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FEASIBILITY OF MAKING SOUND POWER MEASUREMENTS IN THE NASA LANGLEY V/STOL TUNNEL TEST SECTION

by

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and Richard J. Silcox

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ABSTRACT

Based on exploratory acoustic measurements in Langley's V/STOL wind tunnel, recommendations are made on the methodology for making sound power measurements of aircraft components in the closed tunnel test section. During airflow, tunnel self-noise and microphone flow-induced noise place restrictions on the amplitude and spectrum of the sound source to be measured. Models of aircraft components with high sound level sources, such as thrust engines and powered lift systems, seem likely candidates for acoustic testing.

INTRODUCTION

Aeroacoustic data obtained from aircraft models in wind tunnels can be valuable because the effect of forward flight can be simulated and many noise associated aerodynamic parameters can be controlled and/or determined. In recent years, small open jet wind tunnels which are particularly suited for noise measurements have been constructed. For the larger tunnel test sections, which are required for more realistic model sizes and Reynolds numbers, the general trend has been to modify existing facilities rather than construct new large facilities. This approach has resulted from a compromise of cost and quality of data.

Most existing wind tunnels were not designed to be used for acoustical measurements. Because of this, there are two major problem areas that affect the quality of acoustic measurements in most existing tunnels: high background noise, which masks the model noise signal, and acoustic environment complexity, which affects the data interpretation.

Examples of unwanted sources of background noise are boundary layer turbulence, wall surface vibrations, open jet mixing (for open jet tunnels), tunnel drive fans, impingement on the flow collector, sting for support of model, and auxiliary tunnel equipment such as compressors and pumps. When acoustic measurements are made using microphones placed in the airstream, microphone wind noise (or flow-induced noise) adds to the background noise levels.

The quality of the acoustical field is also affected by the condition of wall surfaces. If the wall boundaries have widely differing sound absorption characteristics, the sound field can be very complex. The type of wall surface needed for a quality acoustic field depends on the type of measurement to be performed. If sound power measurements are required, then highly reflective wall boundaries are desirable. Highly sound absorbing wall surfaces are desirable when direct free-field measurements and model directionality are needed.

Reference 1 reports the progress made at the NASA Lewis 2.74 x 4.56 m V/STOL wind tunnel in making acoustic measurements. The Lewis tunnel employs acoustic mufflers, baffles, and wall treatment to reduce sound transmission and reflection.

Acoustic calibrations have been performed in other wind tunnels to determine the suitability of making noise measurements, e.g., see references 2, 3, 4, and 5. In addition to these calibrations, studies have been made to determine methods for improving tunnel acoustic characteristics, e.g., see references 6, 7, and 8.

Acoustic testing in the NASA Langley V/STOL wind tunnel is the subject of this report and three previous studies, references 4, 5, and 6. In this facility, aircraft takeoff, landing, and low-subsonic cruise speeds may be simulated. The test section is 6.6 m wide and 4.4 m high and the maximum speed capability is 103 m/sec. The test section can be operated in an open or closed configuration. In the open configuration, the ceiling and walls of the test section enclosure are lifted above the airstream. The airstream is then surrounded by stationary air in the chamber (large room) enclosing the test section and the model preparation area.

Reference 4 considers the acoustic signal-to-noise ratio of model-produced noise above tunnel and microphone flow-noise in the V/STOL tunnel. Data are presented which describe the tunnel background noise and airframe noise from an unpowered 1/25-scale model of the Boeing 747-200. Data were obtained for the tunnel test section in both its open and closed configurations. The results of the tests (ref. 4) were disappointing because the airframe noise produced by the 8-foot span model could not be detected adequately in this tunnel at model-to-microphone distances of 5 and 15 feet. Because of the background noise, the resolution was not adequate to allow a good description of the model airframe noise spectrum shape, or even the peak-level frequencies.

Reference 5 dealt mainly with the acoustic environment regarding sound power measurements in the open test chamber. This study identified various tunnel noise sources. It also determined that the acoustic field of the open test chamber was semi-reverberant and very complex. Because of this, sound power determination by acoustic measurements in the open chamber reverberant field was discouraged. In addition, determination of sound power by measuring the intensity of the direct sound was investigated. It was concluded that this method would be feasible if measurement microphones could be placed close enough to the model to avoid the open chamber reverberant field. This reference also considered sound power determination in the reverberant field of the closed test section.

In reference 6, methods to reduce unwanted reflections and reverberation in the open tunnel chamber were studied using a scale model of the V/STOL tunnel. Some success was found for reducing reflection, thereby allowing a somewhat larger distance between the noise source and microphone, by lining certain strategically located surfaces with sound absorbing material.

The purpose of this report is to evaluate the feasibility and propose a method for making sound power measurements of model aircraft noise sources in the V/STOL wind tunnel. This report presents acoustic data taken in and near the test section in the open and closed configuration for the flow and zero-flow cases. Tests were conducted with standard microphones and limited use of a porous surface microphone (ref. 9). Results for the porous surface microphone are presented in the appendix. Specific recommendations are given for the methodology of sound power determination to use for the closed test section configuration. The feasibility of acoustic testing is found to depend on the relative spectral shape and level of the source to be tested compared to that of the tunnel's and microphone's induced noise during flow.

APPARATUS AND METHODS

Acoustic tests were performed to determine the feasibility of making sound power measurements in the NASA Langley V/STOL wind tunnel. The tests utilized two separate noise sources. One source with broadband output was used to determine the uniformity of spatial distribution of sound pressure in the closed section in the absence of tunnel airflow. The other source was a turbine engine simulator producing noise with prominent pure tones. This source was tested with and without airflow in both the open and closed tunnel configurations.

Facility

A schematic of the NASA Langley Research Center V/STOL wind tunnel is presented in figure 1. It is a closed circuit tunnel whose closed loop is 234 m (770 ft) in length. The air is driven by an electrical powered fan which has nine blades and is 12.2 m (40 ft) in diameter. The fan can provide airspeeds up to 103 m/sec (338 ft/sec) in the test section with a fan speed of 275 rpm.

The tunnel test section can be used in either the open or closed configuration. The closed test section is 6.6 m wide (21.7 ft), 4.4 m (14.5 ft) high and about 21.3 (70 ft) long and is fully enclosed by hard walls. In the open configuration, the ceiling is raised to a height of 7.5 m(24.5 ft) above the test chamber floor. This is about 3.0 m (10 ft) above the flow stream. The side walls are extended above the raised ceiling. In the open configuration the airstream becomes a free jet on the three open sides and is surrounded by stationary air in the chamber enclosing the test section, see figure 1.

The test section is equipped with a boundary layer suction fan and a ground belt which is used to simulate takeoff and landing conditions. The fan was not operated and the belt was removed for the series of tests reported herein.

Noise Sources

One noise source was a standard centrifugal fan reference source described in references 10 and 11. This broadband source is approximately omnidirectional and is used often for sound power calibration, especially in many industrial noise measurements.

The second noise source consisted of two 14 cm (5.5 in) diameter tip-turbine fan engine simulators. These simulators were driven by compressed air actuated tip tubines which in turn drive the blades providing primary engine thrust. These simulators are commercially available and commonly used for powering wind tunnel models. These two simulators were mounted on an available wind tunnel model (1/12- scale Gulf Stream II with an 2.13 m (7 ft) wing span), a description of which may be found in reference 12. This source offered a high signal-to-noise ratio over a large frequency range, thus allowing a noise distribution comparison between the open chamber and closed test section. A photograph of this model can be seen in figure 2. The simulator thrust and rpm was independent of tunnel speed.

