Target-Type Thrust Reverser Noise

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This paper presents some results of an experimental investigation on the noise generated by model target-type thrust reversers. The experimental data are normalized and scaled up to sizes suitable for reversing the core jets of a four-engine STOL airplane, yielding perceived noise levels well above the 95-PNdB design goal for both sideline and flyover at 152 m. V-gutter and semicylindrical reversers were tested with a 5.24-cm-diam circular nozzle, and a semicylindrical reverser was also tested with a 7.78-cm-diam circular nozzle. The ratio of reverser frontal area to nozzle exit area ranged from 2.4 to 7.0. Other tests variables were the spacing between nozzle and reverser, reverser orientation, and nozzle jet velocity. The thrust reversers, in addition to being noisier than the nozzle alone, also had a more uniform directivity. The maximum over-all sound pressure level and the effective sound power level both varied with the 6th power of the nozzle jet velocity.

Nomenclature

A_f = reverser frontal area, m^2
A_n = nozzle area, m^2
C_1,C_2,C_3 = first, second, and third frequency bands exhibiting ground-reflection cancellations, assuming a point source
c_a = ambient speed of sound, m/sec
D_n = nozzle-exit diameter, m
f_c = ⅓-octave-band center frequency, Hz
f_M = the ⅓-octave-band frequency exhibiting the highest sound pressure level, Hz
K = empirical coefficient in sound power correlation, dB
K_1 = empirical coefficient in acoustic efficiency correlation, dimensionless
OAPWL = over-all sound power level, dB *re* 10^{-13} *W*
OASPL = over-all sound pressure level, dB *re* 20 $\mu N/m^2$
PNL = perceived noise level, PNdB
PWL = ⅓-octave-band sound power level, dB *re* 10^{-13} *W*
R_1,R_2,R_3 = first, second, and third frequency bands exhibiting ground-reflection reinforcements, assuming a point source
S_n = nozzle Strouhal number, f_cD_n/U_j
SPL = sound pressure level, dB *re* 20 $\mu N/m^2$
U_j = isentropic nozzle velocity, m/sec
W = sound power, W
X = spacing between reverser and nozzle, m
Y = reverser height, m
Z = reverser width, m
α = angle of reverser to horizontal, deg
η = effective acoustic efficiency, $W/(\rho_a A_n U_j^3)$, dimensionless
θ = microphone angle from nozzle upstream axis, deg
θ_M = angle from nozzle axis at which maximum OASPL occurs, deg
ρ_a = ambient density, kg/m^3

Introduction

IN order to achieve the goal of landing in short distances, jet STOL aircraft may well employ thrust reversers, both for reducing the ground roll after landing and steepening the approach flight path. In particular, for the augmentor-wing-type airplane, high thrust is required through the wing to maintain high lift during approach. Complete or partial inflight reversal of the core jets is thus being considered as a means of reducing forward speed during descent. At the same time, because of the desired capability to operate from airports in heavily-populated areas, STOL aircraft will have to meet much more severe noise limitations than conventional aircraft. Thus, evaluation of the noise associated with thrust reversal is necessary. This paper summarizes data[1] recently obtained at Lewis Research Center and presents the normalization of these data and scale-up to the core jets of a four-engine STOL airplane. Target-type reversers were chosen for this study, primarily because of their simplicity.

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Experimental Apparatus and Procedure

Two test rigs were used to obtain the experimental data. The acoustic data were taken on a rig designed to minimize internal noises and equipped with sound measuring and analyzing instruments. The flow rig described by Huff and Groesbeck[2] was used to obtain data on the effect of the spacing on flow rate.

Acoustic Rig

The acoustic rig is shown in Fig. 1 and described in more detail by Olsen, Dorsch, and Miles.[3] Air was supplied to the nozzle through a pipe equipped with an orifice for flow measurement, a hand-operated flow-control valve, noise mufflers, and a straight run ending at the nozzle. The thrust reversers were mounted on an independent stand.

