Evaluation of a Correction for Sound Propagation Through Free-Jet Shear Layers

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Acoustic tests of a 6-cm model jet were conducted in the German-Dutch Wind Tunnel (DNW) 6- × 8-m free-jet facility. The purpose of these tests was to evaluate a new free-jet shear-layer correction procedure that adds an empirical correction to the theoretical correction previously used at DNW. Static-to-flight effects on jet noise measured in the flow were used as the basis for evaluating the corresponding out-of-flow results. The experiment demonstrated that the new procedure significantly improves the accuracy of the flight effects measured by the out-of-flow microphones. Comparisons of the out-of-flow free-jet results to results obtained in closed wind tunnels and from aircraft flyovers show consistent trends.

Nomenclature

D = free-jet width (Y direction)
f = frequency, kHz
M = free-jet Mach number
v = velocity
X = distance from free-jet exit to source
Y = distance from shear layer to source
θ = sound emission angle (from upstream direction), deg

Introduction

CURRENT interest in the use of free-jet wind tunnel facilities for aeroacoustic testing led to the initiation of a cooperative program between the German-Dutch Wind Tunnel (DNW) and The Boeing Company. The purpose of this program was to assess the effect on sound due to propagation through the shear layer of the DNW free-jet facility.[1] This joint program was conducted in two phases. The first phase involved acoustic tests of a calibrated noise source—a streamlined body containing four compressed air horns and a speaker. The second phase involved noise tests of a 6-cm, single-flow jet.

The purpose of the calibrated noise source test[2] was to evaluate the accuracy of the theoretical shear-layer correction procedure used by DNW. This correction, developed by Amiet,[3] accounts for refraction, reflection, and transmission of noise as it passes through a plane shear layer of zero thickness. The refraction effect is shown in Fig. 1. Effects due to scattering, turbulence absorption, refraction through a finite thickness shear layer, and other specific shear-layer properties are not accounted for in the correction procedure. Flight effects, which are caused primarily by convective amplification, were measured for the horn and speaker sources using both in-flow and out-of-flow microphone traverse systems. Differences between in-flow and out-of-flow flight effects were used to assess the accuracy of the theoretical shear-layer correction. The results indicate that the theoretical correction is satisfactory for frequencies below 5000 Hz. At higher frequencies an additional shear-layer correction is required. Therefore, based on the results of the calibrated noise source test, an empirical equation was derived to calculate the necessary additional correction as a function of frequency, tunnel Mach number, and source emission angle. The empirical equation and typical sound pressure level (SPL) corrections given by this equation are shown in Fig. 2. For upstream angles, this correction calls for a decrease in the noise level and the magnitude of the correction becomes larger for more shallow angles. For downstream angles the correction is positive and increases up to 120 deg, above which it is constant. The magnitude of the correction increases with both free-jet Mach number and frequency.

The primary purpose of the 6-cm model jet test was to evaluate the new shear-layer correction procedure established by the calibrated noise source test using a different type of noise source. The 6-cm jet was tested in the DNW free-jet facility for a range of nozzle pressure ratios (NPR) and tunnel velocities. Noise measurements were made with in-flow and out-of-flow microphone traverse systems. Out-of-flow wind-on SPL's were determined using the theoretical shear-layer correction and the new procedure (theoretical plus empirical corrections). Static-to-flight effects, in the form of relative velocity exponents, were calculated for the in-flow data and both sets of corrected out-of-flow data.

These results were used to evaluate the accuracy of both of the shear-layer correction procedures. The jet noise flight effects measured in the DNW free jet were also compared to closed wind tunnel model data and aircraft flight-test data to assess the validity of the free-jet results.

DNW Test Description

Model Description

The test model was a single-flow nozzle with an exit diameter of 6 cm, as shown in Fig. 3. A hydrogen peroxide system was used to generate the hot jet exhaust. This system consists of a reaction chamber with a throttling plate and a metal foam silencing plug located downstream of the chamber. Within the reaction chamber is a silvered gauze package in which the liquid hydrogen peroxide decomposes

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into superheated steam and oxygen. During the decomposition energy is released, which results in a hot jet flow. The specific gas constant and ratio of specific heats of the steam-oxygen mixture are different from those of the exhaust gas of a combustion-heated air jet. Therefore, the flow conditions are expressed in terms of equivalent hot air conditions. The total pressure of the jet was controlled by the hydrogen peroxide mass flow rate. The total temperature was controlled by the hydrogen peroxide concentration. In this test the concentration was 75%, giving a total equivalent temperature of about 828 K; the exact temperature depending on the temperature of the hydrogen peroxide liquid.

