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MEASUREMENT OF MODEL PROPULSION SYSTEM NOISE IN A LOW-SPEED WIND TUNNEL

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E-8572

Abstract

Methods are presented for making overall and directional acoustic measurements with forward velocity in the Lewis 9 × 15 V/STOL Wind Tunnel. Overall acoustic measurements are discussed first. The acoustic calibration methods, instrumentation features, and types of experiments are presented. Selected data are presented as examples of the various types of overall measurements that are possible. The method of making directional acoustic measurements is then presented. The necessary alterations to the tunnel, specialized acoustic instrumentation, and calibration details are described. The results indicate that relative overall acoustic measurements can be made successfully and that directional acoustic measurements are feasible.

Introduction

One of the principal national technical goals is to improve the environment and quality of life by the reduction of all forms of pollution. In the vicinity of airports the noise caused by arriving and departing airplanes is one form of environmental pollution that can be alleviated. In response to this goal, the NASA-Lewis Research Center has been active in investigating and reducing propulsion system noise. A low speed wind tunnel originally constructed to study the aerodynamic performance of model propulsion systems at takeoff and approach has recently been modified so that it can also be used to study the acoustic performance of model propulsion systems. Reverberant and directional acoustic measurements are made of propulsion system inlet radiated noise. This paper describes the aerodynamic and acoustic features of the tunnel, presents pertinent design and acoustic validation data, and presents examples of the models used and the data obtained.

Wind Tunnel Description

The low speed test section is located in the return leg of a wind tunnel circuit that includes the 8×6 foot supersonic test section (fig. 1). The low speed test section is 9 feet high and 15 feet wide. Airflow leaves the drive compressor, passes through the high speed test section, is diffused to a low velocity and ducted to the return leg containing the low speed test section. The air velocity in the 9 × 15 foot test section is controlled by the flow control doors shown in Fig. 1. A portion of the flow is removed to reduce the velocity in the test section to the desired value. Makeup air re-enters the inlet doors downstream from the low speed test section to maintain proper conditions at the face of the main drive compressor. Air velocities from 75 to 250 feet/second (50 to 150 mph) can be obtained in this manner.

The test section is a great distance from the main drive compressor. Helmholtz resonators downstream of the 8×6 foot test section remove very low frequency noise. A large acoustic muffler is incorporated in the transverse leg of the tunnel flow circuit downstream of the 8×6 foot test section. Acoustic baffles and wall treatment are located immediately upstream from the flow control doors in the return leg. Consequently, compressor noise at the 9 × 15 foot test section is reduced to a low value. Additional acoustic treatment covers the end wall normal to the flow downstream from the low speed test section adjacent to the air dryer building to reduce the reflection of noise generated in the test section. The air dryer upstream from the tunnel drive compressor suppresses the compressor noise that might propagate upstream to the low speed test section. Further details of the 9 × 15 foot wind tunnel can be found in Ref. 1.

Reverberant Acoustic Measurements

Static Measurements

Overall acoustic measurements are made in the large chambers upstream and downstream of the test section that approximate reverberant rooms. The walls of the flow circuit of the main tunnel are constructed of reinforced concrete and the test section walls are covered with plywood which enhances their use as reverberant enclosures. The slots in the test section walls, evident in Fig. 2(a), reduce the magnitude of the aerodynamic corrections required to arrive at free airstream test results. The "end walls" of the chambers have a significant acoustic absorptivity so the chambers are only approximately reverberant. By definition the characteristics of reverberant rooms are such that the sound pressure level is independent of location.

Four microphones are used in each chamber, as shown in Fig. 2(b). The microphone locations were selected from prior acoustic tests with the objective of avoiding the node points of standing acoustic waves. The variation and reproducibility among the four microphones at each location in response to a calibration noise source in the test section was typically ±2 dB. Research acoustic measurements are made by recording all of the microphone signals simultaneously on tape. The signals are then processed through a one-third octave analyzer and digitized for computer analysis. Further processing is done by a computer program which eliminates the microphone signals in each third octave band that differ from the average signal by 3 dB. The remaining signals are averaged. If all signals fall within 3 dB of the new average, the reading is accepted and the average signal used for data. If any one of the remaining signals differ by 3 dB or more, the reading is rejected. The final third octave spectra are displayed on plots generated by the computer and used to compute overall sound pressure levels. Narrow band spectra can also be obtained directly from the data tapes for detail analysis if desired.

One of the characteristics of reverberant enclosures is that the shape of reverberant sound spectrum differs from the source sound pressure spectrum. This is because there is a frequency selective attenuation of sound pressure in the reverberant field. Corrections are required to account for the effects of room geometry and acoustic properties as well as the temperature and relative humidity of the surrounding atmosphere. For each third octave frequency band, corrections were calculated according to the method given in Ref. 2. Typical results of the calculations are shown in Fig. 3. The data shown were obtained from a test of a 15-inch diameter fan reported in Ref. 2. The correction factor is shown as a function of frequency. As shown, the corrections to the data are greatest for the higher frequencies and approach 30 dB in some cases. Consequently, when comparing reverberant spectra care must be exercised to use the corrected data.

Other characteristics of the assembly of adjoining reverberant rooms (i.e., the upstream chamber, the test section, and the downstream chamber) are discussed in Ref. 3. Calibration tests indicated that there is an unequal division in source sound power between the three chambers. This division of source sound power was found to be dependent upon the location of the source in the test section. Consequently only relative overall acoustic comparisons can be made directly from the microphone measurements but absolute source power levels can be calculated using an acoustic calibration of the assembly of reverberant rooms.

Measurements with forward velocity - Overall acoustic measurements under forward velocity test conditions can also be made using the same microphone installation described previously. Air velocities in the settling chambers where the microphones are located are of the order of 15 to 30 feet per second (10 to 20 mph). The microphones have streamlined nose cones and are positioned facing upstream to further reduce the effect of wind noise. Consequently, microphone wind noise is small.

The general types of acoustic data that are obtained for model propulsion systems under forward velocity test conditions is illustrated by the next series of figures. Figure 4 shows a 20-inch diameter fan model mounted in the low-speed test section. The model fan is powered by an air-driven turbine contained in the fan core section. The turbine drive air supply line is routed through the model support as shown. The model can be positioned at various incidence angles by rotating the entire model about an axis which passes through the centerline of the air supply pipe.