Instrumentation and Test Procedure

The acoustic data was reduced in real time and recorded on an X-Y plotter. For the data presented in this report, the real time analyzer was operated with a bandwidth of 120 Hz on a continuous frequency sweep. The dynamic range was 54 dB.

The microphones used for most of the test were standard 3.17 mm (1/8 inch) pressure microphones with noise cones (references 13, 14, and 15). Microphone positions 1, 2, 3, and 4 and their mountings are shown in figure 2 and the microphone locations are shown in figure 3. The microphones were mounted on stands which were bolted to the tunnel floor. For the closed test section, microphone positions 1, 2, 3, and 4 were used. In the open chamber, microphone positions 1, 2, 5, and 6 were used. Positions 5 and 6 were located outside the free jet shear layer.

In one series of runs, for the closed test section, a porous surface microphone system (ref. 9) was mounted at position 2. Results of these measurements are given in the appendix.

Tests with the broadband noise source were conducted at zero tunnel speed with the walls in the closed configuration only.

The tests with the simulators were conducted with various thrust settings and forward speeds. The thrust settings were at 0,266.9, 489.3, and 667.2 N (0, 60, 110, 150 lbs) which corresponds to blade passing frequencies of 0, 5430, 7350, and 8730 Hz. Tests were conducted at tunnel velocities of 0, 15.2, 23.4, 34.4, and 50.2 m/sec (0, 50, 77, 113, and 165 ft/sec). Both open and closed configurations were employed in this series of tests. A detailed listing of the test conditions is shown in Table I.

RESULTS AND DISCUSSION

Acoustic tests were performed to determine the feasibility of making sound power measurements in NASA Langley V/STOL wind tunnel. The test incorporated two separate noise sources. One source with broadband output was used to determine the uniformity of spatial distribution of sound pressure in the closed section in the absence of tunnel airflow. The other source was a turbine engine simulator producing noise with prominent tones. This source was tested with and without airflow in both the open and closed tunnel configurations. Of interest during the tests was the unwanted tunnel and microphone flow-noise generation as well as spatial distribution of sound from the source.

Broadband Noise Source Test

For the broadband noise spatial distribution test, the broadband noise source was placed beside the model about one meter forward of microphone location 3 (see fig. 2).

The results are plotted in figure 4 which shows the noise spectra recorded at the different microphone positions. Also shown in the figure is the spectrum of the reference source measured in a reverberation chamber. The reverberation chamber data was obtained using a bandwidth of 20 Hz, while the tunnel data presented in figure 4 and the remainder of the report was analyzed at bandwidths of 120 Hz.

The spectrum from microphone position 3 is presented in figure 4 as a point of interest. Microphone position 3 was in the direct and near acoustic fields of the source. The fact that the source is not truly omnidirectional is indicated by the relatively "lumpy" shape of the spectrum for this direct field measurement. It is also seen that the relative spectral levels between position 3 and the other positions indicates a rather intense reverberant field in the closed test section especially in the upstream direction (positions 1 and 2).

The fact that the levels are not generally the same for microphone positions 1, 2, and 4 indicates that the acoustic field is not diffuse. However, the spectral shapes measured at these positions do not deviate greatly from the spectral shape found in the reverberation chamber. These deviations, which are not excessively irregular, may be accounted for by proper calibration. This information indicates that sound power measurements may be made under no-flow conditions for the closed configuration.

Engine Simulator Noise Tests

The simulators were used as a source of noise with tonal content over a large frequency range. This source offered high signal-to-noise ratio thus allowing microphone signal comparison between the open and closed tunnel configuration.

Closed test section configuration. - For the four microphones in the closed test section, figures 5, 6, 7, and 8 show the background noise spectra as a function of tunnel flow velocity while engine thrust is zero. This background noise increases as tunnel speed increases. The background noise is a combination of tunnel flow noise and microphone wind noise. For comparison purposes, the figures also show the spectra of the engines for two test conditions where tunnel velocity is zero.

For microphone positions 1 and 2, upstream in the test section, the flow noise is about equal for the same tunnel velocities. For the downstream microphone positions 3 and 4, the flow-noise is increased above that of the upstream microphone positions. Microphone wind noise due to incident turbulence is responsible for the increased levels. It is expected that positioning of the downstream microphones to avoid the tunnel boundary layer and any wake from the aircraft model would result in significant reductions in this self-noise generation.

Figures 9 and 10 are for an engine thrust of 23.4 N and for a tunnel velocity of 0 and 50.2 m/sec, respectively.

Figure 9 shows good definition for the tonal content in the spectra throughout the 40 kHz frequency range. The apparent spectral "smearing" which results in a loss of detail in the higher frequency range for the downstream microphone position 4 is a characteristic of tones propagating through the turbulent engine exhaust. Exhaust turbulence not only produces noise but also causes Doppler shifts in the simulator turbine noise spectrum which spreads acoustic energy over a broader frequncy range.

The effect on the noise spectra due to a tunnel flow velocity of 50.2 m/sec may be seen by comparing figures 9 and 10. For frequencies below about two kHz for the spectra shown, flow-induced noise masks out the source signal. For frequencies above a few kHz, signal quality is maintained as evidenced by the relative high noise intensity of the source compared to the flow noise in the closed test section as was expected from the results shown in figures 5, 6, 7, and 8.

Open test chamber configuration. - Two microphones were placed at positions 5 and 6 (see figure 3), outside the free jet region, in the preparation area of the test chamber. Microphone positions 1 and 2 were maintained. The spectra for these four microphone locations for two different tunnel speeds are shown in figures 11 and 12.

Comparing figure 11 to figure 9, for the no-flow case, it is seen that one effect of raising the walls to create the open test chamber configuration is to reduce the noise spectral level at positions 1 and 2 on the order of 10 dB. Also, large spectral differences are noticed between the four microphone positions, indicating a very non-diffuse acoustic field.

Figure 12 shows the effect of a tunnel flow velocity of 50.2 m/sec on the noise spectrum for the open configuration. It is seen that the effect of flow is to diminish the quality of the acoustic signal at the microphones, as evidenced by substantial spectral "smearing" in figure 12 compared to figure 11. This effect is found more severe for the open than for the closed configuration (figures 9 and 10).

The out-of-flow microphones, positions 5 and 6, experienced lower background noise than the in-flow microphones, postions 1 and 2. This is because microphone wind noise was eliminated and only the tunnel flow-induced noise was perceived by the out-of-flow microphones. It is interesting to note that the in-flow microphones, positions 1 and 2, experienced increased background noise compared to the same microphones in the closed configuration for the same tunnel speed.

FEASIBILITY AND METHODS OF ACOUSTIC POWER MEASUREMENTS

Various methodologies of sound power determination are reviewed in reference 11. For use in the V/STOL tunnel, the method chosen should be of predictable accuracy and be versatile enough to accommodate various test conditions and model configurations. Tunnel flow background noise, which reduces the signal-to-noise ratio, and the tunnel's acoustic field environment place restrictions on the choice of methods. Both factors, background noise and the acoustic field, are found to be dependent on tunnel configuration.

Test results indicate that the closed wall configuration is highly reverberant. In this configuration, good acoustic signal resolution (or signal-to-noise ratio) is found for the microphones in the tunnel airflow in frequency ranges where the flow-induced noise does not "mask" the source noise.

