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Experimental Study of Sound Radiation from a Subsonic Jet in Simulated Motion

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An experiment has been conducted in an anechoic free-jet facility to determine the effect of motion on noise radiation from a 2.54-cm-diam subsonic unheated model jet. The area ratio of free jet to model jet is 2300:1. The model jet is acoustically clean and only pure jet mixing noise is measured. The far-field measurements obtained outside the free jet are subjected to amplitude and angle corrections due to free-jet shear layer refraction. In addition, corrections are made for the axial distribution of the model jet noise source as a function of frequency. The effect of motion on the jet noise directivity, spectrum, and OASPL scaling are presented. It is shown that a reduction in spectral level and overall level of the radiated noise occurs at all angles. The reduction in noise, however, cannot be adequately predicted based on the ratio of jet velocity to the jet velocity relative to the ambient medium alone.

Introduction

IN recent years one of the important problems in aircraft noise has been that of the effect of aircraft motion on jet exhaust noise. The practical objective is an ability to predict the noise level radiated from the jet exhaust of a flying aircraft. Initial understanding of the motion effect on jet mixing noise was derived from flight tests.[1-4] The effect of flight was found to reduce jet mixing noise at all angles.

Due to the high operating cost and the measurement problems associated with flight tests, several flight simulation techniques using ground-based facilities have been adopted. Among these are 1) engine mounted on ground vehicle,[5,6] 2) acoustic wind tunnel,[7-9] and 3) free-jet anechoic facility.[10-14] The latter two techniques, however, have gained increasing popularity recently. With these two techniques the source is stationary and the motion of the source is simulated by the moving medium.

Of the various simulation techniques discussed above, the free-jet anechoic facility suffers from fewer measurement problems and limitations (see, for instance, discussions given in Ref. 10). The problem of sound refraction through the free-jet shear layer, which was considered previously as a major limitation of the technique, has been largely resolved. It has been shown experimentally[12,17] that analytical schemes[15,16] for shear layer refraction correction can be applied with confidence. Effects such as internal reflection and attenuation and scattering of sound by free-jet turbulence were found[12,17] to be negligible for the measurement conditions and frequency range encountered in the simulation study.

In order to quantify the observed noise reduction due to flight, Cocking and Bryce[7] correlated the noise reduction with the ratio of jet velocity to jet velocity relative to the ambient medium, V_J/V_r. The noise reduction was assumed to scale with $(V_J/V_r)^m$. Stone[18] proposed an empirical method to predict separately the motion effect on jet mixing noise, shock associated noise, and internally generated noise for turbojet and turbofan engines. Recently, Stone[19] examined the correlation method based on the ratio of jet velocities, i.e., $(V_J/V_r)^m$, and concluded that it is inadequate since considerable variability in the exponent m can result due to differences in jet conditions and flight velocities.

The purpose of the present study is to determine the motion effect on the pure jet mixing noise from unheated subsonic jets. The experiment is conducted in a free-jet anechoic facility. The free jet to model jet area ratio used (2300) is large enough to simulate realistically the condition prevailing in the actual flight. The model jet is insured to be acoustically clean. The far-field measurements obtained outside the free jet are subjected to amplitude and angle corrections due to free-jet shear layer refraction. In addition, corrections are made to account for the distributed nature of the jet noise source as a function of frequency. The corrected results, which provide the changes in the jet mixing noise as a result of simulated jet motion, are presented for a range of jet velocities with a fixed free jet velocity. Comparisons are made between the present data and existing simulation and flight measurements. A data correlation scheme which quantifies the changes of the jet mixing noise as a result of jet motion is proposed.

Experimental Facility, Apparatus, Instrumentation and Procedures

Free-Jet Anechoic Facility

The experiment was conducted at NASA Langley Research Center using the free-jet anechoic facility in the Acoustics and Noise Reduction Division. A schematic drawing showing the free-jet anechoic facility and test setup is given in Fig. 1. The designed cutoff frequency of the chamber is 100 Hz.

Model Jet Nozzle

A 2.54-cm-diam conical nozzle (see Fig. 2) was used to generate the subsonic turbulent jet. The model jet nozzle was mounted centrally in the free jet and extended 0.91 m above the free-jet exit plane (¾ of the free-jet nozzle diameter). The

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choice of the model jet nozzle location was based on the considerations that the model jet should be well within the uniform flow region of the free jet and that both forward and rearward arc measurements of the noise field from model jet could be made.

A radial survey using a hot wire probe was made in the free-jet cross section containing the model jet nozzle exit. At the free-jet velocity 30.5 m/s and model jet velocity 152.4 m/s the turbulent intensity in the potential cores were found to be less than 2% for both jets. The model jet nozzle boundary layer at the exit was about 10% of the nozzle diameter. The boundary layer on the nozzle exterior wall was relatively thick, about 30% of the nozzle diameter. The thick exterior boundary layer is a result of the long piping system used to generate the model jet (see Fig. 1) as well as the divergence of the exterior nozzle wall used in the final contraction ($\simeq 14$ deg). Based on the turbulence measurement made at model jet exit plane in the exterior region of the nozzle, the axial turbulence intensity in the boundary layer was about 8% of the free-jet velocity and there was no indication that the nozzle exterior boundary layer was separated upstream of the model jet exit. The importance of model jet initial conditions, especially the exterior boundary layer on free-jet simulation has been demonstrated by Sarohia and Massier.[20] However, a quantitative scheme has yet to be developed to fully account for the effect of the initial conditions on the noise radiation from a turbulent jet in motion.

