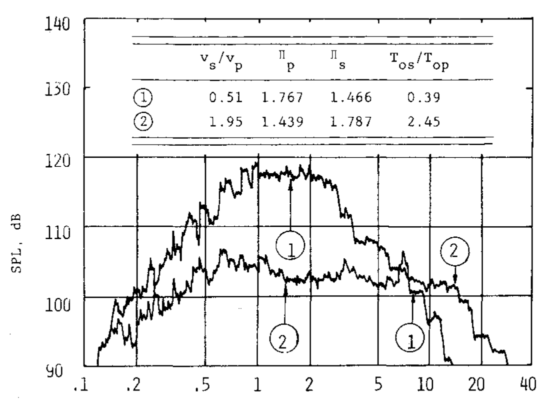


Fig. 7 Comparison of sound spectra at 30 deg for 4-in. nozzle with one stream heated: $\dot{m}/A = 0.4$ lb/s in.^{2}, $Th/A = 14.3$ lb/in.^{2}.

Figure 6 shows a typical comparison of directivities for comparable standard and inverted velocity profiles. The inverted profile exhibits a reduction of over 10 dB compared to the standard velocity profile in the direction of maximum noise radiation. For radiation angles greater than 60 deg, there is very little difference between the noise radiated by conventional and inverted profiles at the same thrust and mass flow. These trends are similar to those obtained in cold flow. However, the difference in maximum noise levels is much greater when one stream is heated.

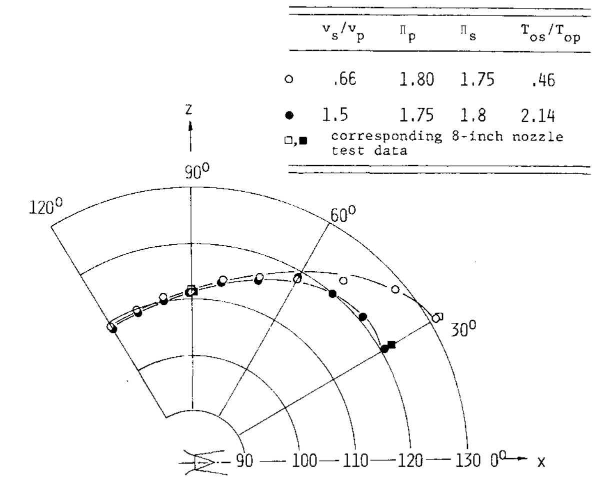


Fig. 8 Comparison of directivity patterns of 4-in. nozzle (scaled up to 8-in. nozzle) and 8-in. nozzle: $\dot{m}/A = 0.483$ lb/s in.^{2}, $Th/A = 17.82$ lb/in.^{2}.

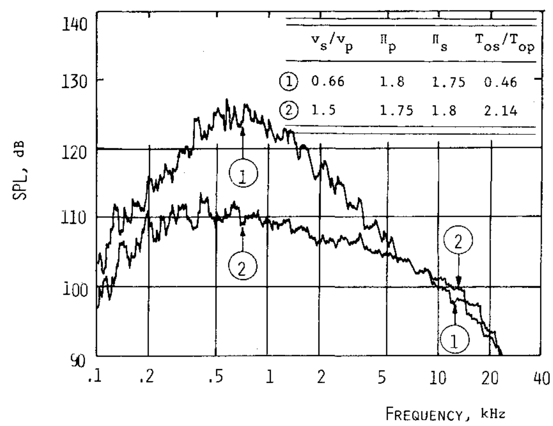


Fig. 9 Comparative spectra at 30 deg for standard and inverted velocity profiles for 8-in. nozzle: $\dot{m}/A = 0.488$ lb/s in.^{2}, $Th/A = 17.86$ lb/in.^{2}.