Figure 5 shows reverberant acoustic data obtained from the 20-inch diameter fan model for a fixed value of tunnel velocity and a single value of fan speed. The variable for this example is the model incidence angle which varies from 0° to 50°. The values of SPL in dB are plotted for the respective one-third octave frequency bands. For reference, the tunnel background noise spectrum is shown for the tunnel alone without the fan operating. As a general rule, any sound pressure level in excess of 10 dB of the background sound pressure level is considered to require no corrections for background noise. Consequently, the data shown in Fig. 5 are valid from at least 1000 to 10,000 hertz. Figure 5 illustrates the effects of inlet flow separation on sound pressure level. It was determined from rake measurements at the fan face that the flow is attached for 0° and 30° incidence angle and is separated at 40° and 50° incidence angle. (The rakes were removed for the acoustic measurements.) The relatively large increase in broadband noise for separated flow is apparent.

This model gives the interaction between the inlet flow distortion and fan source noise. This is an advantage if only the overall realistic result is desired. But this model also has the disadvantage that no distinction can be made between noise propagating from the inlet and exit of the fan duct because it is not possible to separate the two effects in a reverberant enclosure. Hence, if an inlet was used that attenuated inlet noise a great deal, its effectiveness would not be evident.

A model that overcomes the above noted disadvantages and is thus a very useful inlet acoustic research tool is shown in Fig. 6. Here the inlet airflow is achieved by connecting the inlet via ducting to the laboratory exhaust system (fig. 6(a)). The ducting is acoustically wrapped and there is no "fan exit" noise as was the case with the model fan. The noise source is a 5.5-inch diameter fan acting like a siren (fig. 6(b)). Rods and screens were placed in front of the fan to increase the level of the source noise. The fan is contained inside the 12-inch diameter model inlet (fig. 6(a)) with its axis aligned with the inlet axis in an attempt to retain some of the acoustic model characteristics of a fan. The speed and noise of the fan, and the airflow through the research inlet are mutually independent. Aerodynamic and acoustic measurements can be made simultaneously with this apparatus.

Figure 7 illustrates typical narrow band spectra obtained with this apparatus. Spectra are shown of the fan noise for two inlet flow conditions and of the wind tunnel alone noise (fan off and zero inlet flow). The data of interest is usually the suppression of inlet radiated noise that occurs at the blade passage frequency (BPF) of the siren. The significant parameter is denoted as the sound pressure level reduction, $\Delta(SPL)_{BPF}$, and is calculated as shown on Fig. 7. A reference no-suppression condition is usually established as shown and the $\Delta(SPL)_{BPF}$ is merely the difference between this reference curve and the data curve at the frequency of interest. The maximum measurable sound pressure level reduction occurs when the data spectrum level is reduced to the wind tunnel alone level.

Typical results are presented in Fig. 8 for several high throat Mach number inlets, where the reference no-suppression condition is for an average inlet throat Mach number $M_T = 0.6$. The increase in suppression with increasing throat Mach number above $M_T = 0.6$ is very marked. Also, the inlet pressure recovery decreases and this is accompanied by an increase in flow distortion. Additional information on models and test techniques for this apparatus can be found in Refs. 5 to 9 inclusive.

Directional Acoustic Measurements

One of our goals was to make directional noise measurements on a 20-inch diameter fan in the 9 × 15 foot test section. The problem of accomplishing this is perhaps most clearly explained by starting with the discussion of the problem of making directional measurements in a hardwall test section.

Hardwall test section - It is possible to make directional acoustic measurements in a hardwall (reverberant) wind tunnel. The approach taken was to position the microphone sufficiently close to the model so that it is located in the direct acoustic field. This region is where the sound pressure level is inversely proportional to the square of the distance from the source and is above the reverberant noise level. Acoustic measurements made in the direct field have directional properties whereas measurements made in the reverberant field are diffused and have no directional properties. Figure 9 illustrates the direct and reverberant fields as measured in the 9 × 15 foot test section with hard plywood walls. The distance at which the reverberant and direct acoustic levels are equal is called the Hall radius. Measurements in the 9 × 15 foot wind tunnel indicated a Hall radius of above 3 feet at a 30° angle from the tunnel axis (fig. 9).

Another consideration is the wind noise in the microphone. With the microphone located in the test section the microphone wind noise is much higher than for the location in the settling chamber where the microphones were located for the reverberant measurements. However, the source noise level is also greater when the microphone is mounted in the test section so that the margin above the background can remain adequate. Preliminary studies were made using a $5\frac{1}{2}$-inch diameter fan and an array of microphones arranged as shown in Fig. 10. The wind noise was minimized by fitting nose cones to the ends of the microphones and aligning the microphones with the tunnel airflow so their angle relative to the airflow does not exceed ±30°. This also places some constraints on the test angles of attack. The microphones were positioned at a 2-foot radius from the inlet and were therefore, within the Hall radius (see fig. 9). Typical data and the microphone noise obtained from tests using this configuration are shown on Fig. 11. The test model was a 5.5-inch diameter fan (no inlet struts or screens) with an inlet having the profile shown in the insert. The protruding lower lip on the inlet creates a noise shielding effect to reduce the noise level beneath the protuberance. The data indicated that there was a 6-8 dB attenuation of noise in the downward direction beneath the protruding inlet lip. These measurements served to indicate that the fan noise exceed the wind tunnel background plus microphone wind noise so that it was feasible to make directional measurements in the test section.

To make directional noise measurements on a model as large as a 20-inch diameter the Hall radius must be extended to near the test section walls. This can only be done by acoustic treatment of the walls.

Acoustically lined test section - All four walls of the entire test section was covered with acoustic treatment as shown in Fig. 12. The thickness of the lining was chosen to permit accurate measurements at the lowest frequency of interest. A minimum value of 1000 Hz was selected based on the 2000 Hz blade passage frequency of the 20-inch diameter fan simulator (see fig. 4). To prevent acoustic energy from escaping, supplementary acoustic panels are located behind the slots as shown.

A cross section of the tunnel acoustic treatment is also shown on the inset in Fig. 12. The acoustic absorber is a $1\frac{1}{4}$-inch thick panel of fiberglass formboard having an approximate density of 6 pounds per cubic foot. The acoustic material is contained in fiberglass reinforced plastic trays and covered by a layer of fiberglass cloth. The outer covering is a layer of 20-mesh stainless steel screen which serves as protection from the scrubbing action of the tunnel airstream. The acoustic panels are reversible so that the tunnel can be configured for a directional acoustic test (soft wall) or a reverberant sound pressure level test (hard wall).

Tests were performed to evaluate the acoustic absorptance coefficient of the panels for normal incidence (ref. 10) and oblique incidence (ref. 11). The tests were performed over the frequency range of interest. In general, the fiberglass cloth and metal screen had little effect on acoustic absorptance for source frequencies greater than 1000 Hz. However, for source frequencies of 1000 Hz or less, the acoustic absorptance of the acoustic panels was reduced considerably. Consequently, the tunnel acoustic lining can be considered effective for source frequencies above 1000 Hz, the selected lower limit of interest.