Facility Description

The DNW free-jet facility is a closed-circuit tunnel powered by an eight-bladed fan connected directly to a synchronous electric motor. The free- (or open-) jet test section, shown in Fig. 4, consists of an upstream contraction section with a 6-m high × 8-m wide exit and a collector measuring 9.5 × 9.5 m in cross section 20 m downstream.

Acoustic treatment has been applied to the corner turning vanes immediately up- and downstream of the test section, and to the inner surfaces of the collector. Other factors in achieving low wind tunnel noise levels include the absence of a gearbox, sweeping of the stator vanes, and low fan speed.

The free jet is located in a 20-m-high, 30-m-wide, 45-m-long testing hall. All surfaces of the testing hall are treated with sound-absorbing material. Areas that could reflect noise directly to the microphones are covered with 0.8-m-deep wedges with an absorption coefficient of 0.99 and a cutoff frequency of 80 Hz. The remaining areas, about 60% of the total surface, are covered with a flat, 0.2-m-thick material with an absorption coefficient of 0.9 and a cutoff frequency of 200 Hz. The model jet was mounted on a movable, 9.75-m-high support that sat on the testing hall floor. The upper part of the support sturcture, which was within the tunnel flow, was covered with an aerodynamic fairing. The model jet was positioned along the tunnel centerline 4.9 m downstream of the free-jet exit.

Instrumentation

In-flow noise measurements were made using a 4.7-m-long traverse mechanism mounted to the model support structure. The microphone was attached to a streamlined strut such that it moved along a sideline 0.91 m (15 model jet diameters) from the model centerline and covered an angular range of 47-166 deg (relative to the nozzle exit and upstream axis). The traverse was located on the port side of the model, 15 deg below the horizontal plane of the model. The microphone traversed at a nominal rate of 4.5 cm/s and was mounted facing into the tunnel airflow. Inflow measurements were made using a B&K ¼-in. Model 4136 microphone equipped with a B&K Model UA 0385 nosecone. The installation included a flexible adapter between the microphone and the B&K Model 2615 preamplifier to minimize vibration. The preamplifier and microphone were cushioned with foam inside the mounting pods to reduce vibration further.

Out-of-flow noise measurements were made using a microphone traverse system that hangs from the testing hall ceiling. This system consists of a metal lattice structure from which five microphones, spaced 6 m apart, are suspended. The entire traverse mechanism can be moved laterally to the desired sideline. The microphones traversed in unison, each covering a distance of 6 m; thus covering a total sideline distance of 30 m. The out-of-flow data presented herein were obtained with the traverse system on an 8.6-m sideline and cover a range of angles from 41 to 157 deg (Fig. 4). The microphones traversed at a nominal rate of 0.5 m/s and were aligned such that the midtraverse position faced the model jet exit. B&K ¼-in., Model 4135 microphones were used and were equipped with foam balls to reduce wind-induced noise due to the wind tunnel air recirculation within the testing hall.

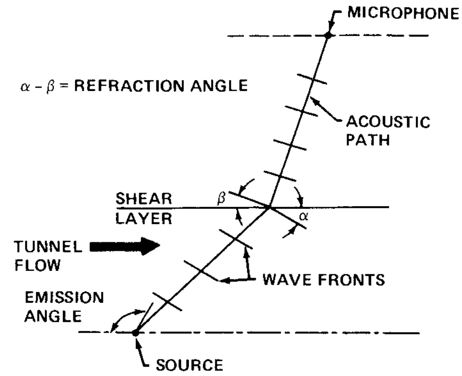
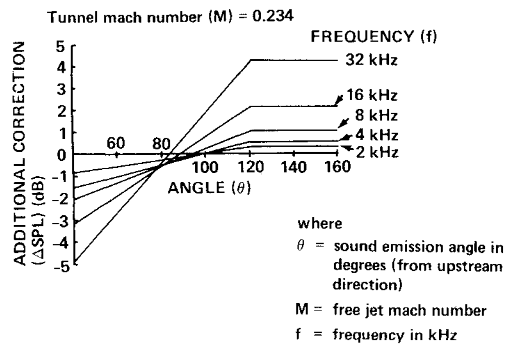


Fig. 1 Schematic diagram of shear-layer refraction.



For $40 \leq \theta < 120$:

$$\Delta SPL = M\ [(0.00927\ f + 0.033\sqrt{f})\ \theta - 0.556\ f - 3.96\ \sqrt{f}\ ]$$

For $\theta \geq 120$:

$$\Delta SPL = 0.556\ M\ f$$

Fig. 2 Additional shear-layer correction based on the calibrated noise source test.

