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OVER-THE-WING MODEL THRUST REVERSER NOISE TESTS

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ABSTRACT

Experimental results are presented for static acoustic tests of a 1/12 scale model over-the-wing target type thrust reverser. The model configuration simulates a design that is applicable to the over-the-wing short-haul advanced technology engine. Aerodynamic screening tests of a variety of reverser designs identified configurations that satisfied a reverse thrust requirement of 35 percent of forward thrust at a nozzle pressure ratio of 1.29. The variations in the reverser configuration included, blocker door angle, blocker door lip angle and shape, and side skirt shape. Acoustic data are presented and compared for the various configurations. The model data scaled to a single full size engine show that peak free field perceived noise levels at a 152.4 meter sideline distance range from 98 to 104 PNdB.

INTRODUCTION

It is expected that future Short Takeoff and Landing (STOL) aircraft will employ jet thrust reversers in order to minimize ground roll on landing. One of the advanced technology engines being built as part of the Quiet, Clean Short-Haul Experimental Engine (QCSEE) Program, currently being sponsored by NASA Lewis Research Center, is to be used in an over-the-wing (OTW) configuration. It appears that a target type reverser which captures the fan and core flows and directs the jet upward and forward from the wing surface has some advantages for this aircraft configuration. This type of reverser will eliminate re-ingestion of exhaust gases and ground debris ingestion, and will also increase wheel loading for additional braking capability (ref. 1).

Target type reversers have received a considerable amount of experimental study in terms of reverse thrust aerodynamic performance. However, the noise generating characteristics of the device have not received as much attention until recently, with the advent of STOL aircraft and their associated stringent noise goals (e.g., refs. 2 to 5). The device is an inherently strong noise source since

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it consists of a surface placed within several diameters downstream of the nozzle exit where the jet impingement velocity is close to the nozzle exhaust velocity. The effect on a sideline observer depends on the radiation pattern and spectral distribution of the source.

This paper presents the results of an experimental program to determine the static noise generating characteristics of a target type reverser employed in an OTW configuration. Specifically, the results were obtained with a 1/12 scale model QCSEE OTW reverser. The scale model was obtained from the Langley Research Center where it was tested for aerodynamic performance. The aerodynamic criterion established for the model was that it provide a reverse thrust value of 35 percent of the forward thrust at a nozzle pressure ratio of 1.29. Various configurations were tested to determine those configurations that satisfied the criterion. The variations consisted of blocker door angle, blocker door lip angle, and side skirt angle and shape. Several configurations were identified that satisfied the aerodynamic requirements. A complete summary of these tests is reported in reference 6. The model was then installed in an acoustic test rig at the Lewis Research Center and tests were performed over a range of nozzle pressure ratios for the various configurations to determine acoustic characteristics.

The acoustic data consist of one-third-octave band spectra at a 4.6 meter radius and various angular locations around the model test setup. Overall sound pressure levels were calculated for the model. Calculations were also made of free field sideline perceived noise levels scaled to a single full size engine. The experimental spectral data and calculated sideline PNL data were obtained for each reverser configuration.

In addition to the acoustic tests, reverse thrust measurements were taken in a separate facility at Lewis. This was done to establish repeatability of test conditions between the two NASA Centers.

APPARATUS AND PROCEDURE

Facility

A schematic drawing of the acoustic facility is shown in figure 1. A butterfly valve controlled the flow of pressurized (0.9 MN/m^2) unheated (290 K) air to the model. An internally baffled and acoustically lined muffler absorbed the noise generated by flow through the valve. The model was mounted at the end of a 2.5-meter long stright section of pipe with the flow discharging vertically upward and to the sides. Nozzle total pressure and temperature were measured at approximately 1.5 meters upstream of the model. Flow rate was measured by an orifice located upstream of the flow control valve.

The noise data were measured by eight 0.635-cm diameter condenser microphones placed at 20° intervals on a 4.6-meter radius semicircle centered at the nozzle exit (charging station, see fig. 2). The microphone circle was in a horizontal plane that was 1.7 meters above grade and passed through the nozzle axis. A standard piston calibrator (124±0.2 dB, 250 Hz tone) was used to calibrate the microphones. Foam rubber pads, 20.3 cm thick, were placed inside the microphone circle to eliminate ground reflections in the frequency range of interest (>630 Hz). The noise data were analyzed by a one-third octave band spectrum analyzer referenced to 2×10^{-5} newtons per square meter.

A separate flow facility was used to make reverse thrust measurements for the models. A detailed description of this facility is given in reference 7. Essentially, it consisted of an air supply system, flow measuring instrumentation (pressure, temperature, weight flows), and force measuring instrumentation (axial and normal directions).

Test Models

Model hardware definitions and dimensions are given in figure 2. Conceptually, the blocker door of the reverser is formed by rotating the upper surface of the forward thrust nozzle about the pivot point shown in the figure. The lip and side skirts on the blocker aid in turning the flow in the forward direction. The throat diameter (charging station) of the nozzle is 13.97 centimeters.

Constant values of the ratios L/D, X_p/D, and H_B/D, were used in the tests for this paper. The numerical values for the ratios listed in figure 2 were recommended in reference 6, after the reverser development program for aerodynamic performance was complete. The test variables for the acoustic results presented herein are shown in the table in figure 2 and include blocker door angle, lip angle and shape, and skirt shape.

A photograph of the model is shown in figure 3(a) In this view the model is equipped with the tabbed skirts and blunt lip. The model is shown mounted in the acoustic facility in figure 3(b) with the plain side skirts and round blocker door lip installed.

Procedure

For each configuration acoustic and aerodynamic data were taken with and without leakage flow, since some leakage might occur in the full scale application. Leakage flow is that part of the nozzle efflux that passes through the spaces between the blocker door and nozzle side walls. To prevent leakage flow, the spaces were merely blocked off with putty and aluminum tape.