Microphone installation - For wind-on testing the microphone is mounted on a boom that can be positioned about a vertical axis through the center of the inlet face. The microphone can be mounted on the boom at radii from 4 to 6 feet in 6-inch increments. Figure 13 shows the boom and several microphones. The two microphones to the left are conventional Bruel and Kjaer (B& K) one-quarter-inch diameter microphones fitted with nose cones. These are essentially omnidirectional microphones, Ref. 12. The microphones are mounted on weathervaning stands so that the microphones always face directly into the tunnel flow, thus minimizing the wind noise. The third microphone is a directional microphone. The porous strip is the directional element and it must always point directly to the source. Additional details on the construction and directional characteristics of porous strip microphones can be found in Ref. 13. The microphone is thus fixed in one position relative to the boom and hence changes its orientation relative to the tunnel airflow as the boom is rotated to various angles. In order to minimize wind noise, the porous strip is incorporated in a streamlined section and the vertical support is covered with a streamlined weathervaning shroud.

Acoustic validation - The validation of the 9 × 15 foot test section for directional acoustic measurements involved several tests. The first three of these tests were performed at zero tunnel flow. The first test dealt with establishing location of Hall radius at static conditions. Figure 14 shows the arrangement used. The noise source was mounted on the exhauster apparatus as shown. Broadband and pure tone noise generators were used in this series of tests. The microphone was mounted on a moveable carriage that traversed on a pair of rails that were attached to the boom. The microphone could thus be traversed along the boom in a radial direction for any boom angle. To acquare the data, the microphone output and carriage radial position were connected to the axes of an x-y plotter. For the test results presented, the rails were actually mounted on the underside of the boom to minimize acoustic reflections. Typical radial traverse data are shown in Fig. 15. The vertical axis is the microphone sound pressure level in dB and the horizontal axis is distance in feet. Both signals required processing through log convergers to permit direct recording. For the results shown a tone at a frequency of 4000 Hz was used. (A tone is a more stringent test than one using white noise.) The inverse square law dictates a 20-dB reduction per decade increase in distance for noise signals that are in the direct flow field and uninfluenced by the reverberant level. The lower line of Fig. 15 shows such a variation out to a 10-foot radius, the limit of the traverse. The Hall radius is thus beyond 10 feet, a more than adequate value for the acoustic testing of a 20-inch diameter fan model. The other two curves on Fig. 15 show the effect of removing the acoustic treatment from the boom upper surface and using a conventional microphone. Both the boom acoustic treatment and the porous strip microphone were required to achieve the best directional acoustic performance.

Another part of the acoustic validation was to compare the acoustic levels of reproducible sources as measured in an anechoic room with those for the same sources in the 9 × 15 foot test section. Figure 16 shows data for a directional noise source. The value of sound pressure level in dB is plotted against the boom angle in degrees. The continuous data were obtained from calibration tests performed in an anechoic room (ref. 14). The individual data points were obtained from tests performed in the 9 × 15 foot test section using an omnidirectional microphone. Data are shown for frequencies of 1000 and 8000 Hz. In general, the anechoic chamber and wind tunnel data agree within 1 or 2 dB.

The next phase of the directional acoustic validation used the source and model discussed earlier and shown in Fig. 6. One of the purposes of this test was to determine an acceptable rate of boom angular traverse. The inlet was mounted on the exhauster apparatus and is shown in Fig. 17. This particular inlet was the asymmetric inlet discussed earlier and shown in Fig. 11. It was chosen for its directional acoustic characteristics. It was felt that too high an angular sweep rate would distort the directional acoustic pattern and/or introduce additional scatter in the data due to a reduced averaging time. The microphone was mounted on the boom 6 feet from the axis of rotation. The center of the boom rotation was located below the center of the inlet face. The results obtained are shown in Fig. 18. This is an on-line plot of sound pressure level in the 1/3-octave band centered at 10,000 Hz versus boom angle in degrees. Data are shown for angular boom rates of $2\frac{1}{2}°$ and 10° per second and were obtained with a source frequency of 9600 Hz. The general shape of the two curves is approximately the same. The smaller scale fluctuations on the curves are believed to be caused by the temporal variations of the noise source. The symbols plotted on curves are the average sound pressure levels computed from a 30-second tape recorded with the boom fixed at discrete angular positions. These average values agree quite well with the visual average for the data obtained with the continual traverse. An angular traverse rate of $2\frac{1}{2}°$ per second appears to be an acceptable rate. At this rate, a one-way traverse from -120° to +120° about the inlet axis would thus take about 1.6 minutes. Data for source frequencies of 6300 and 8000 Hz show essentially the same trends as the data for 9600 Hz. Data for lower frequencies displayed several anomalies in the shape and are being studied further.

Concluding Remarks

The data shown for the 9 × 15 foot wind tunnel generally indicate that with the hard wall test section reverberant acoustic measurements can be made under static and forward velocity test conditions. The relative acoustic performance of a wide range of experimental configurations can be determined and this type of system has proved to be useful in a variety of investigations. With the test section lined with acoustic treatment, it is feasible to make directional acoustic measurements in the test section. A directional porous strip microphone mounted on an acoustically treated rotating microphone boom can be used to acquire directional acoustic data. Validation tests under static conditions have been completed and validation tests under forward velocity conditions are presently being performed.

