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SUMMARY

A 2.54-cm (1.00-in.) nozzle supplied with nitrogen was mounted above an automobile and driven over an asphalt roadway past stationary microphones in an attempt to quantify the effects of the vehicle motion on jet mixing noise. The nozzle was then tested in the Langley anechoic noise facility with a large free jet simulating the relative motion. The results are compared for these two methods of investigating forward speed effects on jet mixing noise.

The nozzle exit Mach number was nominally 0.85 for all tests. In addition to static runs, the vehicle was driven at speeds corresponding to Mach numbers of 0.04, 0.08, and 0.12, whereas the free jet was run at Mach numbers of 0.04, 0.08, and 0.11 (the maximum obtainable).

The vehicle results indicate a noise decrease with forward speed throughout the Doppler-shifted static spectrum. This decrease across the entire frequency range was also apparent in the free-jet results. The similarity of the results indicates that the effects of flight on jet mixing noise can be predicted by simulation of forward speed with a free jet.

Overall sound pressure levels were found to decrease with forward speed at all emission angles for both methods of testing. The fact that tests with actual engines in flight show significant differences from the results observed in the present tests strongly suggests that the flight data include installation effects and/or sources other than pure jet mixing noise.

INTRODUCTION

The effect of aircraft motion on the noise received from jet engines has been a subject of much investigation and controversy over the past few years. It had generally been accepted that jet noise in flight should be reduced from its static level due to the reduced shear resulting from the lower relative velocity between the jet and its surroundings. Measurements with a number of aircraft reported by Bushell (ref. 1), however, showed a smaller flight benefit than expected, and even indicated an adverse effect in the forward direction.

Other investigations utilizing actual motion between the jet and observer (refs. 2 and 3) generally show the same effects as the flight tests. On the other hand, experiments using simulated forward motion, such as with a free jet (refs. 4 to 6) or wind tunnel (refs. 7 and 8), have not produced data indicating an adverse effect of flight on jet noise.

There were two purposes of the experiments reported herein. The first was to test a model subsonic jet in actual forward motion in such a manner as to eliminate noise sources other than those resulting from jet mixing. This was accomplished by placing the model nozzle above an automobile and driving past stationary microphones. The second purpose was to use the same nozzle in an anechoic environment with a free jet simulating the forward motion so that the two methods of obtaining forward speed effects on jet mixing noise could be compared.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

f	frequency
M	Mach number of vehicle or free jet
M_J	model jet exit Mach number
M_{rel}	$= M_J - M$
m	relative velocity exponent
OAPSL	overall sound pressure level, dB
PSD	power spectral density, dB
θ	emission angle (vehicle test: angle between downstream jet center line and observer at emission time; free-jet test: angle that would exist between downstream jet center line and observer if observer was positioned within the free jet, i.e., observer angle corrected for refraction effects), deg

TESTS WITH VEHICLE

The noise generated by the automobile in motion was estimated from previous tests that utilized this vehicle with a point sound source (ref. 9). Since the vehicle noise is predominantly low-frequency noise, a high-pass filter can be used to suppress much of this background noise. This necessitates the use of a high-speed, small-diameter jet to maintain the spectral peak of the jet noise above the low-frequency cutoff. Hence, a 2.54-cm (1.00-in.) exit-diameter nozzle run at a nominal Mach number of 0.85 was chosen along with a 500-Hz high-pass filter. Since the spectral peak of jet noise corresponds to a Strouhal number near 0.25, this peak should then occur at about 3 kHz.

A more obvious reason for the high jet exit velocity was to obtain jet noise levels above that of the vehicle noise throughout most of the spectra. Also, the high jet levels assured minimum contamination from upstream valve noise.

Test Setup

The nozzle flow was provided by a 0.038-m^3 (10-gal) high-flow accumulator filled with nitrogen to 14 MPa (2000 psi). The accumulator was mounted in the trunk of the vehicle along with a regulating system set to reduce the pressure to yield the desired flow rate. For the chosen exit Mach number of 0.85, between 2 and 3 sec of constant mass flow could be obtained.

The discharge from the pressure regulator passed through flexible tubing into the passenger compartment of the vehicle where the instrumentation observer could turn the flow on and off with a small hand valve. The gas then entered the long 5-cm (2-in.) outside-diameter aluminum tubing that passed through the roof of the vehicle and terminated with the 2.54-cm (1.00-in.) inside-diameter nozzle. This tubing was supported by guy wires fastened to the vehicle body (fig. 1).

The jet nozzle was machined to slide over a lip cut out of the supply tube to maintain smooth contours both internally and externally. The internal nozzle geometry allowed the flow to converge from the supply tube diameter (4.45 cm (1.75 in.)) to the nozzle exit diameter (2.54 cm (1.00 in.)) in a length of 5.08 cm (2.00 in.). The nozzle terminated with an additional 1.27-cm (0.50-in.) straight section. The nozzle exit lip thickness was 0.08 cm (0.03 in.).

The nozzle and microphones were positioned approximately 7.6 m (25 ft) above the ground. Since the closest approach distance between vehicle and microphones was about 11 m (38 ft), the height of the nozzle and microphones assured that the large dips in the noise spectra due to ground reflections were below the filter cutoff frequency (500 Hz) for all the angles at which measurements were made. Hence, deviations in the observed spectra due to reflections were limited to a relatively constant increase of 0 to 3 dB throughout the measured spectra.

The jet exit Mach number was determined from an impact probe positioned in the supply tube just above the roof of the vehicle. This probe was calibrated against a similar probe placed at the nozzle exit to determine the pressure drop between the supply tube probe and the nozzle exit plane. This pressure drop was found to be 12 kPa (1.8 psi) for exit Mach numbers between 0.80 and 0.90.

The supply tube impact probe reading was recorded along with the vehicle speed on a strip chart located inside the vehicle. Only those runs yielding a pressure corresponding to exit Mach numbers between 0.83 and 0.86 were retained. Assuming an eighth power dependence of jet noise on velocity, the maximum possible changes in the overall sound pressure level (OASPL) due to exit Mach number variations can then be calculated to be 1.6 dB. Variations in velocity due to the decreasing accumulator temperature (calculated to be less than 5 K (9° F) per sec) were insignificant during the short data-sampling times.

Test Procedure

The test vehicle was driven over an asphalt surface past sideline microphones at a constant speed within the test section (fig. 2). The instrumentation observer within the vehicle activated the nozzle supply control valve at a sufficient distance from the test section to ensure obtaining the desired flow rate at the proper time. He then recorded on the strip chart the instants at which the vehicle entered and left the test section. The strip chart was checked to ensure that the vehicle deviated by no more than ±2 percent of the nominal speed and that the supply tube pressure was maintained within the specified limits during the time the vehicle was within the test section.

Six sideline microphones were positioned at 3-m (10-ft) intervals parallel to the path of the vehicle. Since the nozzle supply system was limited to about 2.5 sec, measurements at all angles of interest could not be obtained during a single run. Hence, each run was set up to obtain data for a single emission angle. The vehicle position with respect to the microphones was determined by long metal strips that functioned as electrical switches. These were placed perpendicular to the path of the vehicle and were activated by its tires. The signals produced by these switches were recorded along with the microphone signals. Each microphone signal was analyzed only over 3 m (10 ft) of vehicle motion such that the midpoint of the signal corresponded to the desired nozzle-microphone angle at the emission time. (This resulted in the processing of the signal over the emission angles from 83° to 97° at the nominal angle of closest approach (90°).) Hence, data segments ranged from 76 msec at the highest vehicle speed to 227 msec at the lowest speed. Vehicle background noise was measured using the same procedure without the jet activated.

Static jet noise data at each emission angle were obtained from two of the six microphones. The stationary vehicle was positioned such that the two microphones were located at the extreme angles of the corresponding motion run (83° and 97° for closest approach).

Five discrete emission angles, equally spaced from 30° to 150°, were tested. Vehicle Mach numbers of 0, 0.04, 0.08, and 0.12 were run at all five angles, with the exception that data were not obtained at the two upstream angles at the highest speed due to a significant masking of the jet signal by the vehicle noise. Each test condition (corresponding to a given vehicle speed and angle) was repeated a number of times, resulting in at least 2 sec of data per condition.

