Effect of Simulated Forward Flight on Subsonic Jet Exhaust Noise

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A wind-tunnel model program was conducted to investigate the effect of aircraft forward speed on the jet noise characteristics of a single subsonic jet. The tests were performed in the United Technologies Research Center Acoustic Research Tunnel, a low-noise open-jet anechoic wind tunnel designed specifically for acoustic testing. Electrically heated air was supplied to a convergent nozzle located on the tunnel centerline. The nozzle diameter of 2.4 in. produced a tunnel to nozzle area ratio of 220. Microphones were located at a radius of 50 nozzle diameters in the anechoic chamber outside the tunnel flow. Nozzle operating conditions covered a range of velocities up to 1670 fps, and temperatures to 900°F. Wind-tunnel speeds ranged from near zero to 350 fps. Measured noise data were corrected for tunnel shear layer refraction and moving medium convection effects, thus simulating the effects on the jet noise sources of relative velocity during an aircraft flyover. Measured overall sound pressure level reductions due to relative velocity were correlated with relative velocity raised to an exponent that increased towards the aft angles. The results showed general agreement with recent National Gas Turbine Establishment (NGTE) test results obtained in a large wind tunnel.

Introduction

AIRCRAFT and powerplant designers are faced with the task of designing the most efficient aircraft in terms of performance and economics, and at the same time satisfying the noise limits as defined by recently imposed government rules. Extensive use of noise absorbing materials in the inlet and exhaust ducting of modern high bypass ratio propulsion engines has reduced the noise from fans, compressors, and turbines to the point where the jet noise (noise generated in the exhaust plume by the mixing of the high-velocity jet with the ambient air) is now a dominant source.

The characteristics of jet noise from turbojet and turbofan engines have been well-documented[1] under static conditions by use of scale model and full-scale engine measurements. However, aircraft certification limits for noise must be satisfied under actual aircraft flyover conditions during takeoff and approach operation with the aircraft reaching speeds of up to 400 fps. Thus the designer, in order to properly optimize an aircraft/engine design, is required to assess the changes that the aircraft speed has on the jet noise.

Methods to determine the effect of aircraft forward motion on jet noise fall into three basic categories: 1) Measurements during actual aircraft flyovers. 2) Simulation of aircraft motion by moving model jets and other land-based methods such as high-speed trains and rocket propelled sleds. 3) Wind-tunnel simulations. The procedure used to obtain results described in this paper is in the third category.

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Index categories: Aircraft Noise, Powerplant; Aircraft Testing (including Component and Wind-Tunnel Testing).

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Methods for Determining Forward Speed Effects

In this section the advantages and limitations of each of the three basic methods used to determine the effects of forward speed on jet noise are discussed.

Aircraft Flyover Measurements

The use of actual flyover measurements to obtain data for determining the effect of flight on jet noise is extremely costly and is complicated by many technical factors including: a) the measurement and analysis of highly transient acoustic signals, b) effects of atmospheric inhomogeneities, c) separation of the pure jet noise component from the multitude of other possible aircraft noise sources present, and d) the effect of aircraft/engine installation. Considering these complications, it is not surprising that the attempts to determine the effects of forward flight on jet noise by using flyover data have resulted in contradictory results being reported by different investigators.

Simulation of Aircraft Motion by Land-Based Vehicles and Rigs

Two experimental methods fall into this category. One method is the use of a high-speed jet propelled train. Results from experiments using the Bertain Aerotrain have been in general agreement with many of the flyover tests. However, similar technical problems present in flyover tests are also present in the train experiments including the problems of transient data measurement and analysis, and the separation of the jet noise from the other engine and train noise sources. A second method is the use of a rotating arm facility in which a scale model exhaust nozzle is mounted on the end of a long arm and rotated about the arm pivot. Preliminary results from recent experiments[2] indicate potential for this method, since the use of scale models allows rapid evaluation of many nozzle designs of significant cost savings over flyover tests. Questions concerning the acquisition and analysis of transient data and the effect of rotational motion on the jet plume development and resulting noise generation must be answered before this method can be accepted as a true flyover simulation.

Wind-Tunnel Simulation

Recently, attempts have been made to use wind-tunnel or free-jet facilities to investigate the effect of flight on jet noise.[3,4] In these types of experiments, the effect of aircraft forward speed is transformed to the case of air moving at the flight speed past a stationary nozzle. The measurements are steady-state since nozzle and microphones are stationary. Good acoustic environments rarely exist in conventional closed wind-tunnels due to problems of noise reflections from the walls, wind noise on the microphones located in the tunnel airflow, and insufficient measuring distance to obtain far-field noise measurements. These problems in wind-tunnel simulation of forward flight can be resolved by the use of an open-jet windtunnel designed specifically for acoustic studies, such as the Untied Technologies Research Center (UTRC) Acoustic Research Tunnel. The open-jet test section allows free-field acoustic measurements to be made outside the tunnel airflow in an anechoic chamber.