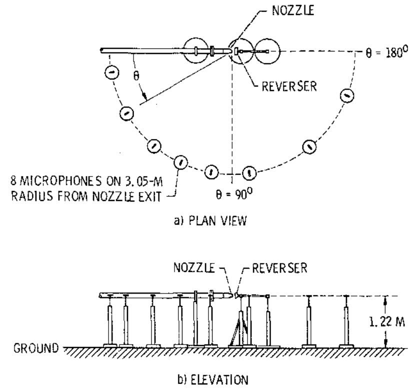

Fig. 1 Acoustic rig schematic diagram.

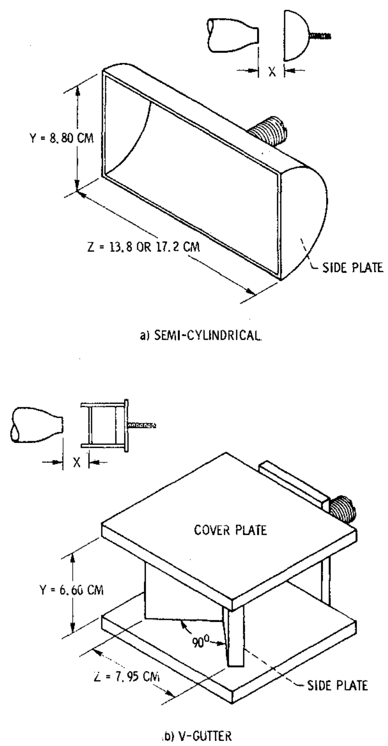

Fig. 2 Small-scale model thrust reversers tested.

The sound was measured by eight condenser microphones on a 3.05-m radius semicircle centered on the nozzle exit and at the same elevation, 1.22 m, from the smooth asphalt surface as the nozzle centerline. The microphones had individual wind screens.

Thrust Reversers

The small-scale thrust reversers used in the experiments are sketched in Fig. 2. Two types of target reversers were tested semicylindrical (Fig. 2a) and V-gutter (Fig. 2b). The reversers had frontal width Z and height Y; the leading edges of the side plates were located at an axial distance X from the nozzle. These reverser dimensions are given in Table 1. Two semicylindrical reversers were used, the only difference between them being the width. Conversion from one to the other was made with removable inserts. The reverser sizes, as indicated by their frontal-area-to-nozzle-area ratio A_f/A_n were selected to fall within the zone of maximum reverse thrust ratio as determined by Povolny, Steffen, and McArdle.[4,5] They found that the maximum thrust-reversal efficiency was obtained at the closest spacing that did not decrease the flow through the nozzle. The acoustic tests were performed at this spacing, termed "optimum," unless otherwise noted.

Experiments

The effect of nozzle jet velocity on noise for various geometric configurations was obtained. The reverser-nozzle combination was set at the spacing and orientation desired. Flow of unheated air was set and regulated by the hand-operated throttle valve controlling the nozzle inlet pressure. After flow conditions stabilized, acoustic data, flow parameters and atmospheric conditions were recorded.

Data analysis

A ⅓-octave-band analyzer determined, for each sample, the sound pressure level in each band from 50 to 20,000 Hz. The three data samples for each microphone were corrected for atmospheric absorption and averaged to eliminate gross errors. The sound pressure levels were 3 dB above freefield values due to ground reflections except for those frequency bands exhibiting cancellations or reinforcements. No correction is made to freefield values in this report. From these data, the over-all sound pressure level OASPL was calculated for each microphone. The effective spectral sound power level PWL was obtained by integration over a hemisphere with radius equal to the microphone circle radius; the integration is performed only over one hemisphere since the sound pressure levels are assumed 3 dB above freefield values. The effective over-all sound power level OAPWL was then computed. In principle, the noise measured may be a function of the angle of the microphone-circle plane to the reverser, and the data are for one plane only; hence, these power levels are termed "effective." However, it should be noted that rotating the reverser 90° had very little effect on the effective power levels, as discussed later herein.

Results

The experimental test conditions and major results are given in Table 1; the detailed results have previously been reported.[1]

Effect of Thrust Reversal on Noise

The effects of thrust reversal on noise directivity pattern and spectral distribution are shown in Fig. 3, at optimum spacing. Data for the smaller nozzle with and without smaller semicylindrical reverser are compared at an isentropic nozzle jet velocity of 294 m/sec, and with the reverser orientation horizontal.