Results

Values of power spectral density (PSD) were obtained using a constant bandwidth filter of 78 Hz over the range from 500 Hz to 20 kHz. Each acceptable data segment was analyzed and those corresponding to a given test condition were averaged.

The values of PSD for all test conditions at an emission angle of 30° are shown in figure 3. The background vehicle noise (jet-off condition) is shown as the continuous traces in the lower part of the figure. For clarity, each data point shown for the jet-on conditions is an average over 234 Hz rather than 78 Hz. Data at the highest speed in the frequency region near 4.5 kHz are not shown since this region was contaminated by background noise due to aeolian tones caused by the guy wires supporting the nozzle supply tube.

There is no discernible difference between the static and motion spectrum at the lowest vehicle speed. At the higher speeds, however, a level difference can be noticed over almost the entire spectrum. This difference increases as the vehicle speed is increased. Also noted is the expected Doppler shift of the peak frequency to lower values with increasing speed.

A better visual comparison between the static and motion spectra can be made by accounting for this Doppler shift. This has been done in figures 4 and 5 for Mach numbers of 0.08 and 0.12, respectively. In each figure the motion PSD is plotted against the frequency, whereas the static PSD is plotted against $f/(1 + M \cos \theta)$, where M is the Mach number of the motion case.

With the Doppler factor thus incorporated, the low-frequency portions of the motion spectra are seen to lie below the static spectra at all emission angles. At higher frequencies these reductions are even larger in the forward direction, but smaller in the downstream direction. This phenomenon could be due to a reduction in shear as the forward speed is increased. This reduction results in higher frequency noise being refracted less and hence directed more toward the downstream jet axis. Other than this slight frequency dependence, the results indicate that the effect of relative velocity is to reduce the entire Doppler-shifted static spectrum in both the forward and aft directions.

Portions of some of the motion spectra in figures 4 and 5 are not shown because of contamination by background (vehicle and guy-wire) noise. Because of this, overall sound pressure levels could not be obtained from the power spectral densities for a number of test conditions. Hence, these overall levels were estimated by the procedure outlined in figure 6. The PSD for each motion condition was compared with the corresponding PSD of the background noise. For those frequencies where the difference was 7 dB or greater, the motion PSD was compared with the static PSD to obtain a static-to-motion difference at these frequencies. An average of these differences was then subtracted from the static OASPL to obtain the estimated OASPL of the motion run. Although there are inherent errors in this method of obtaining the OASPL, agreement within 0.1 dB was found between the estimated result and that obtained directly from the PSD for all cases where the entire spectrum was uncontaminated by background noise.

The estimated overall sound pressure levels are shown in figure 7 along with the results computed from the contaminated power spectral densities. It can be seen that there is a consistent decrease in the estimated OASPL with increasing forward velocity at all emission angles, as expected from the spectral comparisons of figures 4 and 5.

TESTS WITH FREE JET

The free jet used to simulate forward motion was limited to a maximum Mach number of 0.11. Positioning of the model jet in the Langley anechoic noise facility restricted measurements in the upstream direction to 120°. Other than these limitations, test conditions with the vehicle were repeated using the free jet. Air was used instead of pure nitrogen for the model jet.

Test Setup

The free jet exhausted vertically from a 1.2-m (4.0-ft) diameter nozzle into an anechoic environment. The 2.54-cm (1.00-in.) model jet nozzle was positioned at the center of the free jet as shown in figure 8. A 1.3-cm (0.5-in.) condenser microphone designed for free-field linear response up to at least 20 kHz was located on a boom that traversed an arc about the center of the model nozzle exit plane on a 3.7-m (12-ft) radius.

Test Procedure

With the model jet maintained at a Mach number of 0.85 the free jet was run at the static condition (no flow), and Mach numbers of 0.04, 0.08, and the maximum available, 0.11. For each test condition the microphone was held stationary at discrete angles, from the downstream center line, ranging from 30° to 120°.

Results

The noise generated above 500 Hz by the free jet was insignificant at all test conditions. Hence, the problems associated with background noise present in the vehicle tests were nonexistent during the tests with the free jet. However, the presence of the free-jet shear layer requires corrections to correlate noise emission angle with observer angle.

Acoustic pressure power spectral density measurements using a 400-Hz bandwidth are shown in figure 9 for the test conditions corresponding to an observer angle of 90°, the angle at which the shear layer corrections are at a minimum. The same observation can be made here as with the vehicle test - relative motion tends to decrease the jet noise level throughout the spectrum.

The true emission angles corresponding to the measured results were computed in the standard manner (ref. 10) under the assumption that the noise originates at the nozzle exit. (Amplitude corrections due to the shear layer were found to be less than 0.5 dB for all test conditions, and hence were neglected.) The measured OASPL is given in figure 10 as a function of the computed emission angle. Again, a decrease in the OASPL is observed at all angles with increasing forward speed.

COMPARISON OF RESULTS

The difference in sound pressure level between static and motion conditions is generally correlated against the ratio of jet velocity to relative velocity (the difference between jet and forward velocities). This type of comparison should yield consistent results for flight simulation studies (free jet or wind tunnel) since there is no relative motion between the jet and the observer. However, in actual flight the Doppler effect results in a frequency shift of the entire spectrum, so this type of comparison (particularly when done on a frequency-by-frequency basis) can be misleading. Nevertheless, in order to reassert the main findings of this report in a fashion that is commonly presented, the static-to-motion OASPL differences are given in figure 11 as a function of $10 \log M_J/M_{rel}$ for both series of tests. The effects due to convection that are sometimes subtracted from the OASPL difference before this type of correlation is made (ref. 7) were computed to be less than 0.4 dB for all test conditions and hence were neglected.

The uncertainty due to the procedure used in estimating the OASPL for the vehicle tests leads to the considerable scatter shown in figure 11. The relative velocity exponent m lies somewhere between 3 and 6. The data uncertainty as well as the test limitations of high jet velocity/low forward speed prevent a reasonable estimate of this exponent or its variation with emission angle. Nevertheless, an increase in noise reduction with increasing forward speed is again clearly indicated at all angles at these low velocities for both testing methods.

CONCLUDING REMARKS

The effects of motion on the noise produced by a small jet were obtained in tests using an automobile and a free jet to provide both actual and simulated forward speed. Comparisons of the measured power spectral densities indicate that the noise is reduced with increasing forward speed at all emission angles for both methods of testing. The general agreement in the results from the two methods indicates that the effects of flight on jet mixing noise should be obtainable from free-jet tests. The fact that the adverse effects seen in flight testing of actual jet engines do not appear here strongly suggests that these effects are due to reasons other than pure jet mixing noise.

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Figure 1.- Test vehicle with model jet installed.