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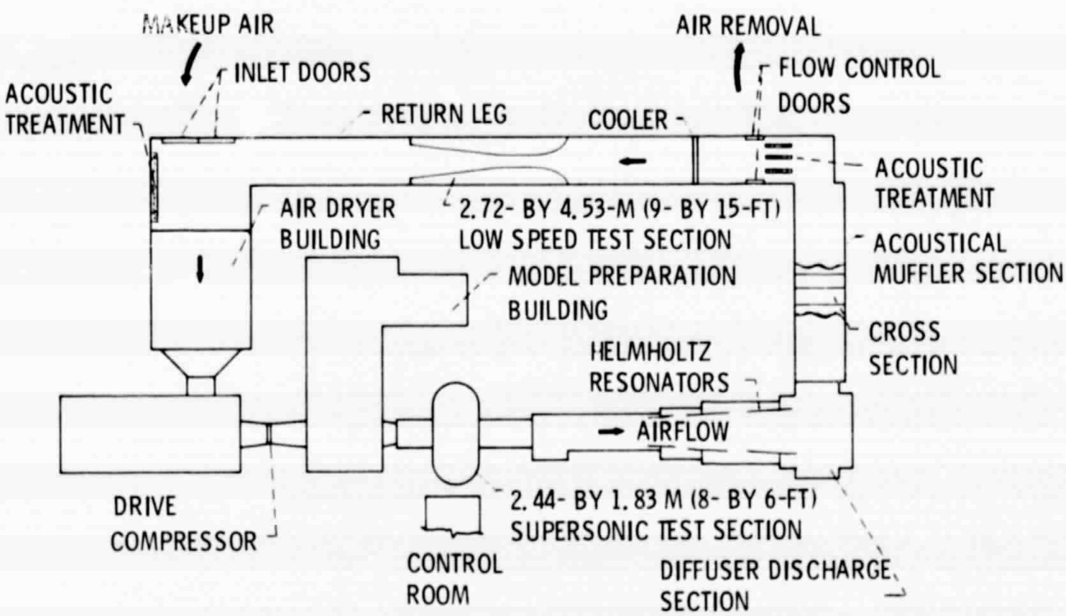
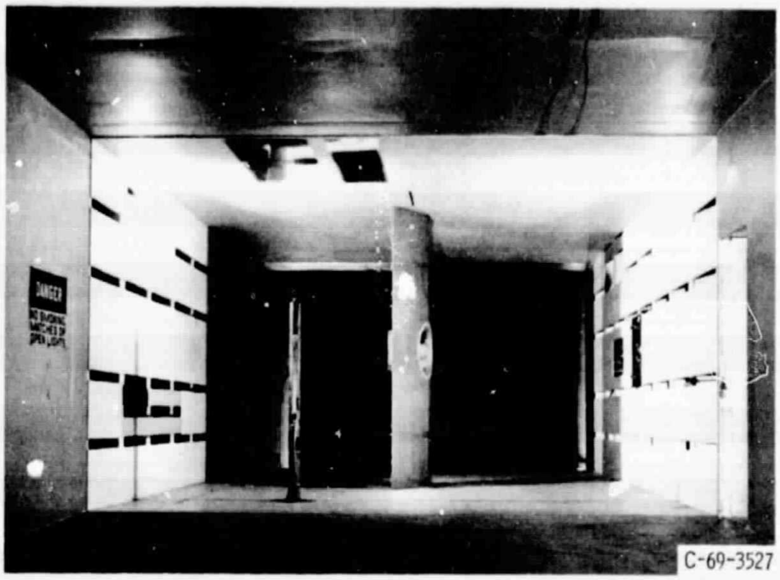
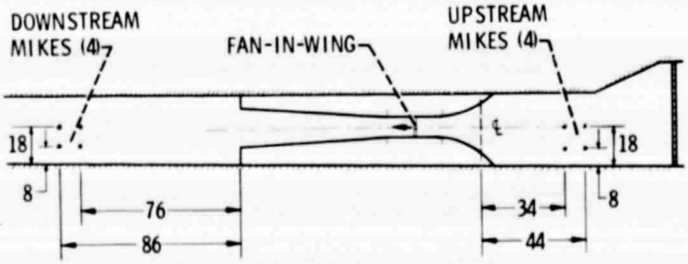


Figure 1. - Overall plan view of low speed wind tunnel test facility.



(a) INTERIOR VIEW OF 9x15 FOOT TEST SECTION SHOWING PLYWOOD WALLS.



(b) REVERBERANT MICROPHONE LOCATIONS.

Figure 2. - Reverberant acoustic measurement system features.

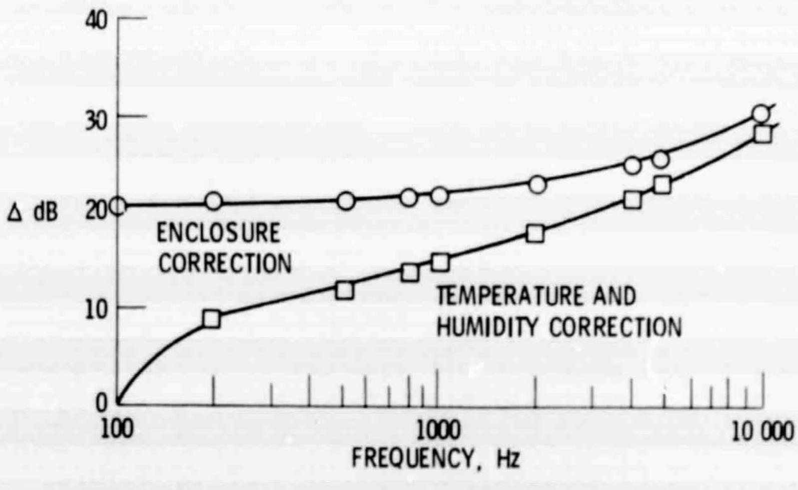
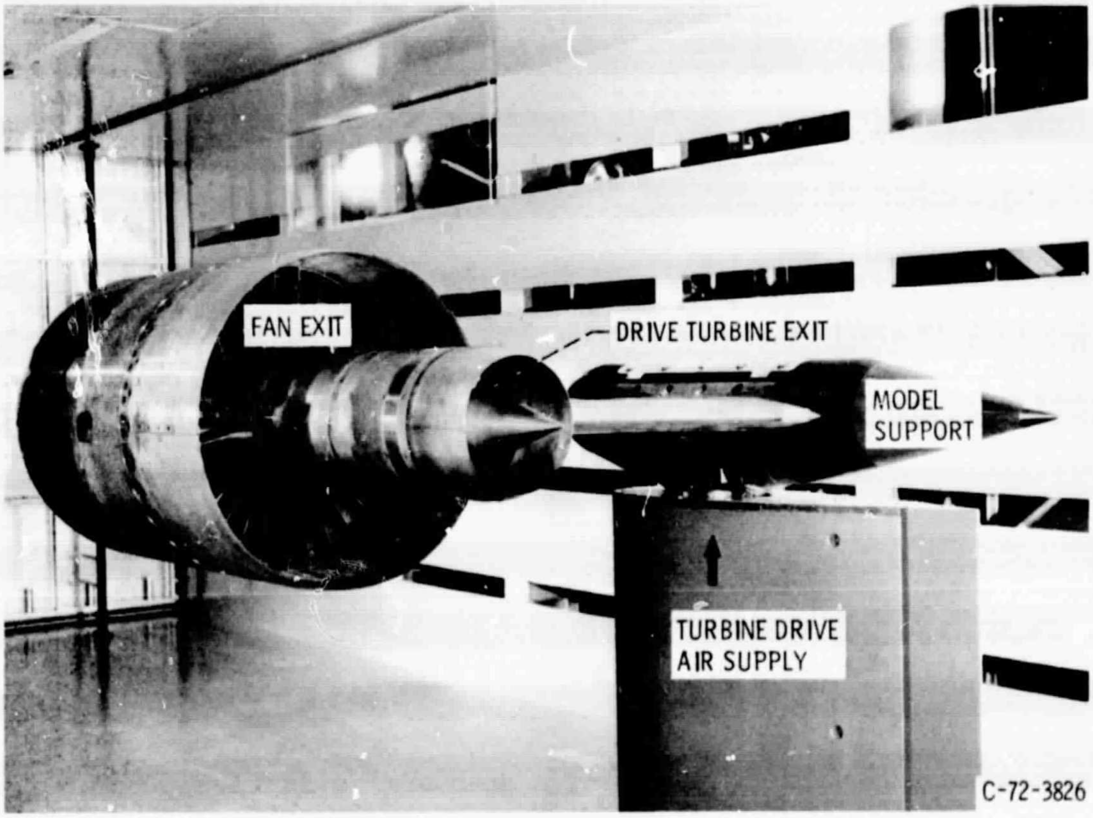


Figure 3. - Correction for reverberant acoustic data.