A comparison of the sound pressure spectra at 30 deg (Fig. 7) shows that the spectrum for the inverted velocity profile is much flatter than that for the conventional profile. At very high thrust levels, the sound pressure spectrum for the inverted profile develops a double peaked character observed by others.[4]

It should be noted that almost all pressure ratios in these experiments were below the critical value of 1.893 and therefore correspond to subsonic jet exit velocities. This restriction was imposed in order to examine the influence of profile inversion on jet mixing noise without the additional complications of shock noise and shock associated noise. In the few cases where slightly supercritical pressure ratios were used, the acoustic data showed no evidence of shock associated noise. Dosanjh et al.[5] carried out experiments similar to those reported here for supercritical pressure ratios and found a substantial reduction in noise for an inverted profile with both streams cold. This reduction was attributed to modification of the flow and shock structure caused by the inverted velocity profile.

Figure 8 shows a comparison of the directivity patterns for both the 4-in. and the 8-in. nozzle for $Th/A = 17.8$ lb/in.^{2} and $V_s/V_p|_{inv} = V_p/V_s|_{std} = 1.50$. The 4-in. nozzle data in this figure has been scaled up to correspond to an 8-in. nozzle for better comparison. Figure 9 shows comparative spectra at 30 deg for the 8-in. nozzle for these conditions and has generally similar characteristics to a similar comparison in Fig. 7.

Figure 10 shows a comparison of the sound pressure level spectra at 90 deg for the conventional and inverted profile

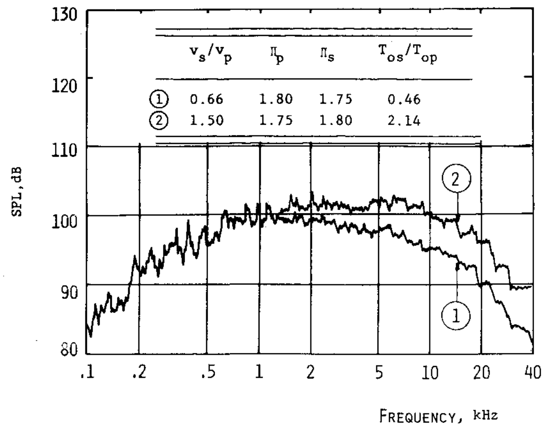


Fig. 10 Comparative spectra at 90 deg for standard and inverted velocity profiles for 8-in. nozzle, $\dot{m}/A = 0.488$ lb/s in.^{2}, $Th/A = 17.86$ lb/in.^{2}.

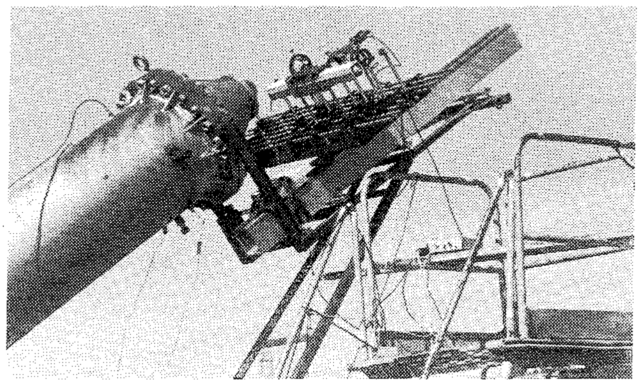


Fig. 11 Photograph of LDV system mounted on free-field test stand.

conditions for the 8-in. nozzle. There is no discernable difference between the two spectra up to about 1000 Hz. However, for higher frequencies, the inverted profile becomes increasingly noisy as compared to the conventional profile. The noise spectra at 90 deg to the jet axis are thought to give the most direct information about the characteristics of the sound sources themselves. This is because the sensor at 90 deg sees the radiation from the source region without that sound being altered significantly due to oblique propagation through the turbulent shear layer, or by the effects of convective amplification and Doppler frequency shifts. The comparative spectra in Fig. 10 seem to indicate that the inverted velocity profile causes an increase in the gross strength of the high frequency sound sources while not appreciably changing the strength of the low frequency sources. Then, if the sound sources themselves are randomly oriented so that there is no inherent preferred orientation to the source radiation, the noise reduction at lower angles associated with the inverted velocity profile must be primarily due to effects other than source modification.