For the open configuration, lower flow-induced background noise is found for the microphones placed out of the flow. Microphones remaining in the flow experience an increase in background noise compared to when the wall configuration is closed. For all microphones in the open wall configuration tests (none placed in the shear layer between the flow stream and stationary air), the amplitude and resolution of the source noise during airflow is diminished compared to when the wall configuration is closed.

Open Tunnel Configuration

The tests, performed in the open tunnel configuration, used microphone positions in the semi-reverberant field of the test chamber. The diminished signal-to-noise ratio, compared to the closed configuration, serves to reduce the value of the open configuration for making acoustic measurements.

In the study of reference 5, no attempt was made to measure a noise source during tunnel flow, so no mention was made of a signal resolution problem. Still reference 5 did not recommend acoustic measurements in the open configuration unless measurements were made in the direct field of the source, to avoid the semi-reverberant field. Reference 6 determined that the radius of the direct field (or free field) could be extended somewhat by the application of sound absorbing materials to the floor and raised ceiling of the open tunnel.

Direct field measurements to determine sound power as suggested in reference 5 is a method to avoid the problems of acoustic data interpretation associated with the complex semi-reverberant field. Successful implementation of this method would also allow evaluation of sound source directionality. However, requirements for the success of this method are restrictive. Measurements must be made on a radius about the source which is in the direct field (or free field) and also the far field of the noise source for the frequency range considered. This requirement is considered to be met when the measurement radius is within a region where doubling the measurement distance from the source would result in a six decibel drop in sound pressure level for all directions from the actual source to be tested (e.g., see reference 11). For example, the above requirements were met in tests where directionality measurements were made on small sources in the NASA Lewis V/STOL wind tunnel (see ref. 1).

However, meeting the requirements of the direct measurement method may be difficult, if not impossible, for larger source configurations. Far field conditions exist roughly at 2 or 3 times the largest linear dimension of a noise source. For many aircraft model configurations, mounted with a noise-producing engine, the length or span of the model must be considered the applicable source dimension and not a dimension of the engine. This would be true where substantial aircraft wing or body shielding, diffracting or reflection, effects are present. In such cases, it is likely there would be no measurement radius at which the direct field method would be accurate.

An additional restriction concerning the signal-to-noise ratio problem is that microphones should not be placed near or in the shear layer between the flow stream and the stationary air. Because of the excessive turbulence in this region, microphone wind noise would likely be unacceptably intense.

To improve the quality of direct measurements, a directional microphone system could be useful in some applications. See Appendix.

Closed Tunnel Configuration

Results obtained in this study suggest that good sound power measurements of certain noise sources can be made in the V/STOL tunnel facility in the closed configuration. Aircraft components with high sound level sources, such as thrust engines and powered lift systems, seem likely candidates for acoustic testing.

The use of measurement positions in the closed configuration upstream and downstream of a source takes advantage of the relatively good signal to noise ratio and uniformity of the sound field compared to that of the open configuration.

Recommended sound power measurement procedures. - In reference 1, where reverberant field measurements were conducted in the NASA Lewis Research Center V/STOL facility, it was assumed that the sound field in the tunnel could be treated as an essentially diffuse field. Factors which were used to connect sound pressure measurements to sound power were computed from reverberation time measurements and general tunnel geometric properties.

Rather than the method used in reference 1 the following alternate approach, which is based on the comparison method, is recommended. The closed circuit tunnel is recognized as a large rectangular duct with variable cross-section and complex absorption and reflection.

Choose two tunnel cross-sections, one upstream and one downstream from the location of the sound source. Sound power produced by the source can be determined from the sound pressure measurements over the cross-sectional areas represented by A_u for the upstream position and by A_d for the downstream position. The total sound power generated is:

$$W = W_u + W_d + LF_u \, W_u + LF_d \, W_d$$

or

$$W = [1 + LF_u] \quad W_u + [1 + LF_d] \quad W_d \tag{1}$$

where for i=u (upstream) or d (downstream)

$$W_i = \int \frac{P^2}{\rho c} \, dA = \frac{\overline{P^2_{mi}}}{\rho c} A_i \tag{2}$$

$\overline{P^2}_{mi}$ = average mean-square sound pressure over area A_i and frequency bandwidth of interest,

ρc = characteristic impedance of air (value subject to temperature and humidity conditions),

LF_i = loss factors for measurement area A_i, which is a function of frequency.

The loss factors as defined here should account for deviation from the ideal case where all power passes through the cross-sections without reflection. Effects that may cause deviation from the ideal include: presence of non-propagating standing wave patterns in the tunnel sections, which may be affected by the source directionality; absorption of sound through the tunnel walls; and any feedback sound from the turning vanes, etc.

For an omnidirectional source in a large duct without flow the following relation is valid:

$$[1 + LF_u]\, W_u \simeq [1 + LF_d]\, W_d \tag{3}$$

i.e., equal power is radiated from source towards A_u and A_d.

The loss factors are found by experiment using an ominidirectional and a directional reference source. Any change in the value ρc for the tunnel air may be accounted for by using equation (2). After calibrating the reference sources for sound power as a function of frequency in a standard reverberation room, the reference sources should be tested in the test section at various model noise source locations. For the reference sources, determination of W_u and W_d, knowledge of W from reverberation room tests, and use of equation (3) would allow the calculation of the loss factors as a function of frequency and bandwidth.

Both a directional and an omnidirectional reference source should be tested so that any variation of the experimentally determined values of the loss factors will provide an indication of the expected measurement accuracy when sources of unknown directionalities are tested. This is especially important since mean tunnel flow can affect the source directionality.

The calibration would be conducted for the tunnel without flow. For tests involving non-zero tunnel flow, the results and subsequent application of equations 1 and 2 should contain correction factors. This is because the relationship between acoustic energy flux and acoustic pressure at the measurement locations is affected by the presence of mean flow. The corrections are derivable with the use of conservation of acoustic energy principles, e.g., see reference 16.

However, for many test conditions the corrections would be minimal. It can be shown, for a noise source that is not highly directional, that with a tunnel flow Mach number, M, equation (1) would underestimate W on the order of $[1 + M^2]$, e.g., this is an error of 0.2 dB for $M = 0.2$. Individually by using equation (2), for any source, where M is measured at the respective areas A_u and A_d: W_u would be overestimated on the order of $[1/(1 - 2M + M^2)]$, or 2 dB for $M = 0.2$; W_d would be underestimated on the order of $(1 + 2M + M^2)$, or 1.6 dB for $M = 0.2$.

Sound absorption in the wall boundary layers is not taken into account in the recommended calibration procedures. It is assumed that this effect is small except for higher frequencies. The main consequence of the boundary layer presence is believed to be a spreading (or smearing) of the acoustic energy over the noise spectrum. Referring to figure 10 for the particular microphone locations chosen for this study, it is seen that the downstream microphone position is more affected by spectral smearing than the upstream microphones.

The microphones recommended are the standard condenser type with nose cone. Their omnidirectional characteristic (improved by the nose cones) make them valuable for reverberant measurements. The diameter of the microphones used should be determined by the frequency range requirements. The smaller diameters give greater frequency amplitude linearity while larger diameters give less wind noise, e.g., see reference 14 and 15.

The flow induced noise from the microphone mounting system can be reduced by streamlining the microphone mount and careful selection of microphone positions to avoid model turbulent wake region and tunnel boundary layer.