Directivity

Figure 3a is a polar plot of the OASPL against angular position θ. The nozzle-alone jet has a maximum OASPL of 107 dB at 160°; its directivity is very pronounced. In comparison, the noise pattern for the reverser appears

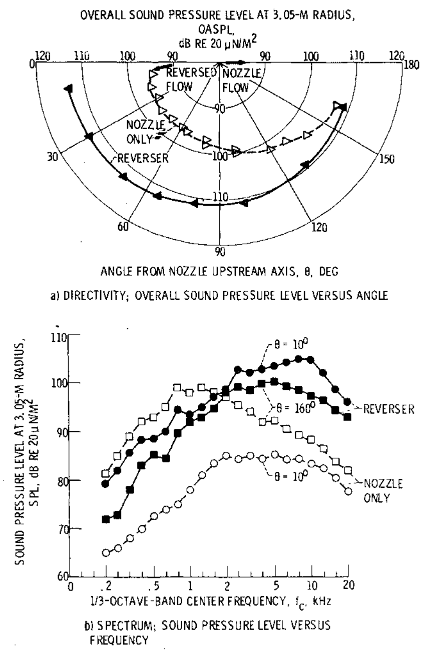

Fig. 3 Effect of thrust reversal on noise; 5.24-cm nozzle with and without smaller semicylindrical reverser at nozzle jet velocity, $U_j \sim$ 294 m/sec; horizontal orientation and zero spacing (optimum).

nearly uniform. The maximum OASPL is 113 dB, 6 dB more than the nozzle alone, and the minimum OASPL of 108 dB is about 1 dB above the maximum for the nozzle alone. The angle of maximum OASPL is 10° with the reverser.

SPL spectrum

Figure 3b shows the effect of thrust reversal on the noise spectra at 10° and 160°, the angles of maximum OASPL for the reverser and nozzle, respectively. For the nozzle alone the peak SPL occurs at 1250 Hz in the direction of the maximum OASPL, $\theta = 160°$, while at $\theta = 10°$, the SPL has a flat peak in the 2000-6300-Hz range. The difference in SPL for the two angles is greatest at low frequencies. The effect of angular position on the noise spectrum is much less with the reverser than for the nozzle alone. The increased noise observed with the reverser is seen to occur at high frequencies, with the low-frequency noise being in the range of that of the nozzle alone. It should be noted that for the nozzle alone, the peak-SPL frequency shifts to higher values as the angle shifts away from the maximum-OASPL direction, whereas with thrust reversal, there is little effect.

Effect of Velocity on Thrust Reverser Noise

Maximum OASPL

The variation of the maximum OASPL with velocity is shown in Fig. 4. This figure includes data for all of the reverser-nozzle combinations tested, at their optimum spacings. In addition to the reverser data, an eighth-power line drawn through the nozzle-alone datum is included for comparison. The reverser data follow a 6th-power relation with nozzle jet velocity over the range tested. All the semicylindrical reverser data fall on nearly the same line and the V-gutter data are about 5 dB higher. Note that the maximum OASPL with the reverser mounted vertically is less than 1 dB more than for the reverser mounted horizontally. At high jet velocity, the quietest of the reversers is 6 dB louder than the nozzle alone, and at lower velocities this difference increases. For the V-gutter the maximum OASPL is 14 dB greater than the nozzle alone at high jet velocity.

SPL spectrum

The effect of nozzle jet velocity on the SPL spectrum at the angle of maximum OASPL is shown for both the smaller semicylindrical reverser (Fig. 5a) and the V-gutter reverser (Fig. 5b), both with the smaller nozzle. The frequencies for cancellations and reinforcements due to ground reflections, assuming a point source, are tagged on the abscissa. In neither configuration is there a definite increase in peak-SPL frequency with increasing velocity; in fact, for the V-gutter, the peak is quite pronounced at 1250 Hz for each velocity. At other angles, for the semicylindrical reversers, the expected relation between peak-SPL frequency and velocity is obtained. This 1250-Hz peak with the V-gutter is observed in all directions.