Results of LDV Measurements

In order to gain further insight into the noise generation mechanism of coannular flows, fluid dynamic measurements were carried out in the flowfield of a coannular nozzle using a laser velocimeter (LDV). Since it was desired to make these measurements for a heated flow where the difference in noise measured for the standard and inverted profiles is greatest, it was necessary to conduct the experiments in the free-field facility where heated flow can be produced. A special support structure was fabricated to mount the LVD in a position to make measurements in this facility. Figure 11 shows the free-field facility with the support structure in position and with laser and optics mounted on a rail-platform assembly. The

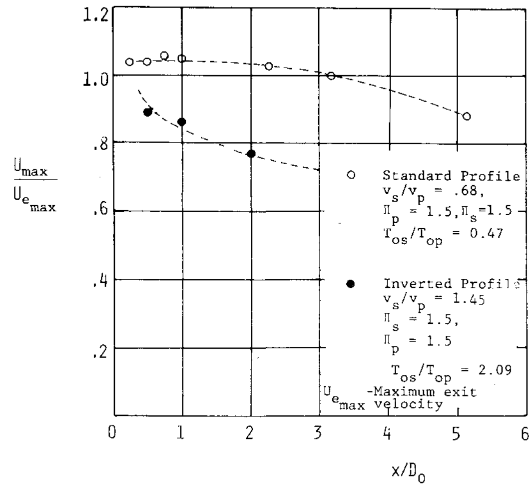


Fig. 12 Comparison of maximum mean velocities for standard and inverted profiles: $\dot{m}/A = 0.337$ lb/s in.^{2}, $Th/A = 12.10$ lb/in.^{2}.

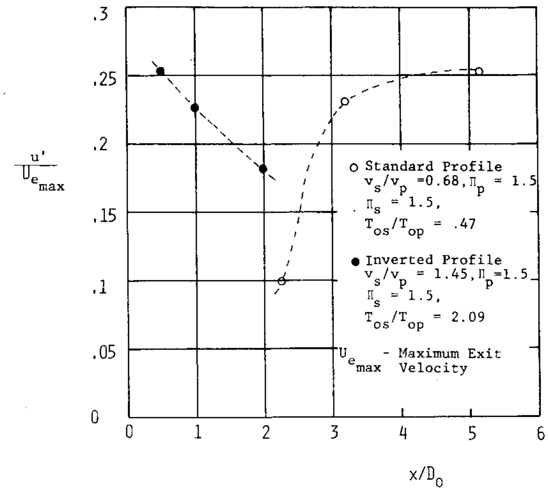


Fig. 13 Comparison of turbulence velocities for standard and inverted conditions: $\dot{m}/A = 0.337$ lb/s in.^{2}, $Th/A = 12.10$ lb/in.^{2}.

support structure was designed to accommodate a traversing system with two degrees of freedom so that velocity and turbulence profiles can be obtained at several axial stations in the flowfield.

Two comparable flow conditions with $Th/A = 12.1$ lb/in.^{2} and $\dot{m}/A = 0.337$ lb/s in.^{2} were selected for the LDV measurements. In order to allow sufficient run time to obtain profile data, the experiments were carried out using the 4-in coannular nozzle. The results of these measurements are summarized in Figs. 12 and 13, showing the decay of the maximum mean velocity and the change in maximum turbulence intensity with axial distance. These results reveal clearly great differences in the flowfields of the conventional and inverted conditions in the first few diameters. For the inverted flow, the maximum mean velocity drops very rapidly initially and quickly reaches a plateau value at about the inner jet velocity. On the other hand, the maximum mean velocity of the conventional profile flow remains near the inner jet exit velocity for several diameters before beginning to decay. Thus, there is a region of several diameters where the maximum velocity of the conventional flow is substantially higher than that of the inverted flow.

The turbulence intensity profiles indicate that, as expected, near the nozzle exit plane the turbulence level for the inverted profile is much higher than for the standard profile. This suggests that the noise sources in that region are greater for the inverted profile, and is consistent with the increase of high frequency noise observed for that type flow.

Unfortunately, this phase of the experimental program had to be curtailed before data could be obtained on the inverted profile for axial positions greater than $x/D_0 = 2$. It is expected that if data were taken further downstream, the curves for the standard and inverted profiles would come together gradually. Both the maximum mean velocity and maximum turbulence velocity should asymptotically approach the $1/x$ decay rate predicted by turbulent jet theory.