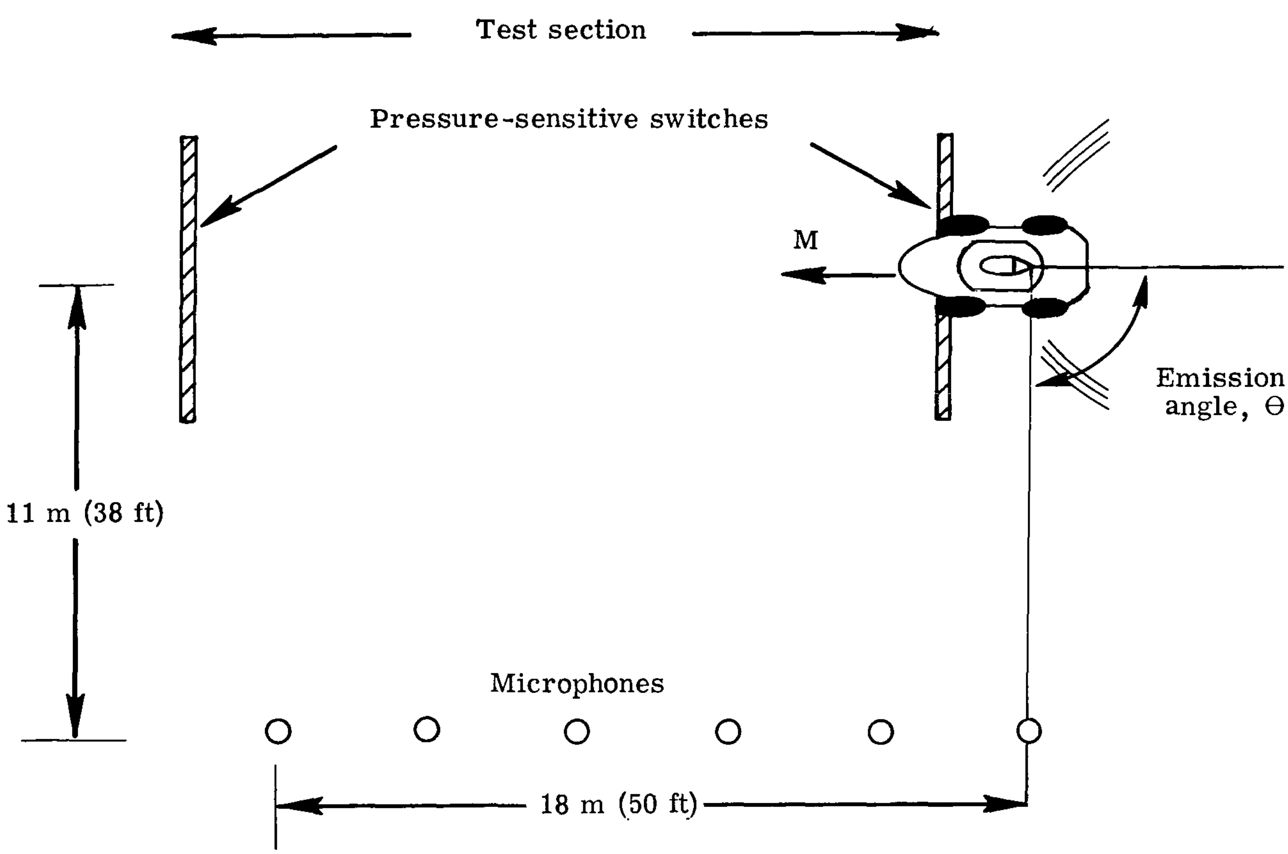


Figure 2.- Plan view schematic of vehicle test.

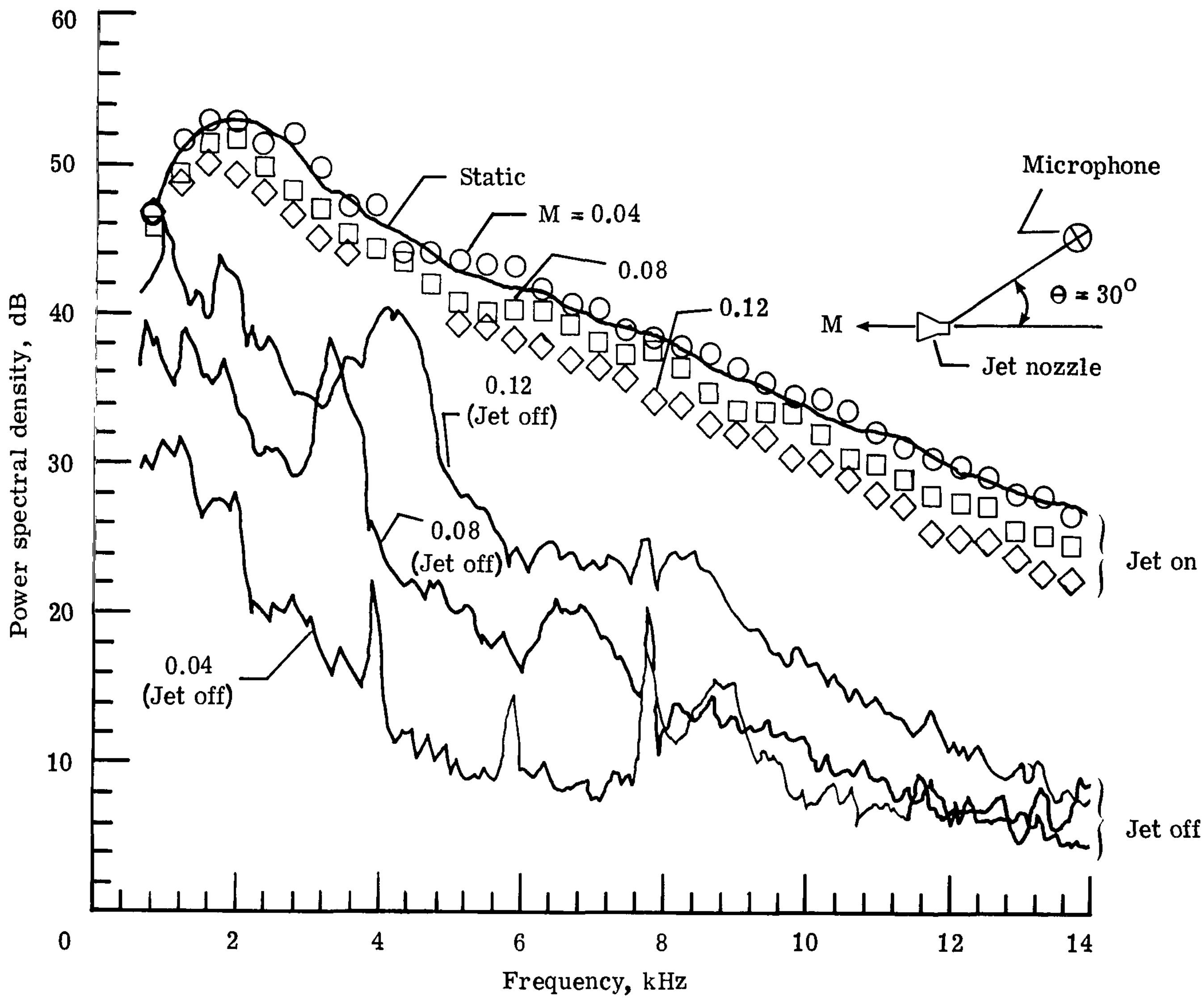


Figure 3.- Measured power spectral densities for jet and vehicle noise at 30° emission angle.