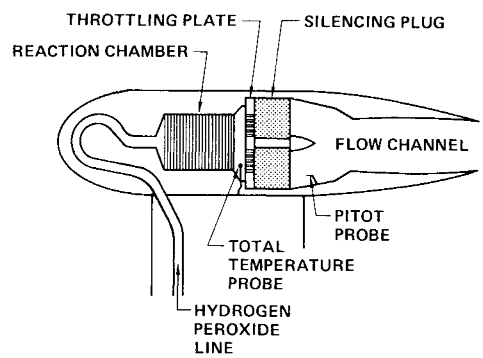


Fig. 3 DNW 6-cm jet.

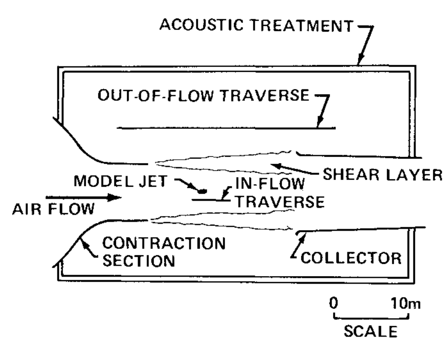


Fig. 4 Plan view of DNW free-jet facility.

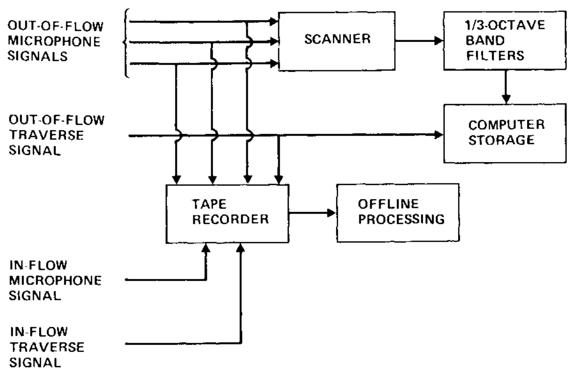


Fig. 5 DNW data acquisition system.

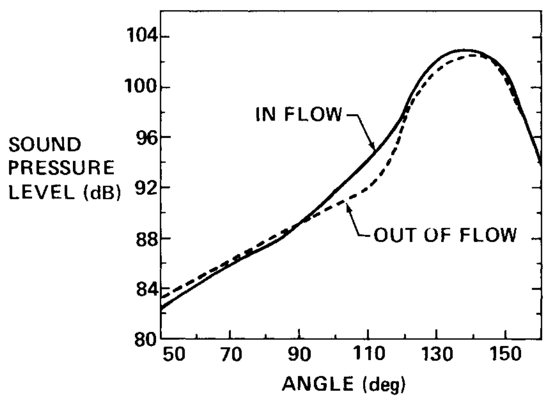


Fig. 6 SPL directivity comparison for NPR = 1.75, tunnel velocity = 0 m/s, and frequency = 125 Hz.

Total pressure and temperature probes were located in the model as shown in Fig. 3. Previously, these probes had been calibrated using a total pressure and total temperature rake placed in the model jet exit plane. Ambient temperature and relative humidity were measured both in and out of the free-jet flow.

Data Acquisition

The analog signals from the out-of-flow microphones were sent directly to the acoustic data acquisition system of the National Aerospace Laboratory (NLR), the Netherlands. This system (Fig. 5) scans a maximum of 14 microphone signals and accepts one dc microphone traverse location signal. For this test a sampling time of 0.5 s was used and each of the five out-of-flow microphones was scanned every 2-3 s. The acoustic signals, after passing through the scanner, were fed through a set of analog one-third-octave band (⅓-OB) filters. The ⅓-OB levels and the dc position signal were digitized and sent to the NLR Control Data Corporation Cyber computer. The raw ⅓-OB data were stored on computer files and used later for the off-line data processing, together with wind tunnel and microphone calibration data that were stored on separate files.

Analog signals from both in-flow and out-of-flow microphones and dc traverse signals from both systems were recorded on two tape recorders connected in parallel. The taped in-flow data were later used for off-line data reduction.

On-line visibility of any selected microphone spectrum was available on a CRT screen and Polaroid hard copies of these spectra could be made.

Data Processing

The out-of-flow data were processed in the following manner:

1) The data stored on computer files were reduced to ⅓-OB form using a 0.5-s integration time.

2) The original and the new shear-layer correction procedures were applied independently along with American National Standards Institute (ANSI) atmospheric absorption corrections to adjust the wind tunnel data to absorption-free conditions as appropriate.

