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Comparison of Measured and Predicted Flight Effects on High-Bypass Coaxial Jet Exhaust Noise

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James R. Stone
Lewis Research Center
Cleveland, Ohio

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COMPARISON OF MEASURED AND PREDICTED FLIGHT EFFECTS ON HIGH-BYPASS COAXIAL JET EXHAUST NOISE

James R. Stone*
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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Abstract

A recently developed semi-empirical model for predicting the noise generated by conventional-velocity-profile coaxial jets is compared with full-scale flight data and model-scale simulated flight data for high-bypass nozzles. The prediction model has been shown to agree with small-scale static data for primary jet velocities from 215 to 795 m/s for a wide range of area, temperature and velocity ratios between streams. However, there were insufficient model nozzle, simulated flight data available at that time to permit validation of the flight effects prediction. The comparisons presented in this paper demonstrate that the prediction method is also valid in flight.

Introduction

Accurate noise prediction methods are required in order to predict the environmental impact of airport operations on the surrounding communities, as well as for the realistic design of new aircraft and the development of noise reducing modifications to existing aircraft. To be credible, these prediction methods must be validated by comparison with experimental data. Recently, an improved prediction method for the noise generated by conventional-velocity-profile coaxial jets was developed and validated with static, model nozzle data.[1] This method was shown to agree with the data for primary jet velocities from 215 to 795 m/s for a wide range of area, temperature and velocity ratios between the streams. The prediction also includes the effects of flight, but there were insufficient simulated-flight model nozzle data available in the open literature to permit the flight effects predicted to be validated. In addition, full-scale engine comparisons require estimation of the contributions of other noise sources, such as engine core and air-frame. Thus, the question of flight effects was not resolved in reference 1, and is the subject of the present paper.

The numerous aspects of the mechanisms of noise generation by coaxial jets are not fully understood, and therefore, the necessity of predicting jet noise has led to the development of empirical procedures. The NASA interim prediction method for jet noise[2] and several different methods based on extension of the Society of Automotive Engineers (SAE) methods for circular jets[3] have been widely used. The NASA interim method, based on extension of the earlier studies of Olsen and Friedman[4] and Williams, et al.[5] has been shown to agree reasonably well with full-scale static and flight data[6] for low to moderately-high bypass ratio coaxial jets. The circular jet method (also in Ref. 2) on which that prediction was based was later improved[7] by incorporating a more fundamentally correct formulation of source convection effects based on the theoretical developments of Goldstein[8] and Ffowcs Williams[9]. The desirability of further minor improvements in the static directivity and spectra near the peak noise angle was shown by the comparisons of Gutierrez[10]. Therefore, the improved method[1] was envolved and validated by comparisons with the static model data of Goodykoontz, et al.[11-12] and Tanna, et al.[13].

In order to validate the coaxial jet noise prediction in flight and eliminate questions about contaminating noise sources such as engine core and airframe, the prediction is first compared with simulated flight model nozzle data. Experimental data are utilzied from the two most commonly used types of flight simulation facilities; namely, wind tunnels[14-15] and free jets [16]. Comparisons with data from both types of facilities are useful since neither method is universally accepted because of the problems involved with correctly making all the transformations and corrections necessary to project such data to actual flight conditions. After establishing the validity of the jet mixing noise prediction, comparions are then made with full-scale flight data[17] with the contributions of airframe noise[18] and core noise[19] also taken into account.

Nomenclature

(All dimensions are in SI units unless noted.)

f	1/3-octave-band center frequency
OASPL	overall sound pressure level, dB re 20 $\mu N/m^2$
R	source-to-observer distance
SPL	1/3-octave-band sound pressure level, dB re 20 $\mu N/m^2$
T	total temperature
V	velocity
Y	minimum (perpendicular) distance of observer from engine axis (Fig. 10).
θ	directivity angle from inlet axis (Fig. 10), deg.
σ	standard deviation, square root of mean square predicted minus experimental OASPL, dB

Subscripts

C	relative to center of core nozzle exit plane
F	flight or simulated flight level
J	relative to assumed jet noise source location
S	static level
0	aircraft (or flight simulation)
1	fully-expanded primary (inner) jet
2	fully-expanded secondary (outer) jet.

*AIAA Member.

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Model Nozzle Wind Tunnel Comparisons

In order to validate the coaxial jet noise prediction in flight, comparisons are shown in this section with model nozzle data obtained from two wind tunnels. The wind tunnel (Fig. 1) offers a relatively straight-forward means of simulating flight effects; however, this approach is not without problems. High background noise levels and reverberations force the noise measurements to be made relatively close to the source, which necessitates correcting for near-field and source distribution. These corrections are quite significant for jet noise.

Overall sound pressure level (OASPL) directivity and spectral sound pressure level (SPL) plots will be shown to facilitate comparisons. In many cases the ordinate scale will be broken to avoid overlap in the data sets shown. Statistical comparisons will be discussed for the OASPL in terms of a standard deviation and an average over-prediction (or under-prediction). These statistical comparisons are described in more detail later under "Summary of Model Nozzle Comparisons."

Boeing Wind Tunnel

The first set of wind tunnel data considered were obtained by Lu and Lanter[14] in a 2.7- by 2.7-m wind tunnel lined with foam wedges. These data were corrected for background noise and extrapolated to the far field using the method of Jaeck [20]. These data were obtained at approximate takeoff power setting for static conditions as well as for two wind tunnel velocities, V_0 = 61 and 98 m/s. The data have been scaled up by a linear factor of 12 to represent a typical full-size single engine nozzle at a 305-m altitude level flyover on a standard day.

Directivity. - Flyover OASPL directivity patterns and the corresponding static-to-flight increments are shown in figure 2. The general agreement is quite good. The static OASPL is underpredicted by an average of 0.2 dB with a standard deviation of 1.3 dB. For simulated flight, the average underprediction is 0.3 dB with a 1.3 dB standard deviation. The flight noise level relative to the static level is underpredicted by 0.1 dB with a 1.4 dB standard deviation.