The test procedure was to obtain steady flow conditions for a given nozzle pressure ratio (nozzle total pressure divided by atmospheric pressure). Nozzle pressure ratios tested were 1.15, 1.20, 1.25, and 1.3. Three noise data samples were taken at each microphone location in the sideline plane for each nozzle pressure ratio. An atmospheric loss correction was applied to the average of the three samples to give lossless sound pressure level data at 4.6 meters. From the lossless sound pressure level spectra, overall sound pressure levels were calculated for each microphone location.

Tests were made with and without the foam pads placed inside the microphone circle. The results showed a reduction of sound pressure levels of 1 to 2 dB from 1000 Hz to 20 kHz when the pads were in place. The theoretical high frequency asymptotic reflection for this facility was 2.1 dB. Therefore, no corrections were made for ground reflections and the data were assumed to be free field; the low frequency error introduced by this assumption does not effect full scale perceived noise levels.

AERODYNAMIC RESULTS

General

Aerodynamic thrust reverser performance is presented to indicate the degree of repeatability between the tests at the Langley and Lewis Research Centers. A comparison of the aerodynamic results from the Langley and Lewis Research Centers for the same configurations (without leakage flow) is shown in figure 4. The reverser thrust at various nozzle pressure ratios is divided by the forward thrust at a pressure ratio of 1.29 (or takeoff thrust) and plotted as a function of the reverse thrust nozzle pressure ratio. The value for the forward thrust was obtained from the work performed at Langley for a given nozzle alone reference configuration.

The air flow rates for the data obtained at Lewis were about 10 percent less, for this configuration, than that reported for the data from Langley. No reason for this discrepancy is available at the present time. Correcting the data for the difference in flow rate would cause less agreement at high values of nozzle pressure ratio and better agreement at low nozzle pressure ratios.

For this particular model, during the aerodynamic tests flow rates with leakage ranged as high as 7 percent greater than those without leakage at a nozzle pressure ratio of 1.3. The ratio of reverse thrust to takeoff thrust for the configurations with leakage ranged from 0.35 to 0.37 at a nozzle pressure ratio of 1.3. Therefore, with this amount of leakage it appears that it is not possible to operate at lower nozzle pressure ratios and still meet the aerodynamic performance requirements.

Effect of Configuration Changes

Several examples of the effect of configuration changes on the performance of the model thrust reverser based on the results obtained at Lewis are given in figure 5.

Effect of flow turning angle. - The variation of the ratio of reverse thrust to takeoff thrust with flow turning angle (variable α and β) is shown in figure 5(a). The trends shown in the figure are similar to results obtained from other combinations where both the blocker door angle, α, and lip angle, β, were varied while holding the other parameters constant (i. e., constant lip shape and skirt configuration). Varying the blocker door angle only, or the lip angle only did not result in any significant change in reverse thrust. Note in figure 5(a) that the flow rate ratio for the 105° blocker door angle is about 11 percent greater than that for the 115° angle setting. This flow rate change is caused primarily by the change in blocker door angle. Results from other configurations where the lip angle was changed while holding the blocker door angle constant gave flow rate changes that were insignificant. It should be noted that increasing the flow turning angle reduced the downward force measured normal to the nozzle axis. Since aircraft wheel loading is augmented by this force component, it follows that increasing the flow turning angle of the thrust reverser reduces the mechanical braking capability of the aircraft.

Effect of skirt configuration. - Increasing the skirt length (tabbed skirt configuration in fig. 2) also gave a small increase in reverse thrust as shown in figure 5(b). As suggested in reference 6 the increased skirt length apparently is more efficient in capturing the spillage flow from the nozzle.

Effect of lip shape. - Variable lip shape (blunt or round) had essentially no effect on the magnitude of reverse thrust (for comparison of lip shapes see figs. 3(a) and (b)). However, the downward normal force component (normal to nozzle axis) was increased by about 50 percent when the blunt shape lip was used in place of the round lip. Apparently, the extended sides of the blunt lip contain the flow so that the normal flow component is increased.

ACOUSTIC RESULTS

The thrust reverser configuration having tabbed skirts, blocker door angle, α, of 115°, lip angle, β, of 25° and blunt lip was identified in reference 6 as most suitable in terms of aerodynamic performance. The presentation of the acoustic data is concentrated on this configuration, but enough data is given to judge the relative merits of other configurations tested. The effect of configuration changes is based on consistent data trends. In order to understand the reasons for the changes in sound levels as a result of configuration changes a more detailed study of the flow from the reverser and correlation with the far field noise data is needed. The acoustic data presented are lossless free field data at a distance of 4.6 meters, except as noted.

General

An example of the noise signature of the model OTW thrust reverser in the sideline plane (plane through nozzle axis and parallel to ground) is shown in figure 6. The overall sound pressure level directivity patterns (at constant radius) shown in figure 6(a) indicate that the peak sound level location occurred in the forward quadrant at 20° from the nozzle inlet. The results show that the device is not a highly directional noise radiator since the change in sound level amounted to only 6 dB over the entire circular arc at a nozzle pressure ratio of 1.3. At lower nozzle pressure ratios the change in sound levels was even less. Overall sound pressure levels varied somewhat between model configurations, but directivity patterns were about the same for all configurations tested.

Variation of one-third-octave band sound pressure level spectra with directivity angle are shown in figure 6(b) for a nozzle pressure ratio of 1.3. The angles shown are of interest since they represent the spectra at the peak sound level location (20°) and the locations where the scaled-up peak sideline perceived noise levels occur for this configuration (80° and 100°) (discussed later).