Instrumentation and Apparatus

Far-field measurements were made with a ½ in. B & K 4133 condenser microphone mounted on a rotating boom with boom radius of 3.12 m measured from the center of model jet nozzle exit. The measured signal was high passed at 200 Hz to eliminate low frequency flow noise of the free jet. A second ½-in. condenser microphone fitted with a nose cone and a specially designed boom mechanism was used to obtain noise measurement within the potential core of the free jet. The boom radius used was 0.46 m. The in-flow boom was designed such that the axis of the microphone was always aligned to the direction of the flow. The frequency response of the nose cone fitted in-flow microphone as a function of sound incidence angle was obtained experimentally.[21]

Experimental Procedures

Initially, the instrument electronic noise, flow noise of the free jet, and internal noise from the model jet air supply was determined in ⅓ octave bands. These data were used to obtain the corrected model jet noise spectra. The baseline static jet noise was measured at jet velocities (V_J) of 121.9 m/s and 152.4 m/s over a range of θ_m (see Fig. 1). Additional static jet noise was obtained at $\theta_m = 30$ and 90 deg over a range of V_J. The effect of simulated flight on jet noise was determined by repeating the above test conditions for the model jet but with a free-jet velocity (V_T) of 30.5 m/s. In a parallel study,[22] two additional free-jet velocities were also used.

In order to verify the validity of the free-jet shear layer correction scheme[15,16] for a distributed source such as a turbulent jet, in-flow measurements in the free-jet potential core were made over a range of θ_m from 30 to 140 deg in 10 deg increments.

In each measurement the operating procedures consisted of a microphone calibration, a boom position readout calibration, establishing the run condition, and then data acquisition. The averaging time used for ⅓ octave band spectral analysis was 8 s. Pink noise was inserted through the on-line ⅓ octave band data acquisition channels before each set of measurements as an overall check on the analysis system and equalization of system response was made if necessary.

Data Reduction

In order to obtain valid jet mixing noise data under static conditions and/or under simulated motion, the measured results are subjected to a set of data corrections. For the static case, the corrections are measurement system response, background and instrument noise, and internal noise from the model jet air supply. For the case of simulated motion, additional corrections consist of free-jet flow noise, angular and amplitude changes due to free-jet shear layer refraction, and corrections for the effect of axial source distribution of the model jet.

Typical data used for background and flow noise corrections are shown in Fig. 3 for $\theta_m = 90$ deg, $V_J = 152.4$ m/s, and $V_T = 30.5$ m/s. Also shown in the figure is the measured ⅓ octave band spectrum in the far field outside the free jet. In applying corrections, data below the center frequency at which the measured far-field level is equal to the combined noise level were discarded. Where the difference between measured far-field level and the combined background noise level was less than 10 dB, the corrected level was obtained by logarithmically subtracting from the measured level the combined background noise. This meant

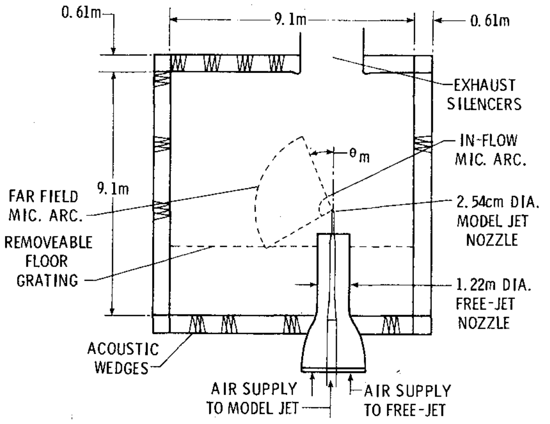

Fig. 1 Schematics showing free-jet anechoic facility.

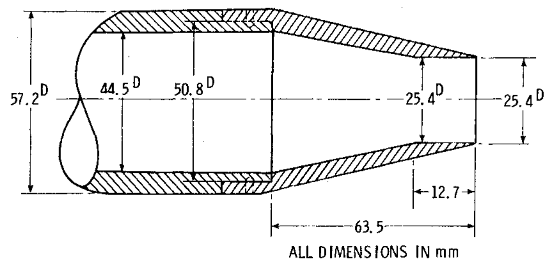

Fig. 2 Model jet nozzle geometry.