Spectra. - Spectral comparisons for the preceding Boeing wind tunnel cases are shown in figure 3. In the forward quadrant (θ = 70 deg.) and simulated overhead position (θ = 90 deg.) the general spectral shape is predicted fairly well except for a mid-frequency dip in the experimental data. This apparent dip may be due in some degree to the presence of some excess facility noise above 400 Hz[22]. Aft quadrant results at θ = 110, 130 and 150 deg. are somewhat similar in agreement to the forward quadrant except that the high frequency noise is overpredicted in the static case. The reduction in peak-SPL frequency with increasing flight velocity is less experimentally than is predicted. This leads to some underprediction of the high frequency noise in flight. If the experimental data are contaminated at high frequency and the high frequency levels should be lower, it might be that the prediction would show better agreement in flight but somewhat poorer agreement under static conditions than figure 3 indicates.

RAE Wind Tunnel

Wind tunnel measurements also were obtained by Cocking[15] in the Royal Aircraft Establishment (RAE) 7.2-m diameter open-throat wind tunnel. No correction was made for distributed source position effects in Ref. 15, so the approximate method of Ref. 1 was used to estimate these effects. These corrections are rather large since the microphones were located on a sideline only 32 primary nozzle diameters from the jet axis. The primary nozzle diameter was 65 mm with a secondary-to-primary area ratio of 2.5 and coplanar exits. The experimental data are reported on a lossless basis; i.e., the predicted effects of atmospheric absorption have been removed from the data.

These results[15] were the first to confirm a key assumption in formulating the NASA prediction procedures; namely, the assumption that the secondary stream has a negligible influence on the flight effect. Based on these findings Cocking[15] suggested a flight effects formulation quite similar to that incorporated in the present prediction[1].

Only limited spectral results were reported in Ref. 15. The data reported here are for a high subsonic primary jet velocity, V_1 = 446 m/s, and primary total temperature, T_1 = 880 K, with a secondary-to-primary velocity ratio, V_2/V_1 = 0.6, and wind tunnel velocities, V_0 = 6 m/s (pseudo-static) and 40 m/s. Results at model scale are shown in Fig. 4 for corrected directivity angles, θ = 81, 111 and 138 deg., corresponding to uncorrected angles of 90, 120 and 145 deg. (Data at 53 deg. appear to exhibit anomalously high low-frequency noise not seen in any other data set, so these results are excluded.) At θ = 138 deg. the agreement is rather good both in spectral shape and, as indicated by the OASPL, in level. At the more forward angles, the agreement in level is still fairly good, but the peaks of the predicted spectra are at somewhat higher frequencies than those of the experimental spectra. On the average, the static OASPL is overpredicted by 0.3 dB with a 0.9 dB standard deviation, and the flight OASPL is overpredicted by 1.3 dB with a 1.5 dB standard deviation. The static to flight OASPL increment is underpredicted by an average of 0.9 dB with a standard deviation of 1.0 dB.

Model Nozzle Free Jet Comparisons

The free jet (Fig. 5) has a significant advantage to offer compared with the wind tunnel in that the microphones can be located outside the flow and in the far field, thus minimizing the reverberation, background noise and source distribution problems. However, the transformation is much more difficult and controversial, especially due to the effect of acoustic propagation through the free jet/ambient shear layer.

The free jet data were obtained by Fogg[16] of General Electric in an anechoic chamber with a 1.22-m diameter free jet containing a 15-cm equivalent diameter coaxial nozzle. These data were projected to flight using the procedure developed in reference 22 and do not include source position corrections. Source position corrections are estimated herein for these comparisons from Ref. 1. The data were obtained under static conditons and with a free jet velocity, V_0, of 107 m/s at approximate takeoff conditions. The results have been scaled by a linear factor of about 9 to represent a full-size engine at a 457-m altitude level flyover on a standard day.

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Directivity. - Flyover OASPL directivity patterns and the corresponding static-to-flight increments are shown in Fig. 6. In general, the agreement is fairly good, except near θ = 90 deg., where there is an apparent inconsistency in the experimental data which is worse under simulated flight conditions. Due largely to this questionable region there is an average overprediction of 0.8 dB in the static case with a standard deviation of 1.1dB while in the flight case the average overprediciton is 1.3 dB with a standard deviation of 2.6 dB. In terms of the static-to-flight increment, there is an overprediction of the flight level by 1.0 dB with a 2.0 dB standard deviation.

Spectra. - Spectral comparisons for the preceding cases are shown in figure 7. There is a tendency, especially under static conditons, for the predicted spectra to peak at a higher frequency than the experimental spectra, leading to an overprediction of high frequency noise. This problem is reduced in flight, particularly in the aft quadrant (θ = 128 and 148 deg.) where jet mixing noise is most important and the agreement with the simulated flight spectra is quite good.

Summary of Model Nozzle Comparisons

The preceding sections established that the prediction[1] agrees with model nozzle data under both static and simulated flight conditions. The variation of agreement as a function of angle for the various data sets is shown in figure 8. The static model OASPL comparisons indicate a combined average overprediction of 0.3 dB and a 1.1 dB standard deviation. This is a slightly smaller overprediction than the 0.5 dB reported in reference 1, and the standard deviation is significantly less than the 1.8 dB reported therein. As used throughout this paper and in reference 1, the standard deviation does not include a correction for the mean error; thus, it represents an absolute measure of agreement. However, for the small mean errors involved, the effect of correcting for the mean error is insignificant (less than 0.1 dB). In terms of the flight level relative to static the combined average overprediction is 0.2 dB and the standard deviation is 1.6 dB. The absolute flight level is overpredicted by an average of 0.3 dB, and the standard deviation is 1.9 dB.

Full-Scale Engine Comparisons

The ultimate application of this prediction procedure is to full-scale engines on flying aircraft, so it is important to demonstrate that full-scale levels are accurately predicted. Comparisons are presented first with static data and then with flight data.

Static

In order for the flight comparions to be meaningful, the accuracy of the prediction must first be established for full-scale static data. Comparions will be limited to low frequency to minimize the influence of turbomachinery noise. Since core noise is also a low frequency source, it must be taken into account. For this purpose the recently developed correlation of von Glahn and Krejsa[19] is used to predict the core noise at $\theta = 120^\circ$, and the directivity of Ref. 6 is used to obtain the core noise spectrum at other angles. Comparison is made with the full-scale CF6 engine data of Doyle and Moore[23].