The measurement areas, i.e., A_u and A_d ,and the microphone positions within the areas should be chosen to maximize source resolution and to minimize background flow noise. Microphones may be placed between, but not close to the upstream diffusing screen and downstream turning vane (see fig. 1). Also, positions close to the source should be avoided to minimize any effect of source directionality.

In practice it is recommended that up to six microphones be positioned along each of the forward and aft cross-sections chosen for measurement. The larger the number of microphones, the smaller the error would be in the determination of the average-mean-square sound pressure over the respective cross-sectional areas. Also, it should be noted that a large number of microphones would allow tests to continue even with an unacceptable signal from one or two of the microphones.

A primary advantage of this method is that the various effects of absorption, reflection etc., are lumped together in one factor which is determined by experiment in the tunnel calibration study. The calibration need not be repeated as long as the tunnel is not altered and the position of the microphones remain unchanged. This fact would permit a rapid and systematic acquisition and analysis of acoustic data. The acoustic data could be stored on tape and the data could be analyzed by a computer program incorporating the calibration information and a signal analysis subroutine.

CONCLUDING REMARKS

A feasibility study of making sound power measurements in the NASA V/STOL tunnel has been conducted for the tunnel in both its open and closed (wall) configurations. Such measurements are found to be feasible for the closed tunnel case for sources with high noise levels. The closed configuration has been found superior to that of the open in regards to the relative levels of source signal compared to tunnel and microphone background noise. Also the acoustic field for the closed configuration is determined to be highly reverberant and fairly diffuse whereas that of the open is less reverberant and more complex.

For the open tunnel configuration, acoustic measurements in the direct and free field of small sources should be possible.

The recommended method of sound power measurement for the closed configuration uses standard microphones, with nose cones, upstream and downstream of the source at cross-sections in the reverberant field. With proper calibration the above method should be of predictable accuracy and accommodate various test conditions and model sizes.

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APPENDIX

POROUS SURFACE MICROPHONE

The porous surface microphone system (reference 9) or some other directional microphone could be used to advantage in some applications. Proper use would tend to improve the direct measurements by essentially extending the effective direct acoustic field of the source for higher frequencies.

The porous surface microphone system which incorporates a standard 1.27 cm microphone was tested so that its response in a reverberant field could be compared to the standard microphone. Using the engine simulators operating at 489.3 N thrust as the noise source, microphone position 2 (see fig. 3) was used alternately as the measurement location for both the standard and porous surface microphone. Both microphones were pointed in the upstream direction. The microphone at position 1 was used as a reference to verify that the conditions of the test were the same. Figure 13 shows the spectral comparison for the closed tunnel configuration and no flow.

For the frequency range shown in figure 13 the standard 3.17 mm (1/8 in) pressure microphone with nose cone is known to have a flat frequency response, see references 14 and 15. Thus the spectrum shown for the standard microphone is considered to be the true sound pressure level spectrum for the sound at position 2. The spectrum rendered from the porous surface microphone deviates from the true spectrum because the microphone is a directional system (details of which are given in reference 9). They are different because the acoustic pressure at a measurement point is comprised of a combination of radial and oblique wave fronts. The porous surface microphone was oriented such that it discriminated against the oblique components.

See reference 1 for an example of an exploratory application of the porous surface microphone.

Tunnel Speed	No Noise Source		Reference Source On		Engine Simulators Running (Total Thrust) 267N Thrust		489N Thrust		667N Thrust	
	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Open	Closed
0		x*+		x*		x*	x*	x*+*		x*
15.4 m/s		x*				x		x +		
23.6 m/s		x*				x				
34.5 m/s		x*				x				
50.5 m/s	x	x*				x	x*	x*		x

+ indicates this configuration was run with porous surface microphone system

* indicates data presented in this report

Table 1. - Test conditions considered in this investigation

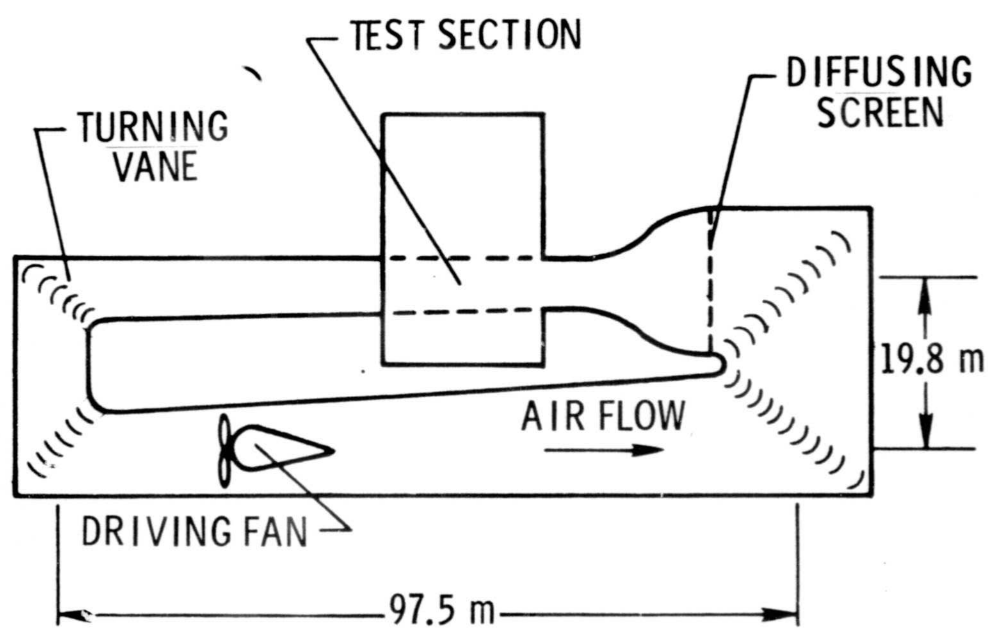

Figure 1.- Schematic of NASA Langley Research Center V/STOL wind-tunnel facility. Dashed lines in test section indicate walls of closed configuration. Solid line indicates walls of open configuration.