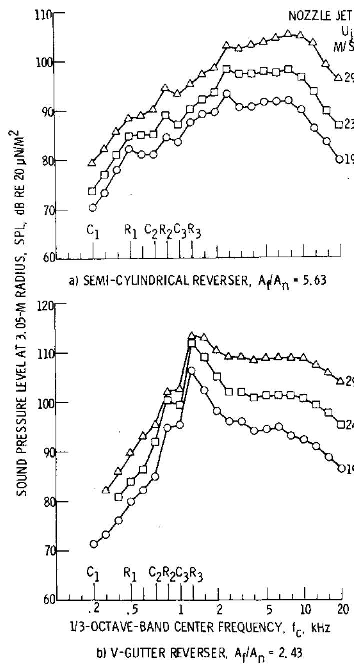

Fig. 5 Effect of nozzle jet velocity on sound pressure level spectrum at angle of maximum over-all sound pressure level, 10°. Horizontal; optimum spacing; nozzle diameter, 5.24 cm.

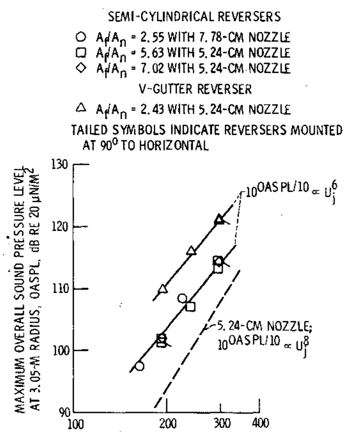

Fig. 4 Effect of nozzle jet velocity on maximum over-all sound pressure level at optimum reverser spacing.

Effects of Geometric Variables on Thrust Reverser Noise

Spacing

Decreasing the spacing from the optimum value sharply reduces the reverser efficiency, while increasing the spacing reduces the efficiency slightly, if at all. For spacings greater than optimum the noise level increases through some range of spacing, and for one case, there was "screech," a dominant single tone.[1]

Area ratio

For the smaller nozzle, increasing the ratio of the area of the semicylindrical reverser to that of the nozzle from 5.6 to 7.0 had very little effect. Similarly, for a fixed reverser area, increasing the nozzle diameter from 5.24 to 7.78 cm yielded no significant increase in noise level for a given velocity, as can be seen in Fig. 4; this is an area ratio decrease from 5.6 to 2.4. This result is somewhat surprising since for a fixed velocity the nozzle area, and hence the airflow, are increased by a factor of 2.2. But, the thrust reversal may be less efficient, which would be consistent with lower exiting velocities and, hence, noise levels. Thus, it appears that for small area ratios, the noise level may decrease with decreasing area ratio, an effect which might offset the increase expected due to nozzle area increase. However, this result has not yet been confirmed by any further tests.

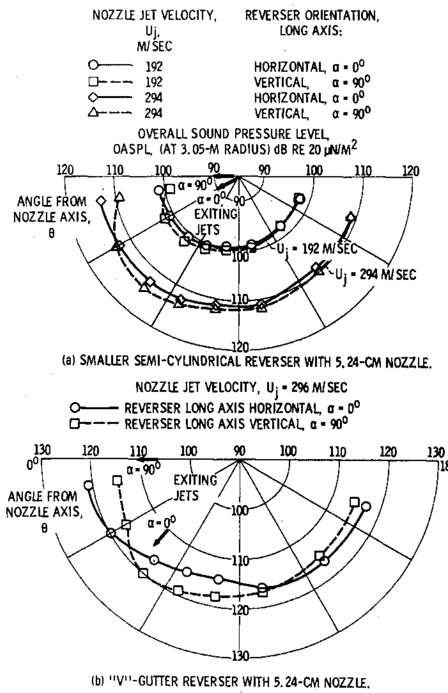

Fig. 6 Effect of reverser orientation on directivity of over-all sound pressure level.

Orientation

The effect of reverser orientation on the noise directivity is illustrated in Fig. 6. The smaller semicylindrical reverser (Fig. 6a) and the V-gutter rerser (Fig. 6b) are mounted vertically with the smaller nozzle. This position simulates flyover. As shown in Fig. 4, the maximum OASPL is about 1 dB greater than for the reversers mounted horizontally. The over-all power level is also increased about 1 dB (Table 1). For the vertical position, the reverser noise pattern is slightly more directional, and the maximum OASPL is at 50° for both reversers.