Spectral comparisons are shown in Fig. 9 for approximate takeoff, cutback and approach conditions at directivity angles of 29, 58, 87, 117, 138 and 159 deg. relative to the center of the core nozzle exit plane. (The corresponding angles for the distributed jet noise source are 27, 54, 82, 112, 134, and 156 deg., and the source position corrections are significant.) The comparisons are limited to frequencies of 2000 Hz or less since turbomachinery tones are dominant at higher frequencies. Jet mixing noise is predicted to be dominant over core noise even for the approach conditions. The agreement is good at low frequencies, especially at large angles approaching the jet axis. The high experimental levels at middle frequencies, especially noticable in the forward quadrant, may be due to boardband turbomachinery noise, as suggested by Krejsa[24]. These full-scale comparions support the validity of the coaxial jet mixing noise prediciton[1], but quantitative comparisons would be questionable because of the uncertain contribution of broadband turbomachinery noise. The core noise levels are too low to permit an assessment of the core noise prediction with far-field data. However, this validation has been successfully performed using a unique triple-coherence technique incorporating internal and far-field data[19].

Flight

Comparison is now made with the flight data obtained in joint NASA-Society of Automotive Engineers experiment[17] on a Boeing 747 airplane powered by JT9D engines. The flight geometry is shown in figure 10. These results were obtained at approximate cutback conditions for a closest approach distance, Y, of 124 m, at a flight velocity, V_0, of 86 m/s. (The microphone was on a 100-m sideline, and the altitude was about 70 m.) In addition to core noise, airframe noise must be accounted for, and the method of Fink[18] is used*.

Spectral comparisons are shown in figure 11 for directivity angles of 30, 60, 90, 120 and 150 deg. (Source position corrections are negligible at this distance.) Jet noise is predicted to be dominant at low frequency, with its frequency range of dominance increasing with increasing θ. At frequencies low enough to be free of turbomachinery noise, which includes the jet noise dominant region, the agreement is rather good. These comparisons provide further support to the prediciton procedures, but quantitative comparisons for any one source would be difficult and the contribution of turbomachinery noise is uncertain.

Conclusions

The recently developed NASA-Lewis prediction model for conventional-velocity-profile coaxial jet mixing noise is shown to agree with flight and simulated flight data. Comparions of the prediction of overall sound pressure level with static, model nozzle data indicates a standard deviation of 1.1 dB, including an average overprediction of 0.3 dB. These results are in better agreement than earlier static, model comparisons. Comparisons with model nozzle wind-tunnel and free-jet simulated flight data, in terms of flight level relative to static indicate a standard deviation of 1.6 dB, including an average overprediction of 0.2 dB. Absolute simulated flight

* Calculations performed by W. Willshire of the NASA Langley Research Center.

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level comparisons indicate a standard deviation of 1.9 dB, including an average overprediction of 0.3 dB. Full-scale static and flight comparions support the accuracy of the prediction method, but quantitative statistical comparions would be uncertain because of the contributions of other noise sources.

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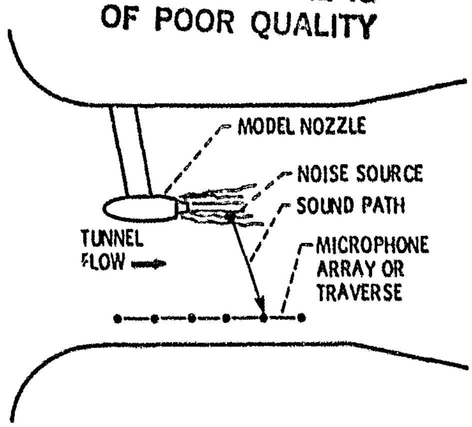
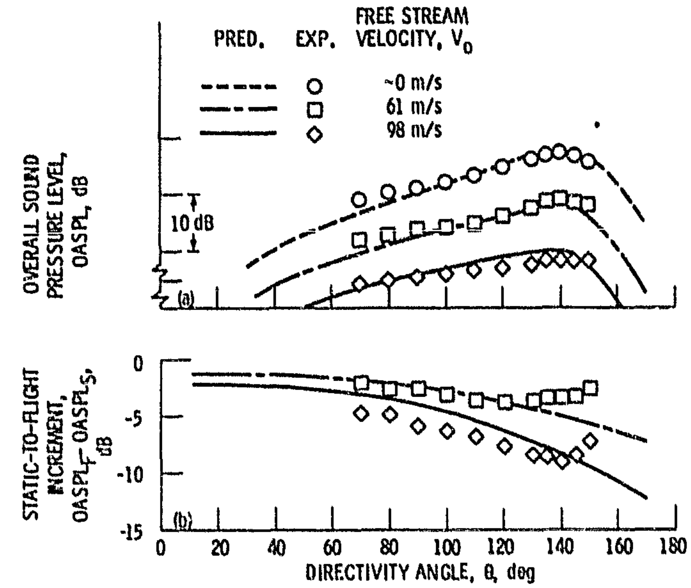
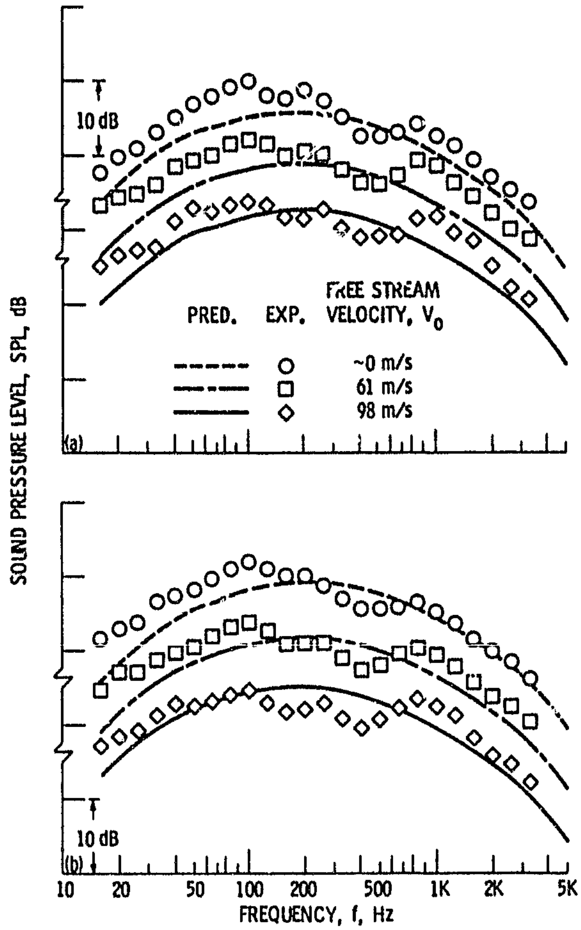


Figure 1. - Wind tunnel flight simulation.