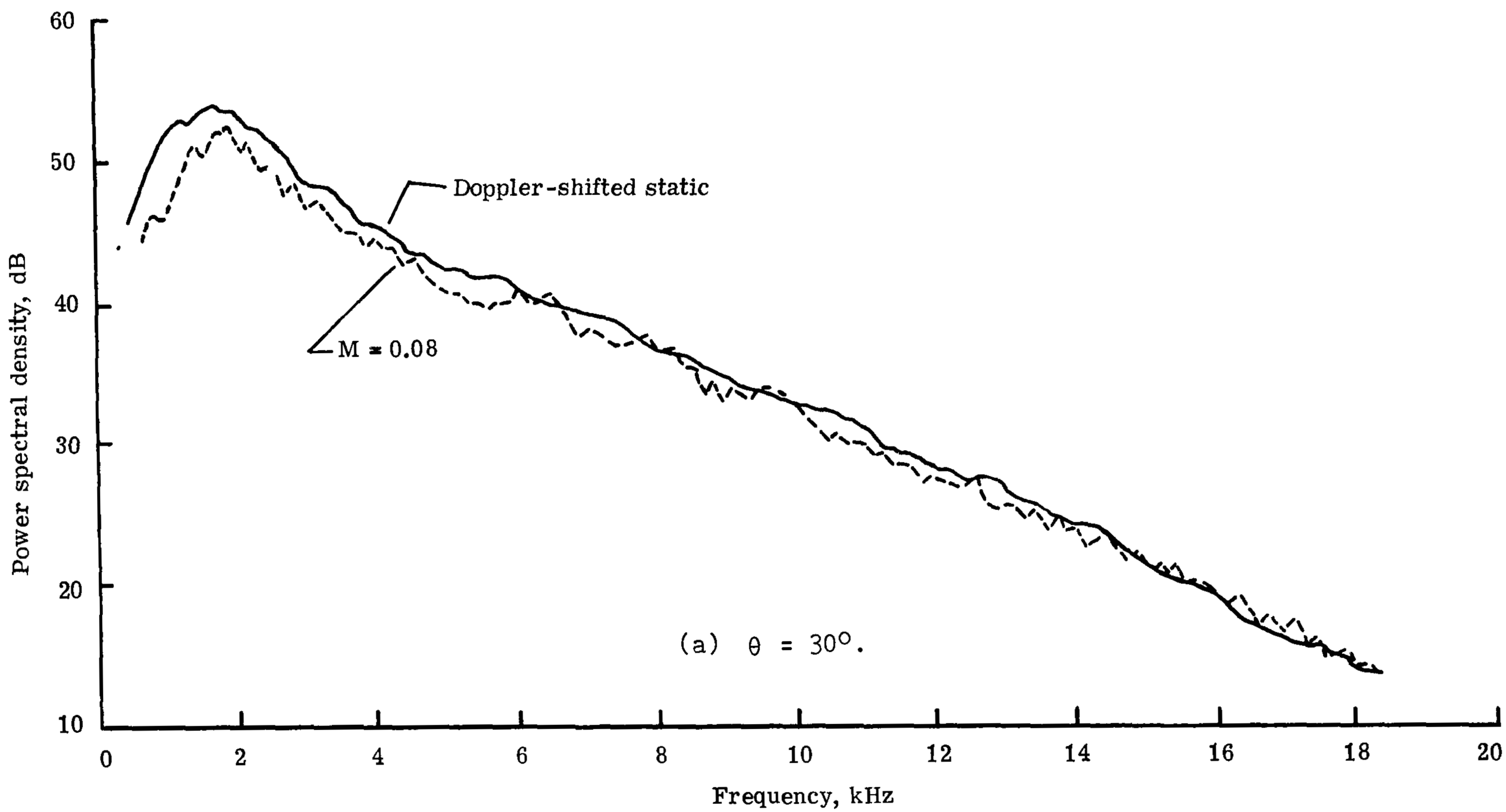


Figure 4.- Comparison of motion spectra with Doppler-shifted static spectra for M = 0.08. (Moving vehicle tests.)

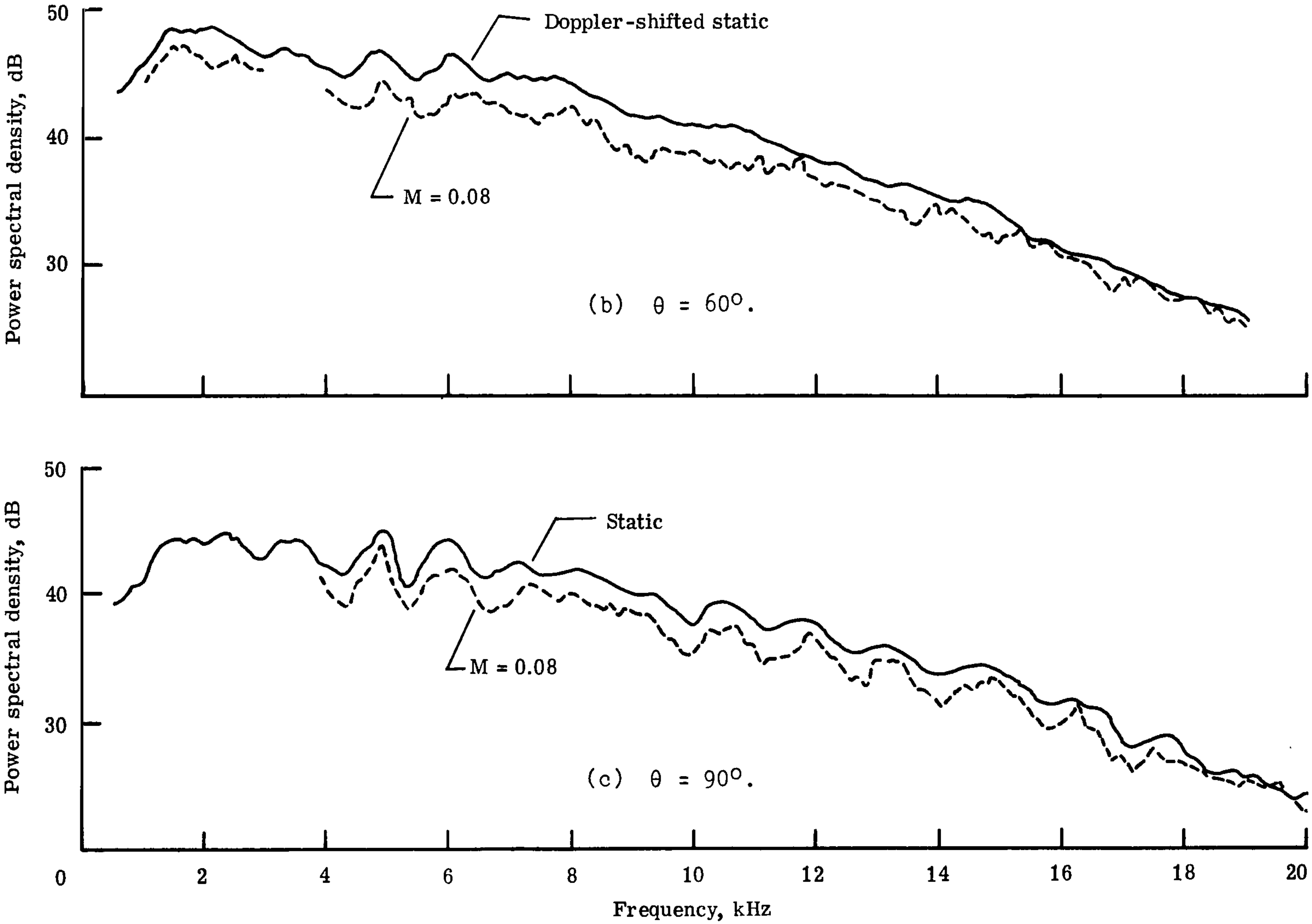


Figure 4.- Continued.