Experimental Arrangement

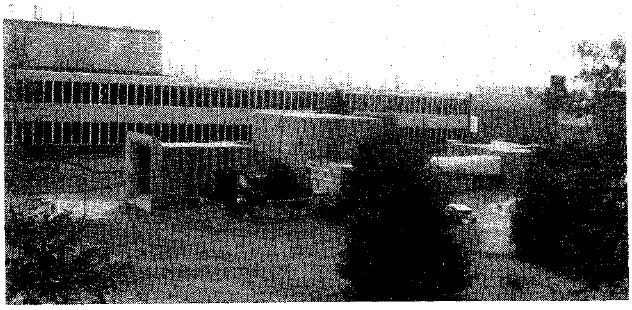
The UTRC tunnel, shown schematically in Fig. 1, is a controlled turbulence level, open-jet wind-tunnel designed specifically for aerodynamic noise research.[5] The test section is surrounded by a sealed anechoic chamber lined with 1-ft acoustic wedges. A centrifugal fan located downstream of a fan noise muffler induces atmospheric air into the test section. Honeycomb and screens located in the inlet in conjunction with a contraction ratio of 11.5 provide a spatially uniform test section flow with a total turbulence level of approximately 0.2%.

Figure 2 shows the test arrangement employed in this study. Air from a 400-psi air system was regulated by a control valve to provide a steady, continuous flow at the desired nozzle pressure ratio. An electric resistance heater and muffler provided quieted and heated air to a simple convergent 2.4-in. diam nozzle located on the test section centerline. The supply pipe crossed the tunnel flow upstream of the contraction producing a negligible wake in the test section. The large contraction ratio also resulted in a small external nozzle boundary-layer thickness (displacement thickness of ¼ in.) relative to the test nozzle diameter. The large supply pipe diameter (6 in.) relative to test nozzle diameter produced low supply pipe velocities and hence low upstream noise generation. With a 36-in. diam tunnel, the large ratio of test section to nozzle area (220) precluded flow interference between the tunnel turbulent shear layer and jet exhaust for the significant noise producing region of the jet. Some previous noise experiments conducted at low area ratio have been affected by such outer stream-jet interference. Figure 3 is a photograph of the anechoic chamber showing the test nozzle installed on the test section centerline.

Jet noise was measured by an array of ¼-in. diam free-field microphones located on a 10-ft radius within the quiescent region which surrounds the open-jet test section. The anechoic chamber has been determined to be anechoic for broadband noise at frequencies above 200 Hz.[5] The ratio of measurement distance to nozzle diameter of 50 provided far-field geometric and acoustic conditions. Nine microphones were positioned at 10-deg increments from 70 to 150-deg relative to the nozzle upstream jet axis. Measurement at angles greater than 150 deg was precluded by excessive wind velocities incident on the microphones. Microphones data were recorded on magnetic tape, analyzed by a third-octave spectrum analyzer and input to a digital computer program to yield data corrected for microphone and cable response. Atmospheric attenuation corrections were negligibly small and therefore not applied. Additional corrections to account for wind-tunnel refraction and convection effects are discussed in the next section.

Precisely static test conditions could not be achieved since the nozzle jet momentum drives the tunnel airstream by an ejector action. Blocking the tunnel flow would produce chamber recirculations not representative of static test conditions. For this reason vanes located at the fan inlet were adjusted to limit the tunnel speed to 25 fps or less for nominally static measurements. The effect of this small velocity was included in the data correlations. Since chamber static pressure decreases with increased tunnel speed, the nozzle total pressure was adjusted at each test condition to provide constant nozzle pressure ratio for various tunnel speeds.

Data were acquired over a pressure ratio range from 1.08 to 1.91, nozzle stagnation temperature range from 160°F to 900°F and tunnel speed range from nominally static conditions to 350 fps. This range of parameters encompass conditions typical of full-scale aircraft applications. Since diameter scaling is straightforward for simple convergent nozzles, the test program provided data that can be directly related to full-scale turbojet engine in-flight jet noise. Although only single stream results are considered in this paper, the rig is a capable of testing coaxial nozzles with simulation of both primary and fan duct temperatures. The results of an extensive coaxial flow test program are currently being analyzed. In addition to these studies an investigation of both subsonic and supersonic single stream nozzle jet noise flight effects has recently been completed in the UTRC Acoustic Research Tunnel.