3) Measured noise floors, consisting of tunnel drive system noise, flow noise, and electronic equipment noise, were subtracted and the data were adjusted for comparison on an F-86 flyover-type basis; scaled to a 51-cm jet diameter, extrapolated to a 61-m sideline (assuming a point source at the nozzle exit), corrected to unconvected emission angles and FAA standard day atmospheric absorption conditions, and Doppler frequency shifted as appropriate.

4) The SPL data were smoothed on a directivity basis.

5) Flight effects in the form of relative velocity exponents were calculated for both sets of shear-layer corrected data, and the resulting curves were smoothed. These so-called n values are defined as follows:

$$n = (\mathrm{SPL}_{\mathrm{static}} - \mathrm{SPL}_{\mathrm{flight}}) / \{10\log\,[(V_{\mathrm{jet}} - V_{\mathrm{ambient}})_{\mathrm{static}} \div (V_{\mathrm{jet}} - V_{\mathrm{ambient}})_{\mathrm{flight}}]\} \qquad (1)$$

The in-flow data were processed in the following manner:

1) The tape-recorded analog data were reduced to ⅓-OB form using a 1-s integration time.

2) Measured noise floors, consisting of a tunnel drive system noise, flow noise, and electronic equipment noise, were subtracted and the data were adjusted for comparison on an F-86 flyover-type basis; scaled to a 51-cm jet diameter, extrapolated to a 61-m sideline (using distributed noise source locations per Ref. 4), corrected to unconvected emission angles and to FAA standard day atmospheric absorption conditions, and Doppler frequency shifted as appropriate.

3) Relative velocity exponents were calculated and the resulting curves smoothed.

DNW Free-Jet Test Results

Extrapolated SPL Directivities

In-flow and out-of-flow scaled and extrapolated SPL directivities are compared in Figs. 6-11 for both wind-off and wind-on cases at an NPR of 1.75 and several frequencies. The wind-on out-of-flow data were corrected for shear-layer effects using the theoretical method of Amiet.[3] There is reasonable agreement between the in-flow and out-of-flow results in terms of level and directivity shape. Precise agreement in absolute level is not expected and, therefore, was ruled out as a means of assessing the shear-layer correction procedure. Reasons for this include: possible jet asymmetry (in-flow and out-of-flow traverses were located on opposite sides of the jet); unaccounted for near-field effects and distributed source location uncertainties that may influence the extrapolated in-flow levels; differences in reflected noise from exposed facility hardware such as traverse mechanisms and support structures; errors in atmospheric absorption coefficients used in data processing; and differences in microphone installations, data acquisition, and data reduction. In order to minimize the influence of these factors, the static-to-flight effect was selected as the best parameter for evaluating the shear-layer correction procedures. Since the change in jet noise due to free-jet velocity occurs at the source, the resulting flight effects for a given emission angle should be equal whether measured in or out of the flow. The in-flow flight effects were assumed to be correct and were taken as the basis of comparison for the out-of-flow values. As mentioned previously, the in-flow data were extrapolated using an experimentally determined source location

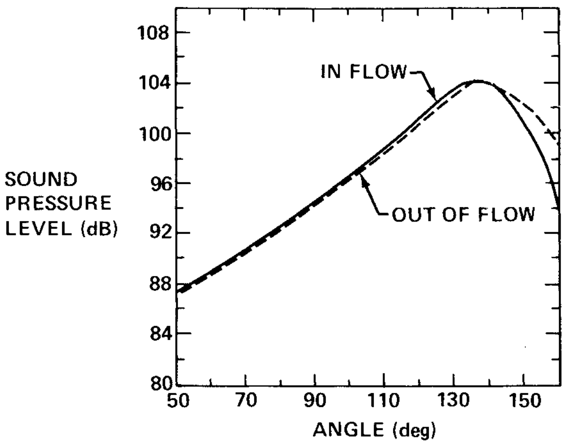


Fig. 7 SPL directivity comparison for NPR = 1.75, tunnel velocity = 0 m/s, and frequency = 500 Hz.

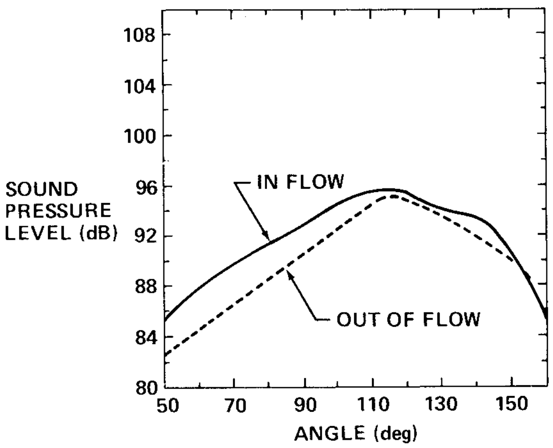


Fig. 8 SPL directivity comparison for NPR = 1.75, tunnel velocity = 0 m/s, and frequency = 2 kHz.