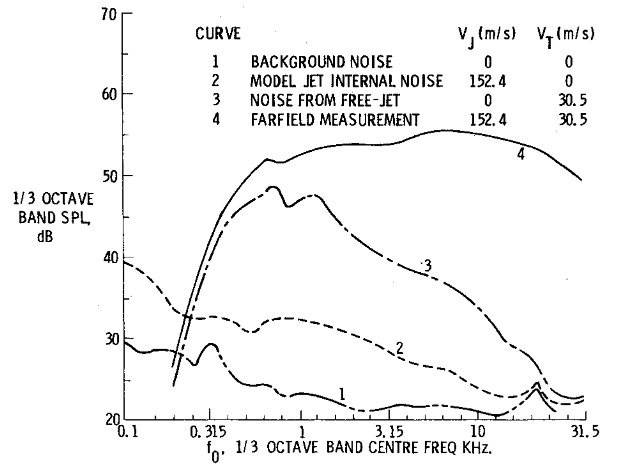

Fig. 3 Comparison of uncorrected far-field data and input data used for correction.

that in most cases there was a lower limit on center frequency of the spectrum of around 400 Hz.

The in-flow measurements taken within the potential core of the free jet were further limited by microphone-induced flow noise and the reduced frequency response of the nose cone fitted microphone. Consequently, the in-flow data below 1 kHz had to be discarded. In comparing data, a provision was made to insure that equal frequency bandwidths were used in the comparison and that no data were extrapolated.

Corrections of acoustic transmission through the free-jet shear layer were made on the far-field noise data measured outside the free jet. The correction scheme proposed in Ref. 15 for the thick cylindrical shear layer was used in the present study. The corrected data are given in terms of wave normal angle θ_T and represent the noise that would have been measured if the measurements were made in a frame of reference attached to the moving jet, as is commonly done in the literature.

The effects of axial distribution of the apparent sources for turbulent mixing noise in subsonic jets were also included in the correction scheme. The apparent source location as a function of Strouhal number was obtained from the measurements reported in Refs. 23 and 24. It should be noted, however, that the source distribution corrections were based on the apparent source distribution measured for static jets. This may not be valid at higher free-jet velocities where the motion effect may change the source distribution. Other details of the facility, apparatus, instrumentation, and procedures may be found in Ref. 21.

Results and Discussion

Experimental results for an unheated model jet presented in this section are divided into three main areas. First the jet mixing noise measured under static conditions is presented and comparisons made with existing pure jet mixing noise data available in the literature. The effects of motion on jet mixing noise are then discussed. Finally, comparisons are made with findings from other simulation studies and flight tests.

Static Jet Noise

Since the purpose of the present investigation is to determine the effects of motion on pure mixing noise from subsonic jets, it is necessary to insure that the noise field of the model jet is dominated only by pure mixing noise. This would require that the model jet be both acoustically and aerodynamically "clean." To validate the model jet used in the present study, comparisons were made between the present results and the corresponding results for pure jet mixing noise reported by Lush[25] and Moore.[26]

Figure 4 shows an OASPL comparison at $M_J = 0.57$, where $M_J = V_J / C_0$ and C_0 is the ambient speed of sound. A V_J^8 dependence was assumed in order to normalize out the small differences in V_J among the different sets of data. Also included in the comparison is the prediction based on the SAE scheme.[27] It is seen that the data collapse is very good, within ½ dB. Similar agreement was found at other values of M_J. Figure 5 shows a comparison of ⅓ octave band spectra for $M_J = 0.57$ measured at $\theta_m = 45$ and 90 deg, respectively, between the present measurements and Lush's data. In making these comparisons, the present results were scaled to the same nozzle diameter and jet velocity as used by Lush.[25] Again good agreement is apparent.

In view of the good agreements obtained from the above comparisons, it may be concluded that the present model jet is both acoustically and aerodynamically clean and that only pure jet mixing noise was measured.

Effects of Motion on Jet Mixing Noise

The effects of simulated motion on the jet mixing noise were investigated at a fixed free-jet velocity of 30.5 m/s. The

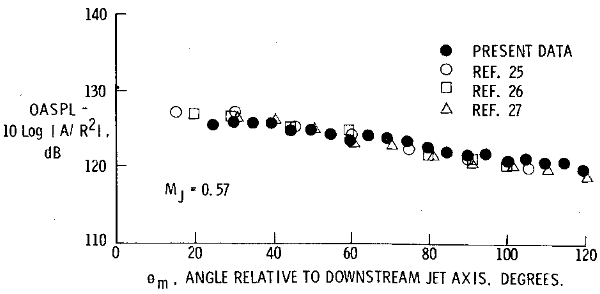

Fig. 4 Comparison of OASPL variation with angle for static jet.

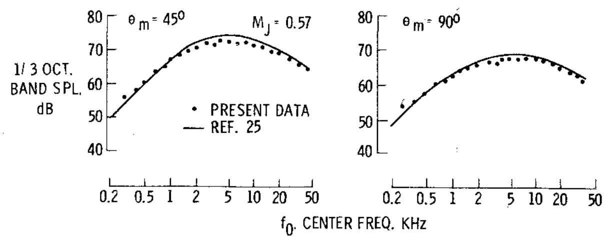

Fig. 5 Comparison of ⅓ octave band SPL spectra for static jet.