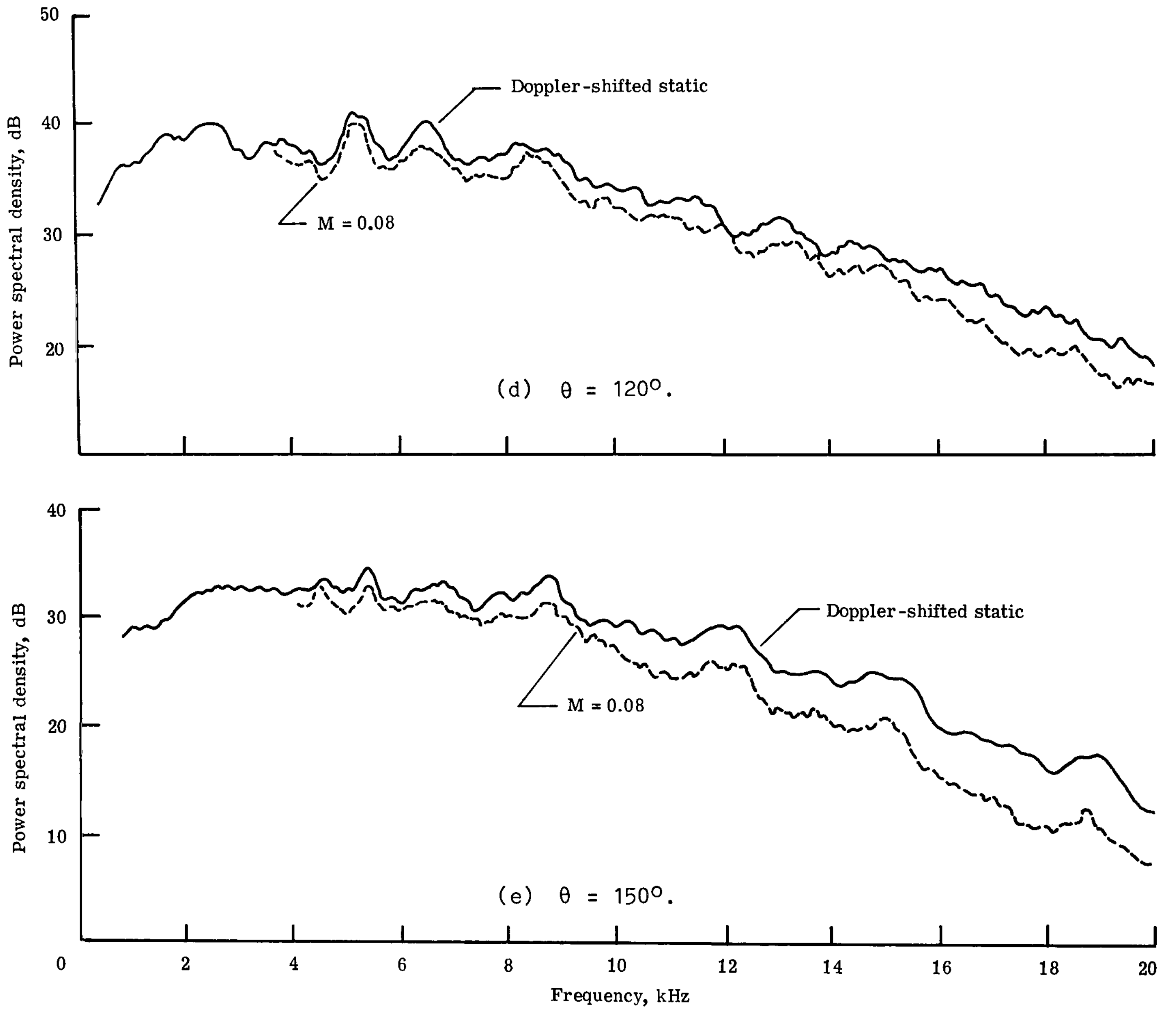
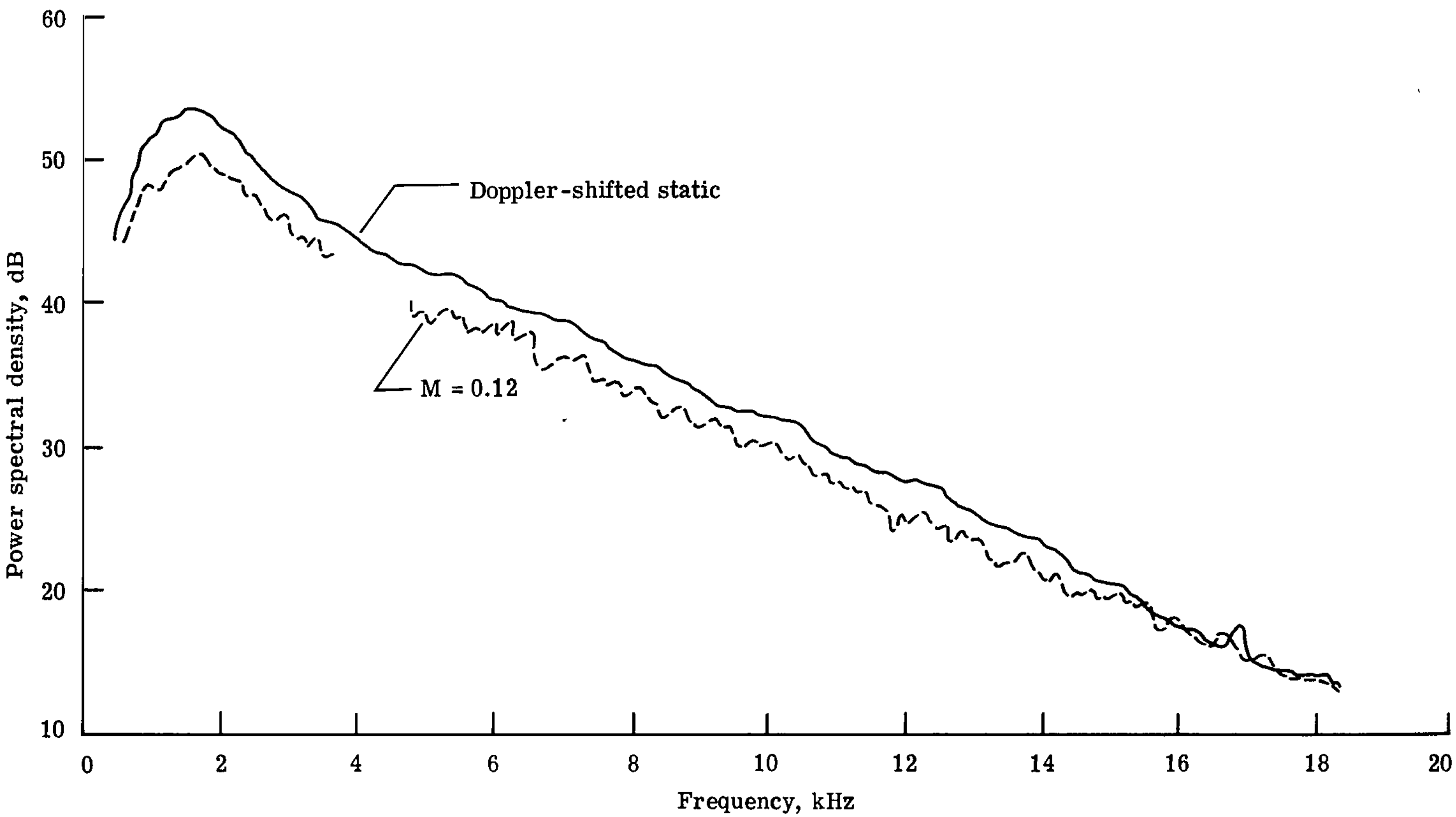
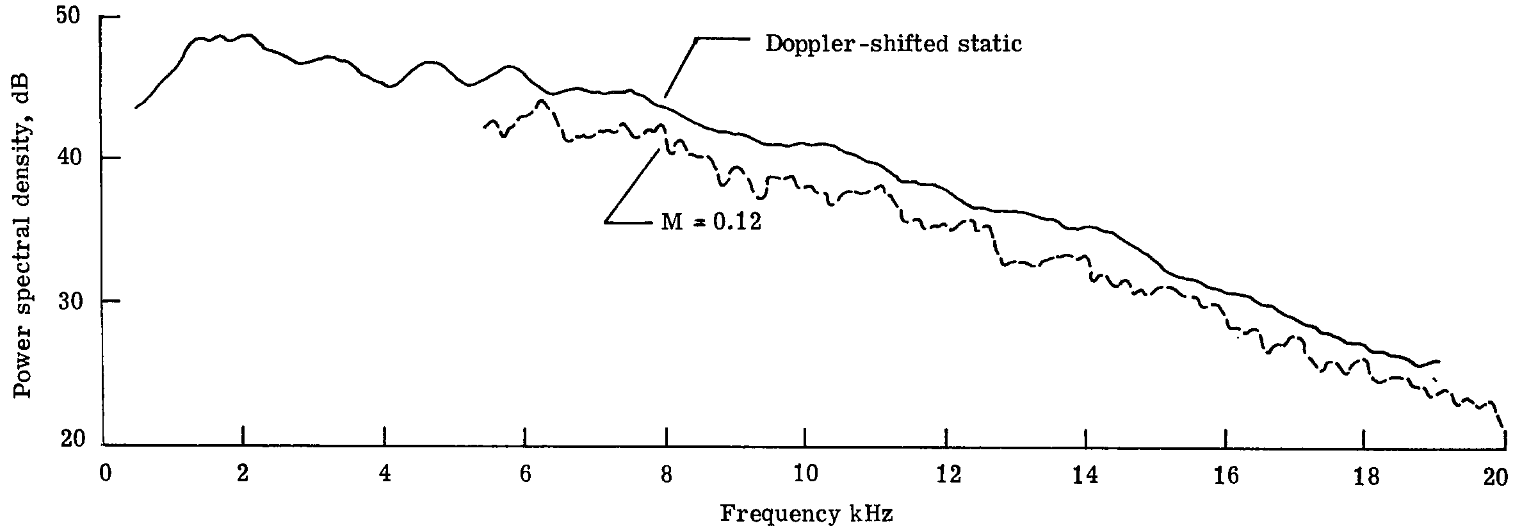


Figure 4.- Concluded.