FORWARD-THRUST CONFIGURATION, REAR VIEW.

Figure 4. - 20 inch diameter fan model in 9 x 15 foot low speed wind tunnel.

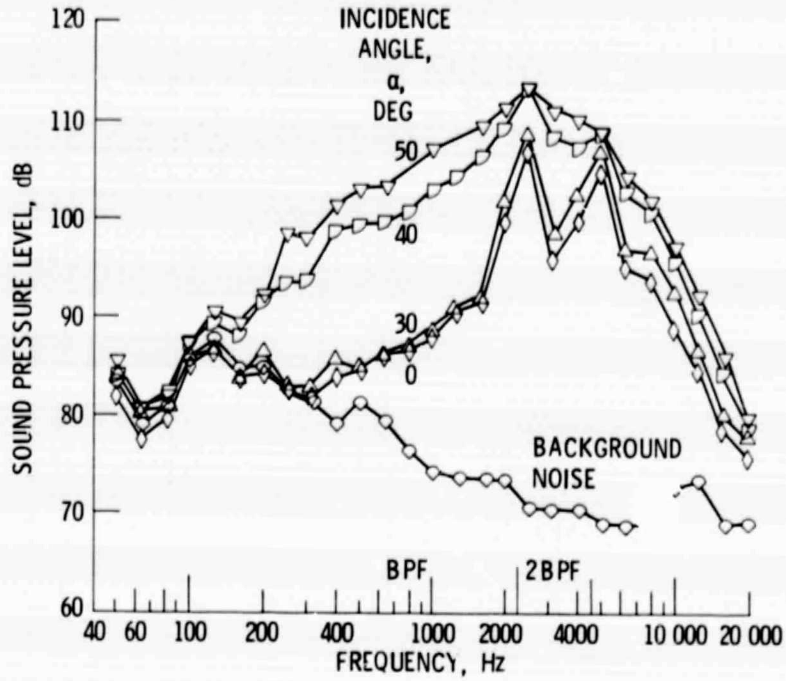
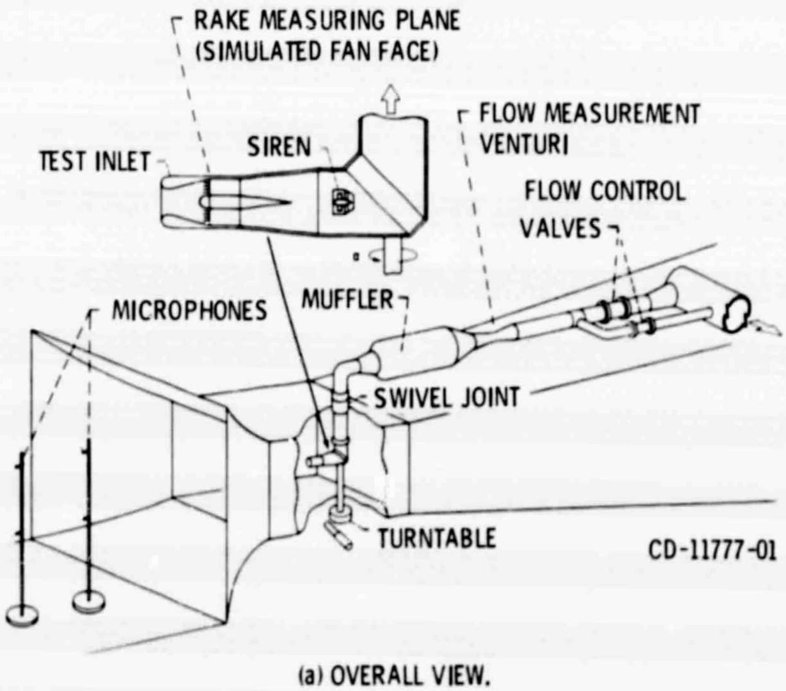
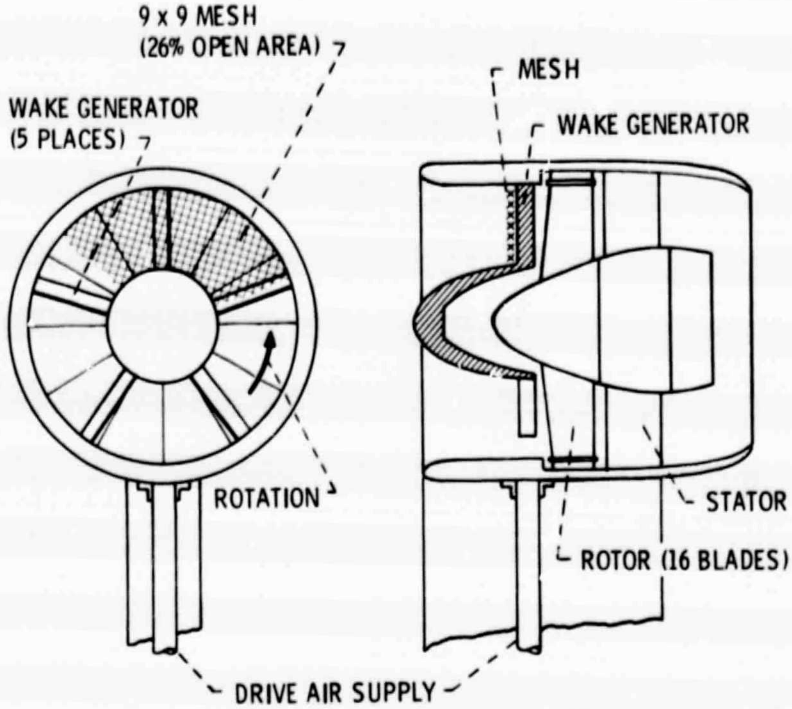


Figure 5. - Noise spectra for 20-inch diameter model fan. Cowl contraction ratio, 1.26; tunnel velocity, 143 ft/sec; N/N_{des} = 120 percent.



(a) OVERALL VIEW.

Figure 6. - 12-Inch diameter inlet acoustic research apparatus.



NOISE OUTPUT: 130 dB AT 1 FT, 5000 Hz (1/3 OCTAVE BAND) 18 000 RPM

(b) SIREN DETAILS.