(a) Overall sound pressure level, OASPL.
(b) Static-to-flight OASPL increment.

Figure 2. - Comparison of prediction[1] with high-bypass-ratio model nozzle static and simulated flight directivity in Boeing wind tunnel[14] at approximate takeoff conditions. Scaled to full-size engine at 305 m flyover.



(a) Directivity angle, θ = 70 deg.
(b) Directivity angle, θ = 90 deg.

Figure 3. - Comparison of prediction with high-bypass-ratio model nozzle static and simulated flight spectra in a Boeing wind tunnel[14] at approximate takeoff conditions. Scaled to full-size engine at 305 m flyover.

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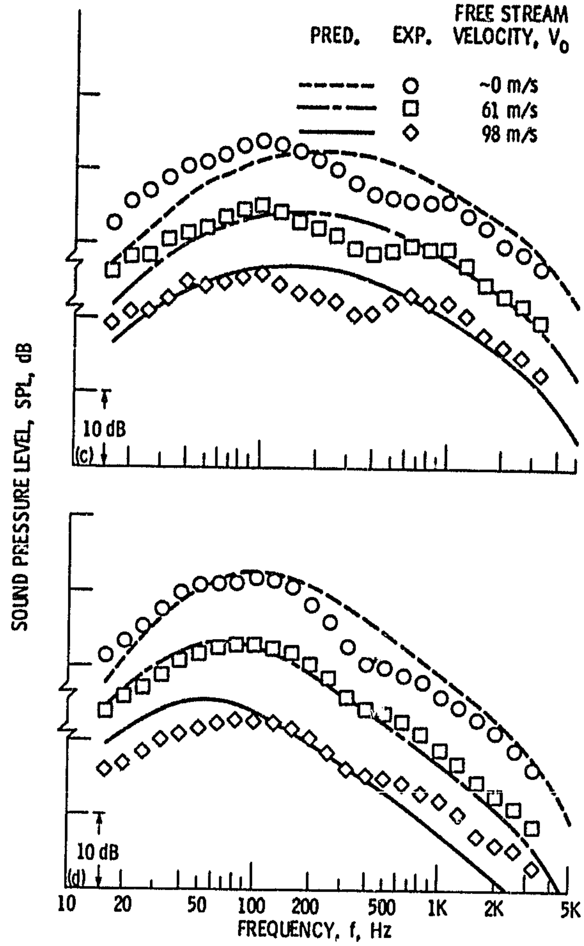
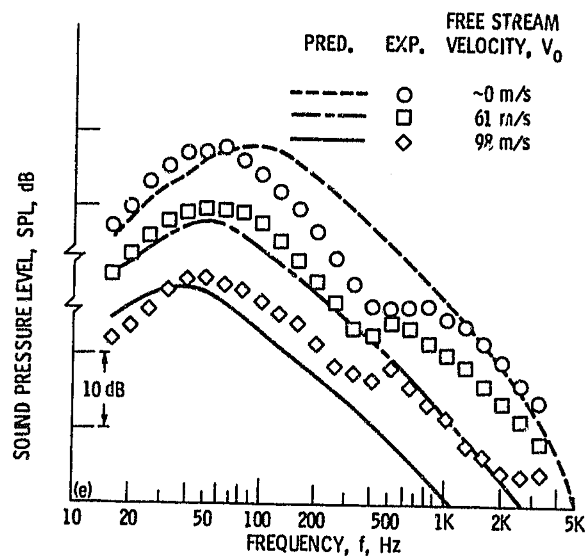


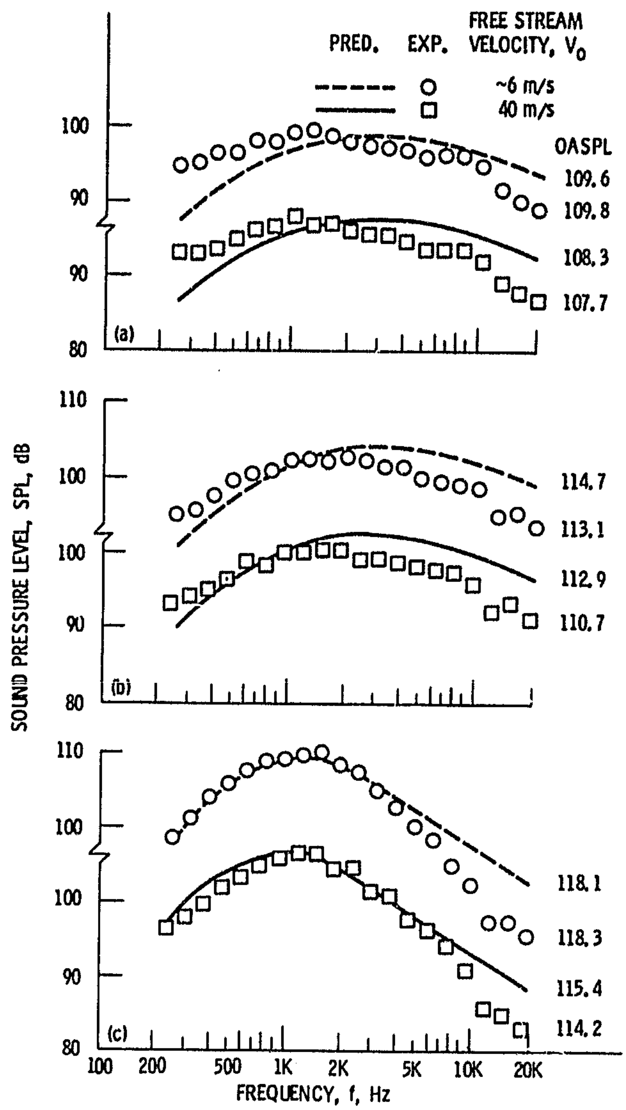
(c) Directivity angle, θ = 110 deg.
(d) Directivity angle, θ = 130 deg.