The data in figure 6(b) show that the spectra are relatively broadbanded at the two sideline locations (80° and 100°) but at the maximum sound level location (20°) there is slight indication that two peaks exist (1250 and 3150 Hz). This trend was noticeable for all configurations tested. Two pronounced peaks in sound pressure level were evident in the data from a large-scale geometrically similar model reported in reference 5 at all angles. This was not the case for the data presented herein. It should be noted that the tests of reference 5 were conducted with an actual engine exhaust at higher temperatures, and therefore higher jet velocities at a given pressure ratio, than the present study. In reference 5, it was suggested that the low frequency peak was caused by jet-surface interaction noise whereas the high frequency peak was caused by the mixing of the exhaust with ambient air. It was difficult to assess the velocity dependence of the high frequency (3150 Hz) spectral peaks from the data presented herein. At the lower jet velocities of the present study, mixing noise would not be expected to be as high relative to surface noise as in reference 5. An example of the variation of the spectra with nozzle pressure ratio, or exhaust velocity, at a directivity angle of 20° is shown in figure 6(c). The peak at 3150 Hz is barely discernible at a pressure ratio of 1.25. At lower pressure ratios the data above 1600 Hz is practically broadband.

As noted in figure 6(a), as the directivity angle increases a smaller change in overall sound pressure level occurs as a result of lowering the nozzle pressure ratio. Thus, the velocity exponent would decrease also. This is illustrated in figure 7 where the variation in overall sound pressure level with nozzle exhaust velocity at two angles from the nozzle inlet is shown. The data in figure 7 are compared with curves representing velocity exponents of the 7th and 8th powers. Six out of the 10 configurations tested showed the 7th and 8th power velocity dependence at 80° and 20°, respectively. The velocity exponents for the other configurations ranged from 7 to 9 at an angle of 20° and from 6 to 8 at 80°. At angles greater than 40°, however, the data shown in figure 6(a) suggests that typical velocity exponents might be expected to approach that of a dipole source.

During the course of the acoustic testing it was noted, subjectively, that superimposed on the general broadband nature of the thrust reverser noise was an intermittent sharp popping or cracking noise. An informal investigation of the source of this noise disclosed that it was caused by intermittent separation of flow streaming from the side skirts. This was determined by placing the hands adjacent and parallel to the flow from the side skirts. Nozzle total pressure remained constant so that the intermittent flow was not caused by internal flow fluctuations. Blocking off the sides of the reverser eliminated the intermittent flow noise. At present, the effect of the intermittent flow noise on the effective perceived noise level of the reverser is uncertain. However, it is felt that intermittent flow could be detrimental in terms of structural considerations.

Differences in flow rates with and without leakage between the blocker door and nozzle side walls ranged from 0.8 to 5 percent for the acoustic tests. Over this range of flow leakage there were no significant differences in the acoustic results for the configuration tested.

Effect of Configuration Changes

Effect of side skirt configuration. - The most pronounced effect on the noise signature of the thrust reverser occurred when the plain side skirts were replaced with the tabbed side skirts (see fig. 2). An example of this effect is shown in figure 8. For the two sets of data shown in the figure the lip shape, lip angle, and blocker door angle were the same. By using the tabbed skirt configuration the sound pressure levels at directivity angles of 20° (fig. 8(a)) and 40° were either less than or about the same as that when the plain side skirts were used. However, starting at a directivity angle of 60° and continuing on through angles of 80° and 100° (fig. 8(b) and (c)), the results from the tabbed side skirt shape consistently displayed an increase in the sound levels at frequencies above 4000 Hz. At directivity angles of 120° and greater, the spectral sound levels were about the same for either configuration. The increase in high frequency sound levels with the tabbed skirt configuration would be detrimental in terms of peak sideline perceived noise levels and is unfortunate because a gain in reverse thrust magnitude was shown to exist when this configuration was used.

Effect of lip shape. - The next most pronounced effect of configuration change on the noise characteristics of the reverser occurred when the lip shape was varied. Using the round lip on the reverser gave sound pressure levels that were greater than when the blunt lip was used with the greatest effect occurring at low directivity angles (fig. 9(a)). At angles of 80° (fig. 9(b)) and 100° (fig. 9(c)) the effect was less. Similar trends were obtained with the other configurations tested. Peak sideline perceived noise levels, therefore, would be nearly independent of lip shape used and the choice would possibly depend on aerodynamic considerations. (It was pointed out earlier that by using the blunt lip the downward force normal to the nozzle axis was increased, implying an increase in aircraft wheel loading; this effect would also have to be considered in the reverser design process.)

Effect of flow turning angle. - A change in either lip angle (β) or blocker door angle (α) alone showed no consistent trends in that changes in the sound level spectra were insignificant for the configurations tested. Typical examples of the spectra at 80° from the nozzle inlet for these configurations are shown in figure 10(a) and (b). The increase in sound level below 1000 Hz for the 105° blocker door angle shown in figure 10(b) was not consistent with other configurations tested. Furthermore, changing both the lip angle and blocker door angle at the same time gave the same results. Typical data for this model change are presented in figure 10(c). It appears, then, that changing the flow turning angle has little or no effect on the sideline plane noise characteristics of the thrust reverser.

Comparison of Data from Various Sources

Comparison of the results obtained from the tests reported herein with those from other experiments is shown in figure 11. The normalized peak sound pressure level is plotted as a function of Strouhal number based on nozzle diameter (or equivalent diameter where applicable). Three sets of data are presented for geometrically similar thrust reversers; data from figure 6 of the present work, an OTW thrust reverser with a nozzle equivalent diameter of 27.4 centimeters from reference 4, and a large scale engine model from reference 5. The other two sets of data are from small scale studies using a semi-cylindrical (ref. 2) and V-gutter type reverser (ref. 3). Data from the present study are bracketed by the results from the references. The results from the other configurations tested herein show approximately the same results.