Figure 6. - Concluded.

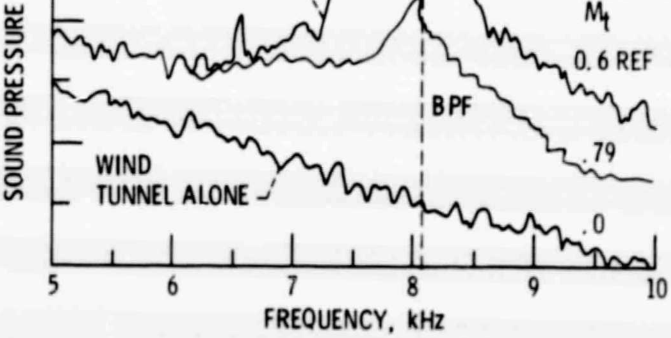


Figure 7. - Narrow band noise spectra showing fan noise and wind tunnel noise. Freestream velocity, 41 meters per second (80 knots).

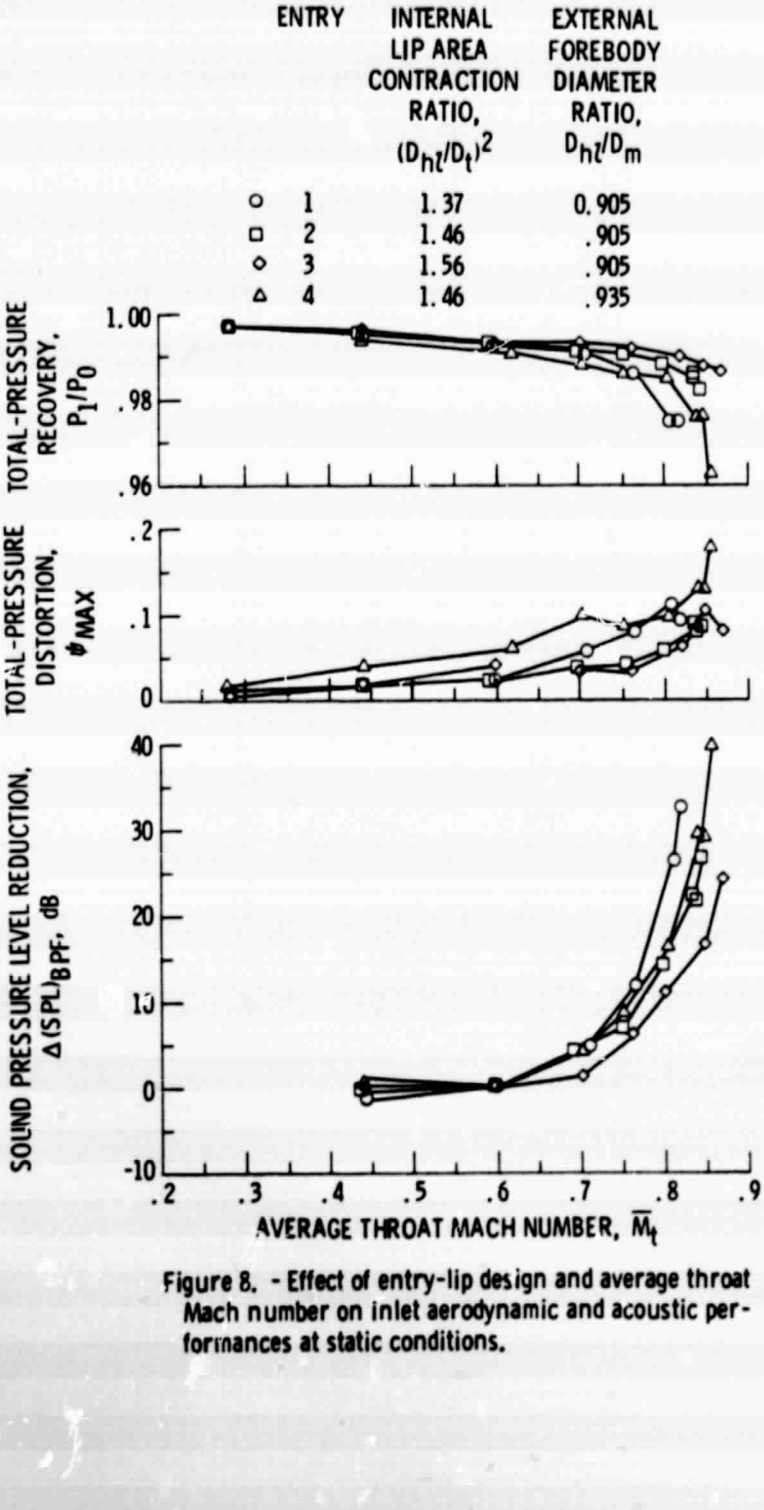


Figure 8. - Effect of entry-lip design and average throat Mach number on inlet aerodynamic and acoustic performances at static conditions.

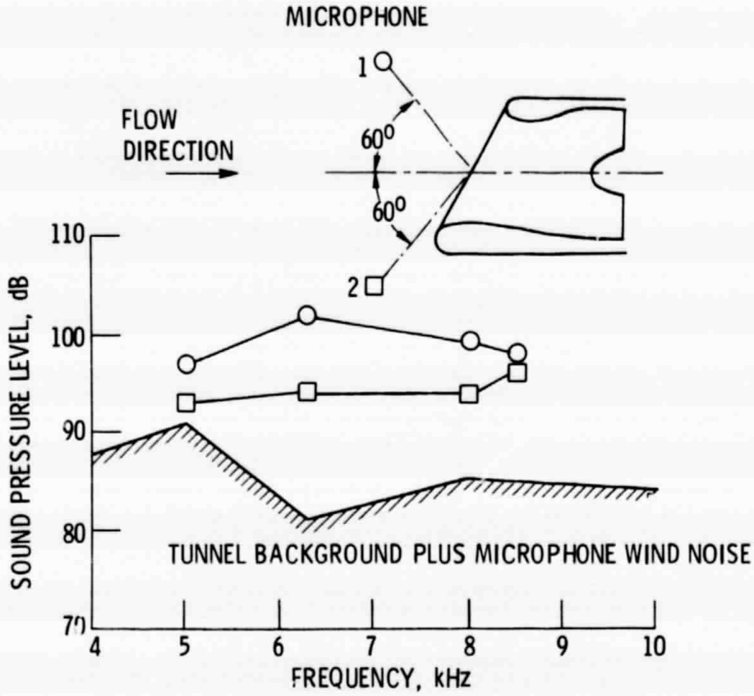


Figure 11. - Directional noise measurements made in the 9- by 15-foot wind tunnel with hard walls. Tunnel velocity, 80 kt.; incidence angle, 0^0.