Figure 3. - Continued.



(e) Directivity angle, θ = 150 deg.

Figure 3. - Concluded.



(a) Directivity angle, θ = 81 deg.
(b) Directivity angle, θ = 111 deg.
(c) Directivity angle, θ = 138 deg.

Figure 4. - Comparison of prediction[1] with coaxial coplanar nozzle static and simulated flight spectra in Royal Aircraft Establishment (RAE) wind tunnel.[15] Primary jet velocity, V_1 = 446 m/s, and total temperature, T_1 = 880 K; secondary-to-primary velocity ratio, V_2/V_1 = 0.6.

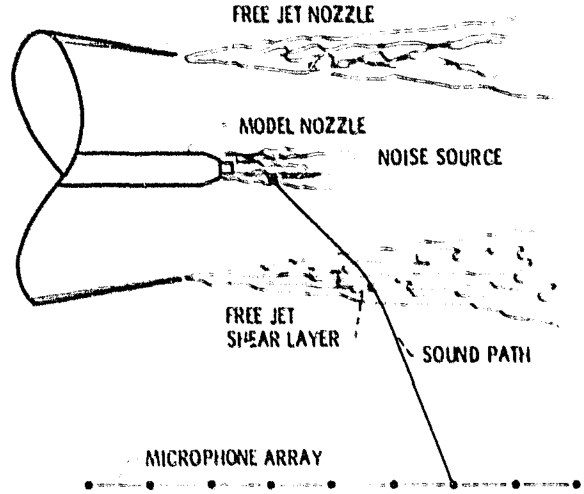
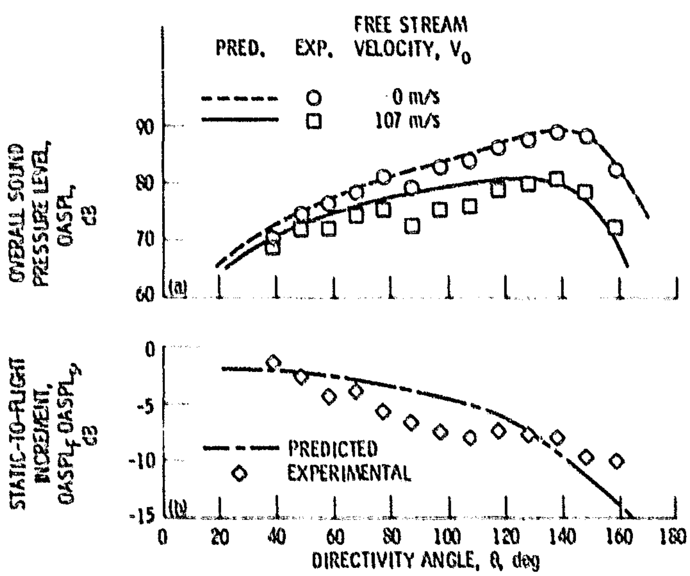
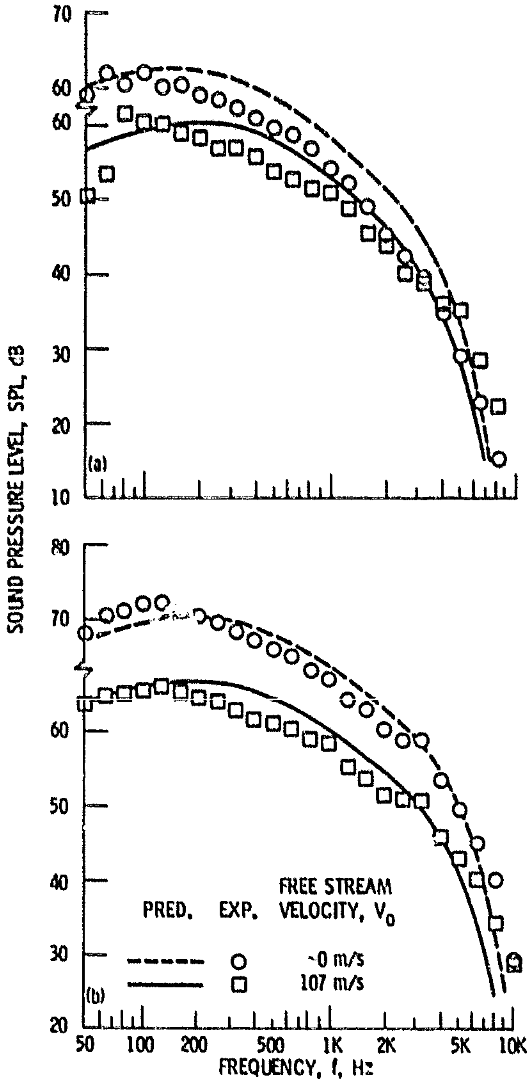


Figure 5. - Free jet flight simulation.