Perceived Noise Levels

An estimate of full size, single engine, perceived noise levels at a sideline distance of 152.4 meters were calculated from the scaled-up model data for a standard day of 15° C and 70 percent relative humidity. The effect of ground reflections and excess attenuation (ground absorption) were not accounted for so that the perceived noise levels are free field estimates. A single engine configuration was chosen due to the uncertainty in shielding effects of the outboard engine on other engines of a multi-engine aircraft configuration. The sideline locations were 152.4 meters from and parallel to the flight path. Model spectral sound pressure levels were increased in proportion to the square of the scale factor (144) to account for nozzle size differences and decreased to account for spherical spreading. Atmospheric absorption values for the standard day were applied to the data.* Full size engine frequencies were obtained by assuming a Strouhal variation with nozzle diameter (inversely proportional to the scale factor) so that the full size frequencies become 1/12 of the model frequencies. Because of the large frequency shift by scaling it was necessary to extrapolate the experimental data to higher frequencies. This was done by taking the average slope in the last 5 one-third-octave bands and assume that the drop-off persisted to the highest frequency needed (125 kHz) for the perceived noise level calculation for the full size engine. Perceived noise levels were then calculated by the method reported in reference 8.

A comparison of the effect of configuration change on the sideline perceived noise levels is shown in figure 12. The data for the PNL calculations are from the model reversers with the tabbed and plain side skirts. As expected from the spectral plots shown earlier for these configurations (fig. 8), the reverser using the tabbed side skirts exhibits larger values of perceived noise levels compared with those for the plain side skirts at locations corresponding to directivity angles of 80° (+28 m) and 100° (-28 m) (and also at 60° or +88 m). At minus 88 meters ($\theta = 120^{\circ}$) the perceived noise levels are the same. The maximum difference is 3 PNdB (at +28 m).

The range of sideline perceived noise levels calculated from the static data presented herein as a function of distance in front of the aircraft, is presented

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*Private communication from F. J. Montegani, unpublished computer program for band attenuations by numerical integration using pure-tone atmospheric attenuation results from ref. 9. (Program available on request.)

in figure 13. The peak values range from 98 to 104 PNdB for a single full size engine and occur near the wing-tip sideline location (zero distance in the figure). These results are consistent with earlier target reverser data scaled to similar conditions (ref. 10) which indicated peak perceived noise levels for semi-cylindrical and V-gutter target reversers of 99 and 104 PNdB, respectively (when 6 dB are subtracted from the ref. 10 data in order to put them on the same free-field single engine basis as in this paper).

Effective perceived noise levels for the limiting curves in figure 13 were calculated by assuming a touchdown velocity of 41 meters per second (80 knots), cut-off velocity of 5 meters per second (10 knots), landing distance of 366 meters (1200 ft) and constant deceleration. The effective perceived noise levels amounted to 102 EPNdB for the upper curve and 97 EPNdB for the lower curve.

SUMMARY OF RESULTS

A 1:12 scale model QCSEE over-the-wing target-type reverser was tested to determine the static noise generating characteristics of the device. The effect of minor configurations changes such as side skirt shape, lip angle and shape, and blocker door angle on the acoustic characteristics were determined. The results of the tests are summarized as follows:

1. Peak full size single engine free field perceived noise levels calculated from the scaled-up model data at a 152.4 meter sideline location ranged from 98 to 104 PNdB and occurred at directivity angles between 80° and 100° from the nozzle inlet.

2. The most pronounced effect of configuration change on the noise characteristics of the reverser occurred as a result of side skirt change. Extending the length of the side skirt caused an increase in the model high frequency sound pressure levels at directivity angles between 60° and 100° from the nozzle inlet. The effect of other configuration changes was negligible.

3. The noise directivity pattern of the reverser was rather uniform with only a maximum of 6 dB change in overall sound pressure level from directivity angles of 20° to 160° from the nozzle inlet with the peak overall sound level occurring at 20°. Sound pressure levels were broadband, with near-peak levels over a range of model scale frequencies from 1000 to 4000 Hz.

4. The occurrence of intermittent flow from the side skirts was subjectively noted during the course of the experimental testing. This flow intermittency occurred with all configurations tested and the effect on the noise signature was not determined. The intermittent flow could possibly be detrimental in terms of reverser structural integrity.

SYMBOLS

D	nozzle equivalent diameter at reverser charging station (fig. 2), cm
f	one-third-octave band center frequency, Hz
H_B	blocker door height (see fig. 2), cm
L	blocker door lip length (see fig. 2), cm
V_j	nozzle isentropic jet velocity, m/sec
w_F	air flow rate in forward thrust mode, kg/sec
w_R	air flow rate in reverse thrust mode, kg/sec
X_p	distance from plane of charging station to blocker door pivot point (see fig. 2), cm
α	blocker door angle (see fig. 2), deg
β	lip angle (see fig. 2), deg
θ	location of microphone from nozzle inlet, or directivity angle (see fig. 1), deg