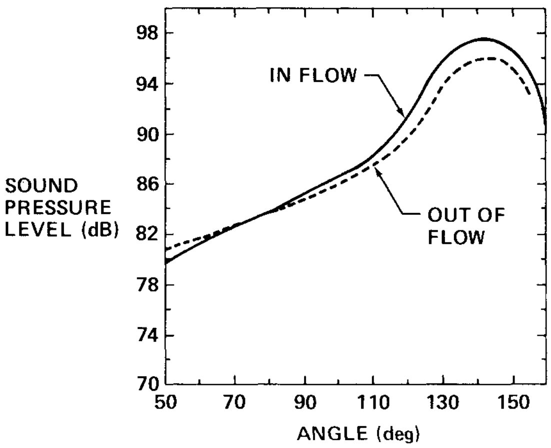


Fig. 9 SPL directivity comparison for NPR = 1.75, tunnel velocity = 80 m/s, and frequency = 125 Hz.

correlation.[4] This minimizes any potential error associated with measurements on a relatively near sideline, as demonstrated by the program in Ref. 5.

Relative Velocity Exponents

Flight effects on jet noise in the form of relative velocity exponents were calculated for both in-flow and out-of-flow data as described previously. Typical comparisons are shown in Figs. 12-15 for overall sound pressure levels (OASPL) and several frequencies. The corrected OASPLs were obtained by applying the corrections at each frequency, then summing the corrected SPLs. The out-of-flow results are shown for both the original (theoretical) and new (theoretical plus empirical) shear-layer corrections. In general, the new correction provides a better match between in-flow and out-of-flow velocity exponents. Another evaluation of the two shear-layer correction procedures was made by averaging the relative velocity exponents for three different jet conditions (NPR's of 1.57, 1.64, and 1.75). The differences in velocity exponents between the averaged out-of-flow and in-flow values are plotted in Fig. 16 for several frequencies. The new shear-layer correction procedure is shown to be effective in reducing the differences between in-flow and out-of-flow flight effects.

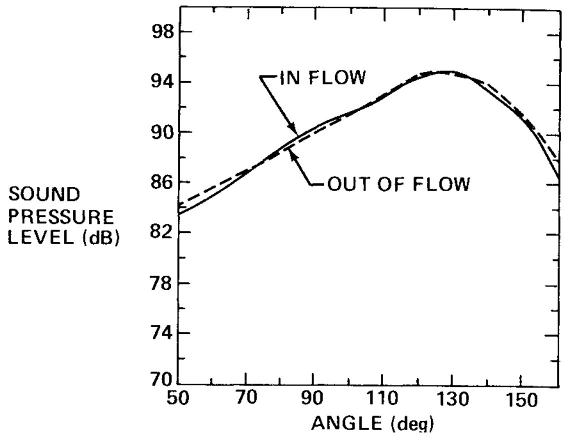


Fig. 10 SPL directivity comparison for NPR = 1.75, tunnel velocity = 80 m/s, and frequency = 500 Hz.

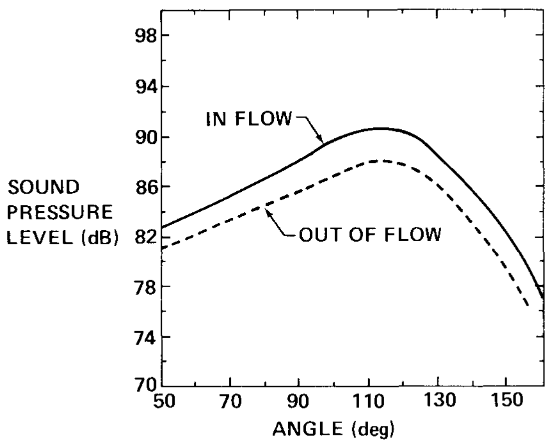


Fig. 11 SPL directivity comparison for NPR = 1.75, tunnel velocity = 80 m/s, and frequency = 2 kHz.

DNW Flight Effects— Comparisons with Boeing Data

To evaluate the validity of the relative velocity exponents measured in the DNW free jet, comparisons were made with existing Boeing results for single-flow jets. These results included closed test-section wind tunnel data acquired for a 6-cm model in the Boeing 9- × 9-ft wind tunnel and for a 15.2-cm model in the NASA Ames 40- × 80-ft wind tunnel.[5] Also included were flight-test results for an F-86 Sabre jet aircraft powered by an Orenda 14 turbojet engine.