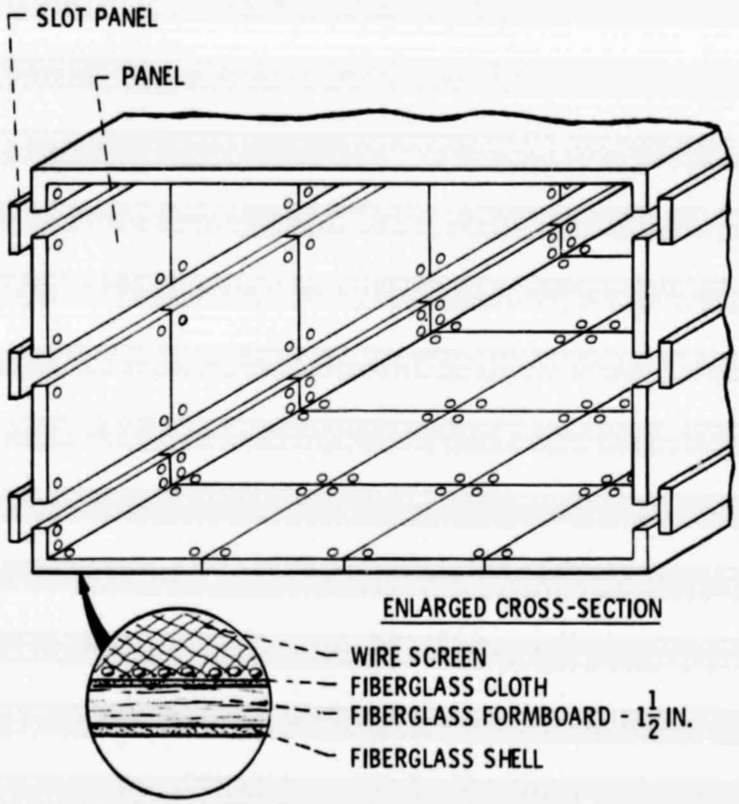


Figure 12. - Acoustic panel installation in the LeRC 9- by 15-foot wind tunnel.

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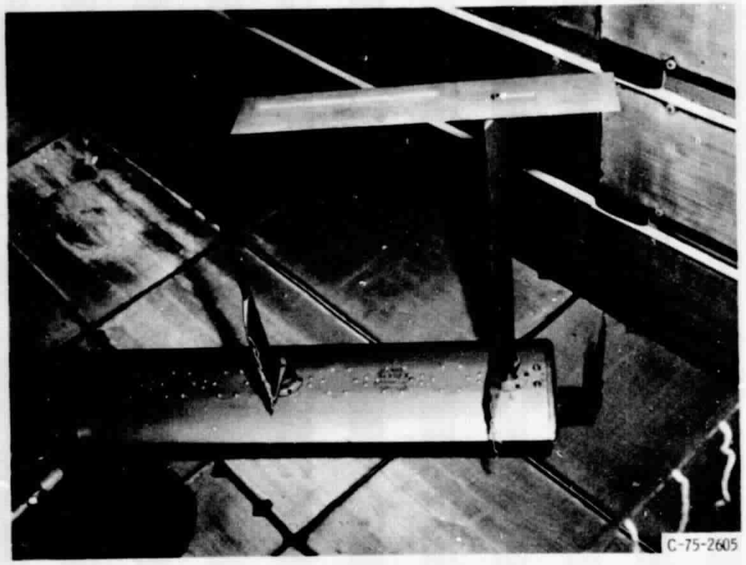


Figure 13. - View of microphones mounted on the rotating microphone boom. Lateral, weathervaning omnidirectional, and porous strip.

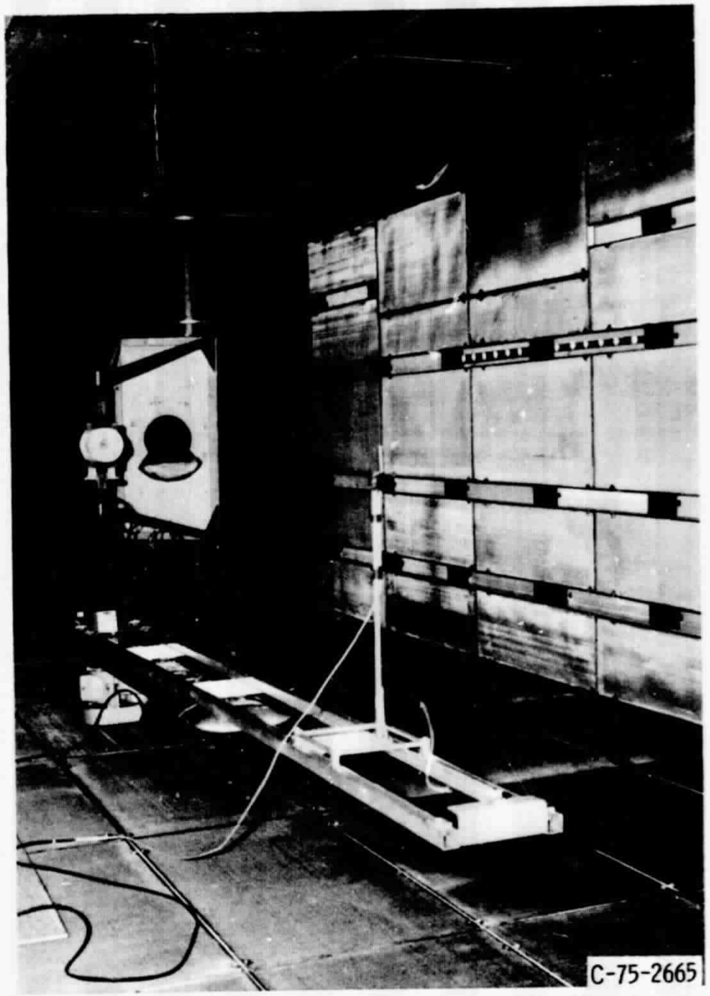


Figure 14. - Radial traversing apparatus, omnidirectional microphone, untreated boom. View looking downstream.