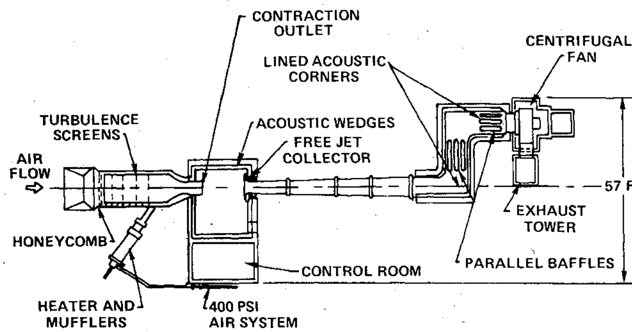


Fig. 1 UTRC acoustic research tunnel.

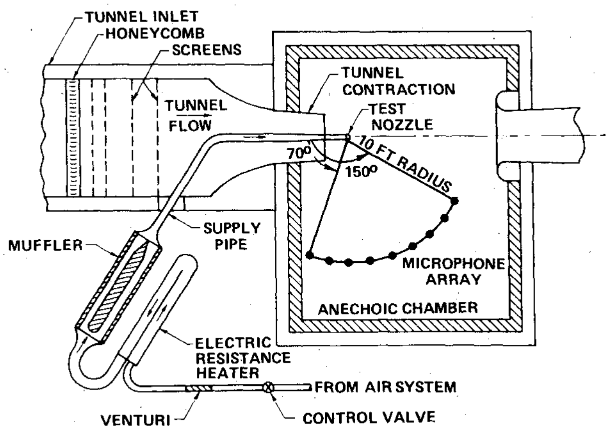


Fig. 2 Test arrangement.

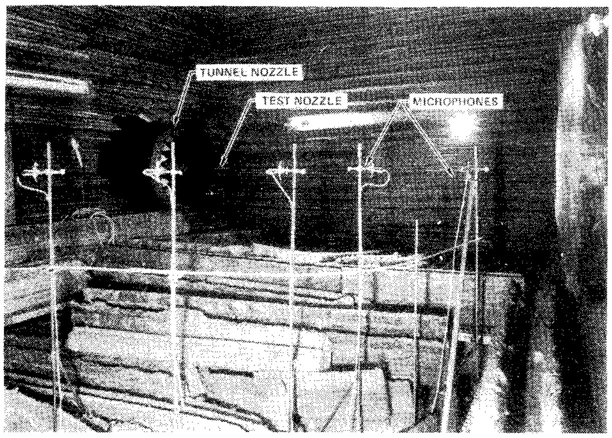
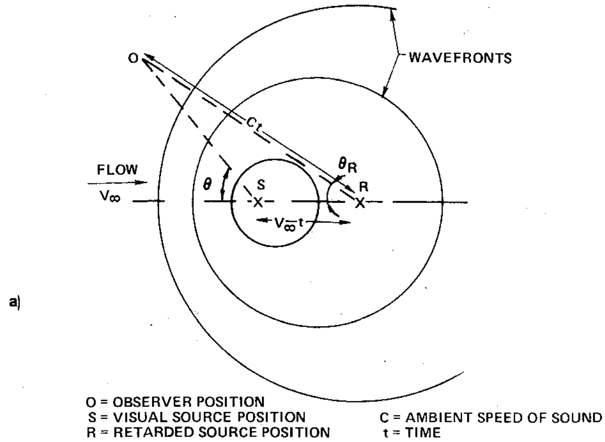


Fig. 3 Model nozzle installation.



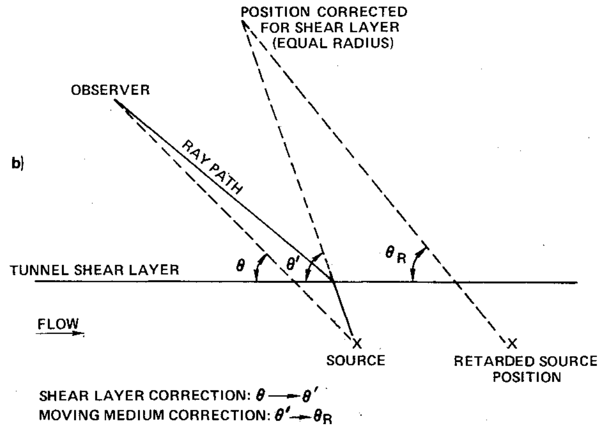


Fig. 4 Schematic of shear layer and moving medium corrections. a) Moving medium correction only. b) Combined corrections.

Frame of Reference Considerations in the Interpretation of Wind-Tunnel Noise Measurements

The purpose of this section is to define the corrections to wind-tunnel measurements that are required to permit comparison of results with aircraft flyovers and static test data. This discussion is based on the analysis of Amiet.[6,7]

In determining flyover effects on static jet noise, static engine data are compared with flyover measurements that have been corrected in frequency for a Doppler shift associated with aircraft motion and also in directivity angle to a retarded source position. The retarded source position represents the position of the aircraft at the time it emitted the sound presently being detected at the mircophone. For rectilinear motion, it is located a distance aft of the aircraft present (visual) position given by the product of flight speed and sound propagation time from the retarded position. The result of these two corrections is to provide modified flyover data that can be compared directly to static noise spectra and directivity for purposes of defining flight effect corrections.