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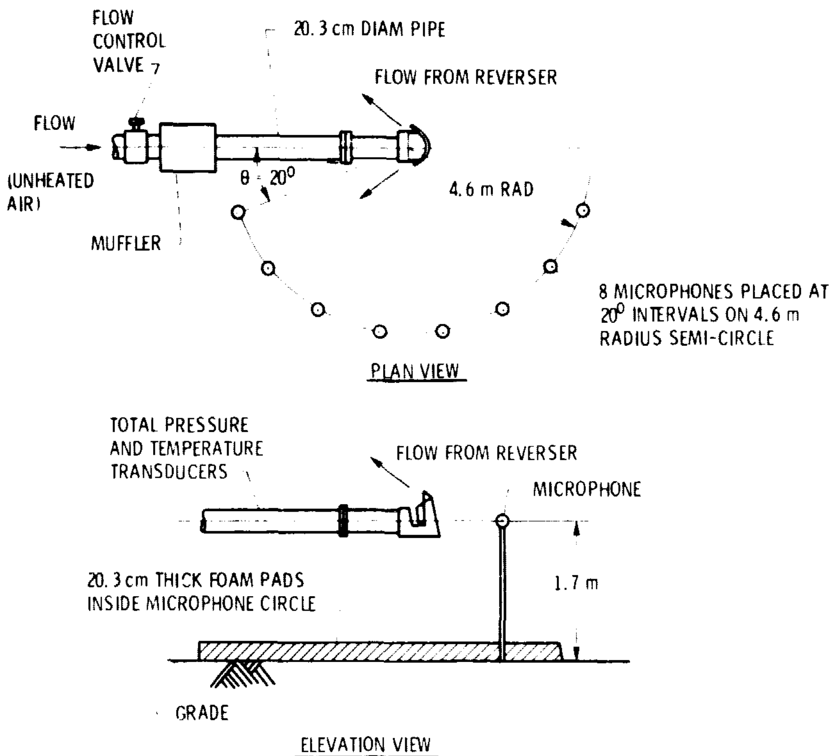
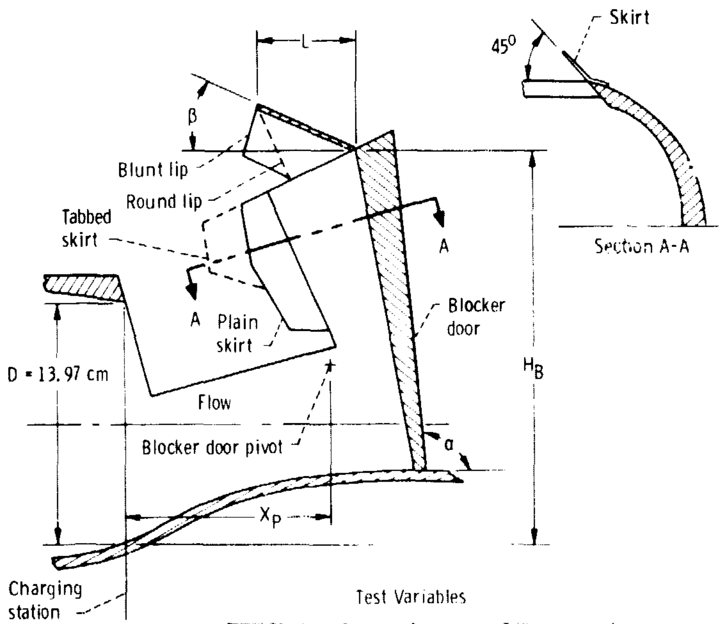


Figure 1. - Schematic of acoustic test facility.



Test Variables

Blocker door angle, α	Lip angle, β	Lip shape	Skirt shape
115° 105°	25° 35°	Blunt Rounded	Plain Tabbed

$L/D = 0.4$, $X_P/D = 0.865$, $H_B/D = 1.63$

Figure 2. - Thrust reverse model test configurations and dimensions.

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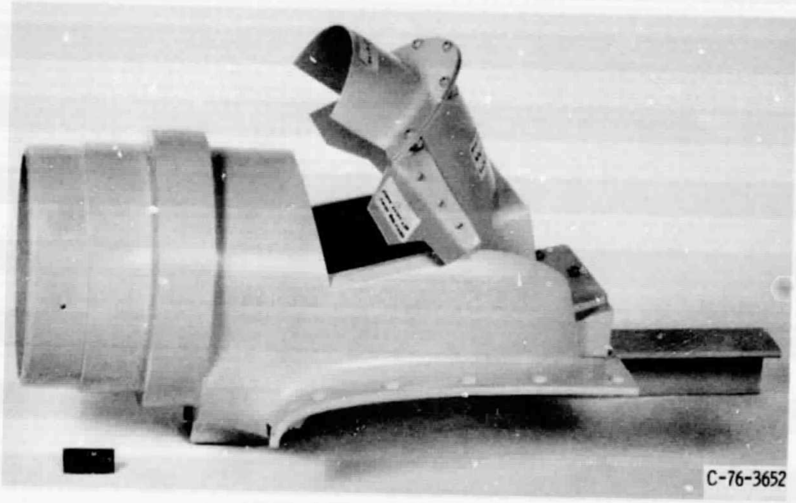

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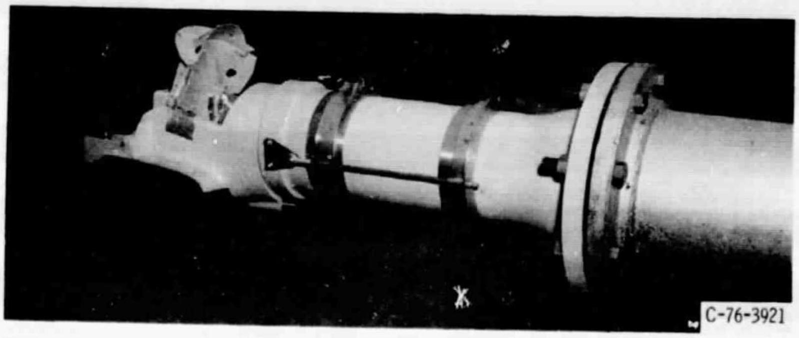
(a) TABBED SKIRTS AND BLUNT LIP CONFIGURATION.



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(b) PLAIN SKIRTS AND ROUND LIP CONFIGURATION.

Figure 3. - OTW model thrust reverser.