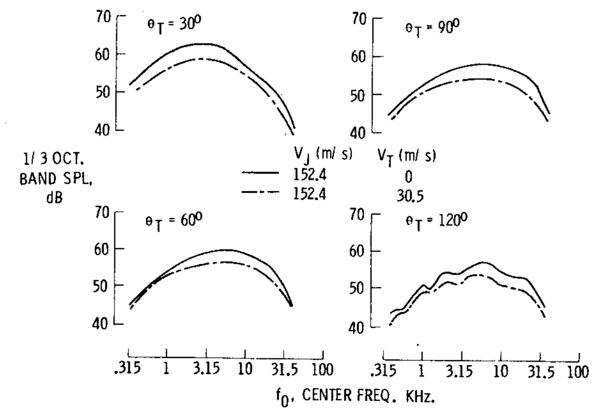

Fig. 6 Effect of motion of ⅓ octave band SPL spectra.

measured data for both static jet and jet under simulated motion were properly corrected using the methods discussed in the last section. Differences between the two sets of results at a given model jet velocity thus yield the effect of motion on jet mixing noise.

One-Third Octave Band SPL Spectrum and Power Spectrum

Figure 6 shows the comparisons of ⅓ octave band SPL spectra between the static jet and the moving jet at $V_J = 152.4$ m/s and $V_T = 30.5$ m/s. The comparison is made at corresponding wavenormal angle θ_T and distance measured along the wavenormal from the source. For the motion case, since the wavenormal angle θ_T differs from the measurement angle θ_m it was necessary to interpolate the data. The interpolation was made where θ_T differs from θ_m by more than 1 deg. It is seen that the effect of jet motion is to reduce radiation over the entire frequency range and that these reductions occur at all angles. The maximum reduction is obtained around the frequency of the spectral peak. The fluctuation in spectral level seen at $\theta_T = 120$ deg is attributed to acoustic reflections from the free jet support structure. Spectral comparisons made at higher jet velocities indicated that the broadband reduction of jet noise decreased as the ratio of jet velocity and free-jet velocity was increased.

In an attempt to establish similarity of radiated noise from a jet in motion, the measured ⅓ octave band SPL were normalized with respect to the OASPL and a Strouhal number based on jet diameter and relative velocity $V_r = V_J - V_T$.

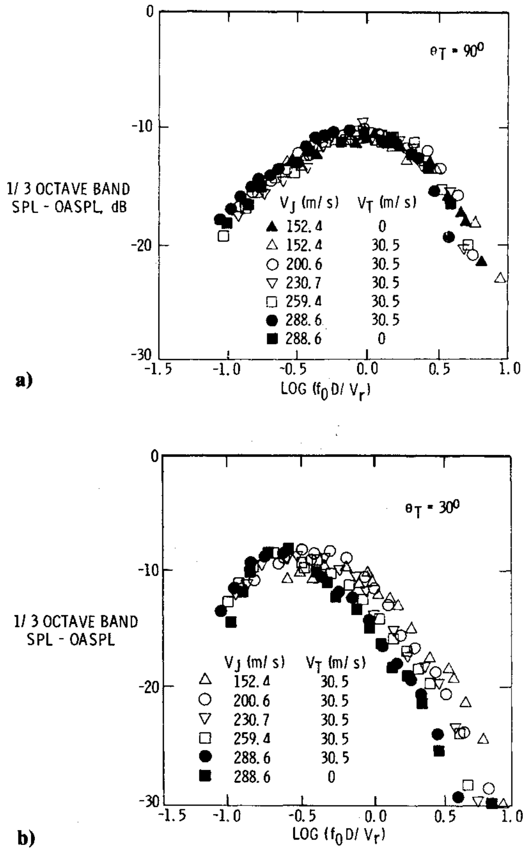

Fig. 7 Similarity of ⅓ octave band SPL spectra under simulated motion, a) $\theta_T = 90$ deg, b) $\theta_T = 30$ deg.

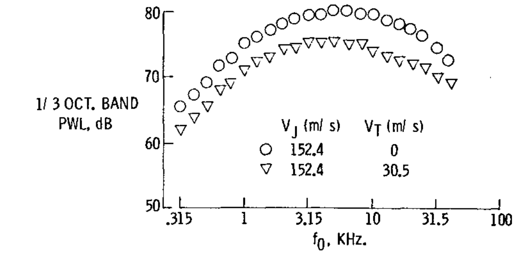

Fig. 8 Effect of motion on ⅓ octave band power spectrum.

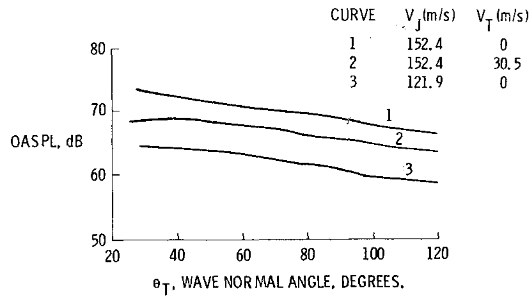

Fig. 9 Effect of motion on OASPL variation with wavenormal angle.