In an open-jet acoustic wind-tunnel where microphones are located outside the tunnel airstream, the nozzle is stationary in a moving airstream and the microphones are stationary in a medium at rest. Two corrections are required to provide data in a frame of reference equivalent to the preceding, i.e., a frame of reference which is fixed to the nozzle and for which the mean velocity is zero. The first correction accounts for sound wave refraction by the tunnel shear layer. Sound propagating through the shear layer is refracted and changed in amplitude. The theory of Amiet[7] provides correction equations for amplitude and angle which in effect move the shear layer to infinity. Data corrected by this method then correspond to a frame of reference in which source and observer are fixed relative to each other in an airstream extending to infinity and would be equivalent to measurements taken by a microphone moving with the aircraft. In this frame of reference, directivity information is in terms of present (visual) position rather than retarded position. The airstream that extends to infinity convects the sound wavefronts during propagation from source to microphone. To retain the proper source strength (as reflected in the measured data) but to convert it to the nozzle fixed coordinate system with zero-mean velocity, the measurement angle θ must be corrected to the retarded angle θ_R. As shown in Fig. 4a, correction of the measured angle θ to retarded angle θ_R at stream Mach number M is given by the relation [6]

$$\cos\theta_R - M = \sin\theta_R \cot\theta \tag{1}$$

where the angles are measured relative to the upstream jet axis. Corrections based on Eq. (1) are referred to as moving medium corrections. The combined shear layer and moving medium correction procedure is illustrated in Fig. 4b. Application of the moving medium and shear layer corrections provides data that can be compared with static test noise spectra and directivity for purposes of determining flight effects. When compared in this manner, wind-tunnel testing should show the same effect of jet relative motion as that obtained from aircraft flyover measurements corrected for retarded time and a Doppler frequency shift. Thus the wind-tunnel measurements corrected as discussed provide an exact simulation of the forward speed effects on the jet noise sources that would exist during an aircraft flyover. Therefore, knowledge of the actual details of the various phenomena involved in the noise source change is not necessary. The possible source effects are discussed elsewhere.[3,8]

In this paper selected uncorrected data are provided for reference purposes. Analysis of results, however, are based on data corrected for refraction and retarded position as discussed in the preceding. Since the refraction correction shifts the directivity angle to values which do not correspond to static measurement angles, the corrected data have been interpolated to effect an equal angle comparison. Although there is theoretical justification for the refraction, direct experimental verification has been limited.[7] However, the results presented in this paper indicate the corrections are valid.

Experimental Results

In order to establish the validity of the noise data measured during this wind-tunnel program, results from the static runs were compared with other recently published static data. A comparison with predictions from the SAE[1] of the noise spectral distribution (SPL) measured under static condition is shown in Fig. 5. Under static conditions with the tunnel fan shut off, a finite amount of secondary flow was induced by ejector action of the model jet. This induced velocity was a

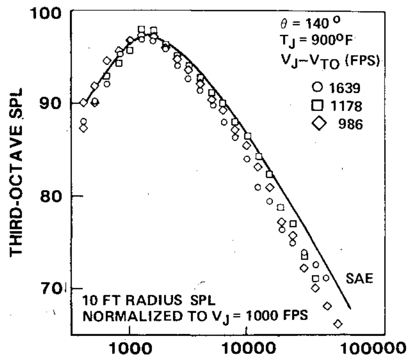


Fig. 5 Comparison of spectral data with SAE.

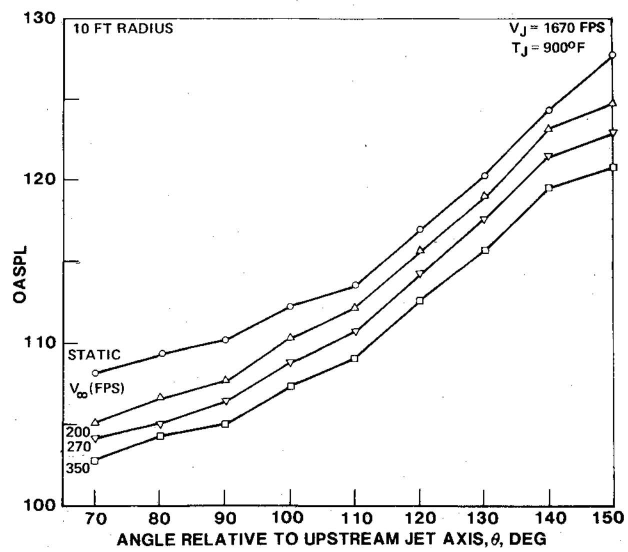


Fig. 6 Effect of relative velocity on OASPL directivity -uncorrected for shear layer and moving medium.