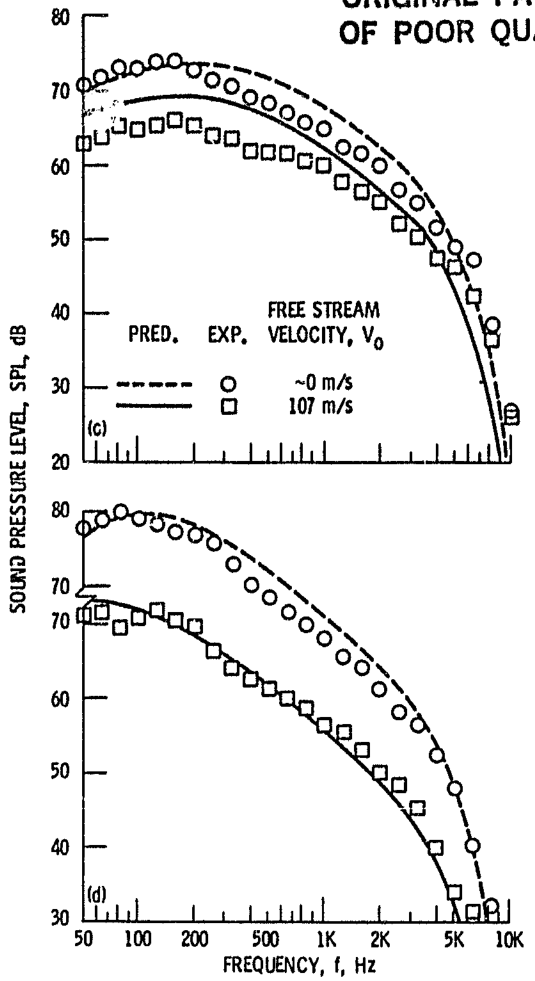
(a) Overall sound pressure level.
(b) Static-to-flight OASPL increment.

Figure 6. - Comparison of prediction[1] with CF6 model nozzle static and simulated flight directivity for General Electric free jet.[16] Primary jet velocity, V_1 = 395 m/s scaled to full-size engine at 458-m flyover.



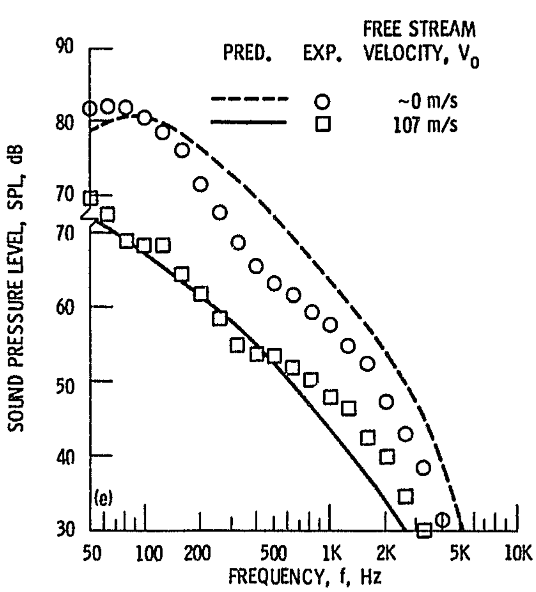
(a) Directivity angle, θ = 38 deg.
(b) Directivity angle, θ = 77 deg.

Figure 7. - Comparison of prediction[1] with high-bypass-ratio model nozzle static and simulated flight spectra in General Electric free jet.[16] Primary jet velocity, V_1 = 395 m/s; scaled to full-size engine at 457 m flyover.



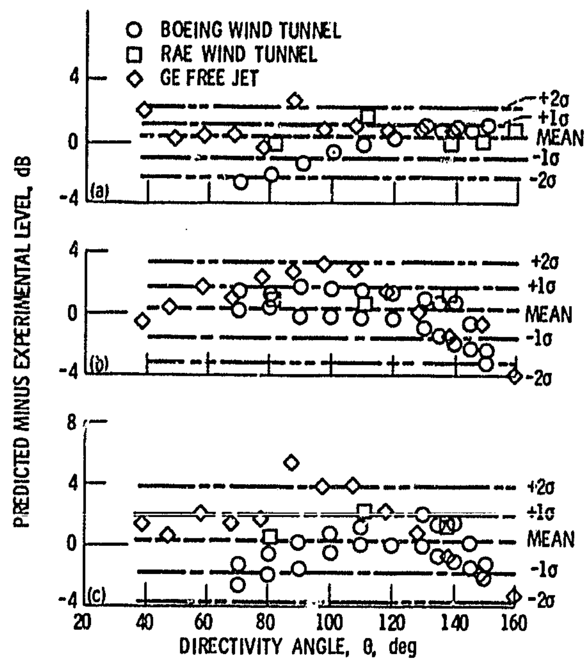
(c) Directivity angle, θ = 97 deg.
(d) Directivity angle, θ = 128 deg.

Figure 7. - Continued.



(e) Directivity angle, θ = 148 deg.

Figure 7. - Concluded.



(a) Static OASPL.

(b) Static-to-flight increment, $OASPL_F - OASPL_S$.

(c) Simulated flight OASPL.

Figure 8. - Differences between experimental and predicted levels as a function of directivity angle for model nozzles, with statistical comparisons.