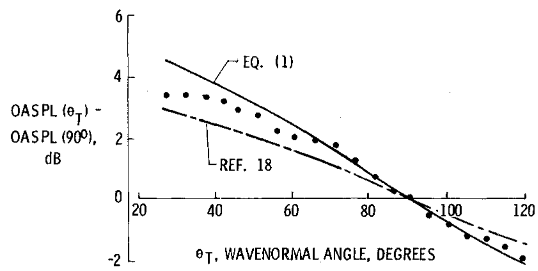

Fig. 10 Comparison between OASPL directivity measured under simulated motion with predictions.

Results are shown in Fig. 7. It is seen that while good data collapse is obtained at $\theta_T = 90$ deg., poor agreement appears at higher frequencies for $\theta_T = 30$ deg. The lack of spectral similarity at shallow angles to the jet axis is apparently also a well-known feature for static jet noise (see, for instance, Ref. 25).

To quantify the effect of motion on the source strength and/or radiation efficiency of jet mixing noise, ⅓ octave band power spectra were calculated for the static and motion cases and are shown in Fig. 8. This was done by integrating the ⅓ octave band SPL spectrum over the part of a spherical surface defined by $\theta_T = 25$–120 deg. It is apparent from Fig. 8 that the effect of jet motion is to reduce the source strength and/or radiation efficiency at all frequencies with most reductions at frequencies around the spectral peak.

OASPL Directivity

The effect of motion on OASPL variation with angle is illustrated in Fig. 9 for $V_J = 152.4$ m/s and $V_T = 30.5$ m/s. Included in the same figure for comparison is the static data obtained at $V_J = 121.9$ m/s, which is the same as the relative velocity of the 152.4 m/s jet. Comparison between curves 1 and 2 in Fig. 9 shows that the effect of motion is to reduce the jet mixing noise by nearly a constant amount over most of the angular range, about 3.5 dB. Comparison between curves 2 and 3 indicates that a difference of 5 dB exists between the two cases even though the jet velocity for curve 3 is equal to the relative velocity in curve 2. This observation reconfirms the fact that a moving jet radiates quite differently from that of an "equivalent" static jet. The source strength and/or radiation efficiency of jet mixing noise are altered as a result of motion as has been shown in the previous section.

According to Ffowcs-Williams[28] and Ribner,[29] the noise intensity for a subsonic jet in motion should scale with $V_r^7 V_J$ in a frame attached to the jet nozzle. If this scaling is applied to the results given by curves 2 and 3 in Fig. 9, a discrepancy of about 4 dB results. A similar conclusion was reached by Cocking and Bryce[7] based on their simulation study made in an acoustic wind tunnel. They also proposed an alternative scaling based on $V_r^m V_J^n$. The merits of this alternative scaling will be discussed in the subsequent sections.

The measured OASPL variation with angle as given in curve 2 of Fig. 9 was converted to OASPL directivity by normalizing the measured results with respect to the value obtained at $\theta_T = 90$ deg. The experimental OASPL directivity for the moving jet is then compared in Fig. 10 with the prediction of Stone[18] and the prediction based on the quadrupole convective amplification, derived by Ribner[29] and Ffowcs-Williams,[28] given by

$$\mathrm{OASPL}(\theta_T) - \mathrm{OASPL}(90\,\mathrm{deg}) = -25\log \times \left\{ \frac{(1 - M_{cr}\cos\theta_T)^2 + (\alpha M_{cr})^2}{1 + (\alpha M_{cr})^2} \right\} \tag{1}$$

where α is taken as 0.5 and $M_{cr} = 0.6 V_r / C_0$. It is seen that both predictions fall within 1 dB of the measurement.

Scaling of OASPL

Two different methods of scaling OASPL for jet mixing noise under motion were examined. The first method is that proposed by Cocking and Bryce[7] where OASPL ~ $V_r^m V_J^n$. Based on this method the difference in OASPL between that

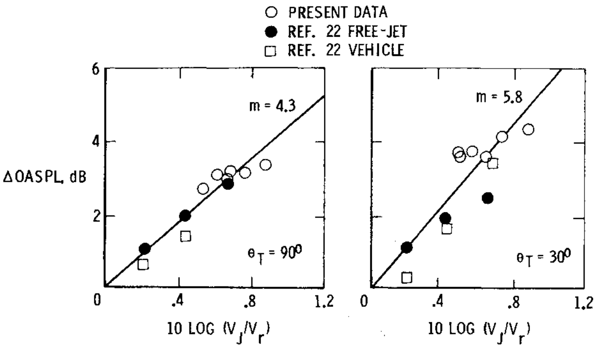

Fig. 11 Correlation of OASPL with vilocity ratio.