funciton of the model jet velocity tested. This finite induced velocity V_{to} reaching a maximum of 25 fps, was subtracted from the absolute jet velocity in the following static correlations. Spectra at 140° are shown for various jet velocities, and are normalized to a jet having a velocity of 1000 fps by use of the SAE scaling procedure. The measured spectra agree very well with those predicted by the SAE over most of the frequency range. The close agreement in spectra between the measurements and the SAE static predictions establishes the validity of the jet rig, measurement environment, and the electronic measuring and analyzing systems.

The noise level produced by the jet with velocity of 1200 fps at the tunnel flow of 350 fps is approximately 10 dB above the background noise except at very high frequencies, thus showing that for those conditions the tunnel background noise has a negligible effect on the jet noise overall sound pressure level (OASPL). For the correlations of data presented in later sections, it was decided that data having background noise less than 10 dB below jet noise (i.e., causing an error of ½ dB or more) would not be considered. Additional examinations of the noise spectra revealed that to meet this stringent criterion, the jet velocity had to be approximately four times the velocity of the tunnel flow.

A sample of the far-field noise measurements are presented for reference purposes without shear layer and moving medium corrections in Fig. 6. The effect on polar overall sound pressure level of increasing tunnel velocity at constant jet absolute velocity is shown. The reduction of the noise is significant and approximately constant at all angles. This agrees with the trends from the simulated flight tests by Von Glahn et al.,[4] in which the data were not corrected for the shear layer refraction effect.

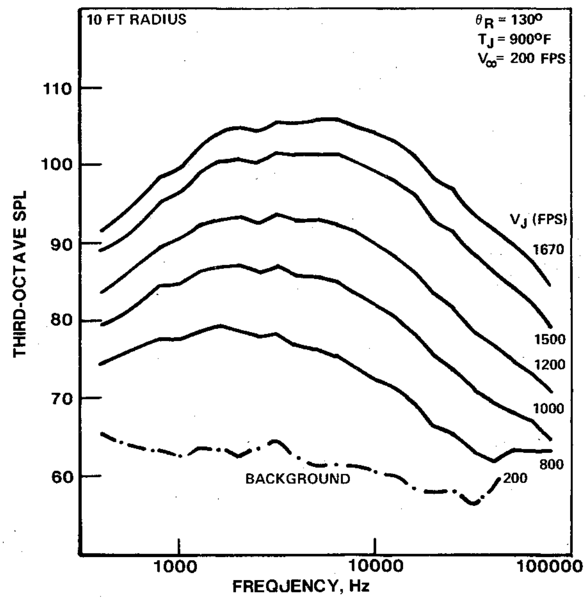


Fig. 7 Effect of jet velocity on spectra at constant tunnel speed -corrected for shear layer and moving medium.

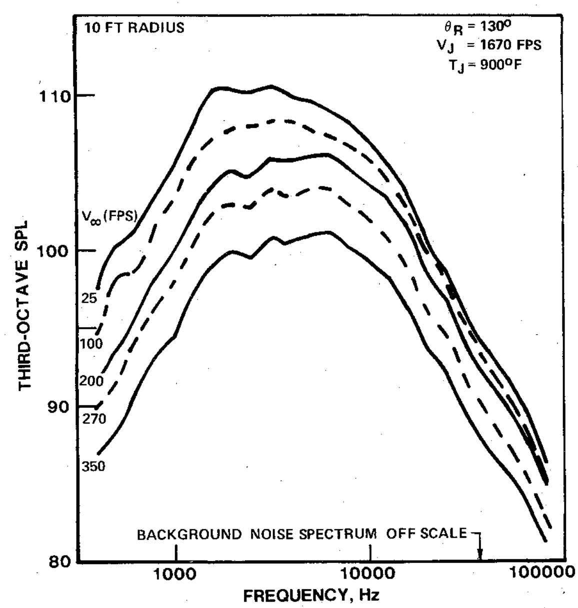


Fig. 8 Effect of relative velocity on 130 deg spectra at constant jet velocity – corrected for shear layer and moving medium.

Presentation of Corrected Data

The data discussed in this section have been corrected for the shear layer refractions and convection of the tunnel flow. The shear layer correction assumes the dominant noise source is located at the exit of the jet nozzle. In this experimental setup, the ratio of the microphone distance to the jet diameter is approximately 50. Since the actual distribution of sources producing the bulk of the jet noise extends for 5 - 7 nozzle diameters in the jet plume, the jet can be approximated by a point source at the nozzle exit. A second correction to the data is necessary to remove convection of sound downstream by the moving medium (or tunnel flow), as described earlier. Application of this correction is equivalent to the NGTE[3] procedure of physically moving the microphones axially downstream by the angle determined from the moving medium correction.