Normalization of Data

Over-all sound power level

As shown in Fig. 4, the maximum OASPL increases with the 6th power of the nozzle jet velocity, as expected for dipole noise. This is also true of the effective total power as shown in Fig. 7, where the effective acoustic efficiency $\eta = W/\rho_a A_n U_j^3$ is plotted against the ratio of nozzle jet velocity to the ambient speed of sound. The data for each reverser-nozzle combination at the optimum spacing follow a relation of the type $\eta = K_1(U_j/c_a)^3$ over the range tested, or in OAPWL

$$\text{OAPWL} = 130 + K + 10 \log \frac{\rho_a A_n U_j^6}{c_a^3}$$

The data agree within ±1 dB with the faired line for each configuration, where K is −31.3 dB for the V-gutter reverser, −37.0 dB for the semicylindrical reversers with the smaller nozzle, and −39.5 dB for the smaller semicylindrical reverser with the larger nozzle.

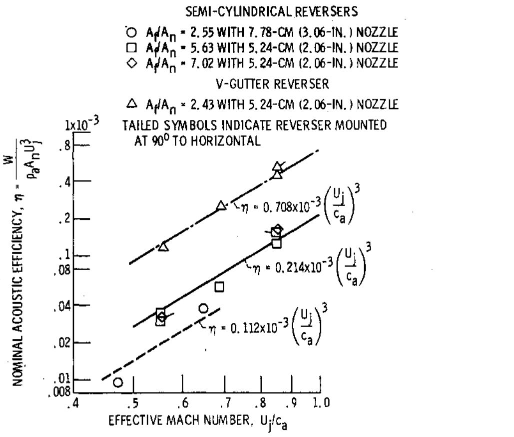

Fig. 7 Nominal acoustic efficiency as a function of effective Mach number at optimum reverser spacing.

Sound-pressure-level spectra on sideline

In order to facilitate sideline and flyover noise calculations, normalized SPL at 3.05 m are given. The normalized sound pressure level SPL-OAPWL for the 3.05-m sideline is plotted against nozzle Strouhal number $S_n = f_c D_n/U_j$. Figure 8 presents such a normalization for the smaller semicylindrical reverser mounted at 90° to the horizontal, simulating flyover, with the smaller nozzle.

Table 1 Summary of experimental data at optimum spacing

Test conditions							Major results			
Height, Y, cm	Reverser Width, z, cm	Reverser Area ratio, A_f/A_n	Nozzle diameter, D_n, cm	Spacing ratio, X/D_n	Angle to horizontal, α, deg	Nozzle jet velocity, U_j, m/sec	Effective over-all power, OAPWL, dB re 10^{-13} W	Frequency for maximum PWL, f_M, Hz	Maximum OASPL, (at 3.05 m) dB re 20 $\mu N/m^2$	Angle for maximum OASPL, θ_M, deg
No reverser										
—	—	—	5.24	—	—	294	129	1250	107	160
Cylindrical reverser										
8.80	13.8	5.63	5.24	0	0	294	139	6300	113	10
					0	238	133	4000	107	10
					0	192	127	2000	101	10
					90	293	140	6300	114	50
					90	192	128	6300	102	30–50
	17.2	7.02			0	296	140	10000	114	10
	17.2	7.02				193	128	5000	102	10
	13.8	2.55	7.78	0.84		225	134	2500	108	30
	13.8	2.55	7.78	0.84		164	124	1250	98	30
V-gutter reverser										
6.60	7.95	2.43	5.24	0.85	0	296	144	1250	121	10
					0	240	139		116	10
					0	194	133		110	10
					90	296	145		120	50

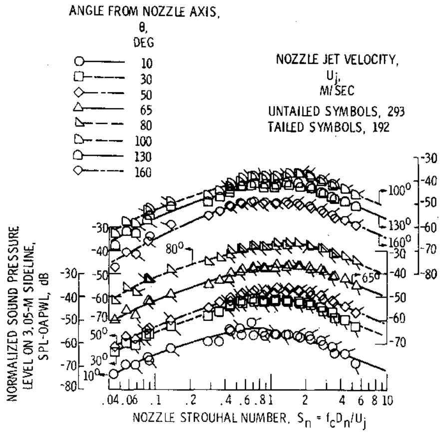

Fig. 8 Normalized sound pressure level on 3.05-m sideline for smaller semicylindrical reverser mounted vertically with 5.24-cm nozzle.