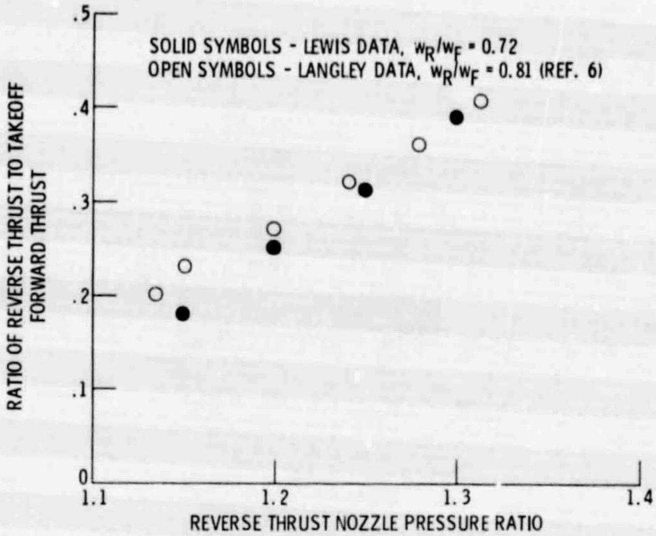


Figure 4. - Comparison of aerodynamic reverse thrust data from tests performed at Lewis and Langley Research Centers. Round lip, tabbed skirts, $\alpha = 115^0$, $\beta = 25^0$.

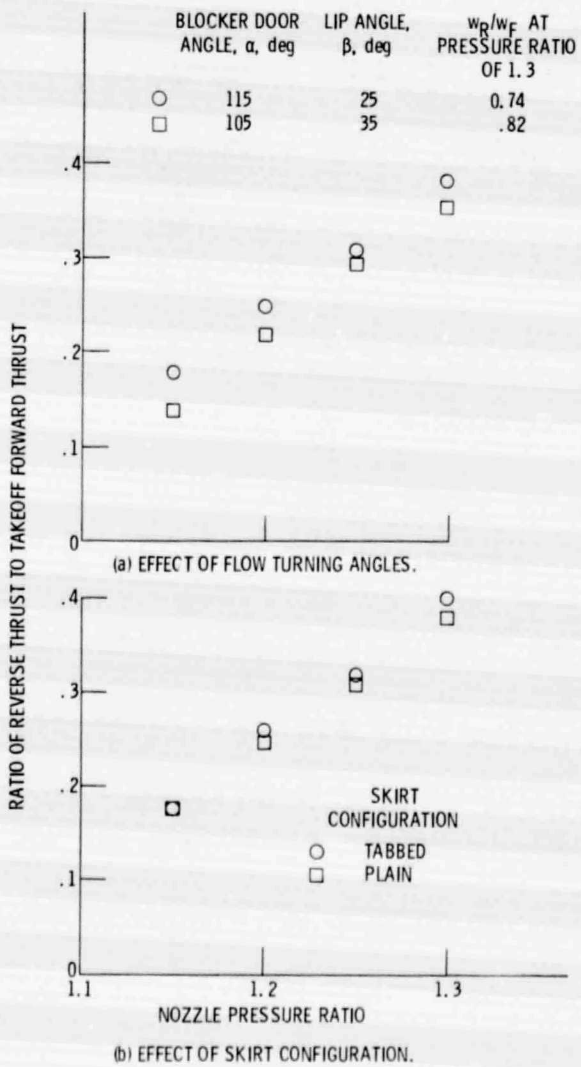
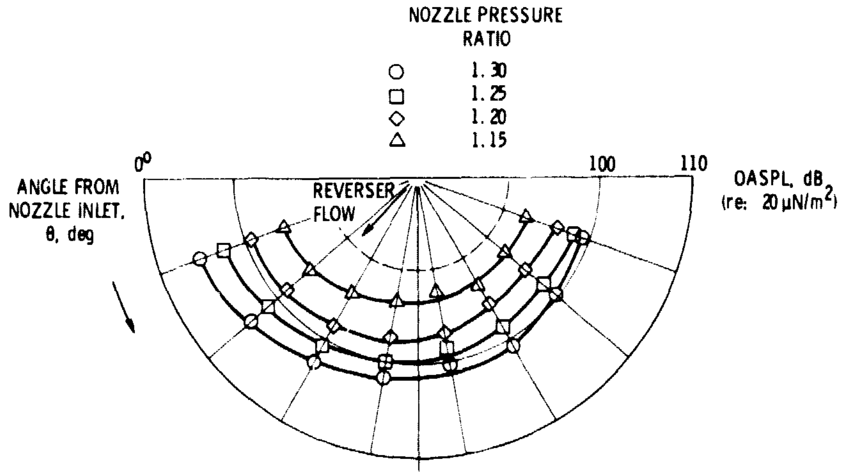
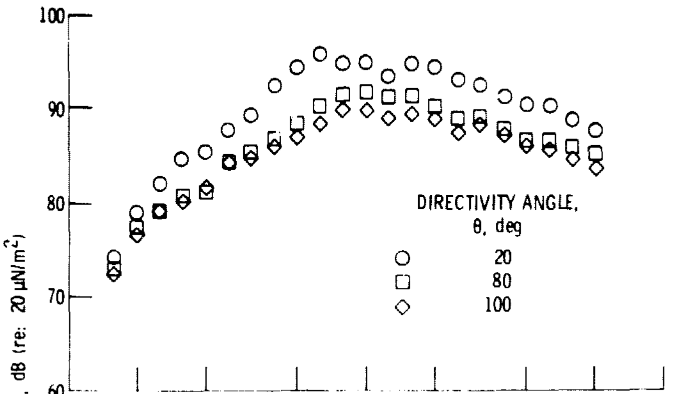


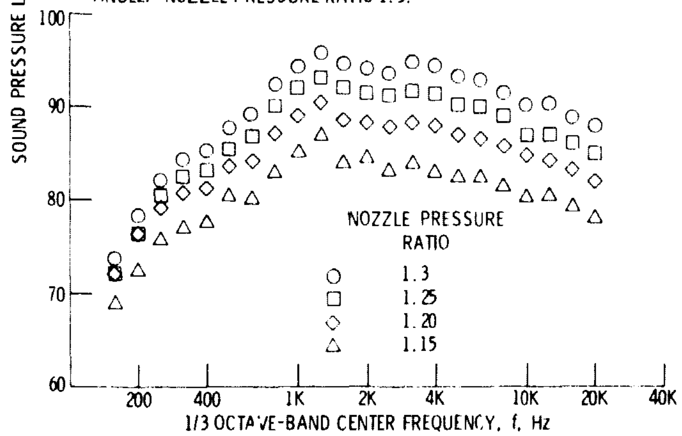
Figure 5. - Effect of configuration changes on the performance of the model thrust reverser.