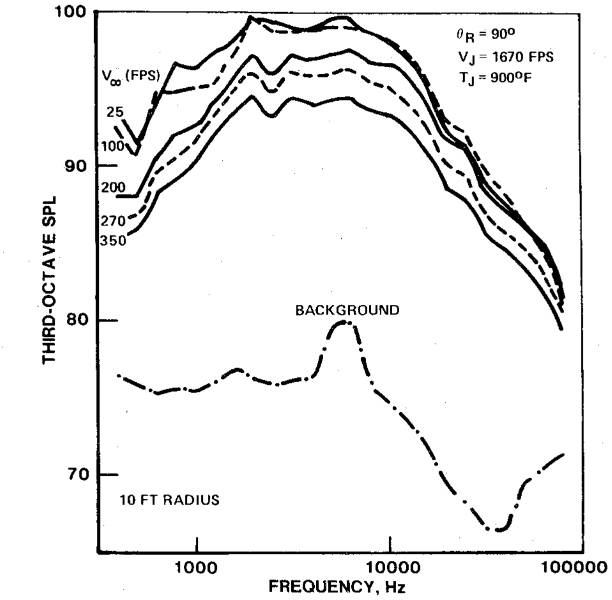


Fig. 9 Effect of relative velocity on 90 deg spectra at constant jet velocity – corrected for shear layer and moving medium.

In order to establish the data correlations necessary for the development of prediction methods to account for the forward speed effect, data (corrected to be a function of θ_R) were then input to a computer routine which interpolated each SPL value back to the original measuring angle. A sample of the SPL spectra resulting from the corrected data is shown in Fig. 7 for a range of jet velocities from 800 to 1670 fps with tunnel speed of 200 fps. The data are essentially free of distortion from background noise, except for the lowest jet velocity at the very high frequencies. This small distortion has no effect on the OASPL value. The effect of increasing tunnel speed on the jet noise spectrum for an absolute jet velocity of 1670 fps at 130° and 90° is shown in Figs. 8 and 9. These data are representative of all the data measured and show two important factors. First, the noise reductions are much larger at rear angles than side angles. It is noted that the raw data shown previously (without shear layer and moving medium corrections) did not show this trend. Secondly, spectral comparisons of both angles show more noise reduction obtained in the lower frequencies. Since the spectra of the jet mixing noise are broadband and change only slightly with tunnel speed for a given jet velocity (see Figs. 8 and 9), the overall sound pressure level will be used to correlate the changes in jet noise due to forward speed. To illustrate the differences in OASPL with and without the shear layer refraction and convection corrections, a polar OASPL directivity at the highest jet velocity is shown in Fig. 10a for a jet velocity of 1670 fps and a tunnel speed of 350 fps. These corrections can lower the measured noise level by 4.5 dB at 150°. Near 100°, the correction is nearly zero and at the forward angles, the corrected levels are higher than the as-measured values. Polar OASPL directivity plots with corrections are shown in Fig. 10b for all tunnel velocities. The noise reduction due to the relative velocity effect can be seen to increase significantly toward the jet axis, thus resulting in a substantial difference from the uncorrected data shown in Fig. 6. It will be shown in a later section that the shear layer and moving medium corrected OASPL's agree with the data of NGTE[3] (in which noise measurements were made within the tunnel flow field), just as the uncorrected data agreed with the results of Von Glahn.[4]

Correlation of Data

The results presented in the previous section, which were corrected for shear layer convection effects, form the data base for the correlations of jet noise with forward speed. The correlations of OASPL versus relative velocity for all