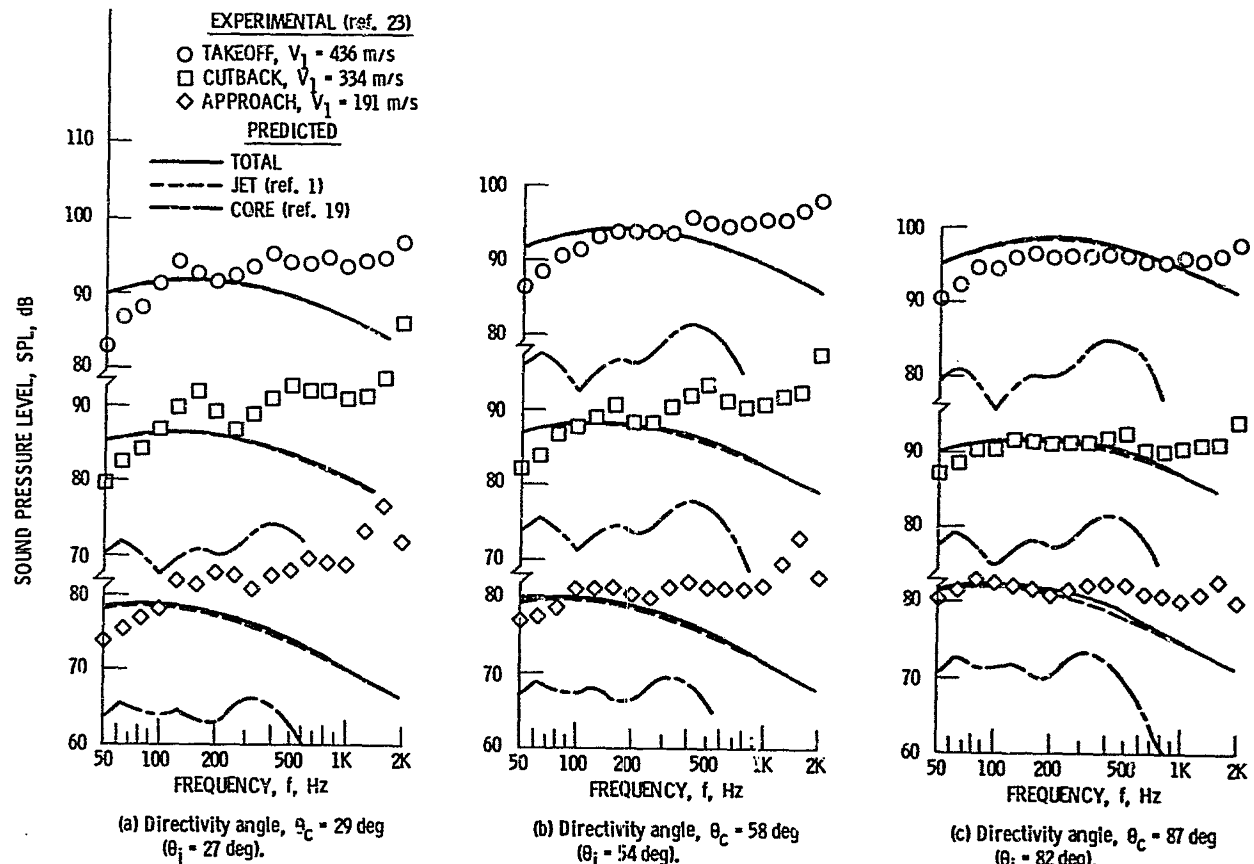
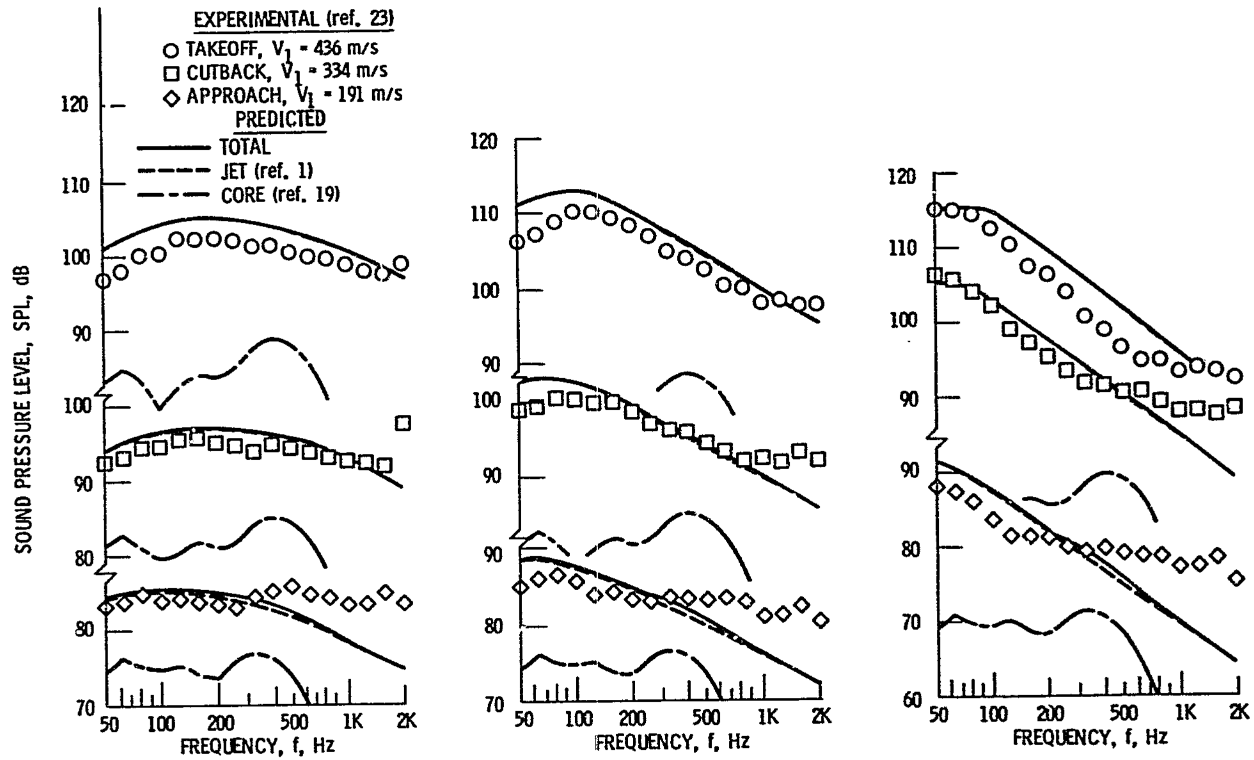


Figure 9. - Comparison of prediction[1, 19] with CF6 engine static spectra on a 45.7 m arc[25].



(d) Directivity angle, θ_c = 117 deg (θ_j = 112 deg).

(e) Directivity angle, θ_c = 138 deg (θ_j = 134 deg).

(f) Directivity angle, θ_c = 159 deg (θ_j = 156 deg).

Figure 9. - Concluded.

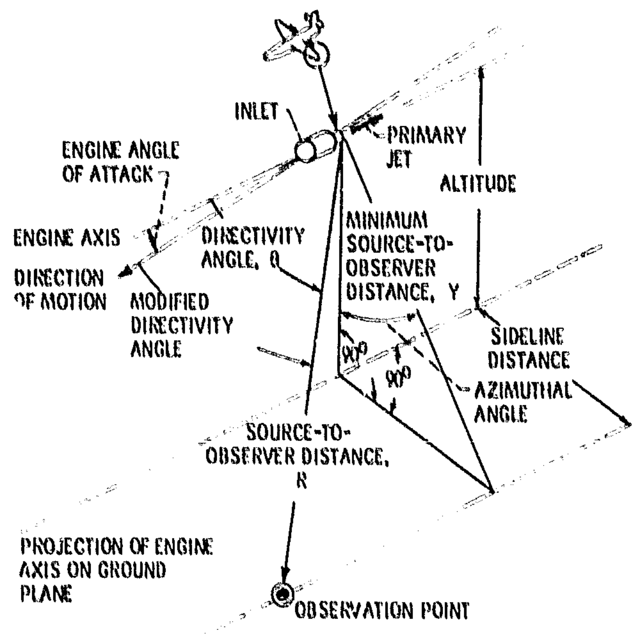


Figure 10. - Geometric variables describing position of airplane noise source with respect to an observation point.