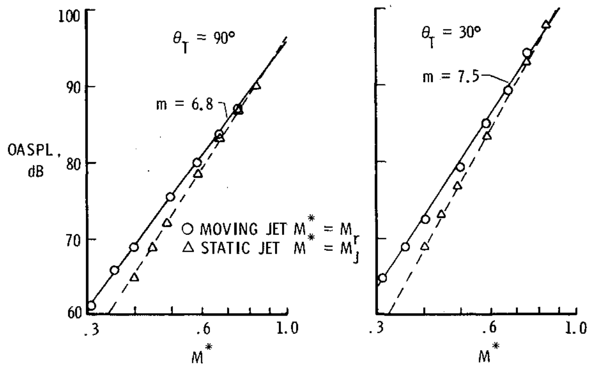

Fig. 12 Scaling of OASPL with Mach number.

measured statically and that for the same jet under motion is given by

$$\Delta\text{OASPL} = \text{OASPL}_{\text{static}} - \text{OASPL}_{\text{flight}} = (V_J/V_r)^m \qquad (2)$$

This method of scaling has been widely used in the literature. The ΔOASPL measured in the present study is plotted against V_J/V_r in Fig. 11. Included in the same figure are data obtained in a parallel study conducted by Norum[22] using different free-jet velocities and the corresponding data gathered with the model jet mounted above a moving automobile. At $\theta_T = 90$ deg, the line that best fits the data yielded a value of $m = 4.3$ with a scatter of the order of 0.5 dB. At $\theta_T = 30$ deg, m was found to be 5.8 with a scatter of the order of 1 dB. It should be noted that although good correlation is found with Eq. (2) the m values obtained, however, are in variance with those reported by previous investigators.

A second method of scaling OASPL measured under simulated motion was examined. This method is essentially an extension of the well-established scaling law for subsonic jet mixing noise under static conditions. It can be easily shown that

$$\hat{I}_s = K_s(\rho_J/\rho_0)^2 (D/r)^2 M_J^n \{(1-M_c\cos\theta)^2 + (\alpha M_c)^2\}^{-5/2} \qquad (3)$$

where $\hat{I}_s$ is the intensity nondimensionalized with respect to $\rho_0 C_0{}^3$. K_s is a proportionality constant which when combined with a $M_J{}^{n-3}$ term determines the efficiency of noise production. M_c is the eddy convection Mach number, $M_c = 0.6\ M_J$, and θ is the angle measured with respect to the downstream jet axis. When a subsonic jet is in motion, it is reasonable to assume that the noise intensity scales as

$$\hat{I}_f = K_f(\rho_J/\rho_0)^2 (D/r)^2 M_r^m \{(1-M_{cr}\cos\theta_T)^2 + (\alpha M_{cr})^2\}^{-5/2} \qquad (4)$$

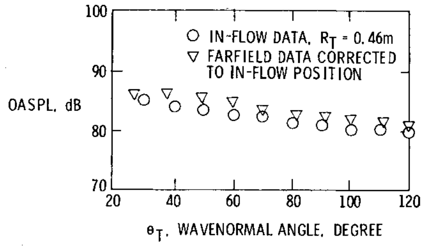

Fig. 13 Comparison of in-flow and far-field OASPL, $V_J = 152.4$ m/s, $V_T = 30.5$ m/s.

Equation (4) is arrived at on the basis that V_r is a characteristic velocity in scaling the ⅓ octave band spectrum and in predicting the OASPL directivity. It should be noted, however, that the semiempirical relationship given by Eq. (4) would probably be invalid at very low values of jet forward speed where M_r approaches M_J. The variation of noise intensity of subsonic jet at a forward velocity much lower than the jet velocity is expected to be more characteristic of a static jet and is described by Eq. (3).

In Fig. 12 the OASPL measured under simulated motion is plotted against the relative Mach number M_r for $\theta_T = 30$ and 90 deg. It is seen that $M_r{}^m$ scaling provides good correlations with data at both wave-normal angles. The scattering about the fitted solid lines is within 0.5 dB. OASPL data measured under static condition are also included in the same figure for comparison. Note that at higher values of M_r where the ratio of M_r/M_J approaches unity, the line that best fits the moving jet data merges into that for the static jet.

Comparison Between Far-Field Measurement and In-Flow Measurement

One of the important aspects of this study was to verify the validity of shear layer transmission corrections for a distributed noise source such as a turbulent jet. In order to accomplish this, measurements were made inside the potential core of the free jet at a distance 0.46 m from the model jet nozzle exit. The in-flow data were corrected for the background noise, flow noise, and the source distribution effects as were done for the far-field data. A further correction was made on the in-flow data for the nose cone and variable sound incidence angle effect. The far-field ⅓ octave band SPL were then adjusted to the same distance as that used in the in-flow measurement by assuming an inverse square dependence of SPL on distance. The corrected ⅓ octave band SPL spectra for both in-flow measurement and the distance adjusted far-field measurement were integrated over a band width from 1 kHz to 40 kHz at corresponding angles to give OASPL. The results so obtained are compared in Fig. 13. It is seen that the agreement between the in-flow measurement and the adjusted far-field measurement is good. This comparison illustrates that the shear layer transmission correction method used in the present study is valid for a distributed source such as a turbulent jet. The three main corrections used (the angle correction, the amplitude correction, and source distribution correction) are shown to account for the major aspects of the shear layer transmission effects in free-jet simulation measurements.