(a) NOISE DIRECTIVITY PATTERNS.



(b) VARIATION OF SOUND PRESSURE LEVEL SPECTRA WITH DIRECTIVITY ANGLE. NOZZLE PRESSURE RATIO 1.3.



(c) VARIATION OF SOUND PRESSURE LEVEL SPECTRA WITH NOZZLE PRESSURE RATIO AT θ = 20°.

Figure 6. - Noise characteristics of OTW thrust reverser. Blunt lip, α = 115°, β = 25°, tabbed skirts.

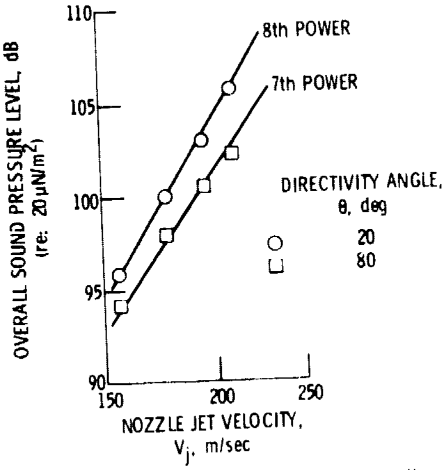


Figure 7. - Effect of nozzle jet velocity on overall sound pressure level. Blunt lip; $\alpha = 115^0$, $\beta = 25^0$, tabbed skirts.

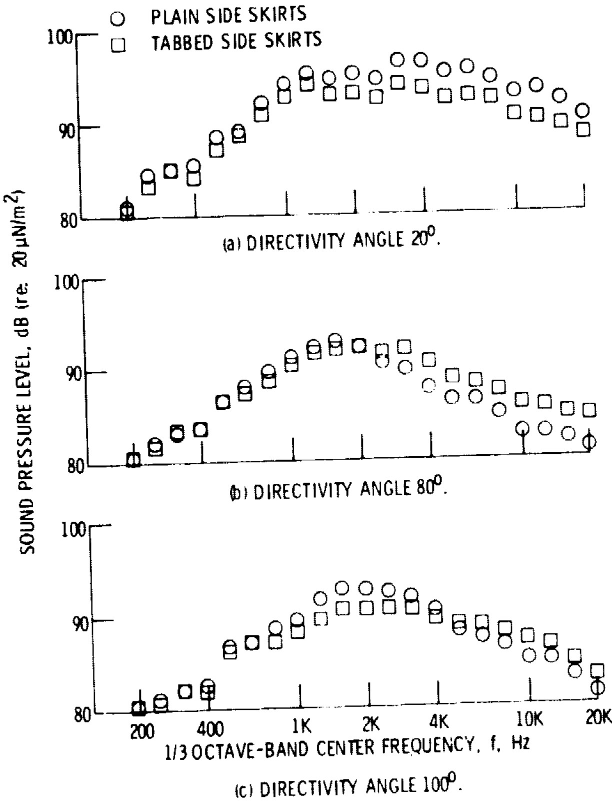


Figure 8. - Effect of side skirt shape on thrust reverser noise. Pressure ratio 1.3; blunt lip; $\alpha = 105^0$; $\beta = 35^0$.

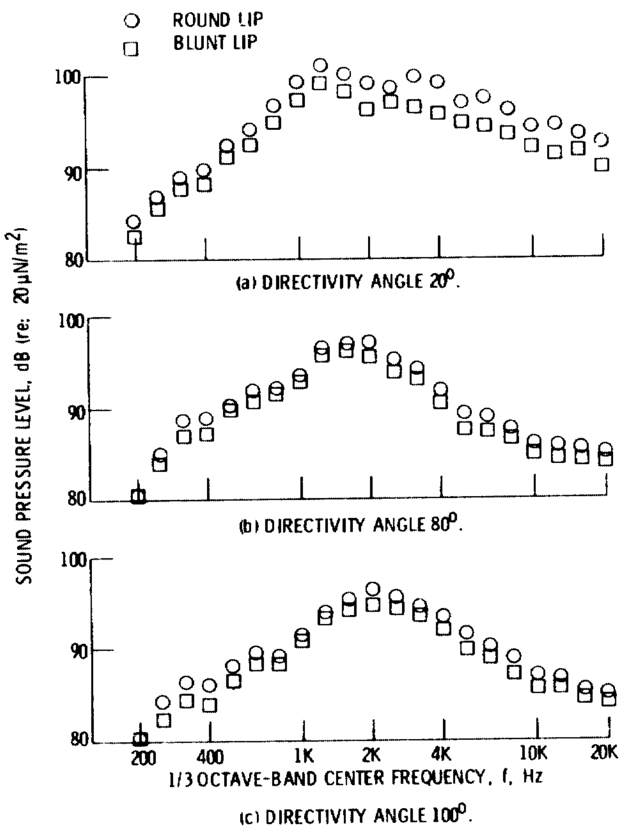


Figure 9. - Effect of lip shape on thrust reverser noise. Nozzle pressure ratio 1.3; plain skirts; $\alpha = 115^0$; $\beta = 25^0$.