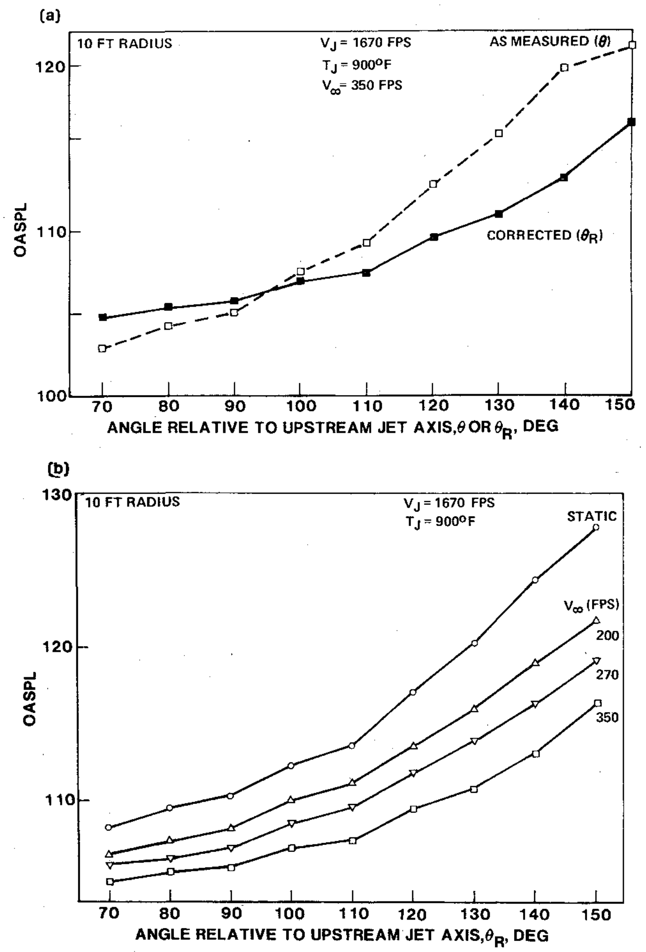


Fig. 10 a) OASPL directivity with and without shear layer and moving medium corrections. b) Effect of relative velocity on OASPL directivity–corrected for shear layer and moving medium.

emission angles at two values of absolute jet velocity are shown in Figs. 11 and 12. Since the data follow a relatively straight line, the characteristics behavior is established by the slope of a line through the data at each angle. The value of the slope n of each curve is used to determine the change in OASPL (relative to the static case) due to forward speed, as shown in the following equations

$$\Delta \text{OASPL}/[10 \log V_j - 10 \log (V_j - V_\infty)]$$

$$= \Delta \text{OASPL}/10 \log (V_j / V_{\text{rel}}) = n \tag{2}$$

or

$$\Delta\, \text{OASPL} = 10 \log (V_j / V_{\text{rel}})^n \tag{3}$$

where Δ OASPL = OASPL (static case) = OASPL (with flow). Values of n are plotted in Fig. 13 as a function of θ_R for various values of V_j. It is seen that the exponent n increases consistently as values of θ_R approach the jet axis, and that the exponents increase with the absolute jet velocity for $\theta_R > 120°$. Figure 13 also shows the values of the exponents obtained by correlation of aircraft flyover tests (prepared by Rolls Royce) and proposed to the SAE[9] as a new forward flight jet noise prediction precedure. Comparing the proposed SAE values to those calculated in this paper shows that the model flight simulation yielded higher values for all angles with the differences increasing with decreased angle from the upstream jet axis. A large discrepancy is apparent at the for-

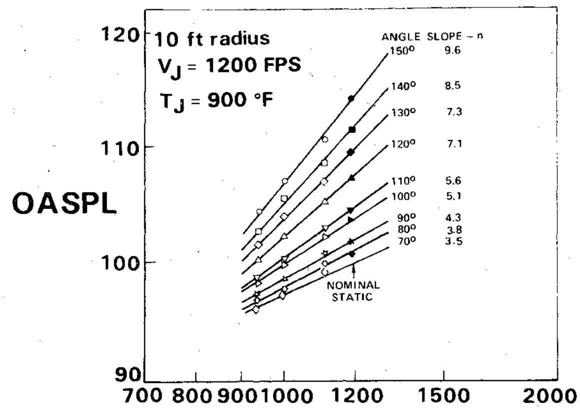


Fig. 11 Effect of relative jet velocity on OASPL as a function of angle $V_J = 1200$ fps.

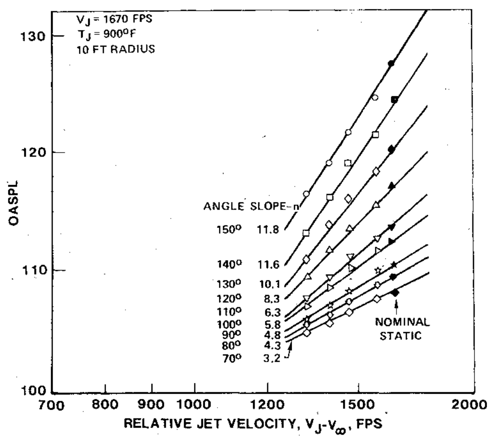


Fig. 12 Effect of relative jet velocity on OASPL as a function of angle $V_J = 1670$ fps.

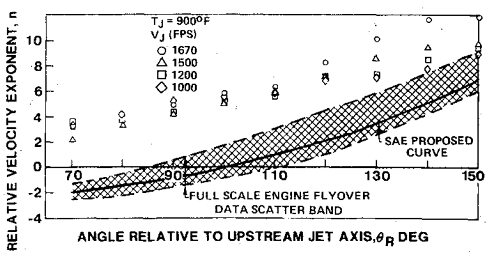


Fig. 13 Variation of relative velocity exponent with angle for various jet velocities.