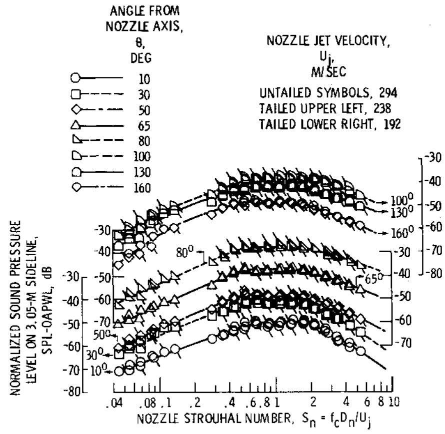

Fig. 10 Normalized sound pressure level on 3.05-m sideline for smaller semicylindrical reverser mounted horizontally with 5.24-cm nozzle.

Frequency bands influenced by ground reflections, assuming a point source, are not plotted. Such normalized SPL data are a function of angle from the nozzle axis, or distance from the source, as can be seen in Fig. 8. Similar normalization plots are given for the other configurations in Appendix A.

Scale-Up Calculations

From the normalized data given in Fig. 8 and Appendix A, and the over-all sound power level relation, the thrust reversal noise may be computed for fullscale applications. The example illustrated here is for inflight core-jet reversal on a 45 400-kg four-engine, augmentor-wing-type airplane at the 152-m flyover point.

The performance of a single engine with reverser may be calculated from Fig. 8 and the OAPWL equation. First, the SPL along the ground at the 152-m flyover point is calculated. These data are corrected for standard-day atmospheric absorption and the perceived noise level then calculated; 6 PNdB are added to account for the four engines. No account is made of any reflection by the wing, but the 3-dB broadband ground reflection is included. This series of calculations is performed for three different velocities, with the size of the nozzle adjusted to maintain the same thrust.

The results of these calculations are shown in Fig. 9; for even the lowest velocity, the calculated noise levels are well in excess of the 95-PNdB design goal. At higher velocities, the peak noise level is increased, and a larger area is exposed to noise levels in excess of 95 PNdB. From these results, it is apparent that noise considerations may well limit the use of reversers, at least of the target type, for STOL applications.

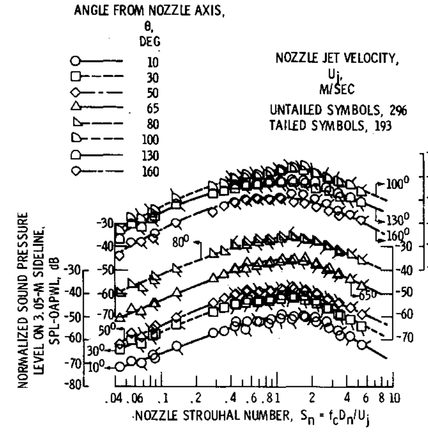

Fig. 11 Normalized sound pressure level on 3.05-m sideline for larger semicylindrical reverser mounted horizontally with 5.24-cm nozzle.

Conclusions

1) The model target-type reversers were significantly noisier than the nozzle alone by at least 6 dB. Test results, when scaled up to conditions suitable for a four-engine STOL aircraft, showed that noise levels would be above the present design goal of 95 PNdB. This indicates that target-type core flow reversers used during STOL flights will constitute an important noise source.

2) The noise directivity patterns for target-type reversers are very uniform. No more than 6 dB variation in OASPL was encountered among all of the angular direc-

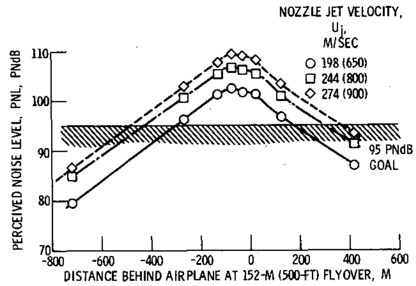

Fig. 9 Perceived noise level at 152-m (500 ft) flyover for inflight core-jet reversal on 45 400-kg (100,000 lb) augmentor-wing-type airplane at various nozzle jet velocities.