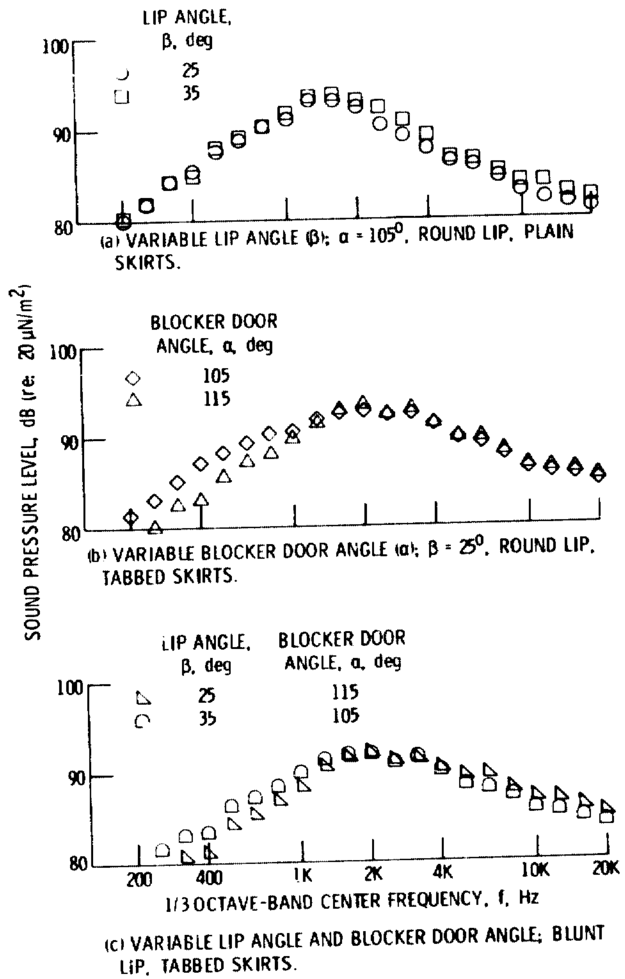


Figure 10. - Effect of flow turning angle on thrust reverser noise characteristic. $\theta = 80^0$; nozzle pressure ratio 1.3.

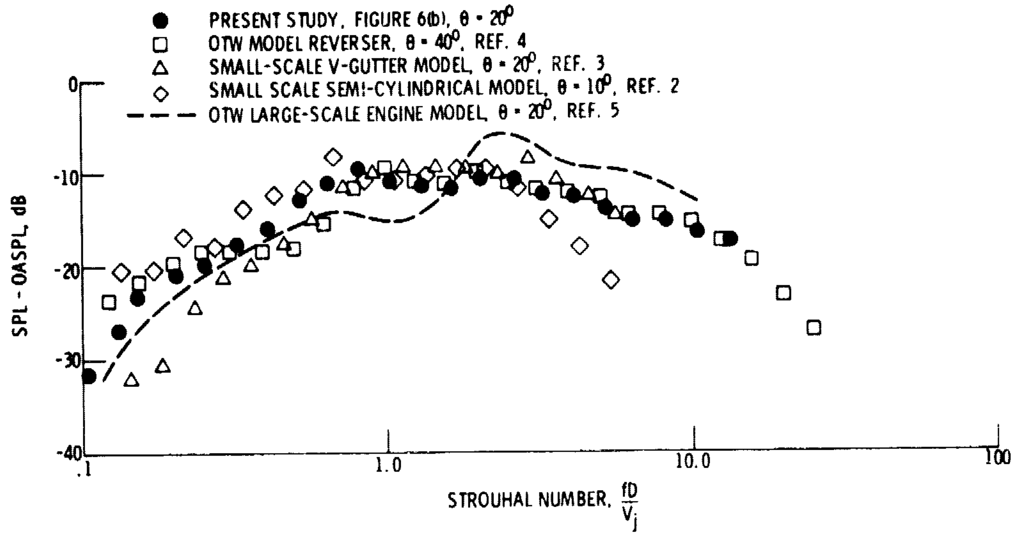


Figure 11. - Comparison of normalized sound level spectra at peak noise angle for thrust reverser data from various sources.

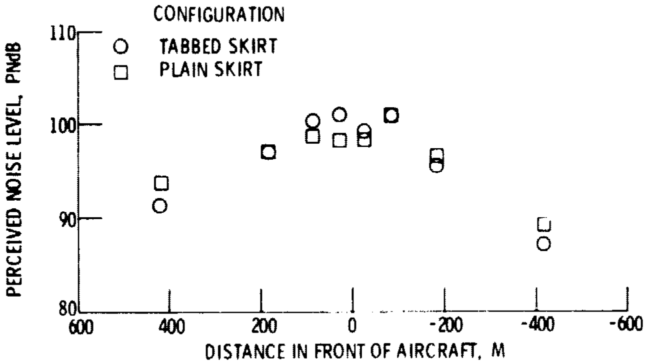


Figure 12. - Effect of skirt configuration on full size single engine thrust reverser perceived noise levels on a 152.4 meter sideline. Nozzle pressure ratio 1.3, α = 105°, β = 35°, blunt lip, standard day 15° C, 70 percent relative humidity.

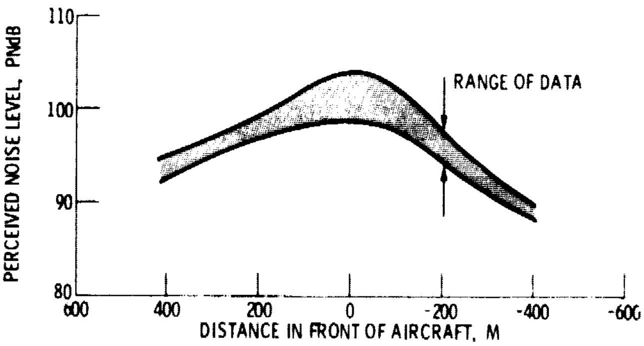


Figure 13. - Range of full size single engine thrust reverser perceived noise level calculations on a 152.4 sideline. Nozzle pressure ratio 1.3, standard day 15° C 70 percent relative humidity.