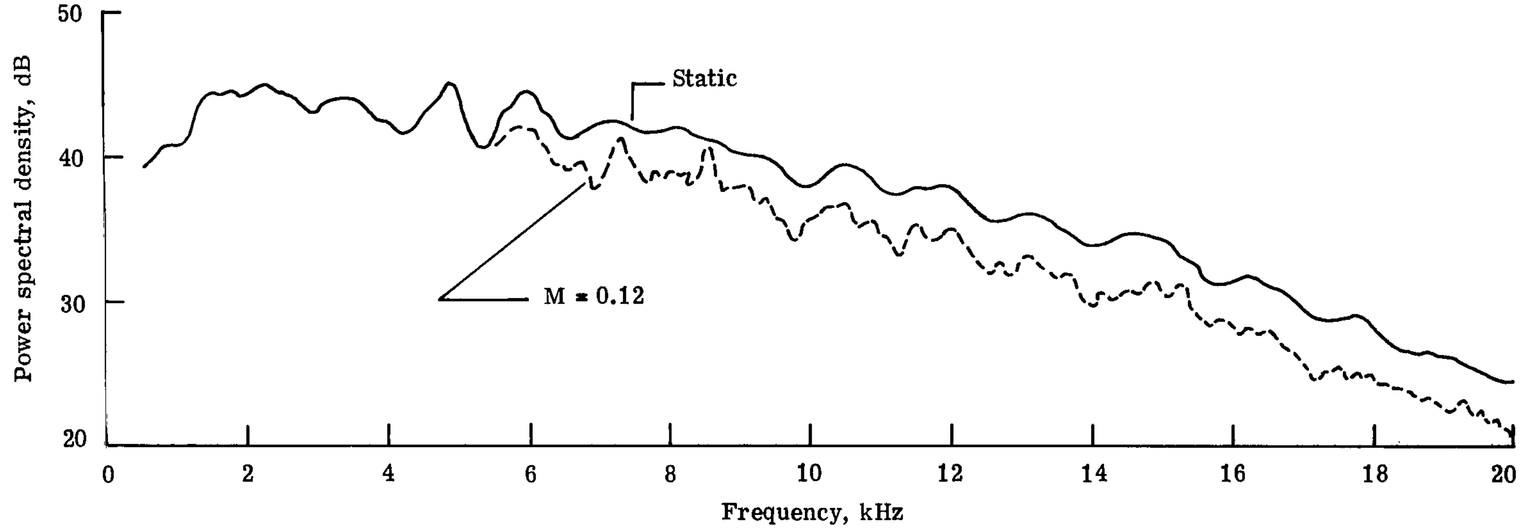


(a) $\theta = 30^\circ$.

Figure 5.- Comparison of motion spectra with Doppler-shifted static spectra for M = 0.12. (Moving vehicle tests.)



(b) θ = 60°.



(c) θ = 90°.

Figure 5.- Concluded.

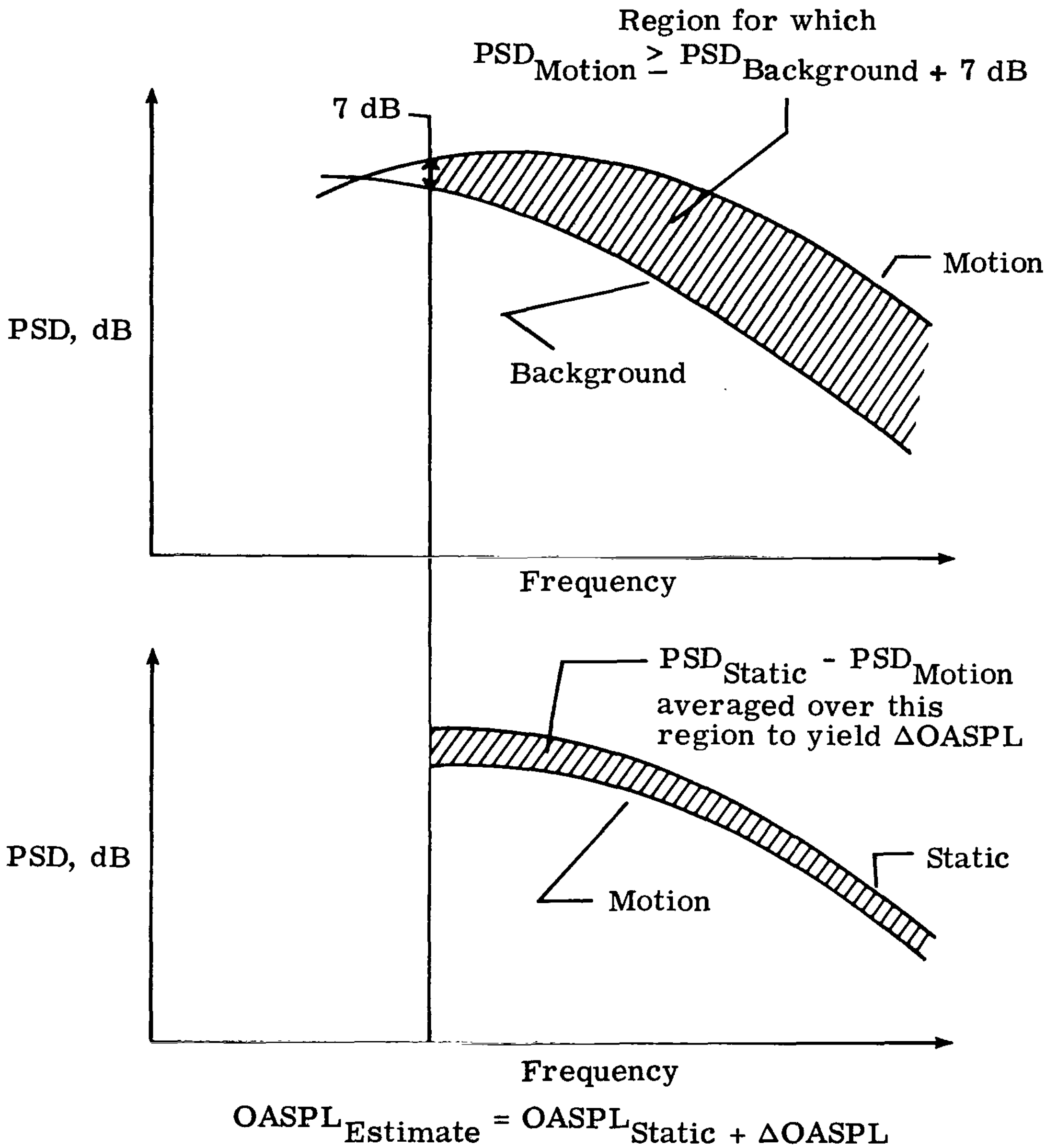


Figure 6.- Procedure for obtaining estimated OASPL for tests with vehicle.