A comparison of DNW out-of-flow results, corrected using the new procedure, and results from the various sources is shown in Fig. 17 for a nominal NPR of 1.75 and a frequency of 500 Hz. This example is representative of trends observed for all of the test conditions and frequencies of interest. At high aft arc angles (130 deg and above) there is reasonably good agreement between the DNW free-jet and closed wind tunnel model results. The F-86 velocity exponent is consistently lower than the model results in this region. At angles below 130 deg a significant separation of velocity exponent levels is observed. The relative levels shown in Fig. 17 are typical, with the DNW velocity exponents having the highest values followed by the 9×9, 40×80, and F-86 results. It is likely that the DNW velocity exponents are representative of pure jet noise flight effects since the hydrogen-peroxide-generated jet has little contaminating internal noise. The nacelle is also quite small and therefore has a thin boundary layer that is conducive to higher flight effects. In contrast to this, the 9×9 and 40×80 installations have some upstream noise contamination (flow and burner noise) and relatively thicker boundary layers. This tends to reduce the flight effects, in particular at forward arc angles. The F-86 also includes significant internal noise sources (compressor and core noise) that cause reduced flight effects. There also may be installation effects (due to nozzle configuration, external boundary layers and flowfield, and angle of attack) and increased jet turbulence that contribute to the lower flight effects. Thus the differences in results are consistent in direction with physical reasoning.

Flight effects analysis was also done by comparing the flight noise levels in relation to static throttle lines (a line through the static data points plotted against jet velocity). Comparisons for OASPL at 150 deg are shown in Figs. 18-21, where the wind-on or flight data are plotted as a function of relative jet velocity. At this angle the OASPL is dominated by low- to mid-frequency jet noise and is not likely to be affected by internal noise sources or boundary-layer thickness. For the wind-on model data and the high-power F-86 flight data, the OASPL's generally have the same relationship to their respective throttle lines. Slopes of the throttle lines vary as indicated, suggesting that each jet has somewhat distinct characteristics. The F-86 slope is significantly less than the model results, which is consistent with the flight effects shown in Fig. 17.

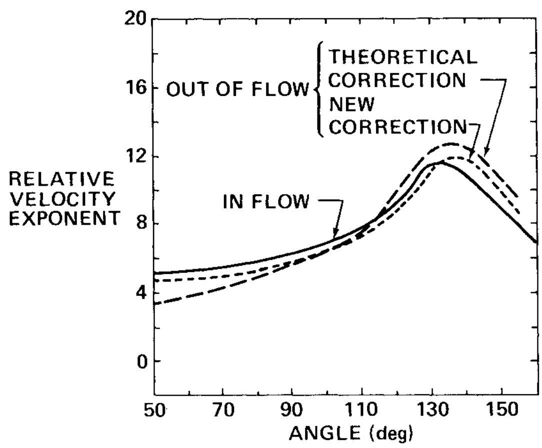


Fig. 12 Relative velocity exponent comparison for NPR = 1.75, tunnel velocity = 80 m/s, and overall SPL.

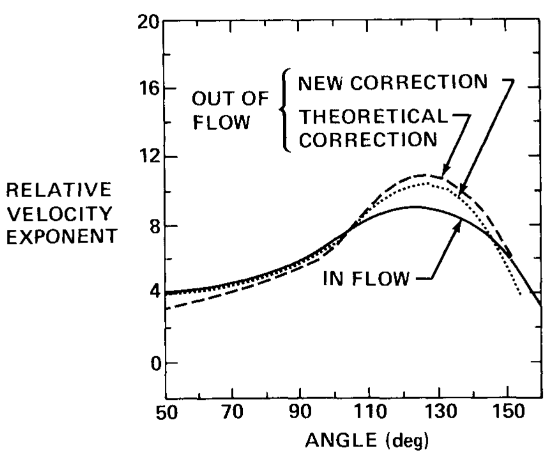


Fig. 13 Relative velocity exponent comparison for NPR = 1.75, tunnel velocity = 80 m/s, and frequency = 125 Hz.