Comparison with Simulation and Flight Data

To quantify the amount of reduction in jet mixing noise due to motion, it has been conventional to correlate the reduction obtained with velocity ratio V_J/V_r as shown in Eq. (2). Figure 14 is a comparison of ΔOASPL variation with V_J/V_r at $\theta_T = 90$ deg. It is seen that there is a rather large variation in ΔOASPL among different data sets. The value of the exponent m for the simulation studies using model jet data varies from 3.5 to 8. Although Low's[3] flight data also fall within this range of m, engine data obtained from Bertin

Table 1 Comparison of correlation parameters used in Eq. (5)

Source of data	Simulation method	K_s	n	K_f	m	$n-m$	C_K
Present study	Free jet	1.4×10^{-6}	7.8	1.2×10^{-6}	6.7	1.1	0.7
Ref. 7	Acoustic wind tunnel	3.2×10^{-6}	9.1	1.8×10^{-6}	7.6	1.5	2.5
Ref. 10	Free jet	2.0×10^{-6}	7.5	2.4×10^{-6}	6.8	0.7	−0.8
Ref. 13	Free jet	1.4×10^{-6}	8.6	1.8×10^{-6}	8.4	0.2	−1.1
Ref. 27	Prediction	1.6×10^{-6}	7.6	—	—	—	

Aerotrain simulation[6] and the F-86 Sabre jet taxi-by data reported in Ref. 9 indicate m values lower than 3.5. From this comparison it becomes apparent that $(V_J/V_r)^m$ scaling of ΔOASPL provides an unsatisfactory correlation with the measured data and that a large discrepancy occurs in the ΔOASPL prediction at higher values of V_J/V_r. This problem has also been considered recently by Stone.[19] Stone attributes the observed variation of the exponent m partly to the contamination by non-jet mixing noise which could occur in tests involving engines, and partly to the difference in the jet conditions and jet velocities used in the tests.

In an attempt to resolve the discrepancy in ΔOASPL scaling discussed above, an alternative data correlation scheme was examined. This scheme is based on the semiempirical scaling relationships Eqs. (3) and (4) given in the previous section. The reduction of the mixing noise due to jet motion is obtained by taking the ratio of Eq. (3) and Eq. (4), and is given by

$$\Delta\text{OASPL}\,(\theta_T) = 10\log\,(M_J/M_r)^m + 10\log M_J^{\,n-m} - 25\log\left\{\frac{(1-M_c\cos\theta_T)^2+(\alpha M_c)^2}{(1-M_{cr}\cos\theta_T)^2+(\alpha M_{cr})^2}\right\} + C_K \qquad (5)$$

where $C_K = 10\log(K_s/K_f)$. Note that the leading term in Eq. (5) is just the V_J/V_r term used in the existing correlation scheme, Eq. (2). In addition, Eq. (5) contains a term that depends on jet velocity, a term to account for the convective amplification of the source and a term related to the ratio of source efficiencies. The main difference between Eq. (5) and the existing scheme is that, for a given ratio of M_J/M_r, Eq. (5) predicts an increase of ΔOASPL with M_J while the existing scheme predicts a ΔOASPL independent of M_J.

In order to establish the general validity of Eq. (5), the variations in correlation parameters K_s, K_f, n, and m were first determined by applying Eqs. (3) and (4) to the present data and other available model jet simulation data. These include the free-jet data of Refs. 10 and 13 and the acoustic wind tunnel data of Ref. 7. The reason for using only model jet data in the correlation is to avoid the possible complication of engine internal noise. Data reported in Ref. 13 were obtained with a heated model jet. Therefore, it was necessary to first apply temperature correction to the data. This was done by using the method given in Ref. 27 for static jet. It was assumed that the exponent for density ratio given in Ref. 27 to be valid if relative velocity was substituted for absolute jet velocity.

It should be pointed out that only limited data could be extracted from each reference for the present correlation since it has been conventional to present the result in ΔOASPL rather than OASPL. Consequently, reliable correlations with Eqs. (3) and (4) could only be made at $\theta_T = 90$ deg. For each data set, the correlations with Eqs. (3) and (4) were found to be within 1 dB. A comparison of correlation parameters determined from each data set is given in Table 1. K_s and n computed from SAE prediction[27] for $M_J < 1$ are also included in the table for reference. Although variations are noted in these correlation parameters, a general agreement is evident. The observed variations are not entirely unexpected. This is because differences may exist even among carefully controlled simulation experiments. Parameters such as initial conditions of the jet, microphone distance from the source, method of simulation, and data reduction procedures can all introduce variations in the measured results.