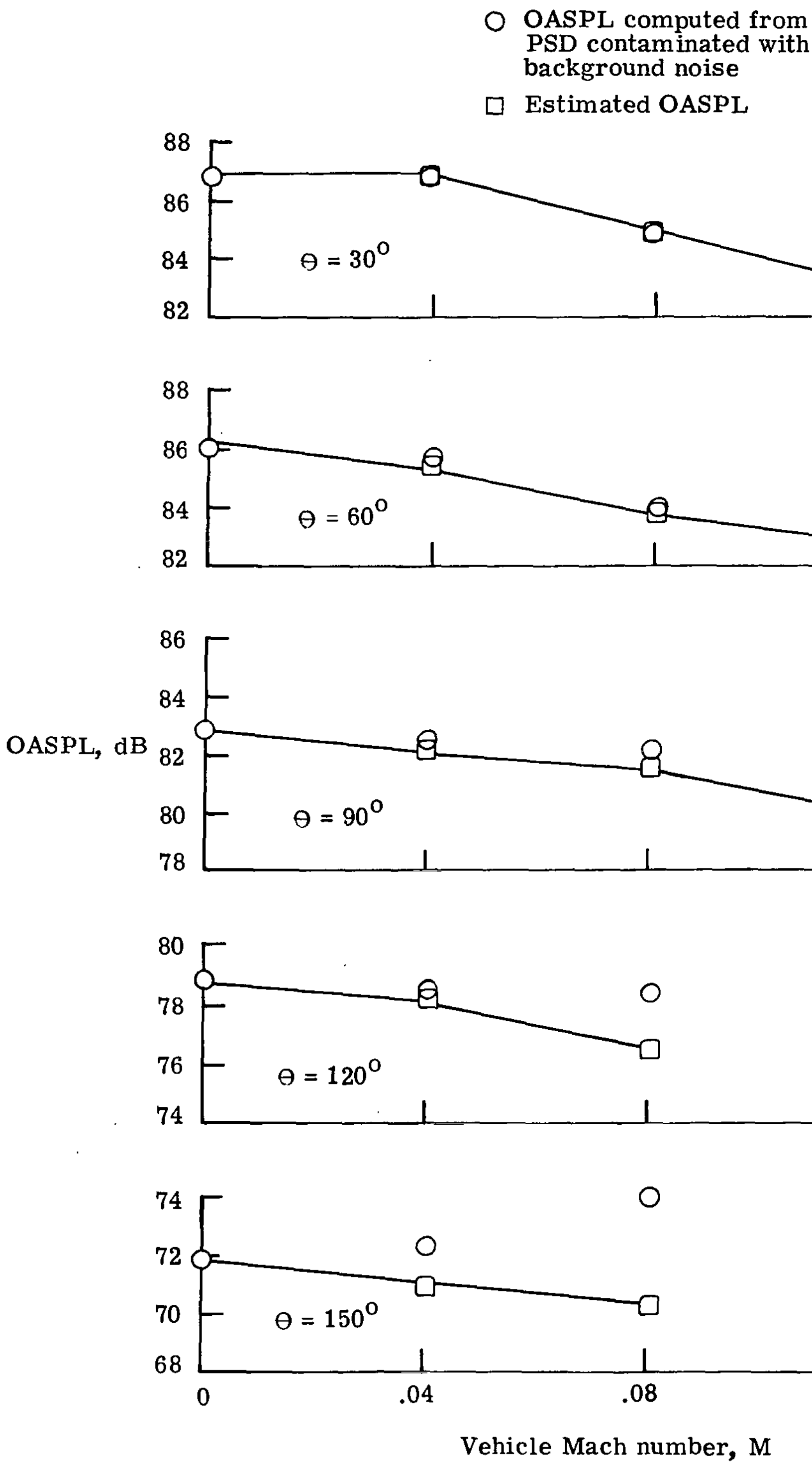


Figure 7.- Variation of overall sound pressure level with forward velocity. (Moving vehicle tests.)

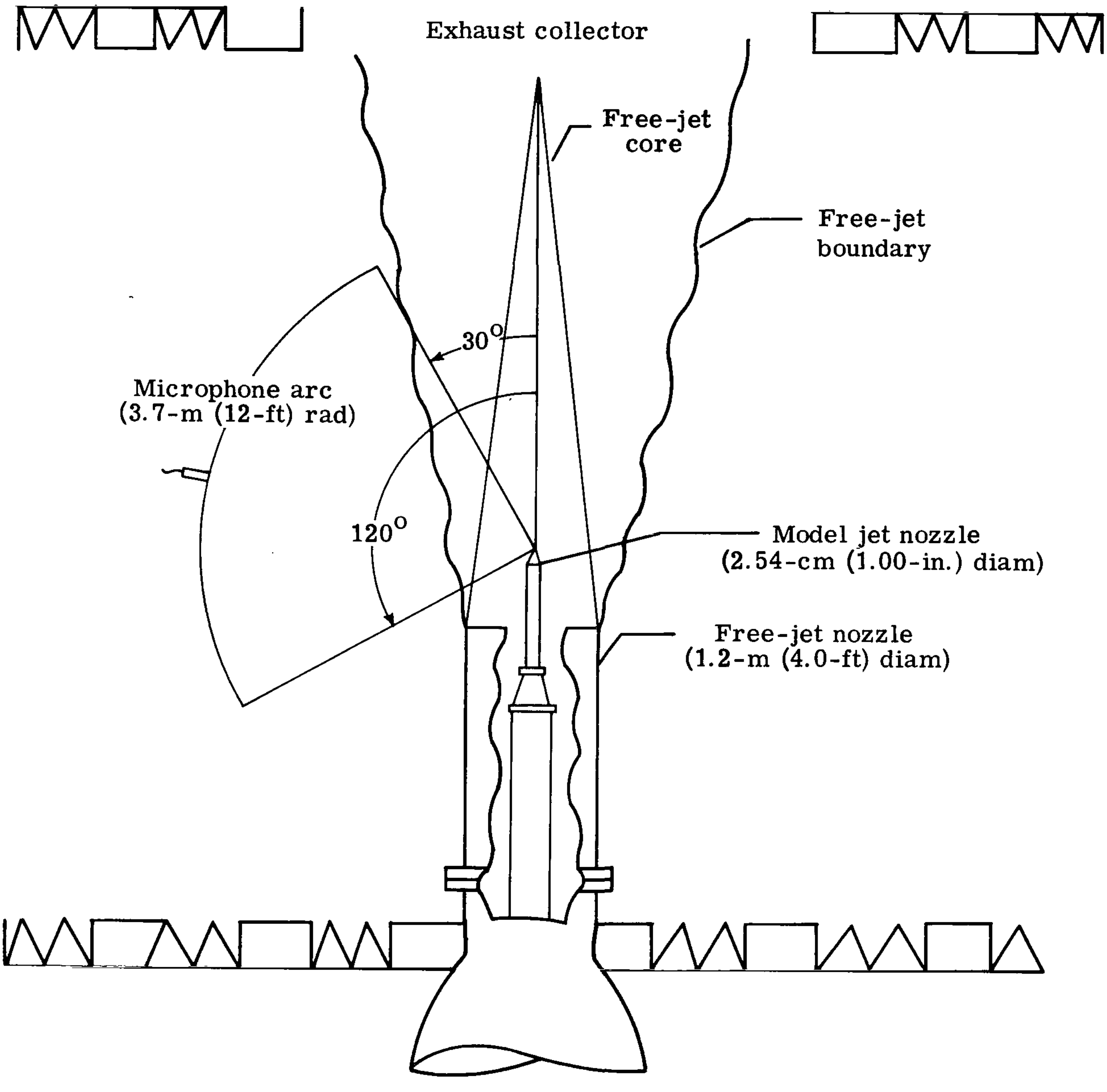


Figure 8.- Sketch of free-jet test setup in Langley anechoic noise facility.

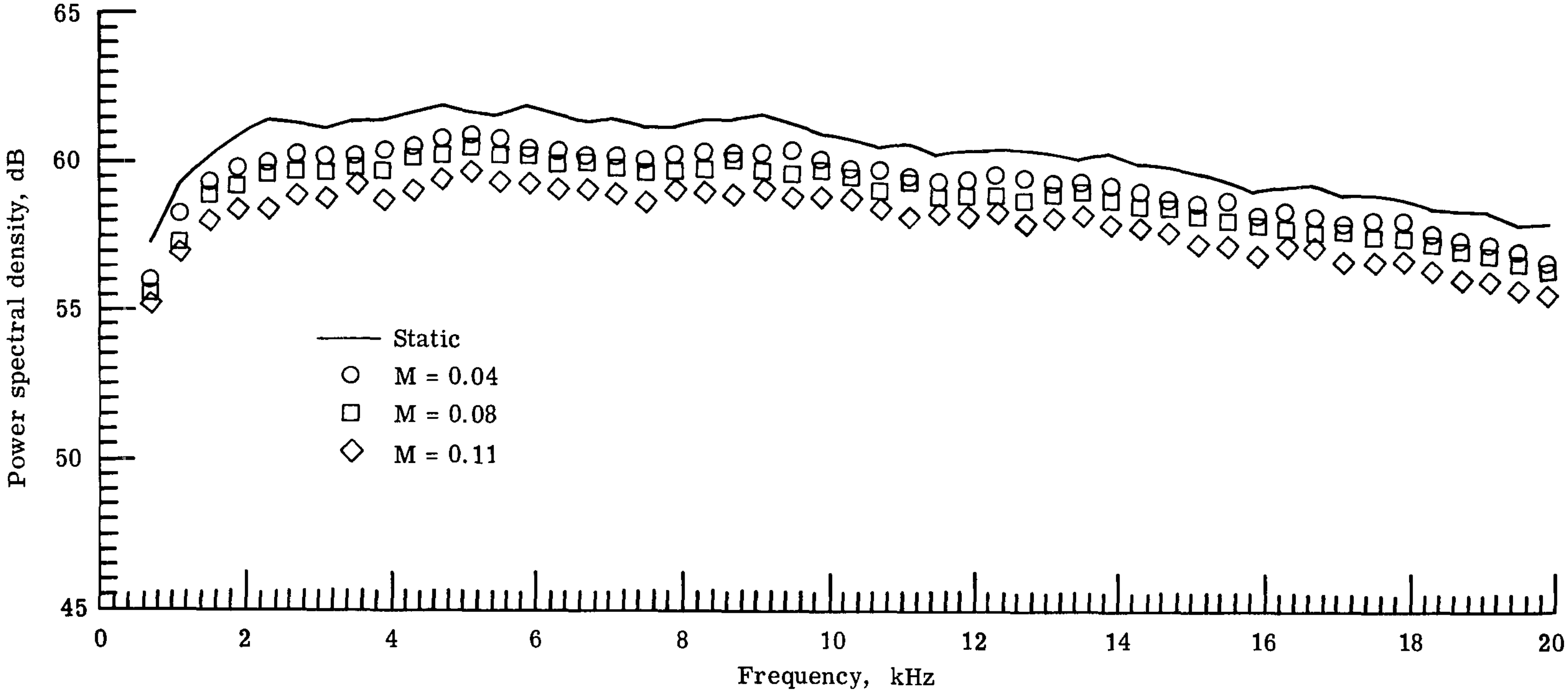


Figure 9.- Power spectral densities from free-jet test at 90° observer angle.