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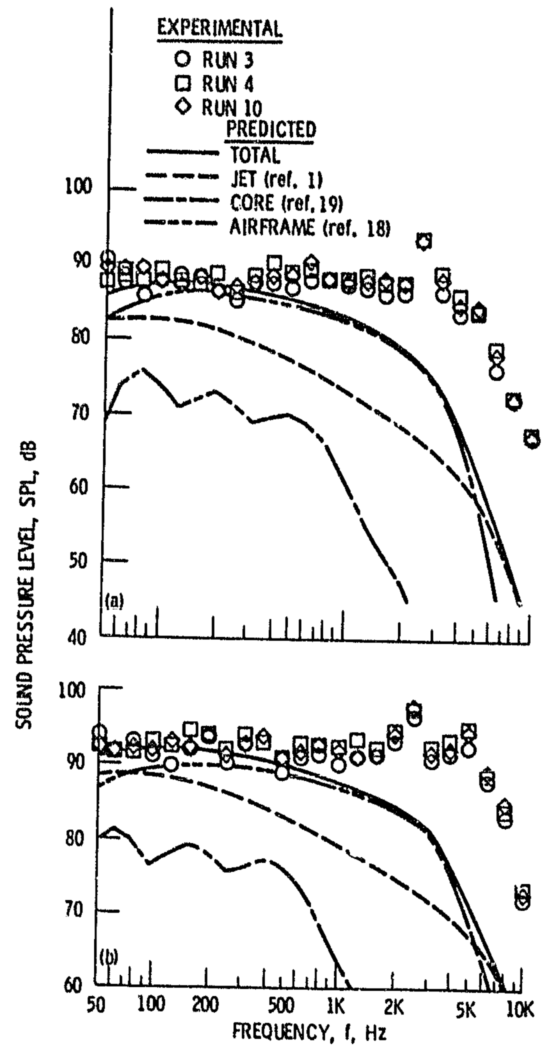

(a) Directivity angle, θ = 30 deg.
(b) Directivity angle, θ = 60 deg.

Figure 11. - Comparison of prediction[1, 18, 19] with flight spectra[17] for B-747 airplane with JT9D engines at 79 percent speed. Ground microphone; minimum source-to-observer distance, Y ≈ 124 m (Fig. 10.); flight velocity, V_0 ≈ 86 m/s.

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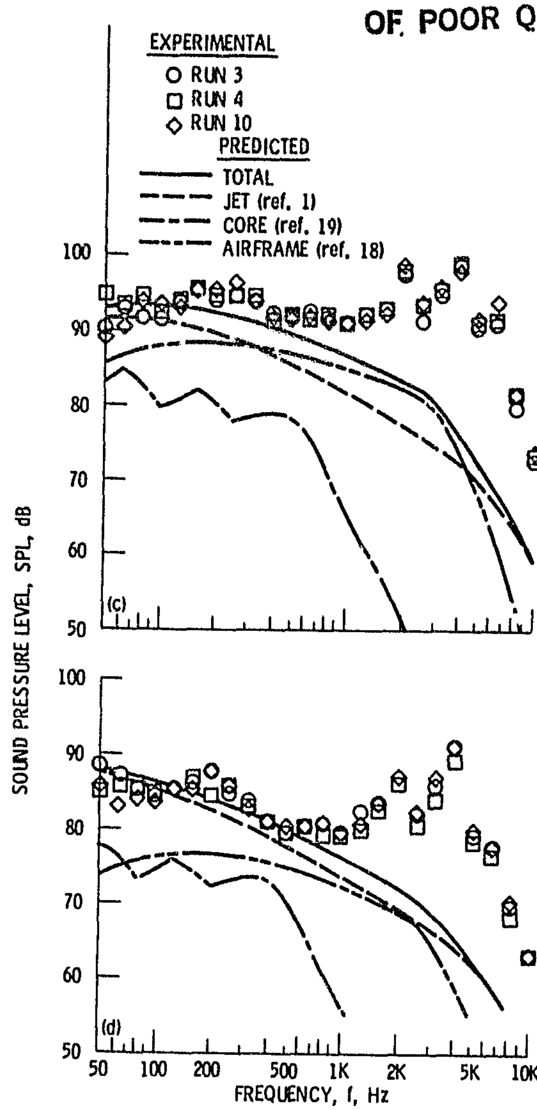
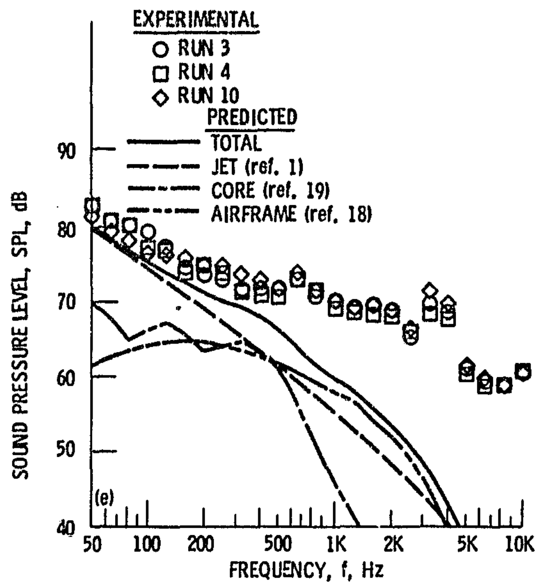


(c) Directivity angle, θ = 90 deg.
(d) Directivity angle, θ = 120 deg.

Figure 11. - Continued.



(e) Directivity angle, θ = 150 deg.

Figure 11. - Concluded.