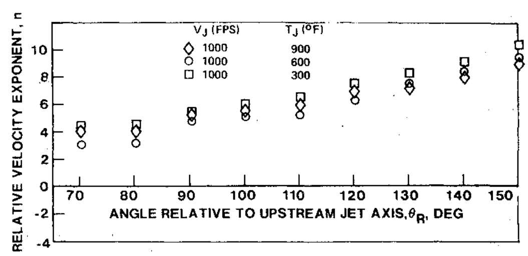


Fig. 14 Variation of relative velocity exponent with angle for various temperatures.

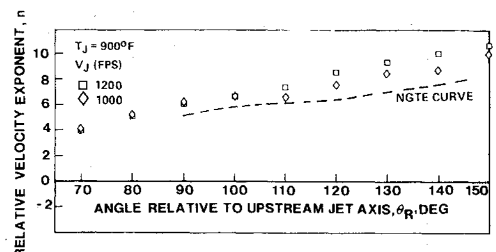


Fig. 15 Variation of relative velocity exponent with angle – normalized to ambient conditions.

ward angles where the model results show noise reduction with forward speed while the aircraft flyover correlation shows increased jet noise (negative values of n). Theoretical considerations of the effects of relative velocity and aircraft motion on jet noise cannot explain the differences, in particular those at the forward angles. It is tentatively assumed that the differences are due to extraneous sources present in the full-scale flyover tests such as aircraft aerodynamic noise and internally generated engine noise. These differences require further investigation, since both flyover and wind-tunnel measurements should produce similar results.

Since the objective of this investigation is the determination of the effect of flight on actual jet engine exhaust noise, real turbojet exhaust flow conditions such as velocity and pressure ratio of the jet at high temperatures and flight speed have been closely simulated and the correlations developed are based on data obtained for these conditions. In addition, data were also obtained for lower temperatures, i.e., for 600°F and 300°F at one of the jet velocities. The correlation of noise data at the absolute jet velocity of 1000 fps at the various temperatures is shown in Fig. 14. The value of n increases as the jet temperature decreases.

In order to compare the results of these tests with the results obtained by Cocking and Bryce[3] of NGTE on a cold flow turbojet model, the results were corrected to account for the temperature differences of the two tests by using the recently proposed modification to the SAE[1] jet noise prediction procedure. After correcting for temperature (or density), the static jet at 130° data obey a $V_j^{9.4}$ power law, agreeing with the NGTE cold static model jet data. Based on this agreement under static conditions, the wind-tunnel relative velocity data were also corrected to simulated cold flow conditions in order to attempt comparisons with the NGTE data. As the static data were corrected by the relationship

$$\text{OASPL}_{\text{cold}} = \text{OASPL}_{\text{hot}} - 10\log\left(\rho/\rho_{\text{ISA}}\right)^{\omega} \qquad (4)$$

(where ρ = jet density and ω is a function of absolute jet velocity varying smoothly from -1 at low velocities to 2.0 at high velocities), it was assumed that under relative velocity conditions the same relationship holds if the ω is based on the relative velocity. Corrections for cold jets similar to those shown in Figs. 11 and 12 were then established by correcting the hot jet data to reflect the effect of reducing jet temperatures to ambient values.

From those correlations, the variation in relative velocity exponent n with θ_R was derived and is shown in Fig. 15 with the NGTE results.[3] The agreement of the model results with the NGTE data is much better than the agreement between the model results and the flyover correlation for n. This agreement also indicated the equivalence of measuring within a large tunnel flow (as in the NGTE tests), and measuring outside the flow in a smaller tunnel and correcting for the shear layer (as in the current UTRC tests). The small differences remaining could be due to either the normalization of hot to cold jets or inaccuracies of the shear layer corrections. The main advantage with the latter method is that testing at significantly higher tunnel speeds for the same model jet velocity is possible due to the lower background noise associated with the small tunnel size.

Conclusions

The effects of relative velocity on jet mixing noise was investigated in the Acoustic Research Tunnel over a realistic range of jet velocities, temperatures and simulated flight velocities. The acoustic data were free from contamination by tunnel flow noise or from other facility background noise sources.

Favorable comparisons of tunnel acoustic data, taken with microphones located outside the tunnel flow, with NGTE measurements, taken with microphones in the tunnel flow, were obtained by the use of analytically drived shear layer propagation corrections.

Results of the program show that for a subsonic jet, exhausting at typical engine operating conditions with simulated takeoff and landing flight speeds, jet noise is reduced with increasing flight velocity. Reductions at the rearward angles are the greatest, proportional to the 11th power of relative velocity, and decreasing to about the 4th power of relative velocity at the forward angles. This result is significantly different from the flyover results proposed by the SAE for use in aircraft noise prediction.

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