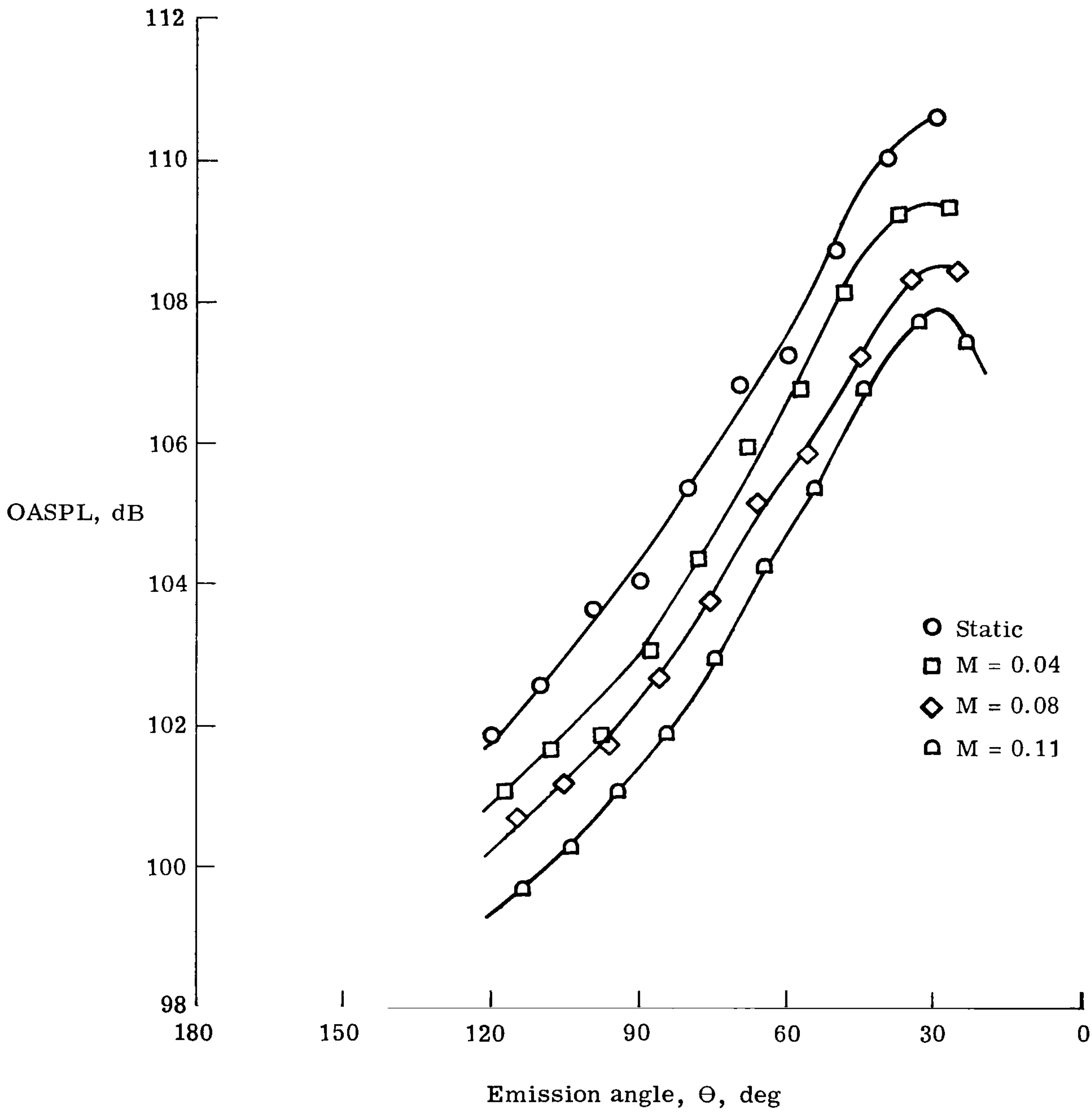


Figure 10.- Overall sound pressure levels including angular refraction correction. (Free-jet tests.)

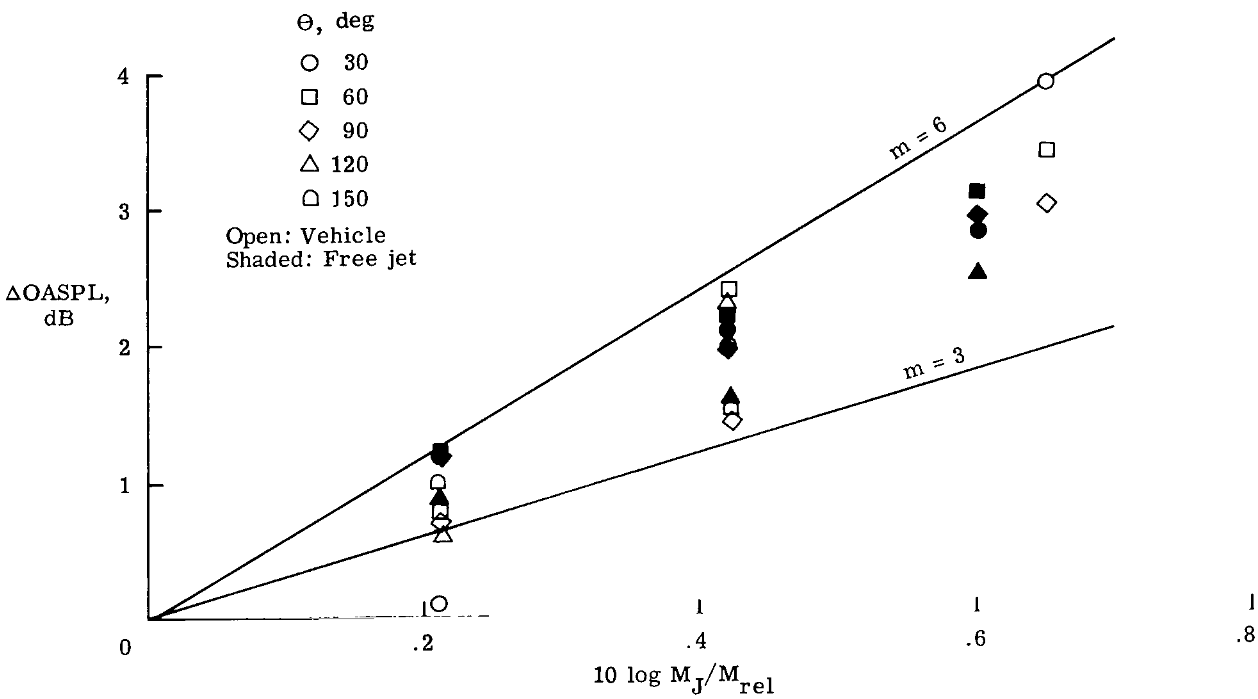


Figure 11.- Change in overall sound pressure level between static and motion conditions.

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15. Supplementary Notes

16. Abstract

A 2.54-cm (1.00-in.) nozzle supplied with nitrogen was mounted above an automobile and driven over an asphalt roadway past stationary microphones in an attempt to quantify the effects of the vehicle motion on jet mixing noise. The nozzle was then tested in the Langley anechoic noise facility with a large free jet simulating the relative motion. The results are compared for these two methods of investigating forward speed effects on jet mixing noise.

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