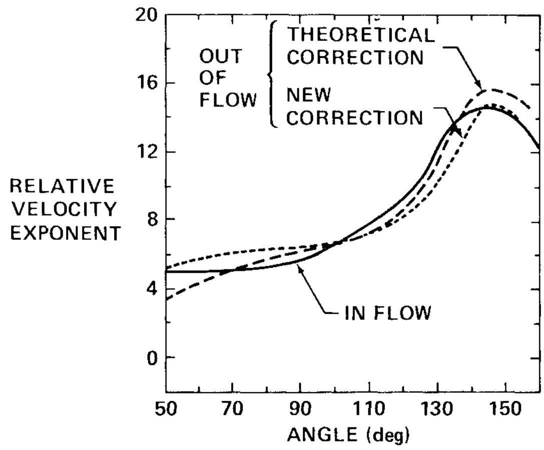


Fig. 14 Relative velocity exponent comparison for NPR = 1.75, tunnel velocity = 80 m/s, and frequency = 500 Hz.

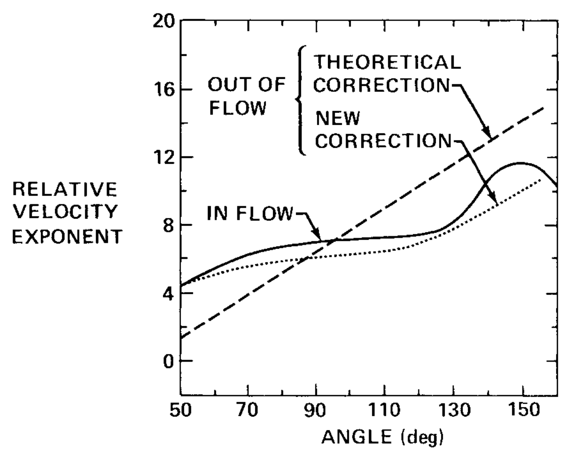


Fig. 15 Relative velocity exponent comparison for NPR = 1.75, tunnel velocity = 80 m/s, and frequency = 2 kHz.

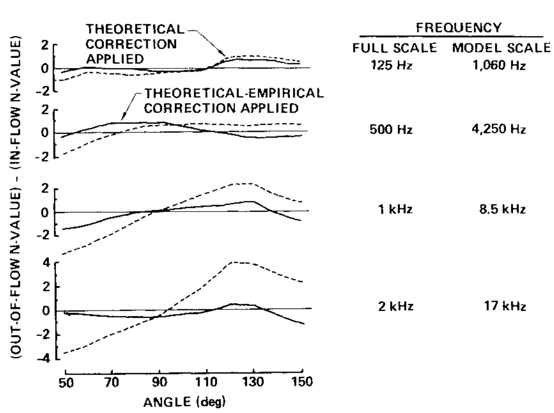


Fig. 16 Comparison of average out-of-flow and average in-flow relative velocity exponents.

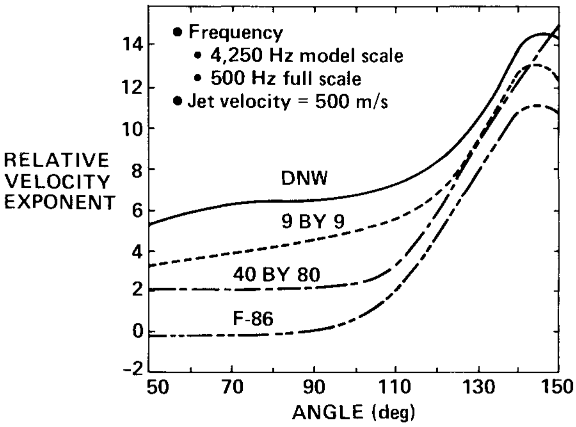


Fig. 17 Relative velocity exponent comparison.

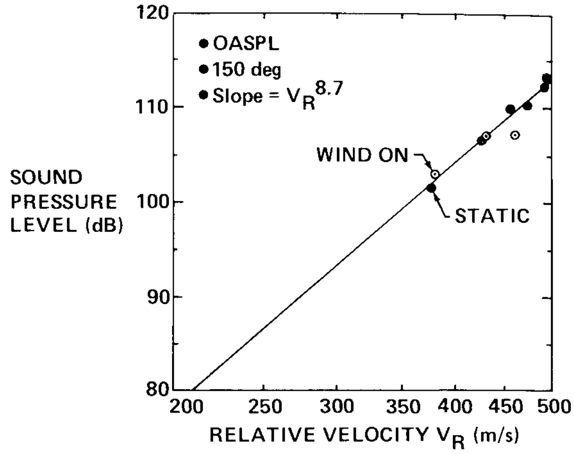


Fig. 20 Static throttle line comparison for 40×80 data.