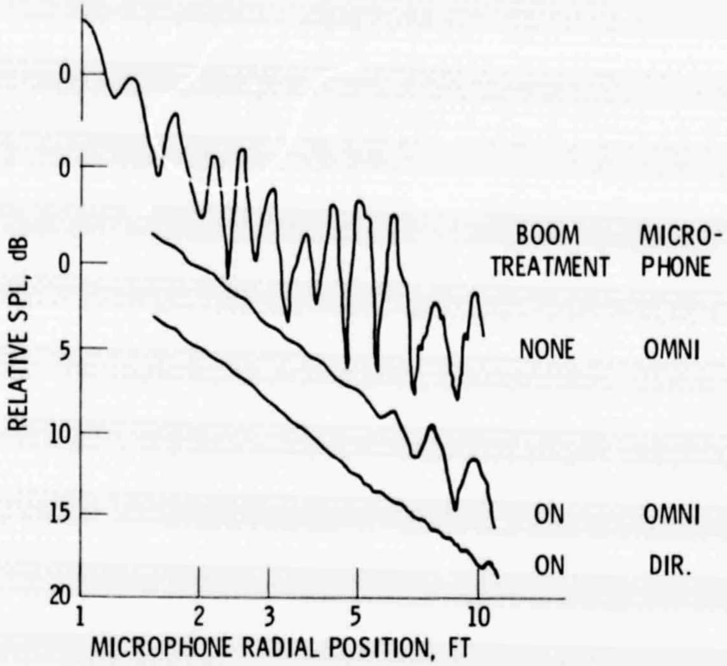
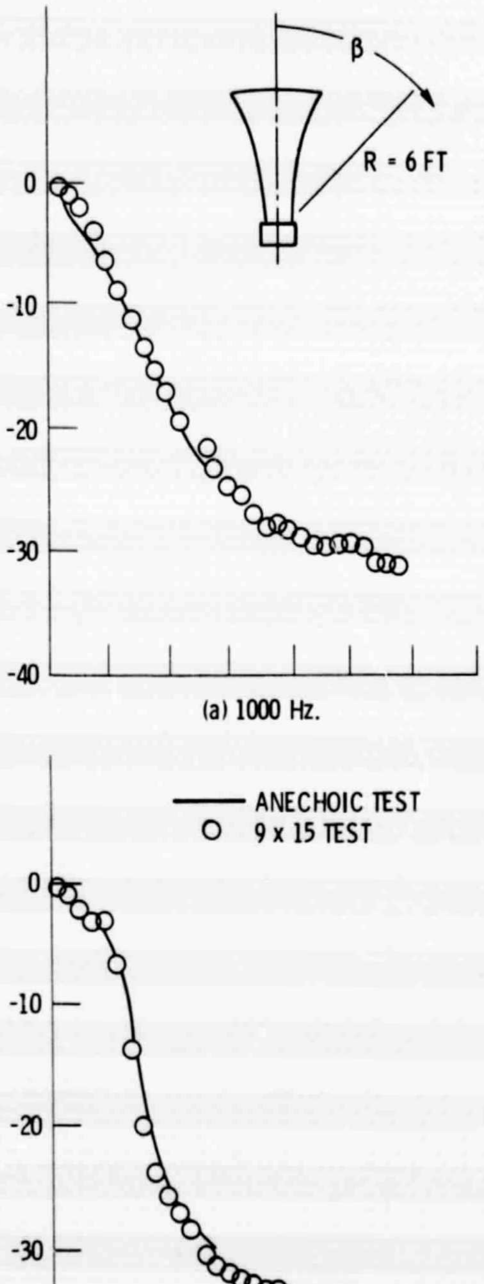


Figure 15. - Microphone boom reflectance test results noise source-speaker, type-oscillator, frequency-4000 Hz.



(b) 8000 Hz.

Figure 16. - Directional source characteristics. Tunnel off.

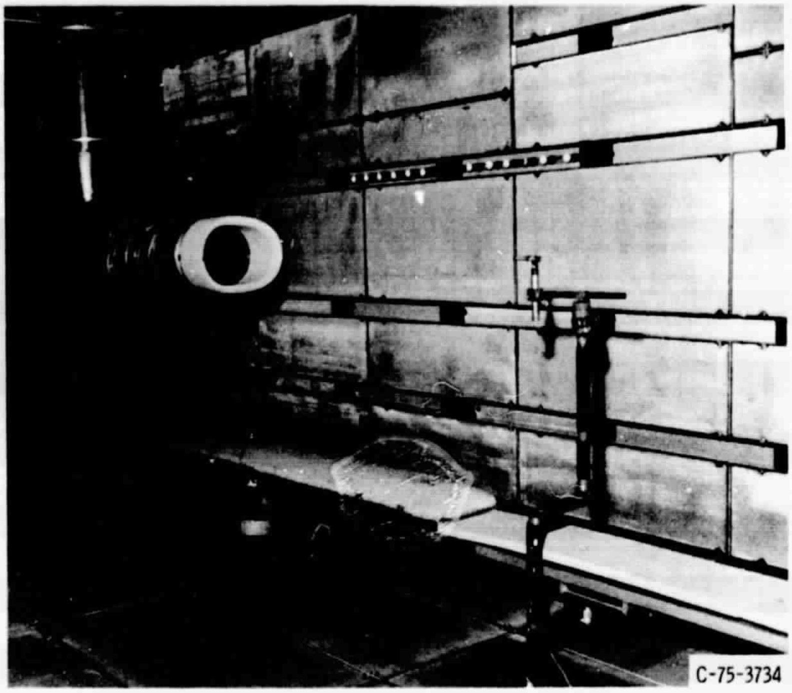


Figure 17. - Test inlet and acoustic instrumentation.

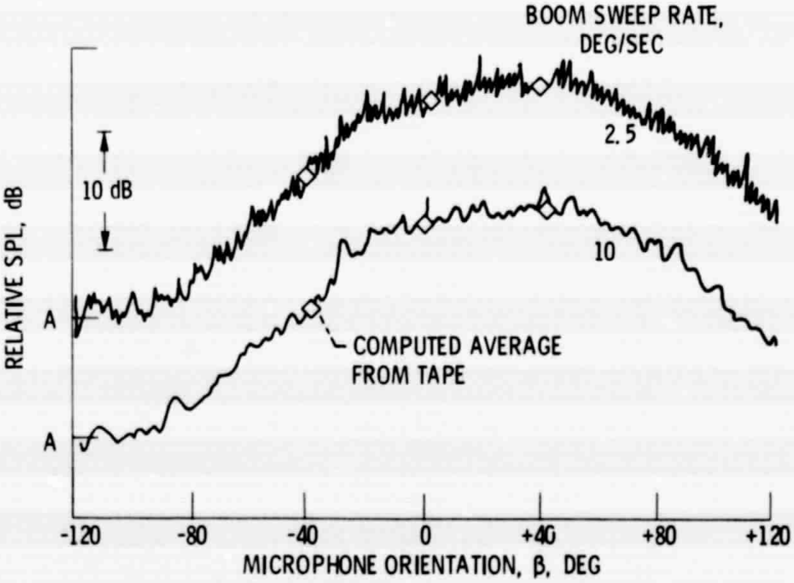


Figure 18. - Directional inlet characteristics. Source frequency, 9600 Hz. 1/3 octave filter, 10 000 Hz. Center frequency. Rake position, 6 feet. Tunnel off.