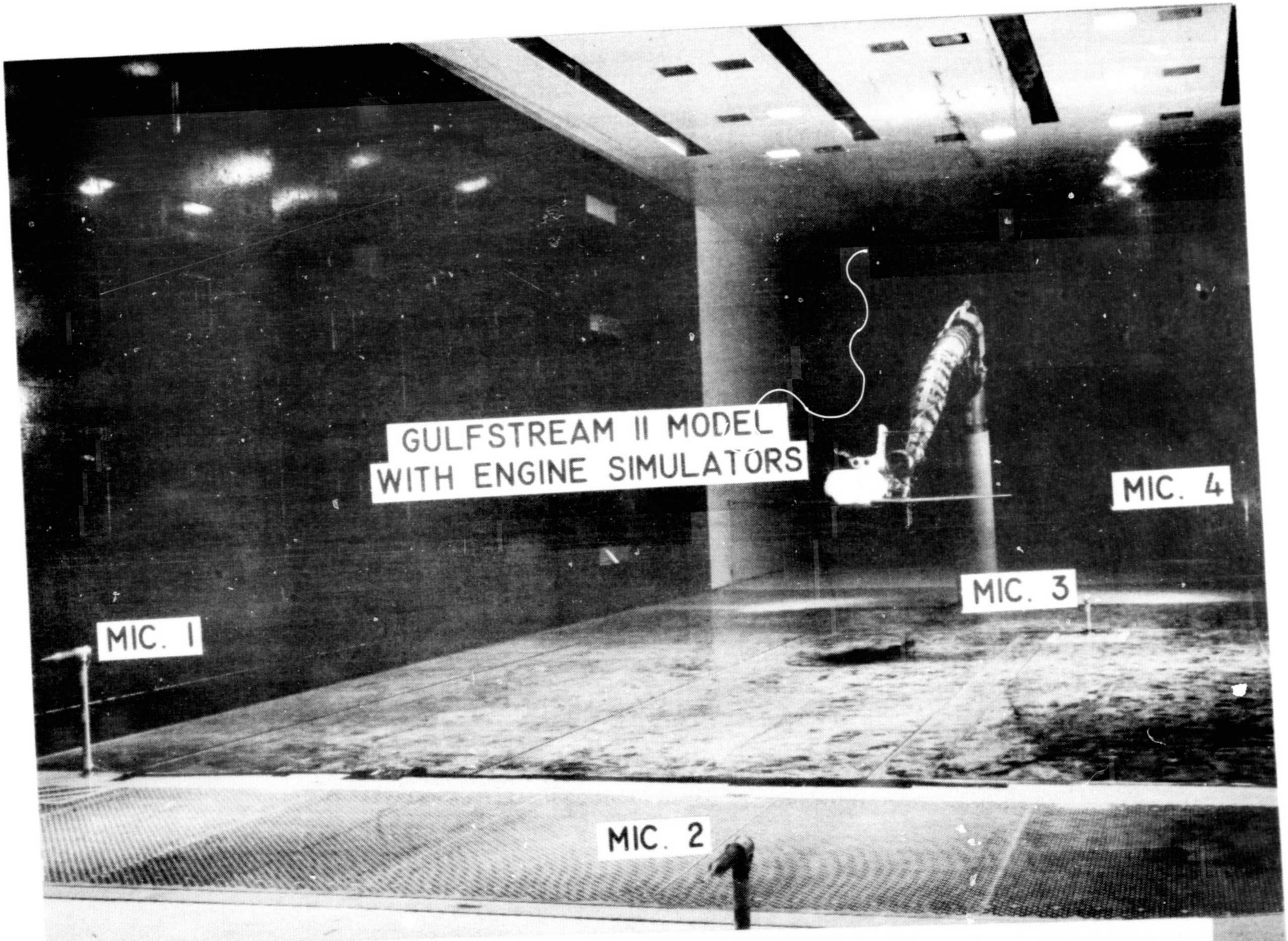

Figure 2.- Photograph of Langley Research Center V/STOL tunnel test section in closed configuration showing microphone and model locations.

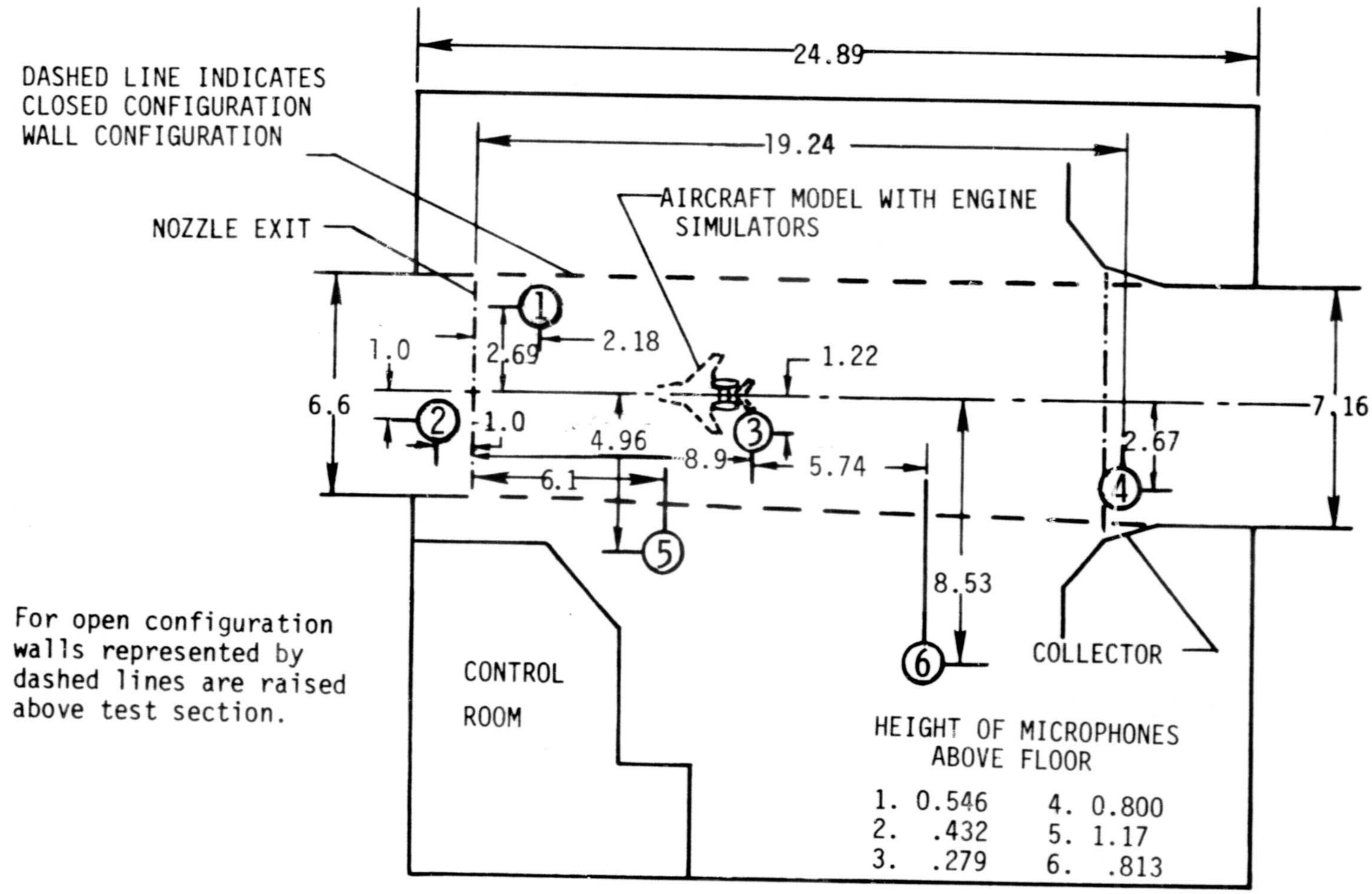

Figure 3.- Plan view of the Langley Research Center V/STOL Tunnel Test Section showing microphone and model location. Circled numbers refer to microphone locations. All dimensions are in meters.