ΔOASPL computed from Eq. (5) using the values of correlation parameters given in Table I are compared in Fig. 15 for two values of M_J. Predictions based on the empirical scheme of Stone[18] are also included in the same figure for comparison. At the maximum value of $M_J/M_r = 1.44$ used in the figure, the difference in the computed ΔOASPL is 4.5 dB at $M_J = 0.9$ and 3.7 dB at $M_J = 0.6$. These differences should be compared with the corresponding value of 7.2 dB expected from the $(V_J/V_r)^m$ scaling discussed earlier where m was shown to vary from 3.5 to 8 (see Fig. 14). At lower values of M_J/M_r, Fig. 15 indicates that Eq. (5) provides rather poor correlation as compared to the $(V_J/V_r)^m$ scaling. This discrepancy is attributed to the fact that Eq. (5) does not necessarily predict zero ΔOASPL at $M_J/M_r = 1$. There are two reasons for this: first, the validity of Eq. (4) is questionable as M_J/M_r approaches unity and second, the reliability of data becomes poor at low values of M_J/M_r where the ΔOASPL to be measured could be within the accuracy of the measurement. Stone's predictions provide good

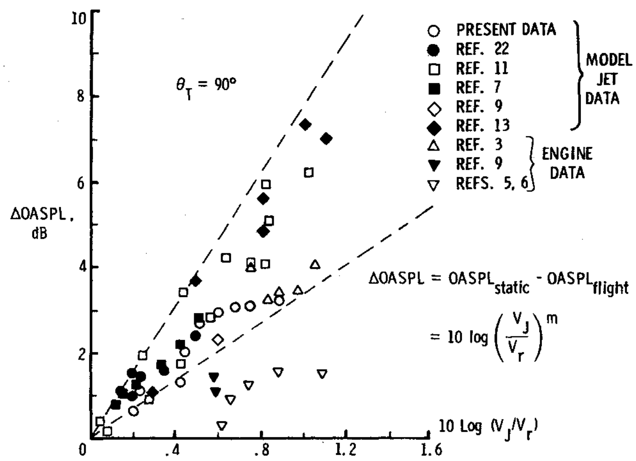

Fig. 14 Variation of ΔOASPL with velocity ratio, $\theta_T = 90$ deg.

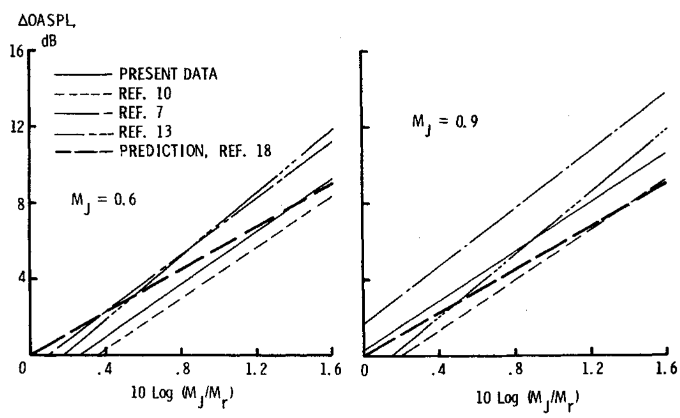

Fig. 15 Correlation of ΔOASPL with Eq. (5), $\theta_T = 90$ deg.

comparisons with the computed ΔOASPL at both values of M_J. However, due to the fact that Stone allows a much weaker dependence of ΔOASPL on M_J, slight underprediction is evident at $M_J = 0.9$.

Conclusions

The effect of motion on the noise radiation from a subsonic model jet has been investigated experimentally in the NASA Langley anechoic free-jet facility. The large free jet to model jet area ratio used provides a realistic simulation of actual flight. The model jet was verified to be acoustically clean so that only pure jet mixing noise was measured. The data correction scheme used takes into account free-jet shear layer refraction and the distributed nature of the source. The validity of the scheme was confirmed experimentally.

Based on the results obtained in the present study, it may be concluded that the effect of motion is to reduce jet mixing noise at all angles of measurement and the reduction is broadband with the largest magnitude occurring around the spectral peak. The amount of reduction, however, is not predicted by the existing theory. The relative velocity is found to be a characteristic variable in the scalings of ⅓ octave band spectra, OASPL at a given wave-normal angle, and the OASPL directivity. The measured OASPL directivity compares well with the existing predictions. An alternative OASPL scaling relation based on the relative velocity alone is found to provide good correlation with the present data.

Based on the comparisons made between the present data and other model jet simulation data and flight data, it may be concluded that the existing method of scaling ΔOASPL based on the velocity ratio V_J/V_r alone appears to be inadequate at large values of V_J/V_r. A different scheme for scaling ΔOASPL is proposed. In this scheme ΔOASPL depends on both V_J/V_r and V_J, predicting an increase in ΔOASPL with V_J at constant V_J/V_r. Correlations made between this scheme and limited model jet simulation data suggest that ΔOASPL may be better predicted as compared to the existing method based on V_J/V_r alone. The general validity of this scheme, however, can only be established by more extensive data correlation.

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