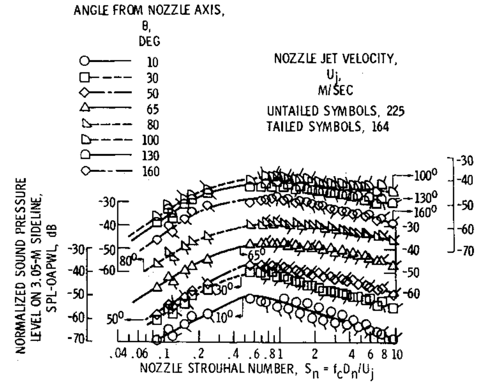

Fig. 12 Normalized sound pressure level on 3.05-m sideline for smaller semicylindrical reverser mounted horizontally with 7.78-cm nozzle.

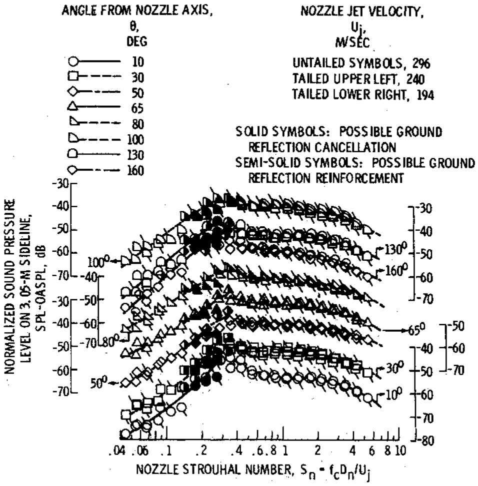

Fig. 13 Normalized sound pressure level on 3.05-m sideline for V-gutter reverser mounted horizontally with 5.24-cm nozzle.

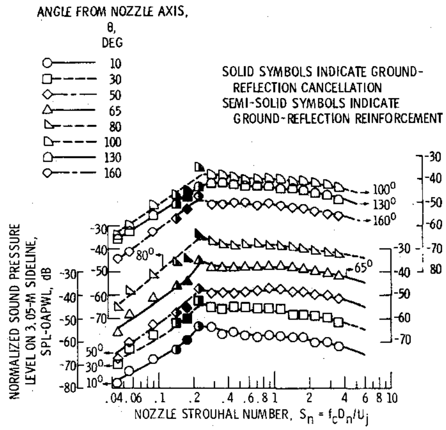

Fig. 14 Normalized sound pressure level on 3.05-m sideline for V-gutter reverser mounted vertically with 5.24-cm nozzle. Nozzle jet velocity, U_j = 296 m/sec.

tions tested, either in the plane of the exiting jets or at 90° to that plane. Maximum values of OASPL occurred between the angles of 10–50° from the nozzle upstream axis, depending on the particular configuration. The uniformity of the noise directivity extended to the spectral distribution.

3) The maximum over-all sound pressure level and the effective over-all sound power level at optimum spacing followed a 6th-power relation to isentropic nozzle jet velocity over the range of velocity tested for each geometric configuration. The effective over-all sound power level was correlated empirically as a function of the jet velocity and area and ambient density and speed of sound for each configuration.

4) Plots are given of normalized sideline sound pressure levels against nozzle Strouhal number. The plots at each microphone angle for each configuration, along with the overall power level correlation, allow scale-up calculations to be performed.

Appendix A: Normalized Sideline Spectra

In order to facilitate sideline and flyover noise calculations, plots of the normalized sound pressure level against nozzle Strouhal number are given herein. Frequency bands influenced by ground reflections, assuming a point source, are generally not plotted.

Figure 8 is for the smaller semicylindrical reverser mounted vertically with the smaller nozzle; in Fig. 10, the same configuration is rotated to the horizontal position. Figure 11 is for the larger semicylindrical reverser mounted horizontally with the smaller nozzle. The spectra for the smaller semicylindrical reverser mounted horizontally with the larger nozzle are shown in Fig. 12.

Data for the V-gutter reverser with the smaller nozzle are shown in Fig. 13 and 14. Because the peak sound pressure levels occur in ground-reflection-affected bands of 1000 and 1250 Hz, these values are plotted without correction. Since these are the third cancellation and reinforcement, respectively, any corrections would be small. Figure 13 is for the normal horizontal position, and Fig. 14 is for the vertical position.

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