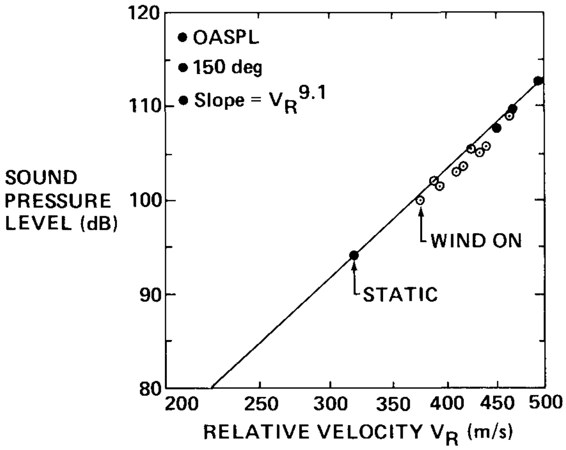


Fig. 18 Static throttle line comparison for DNW out-of-flow data corrected using new procedure.

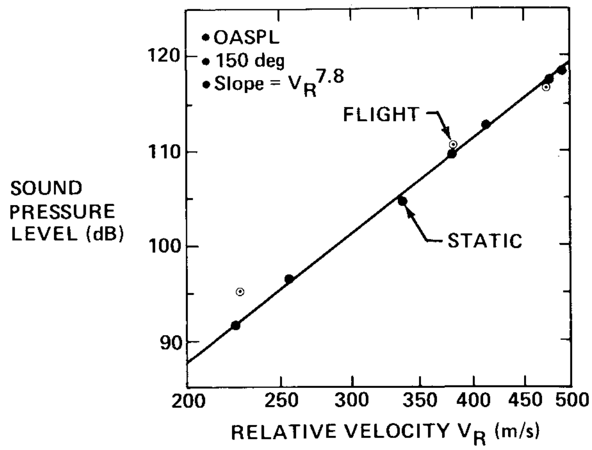


Fig. 21 Static throttle line comparison for F-86 data.

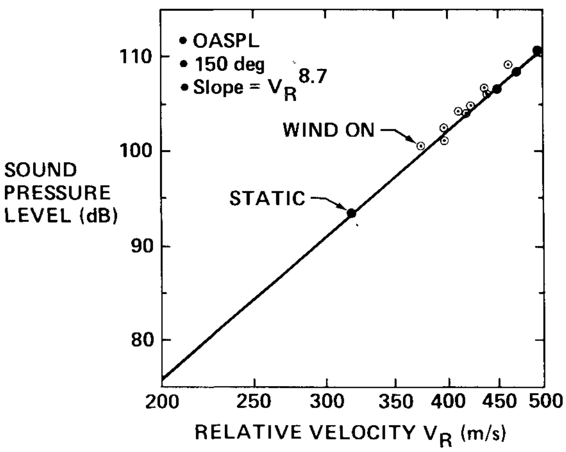


Fig. 19 Static throttle line comparison for 9×9 data.

Generalized Correction Procedure

The new shear-layer correction procedure previously discussed is applicable to data taken in the DNW free jet with the noise source at a specific location. It is desirable to generalize this correction procedure for sources at other locations and for data obtained in other free jets. This objective is currently being pursued. By making use of data obtained in a small (30.5-cm-diam) free-jet experiment conducted in the Boeing large anechoic test chamber, as well as data from the calibrated noise source test in the DNW free jet, the following preliminary generalized correction has been derived:

$$\Delta SPL = -M\Big\{ f\,[(\theta-170+0.43f)^2(1.4\times10^{-4})-0.86] - 210M^{2.4}\Big[\Big(\frac{X}{D}-0.61\Big)+\Big(\frac{Y}{D}-0.5\Big) \times\Big(\frac{\cos^2(180-\theta)}{1-\cos^2(180-\theta)}\Big)^{1/2}\Big]\Big\} \qquad (2)$$

This equation will be modified as more free-jet data are obtained and as the phenomena necessitating the correction become better understood.

Concluding Remarks

The purpose of this study was to evaluate the new shear-layer correction derived in the calibrated noise source test by applying it in a model jet test. This evaluation was done by comparing in-flow and corrected out-of-flow flight effects on jet noise on the basis that application of the shear-layer corrections should cause these levels to be the same.

After appropriate smoothing of the sound press level and flight effects data, application of the additional correction significantly improved the agreement between the in-flow and out-of-flow relative velocity exponents. The results of an averaging procedure showed that the additional correction derived from the calibrated noise source test produced good agreement, generally within an n value of ± 1, between in-flow and out-of-flow jet noise flight effects.

Comparisons of the fully corrected DNW free jet out-of-flow results with a Boeing data base show the DNW flight effects to be generally higher. This is as expected, since the DNW model jet was the cleanest configuration studied. However, in jet-noise-dominated conditions, static throttle line and flight-data relationships show close agreement between DNW and data-base results.

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