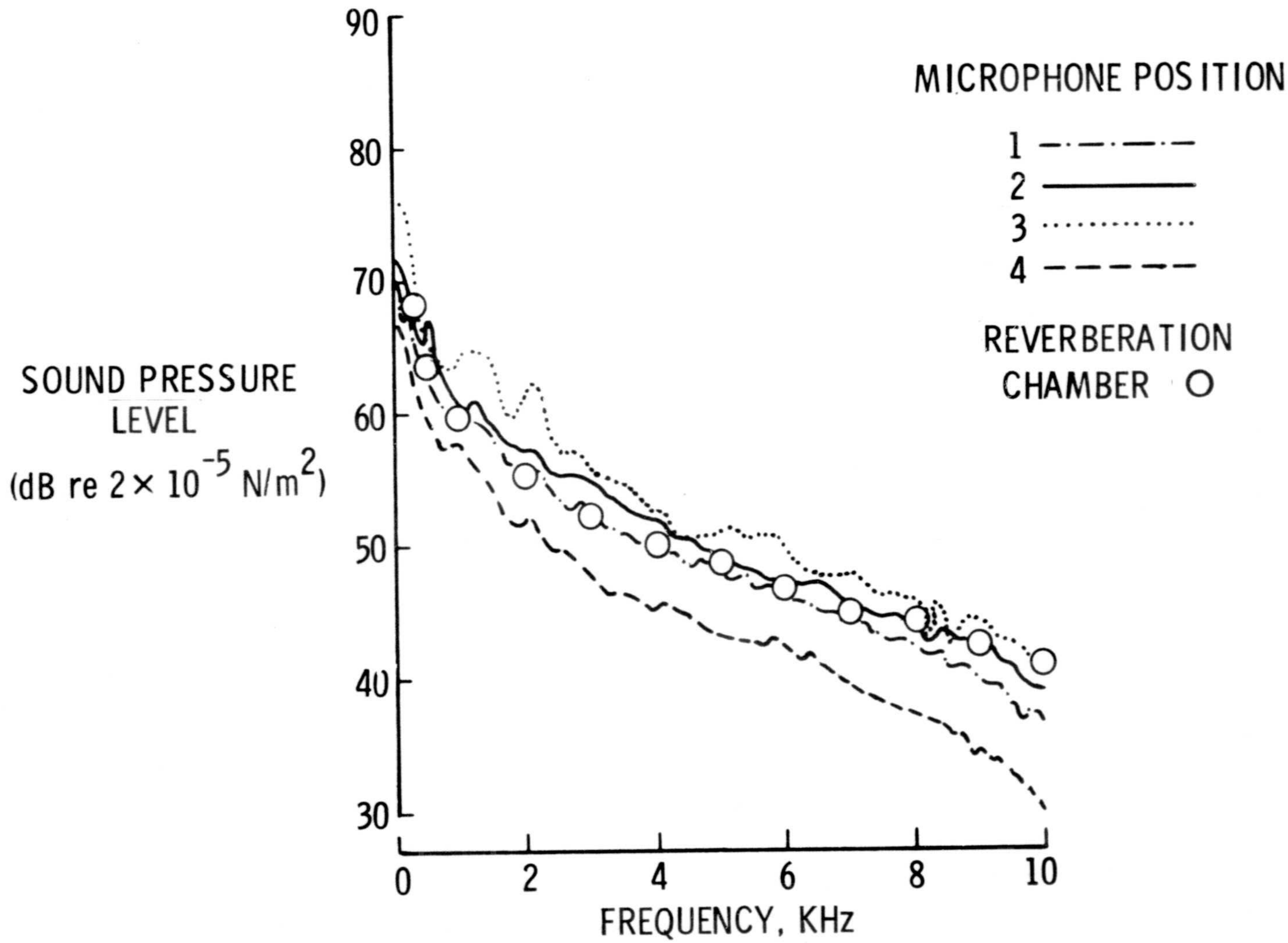

Figure 4.- Sound pressure level spectra generated by reference source in V/STOL tunnel facility (closed configuration)

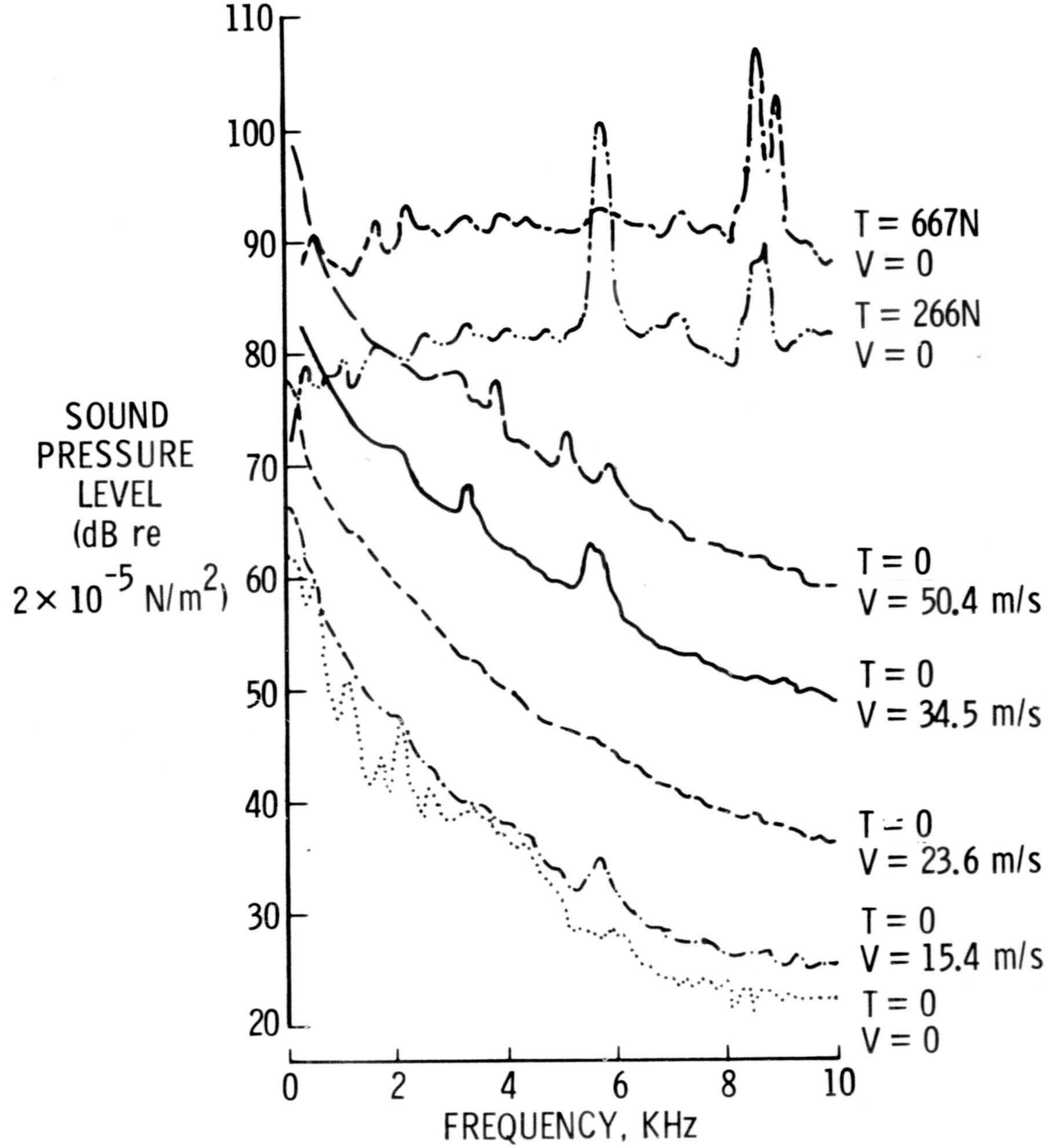

Figure 5.- Sound pressure level spectra at microphone position 1 for the test condition shown. (Closed configuration)