Mechanism of Noise Reduction

The most widely accepted current theories of jet noise view the sound radiation from turbulent jets as originating from moving quadrupole sources embedded in a co-moving fluid. In this view, the major factors contributing to the jet noise radiation pattern are: the strength and directivity of the quadrupole sources associated with turbulent velocity fluctuation, the convective amplification and Doppler frequency shift associated with the motion of these sources, and the alteration of the emitted sound field due to its transmission through a turbulent moving medium.

In the theory developed by Lighthill,[6] in which the interaction of the sound with the flow is neglected, the far-field intensity distribution for subsonic jets is given by:

$$I(R,\theta) \propto \frac{\rho_m^2 V_j^8 D^2}{\rho_0 a_0^5 R^2} \times \frac{f(\theta)}{(1-M_c\cos\theta)^5}$$

The convection velocity V_c is normally taken as 0.65 of the jet velocity. The function $f(\theta)$ allows for the inherent directionality of the source distribution and it is argued that this should be constant. The factor $(1-M_c\cos\theta)^{-5}$ that appears in the equation accounts for the motion of the quadrupole sound sources and is referred to as the convective amplification factor. This factor produces a sound intensity distribution that is focused forward, in the direction of the jet flow.

The interaction of the sound generated by the moving quadrupoles with the mean flow cannot be simply expressed quantitatively. One can say that the sound field should be governed by some kind of convected wave equation in the moving medium rather than the usual acoustic wave equation for a medium at rest. Qualitatively, one of the major effects of the sound-flow interaction is a refraction effect which for circular jets and coannular jets with conventional profiles tends to refract the sound away from the jet axis and creates a quiet zone along that axis. This effect is accentuated for heated jets and for coannular flows with the inner flow heated where temperature gradients, as well as velocity gradients, affect the sound transmission.

Comparison of the sound pressure spectra at 90 deg for the inverted and conventional profiles presented in Fig. 10 revealed very little difference between the low and mid frequencies with the inverted profiles being slightly louder at high frequencies. The conclusion was, therefore, drawn that the sound reduction at 30 deg was not mainly due to source modification, but rather had to be associated with either convective or refractive effects as well. Each of these will now be examined to determine whether they offer a possible explanation for the noise reduction.

The forward beaming of sound due to the motion of the sound sources depends primarily on the mean flow velocity through the convective Mach number in the factor $(1-M_c\cos\theta)^{-5}$. If the maximum mean velocity of the flow is reduced, the sound intensity at small and moderate angles to the jet axis will be reduced in accordance with the stated convection factor. This reduction is over and above any due to the source strength modification. Comparative mean velocity data of Fig. 12 for the conventional profile and the inverted profiles show that the maximum mean velocity for the inverted profiles decays much more quickly than for the conventional profiles. This is because the high velocity jet exhausting from a comparatively thin annulus is slowed relatively quickly by the high turbulent shear forces acting on it. Thus the overall convective amplification effects should be smaller for the inverted profile causing a reduction of noise at small and moderate angles to the jet axis.

An estimate of the difference in intensity level at 30 deg due to the difference in convection effects can be made for the standard and inverted profile conditions given in Fig. 12. Taking $V_c(x) = 0.65\ U_{max}(x)$ and calculating the ratio of contributions to the intensity over the range of axial distances where $U_{max}|_{inv} \approx 0.75 U_{max}|_{std}$ yields

$$\left.\frac{I_{std}}{I_{inv}}\right|_{30\,deg} = 25.8$$

or

$$\Delta IL = \Delta SPL = 14 \text{ dB}$$

Finally, it has been observed that the differences between the conventional and inverted profiles are greatly enhanced when the velocity differences are produced by increasing the temperature ratio of the two streams. This result can be explained by considering the mass flow and momentum of the individual streams. When the inverted profile is produced by increasing the pressure ratio of the outer stream while holding the temperature constant, both the mass flow and the momentum of the outer flow are increased. On the other hand, if the inverted profile is produced by increasing the total temperature of the bypass stream while maintaining the same pressure ratio, the mass flow of the outer stream decreases inversely with the square root of the temperature and momentum remains constant. In this case, the hot bypass air will rapidly lose its momentum by mixing with the cold ambient air and the convective amplification effect will be decreased.