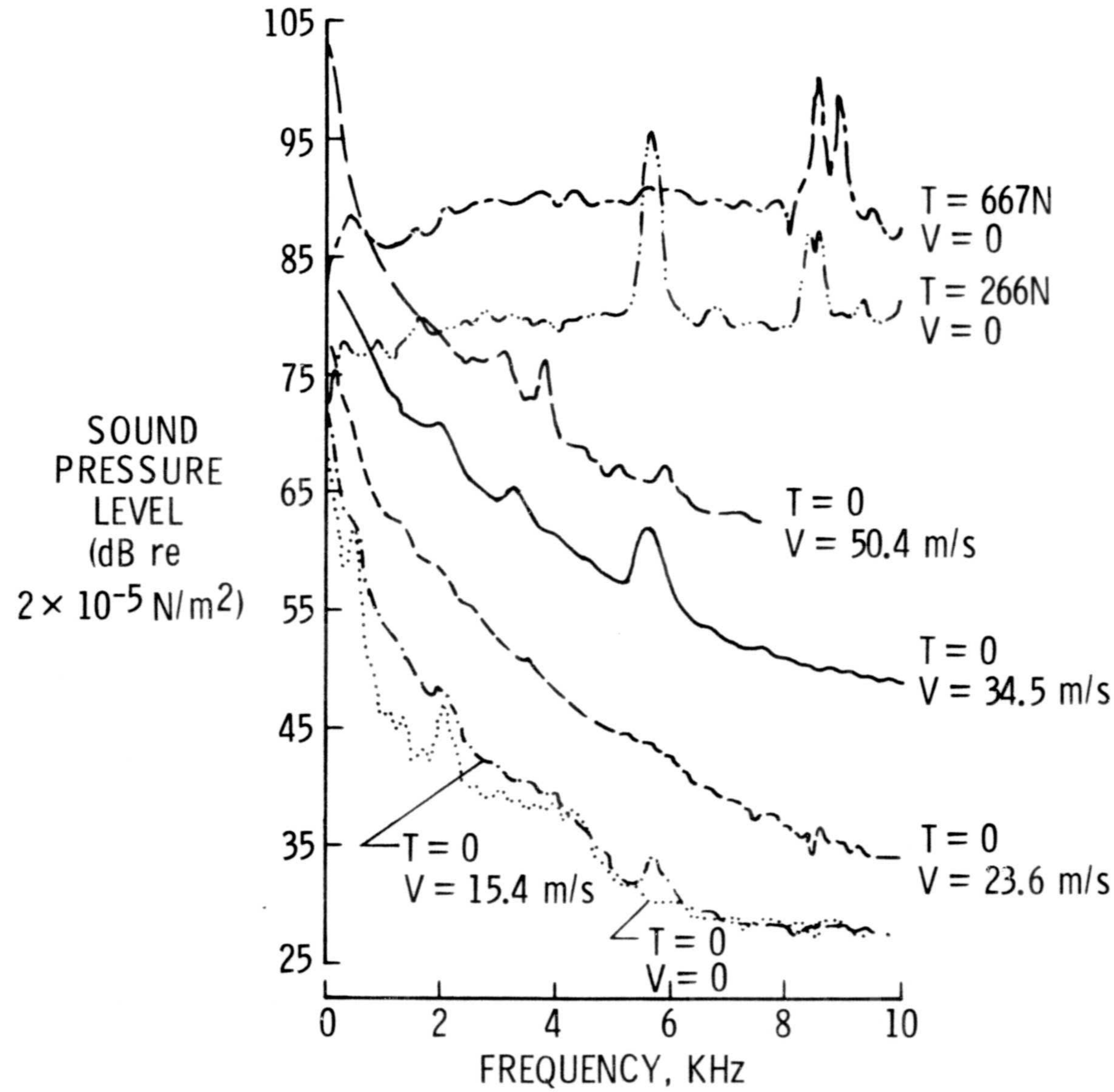

Figure 6.- Sound pressure level spectra at microphone position 2 for the test conditions shown. (Closed configuration)

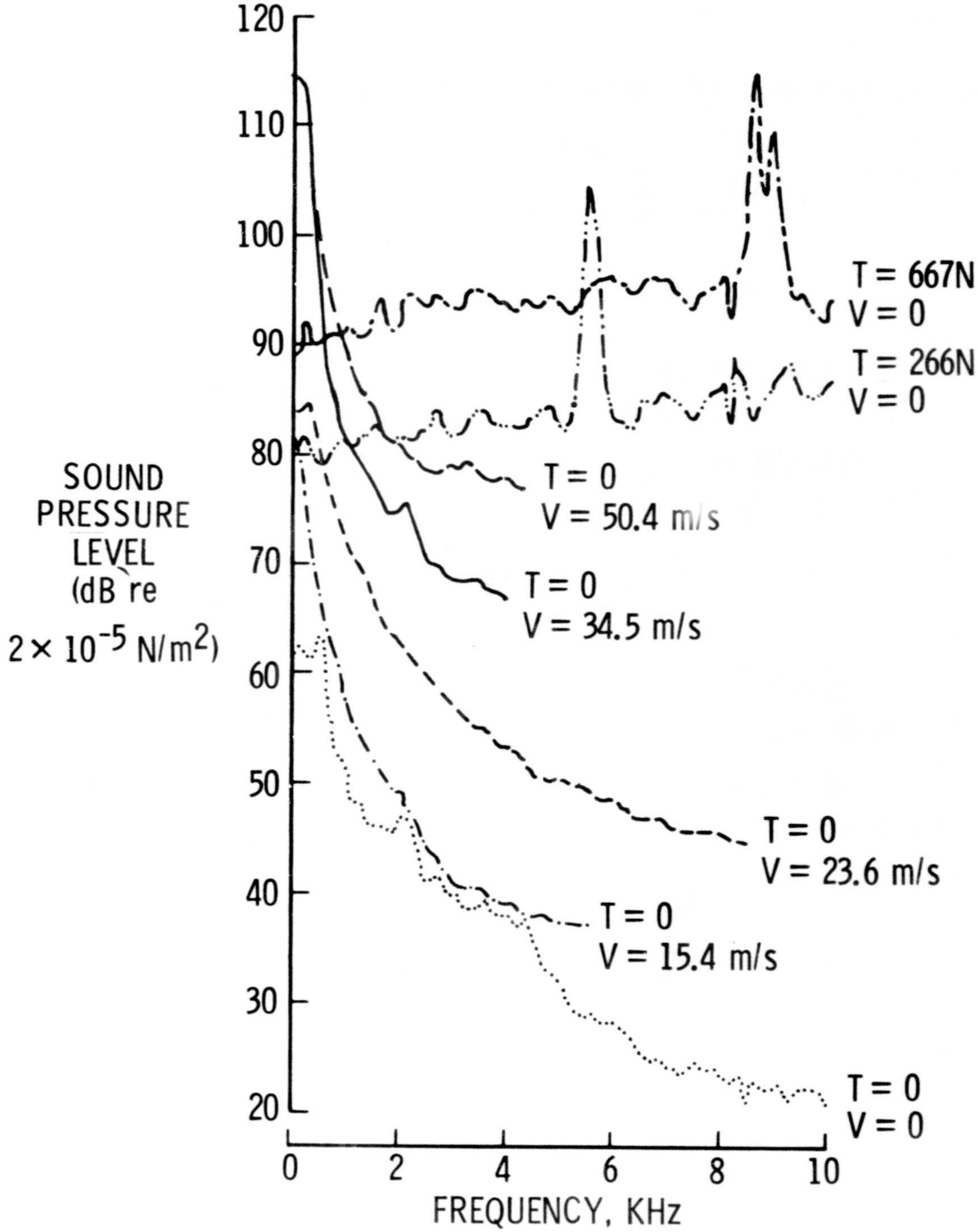

Figure 7.- Sound pressure level spectra at microphone position 3 for the test conditions shown. (Closed configuration)