Next, consider the interaction between the radiated sound and the mean flow to determine whether the refractive effects can be responsible for the noise reduction observed for the inverted profiles. Mention has been made of the fact that conventional velocity and temperature profiles, where the velocity and temperature are decreasing radially, tend to bend the sound rays outward away from the jet axis and create a "quiet zone" along the axis. Conversely, sound rays encountering velocity and temperature increases radially, tend to bend back toward the jet axis. Sound rays impinging normally on this shear layer in the 90 deg direction, tend to be transmitted through with very little alteration, while sound rays striking the shear layer obliquely tend to be partially reflected back into the flow and thus partially ducted down the flow tube.

Since the characteristic impedance of air is a strong function of temperature, it is clear that increasing the temperature of the outer stream would enhance the effect of the inverted velocity profile on sound transmission. Indeed, Ahuja and Dosanjh[7] have shown that a heated annular flow can act as a shield to the noise generated by a cold inner jet even if the flow velocities are the same.

It appears then that both the convective amplification phenomena and the interaction of the transmitted sound with the mean flow could be contributing to the advantage that the inverted profile exhibits in sound radiation over the conventional profile. Cargill and Duponchel[2] have mentioned both of these phenomena as possibly being responsible for the noise reduction although they favor the acoustic-flow interaction. It appears to the authors of this paper that the reduced convective amplification is at least as important as the acoustic-flow interaction.

Conclusions

The results of this study show that coannular flows with inverted velocity profiles are quieter than standard velocity profiles at the same thrust and mass flow. The acoustic differences between these two types of flow are much greater when the velocity differences between the inner and outer streams are caused by changes in the stagnation temperatures rather than by changes in the stagnation pressure ratios of the primary and secondary flows. The major differences in the sound fields occur at angles less than 45 deg from the jet axis, where the greatest noise is radiated, and result from a reduction of the peak frequency noise of the standard profile.

The reduction in noise obtained by the inverted velocity profile is thought to be largely due to the rapid decay of the maximum mean velocity that occurs compared to the standard velocity profiles. This implies that the source convection velocity is reduced with a corresponding reduction in sound radiated near the jet axis. The fact that the effect is enhanced when the secondary flow is heated is due to the fact that the low density, high temperature secondary air loses its momentum more rapidly by mixing with the cold ambient air.

Acknowledgments

The authors express their appreciation to the Federal Aviation Administration which sponsored this research under Contract DOT-FA72WA-3053. Program managers for the contract were Robert Zuckerman and Ron Padgett. Appreciation is also expressed to Michael Farmer and James Hornkohl who performed the LDV measurements. James Goodman provided valuable assistance in all phases of the experimental program.

References

[1] Packman, A. B., Kozlowski, H., and Gutierrez, O., "Jet Noise Characteristics of Unsuppressed Duct Burning Turbofan Exhaust System," AIAA Paper 76-149, Jan. 1976.

[2] Cargill, A.M. and Duponchel, J.P., "The Noise Characteristics of Inverted Velocity Profile Coannular Jets," AIAA Paper 77-1263, Oct. 1977.

[3] Goethert, B.H., Maus, J.R., Dunnill, W.A., Dathe, I., Venkitarama, S., and Batis, L., "Investigation of Coannular Nozzles with Conventional and Inverted Velocity Profiles," Federal Aviation Administration Rept. FAA-RD-78-32, April 1978.

[4] Kozlowski, H. and Packman, A.B., "Aerodynamic and Acoustic Tests of Duct Burning Turbofan Exhaust Nozzles," NASA CR 2628, Dec. 1978.

[5] Dosanjh, D.S., Bhutiani, P.K., and Ahuja, K.K., "Supersonic Jet Noise Suppression by Coaxial Cold/Heated Jet Flows," *AIAA Journal*, Vol. 16, March 1978, pp. 268-270.

[6] Lighthill, M.J., "Jet Noise," *AIAA Journal*, Vol. 1, June 1963, pp. 1507-1517.

[7] Ahuja, K.K. and Dosanjh, D.S., "Heated Fluid Shroud for Noise Reduction—An Experimental Study," AIAA Paper 77-1286, Oct. 1977.