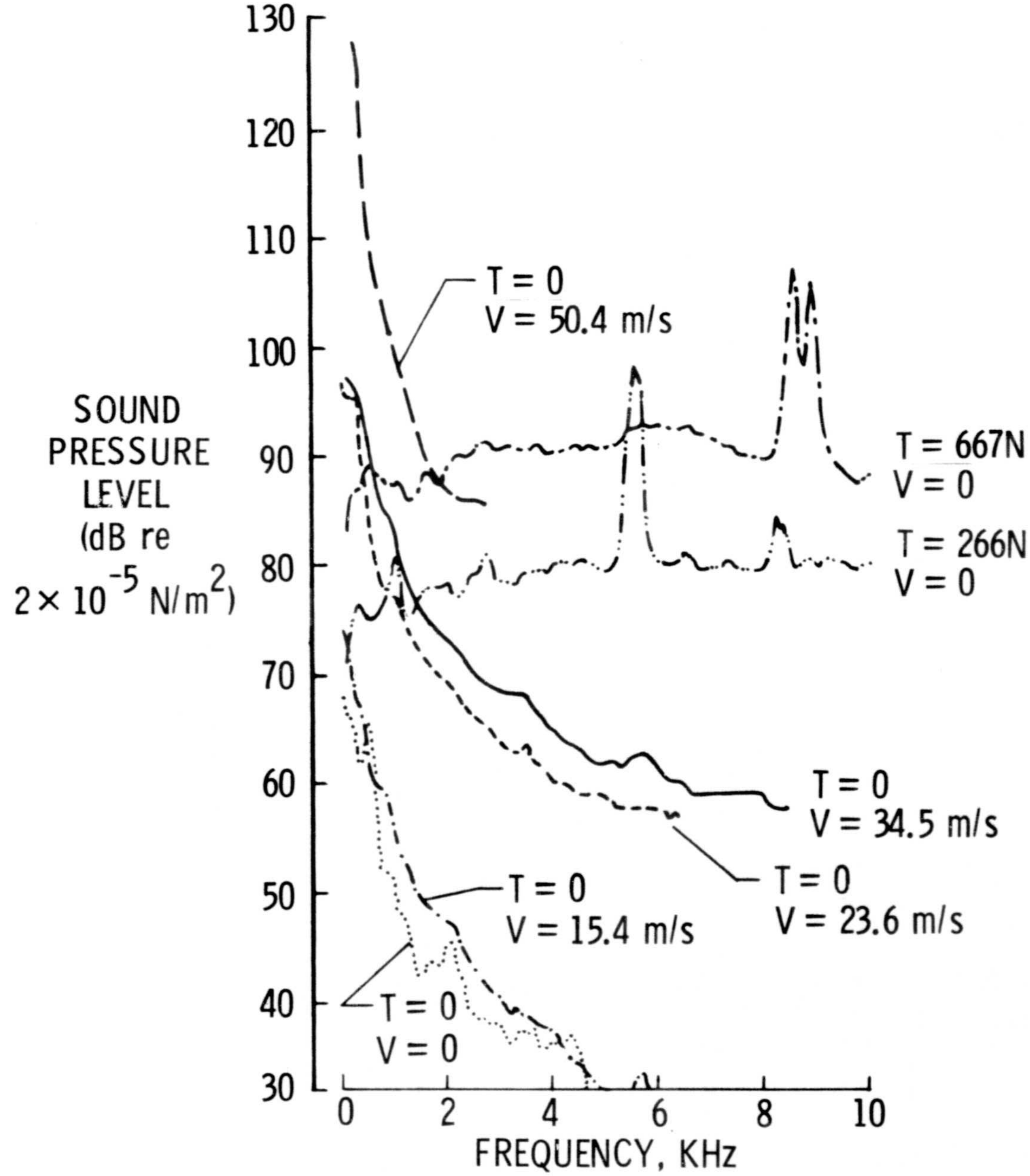

Figure 8.- Sound pressure level spectra at microphone position 4 for the test conditions shown. (Closed configuration)

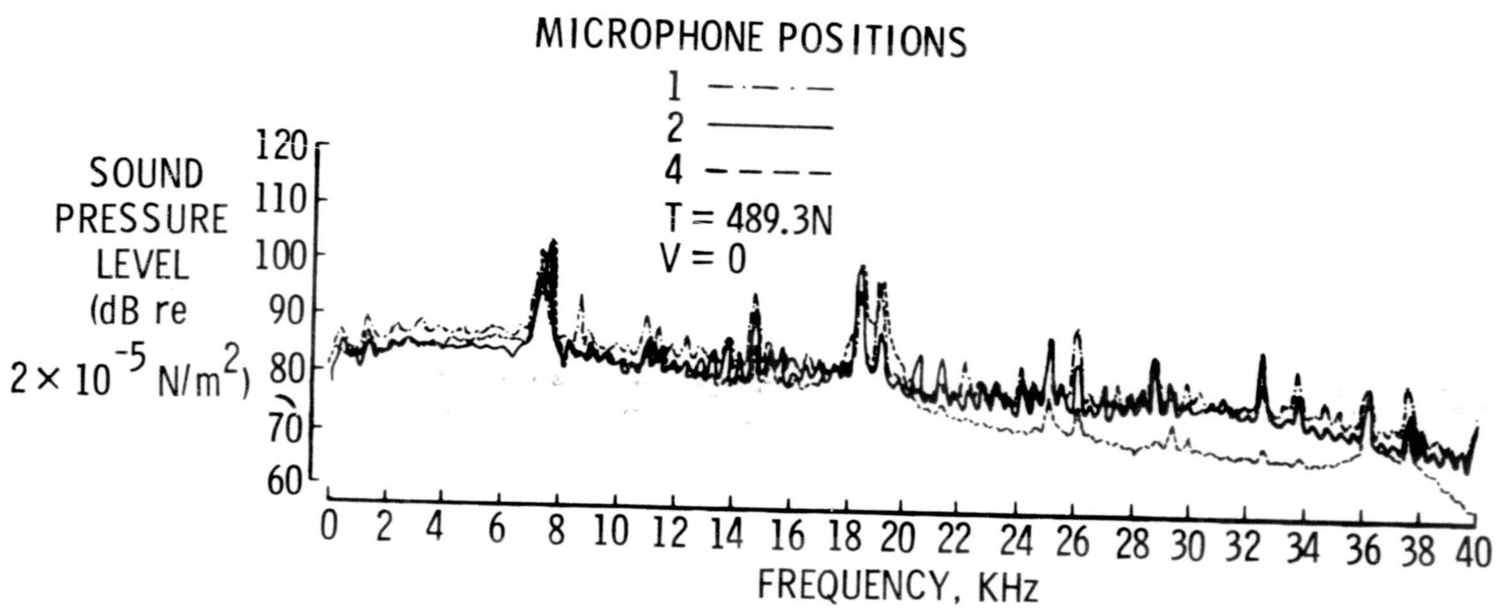

Figure 9.- Sound pressure level spectra produced by engine simulators for three microphone positions. (Closed configuration) The tunnel velocity and engine thrust were 0 and 498.3N, respectively.

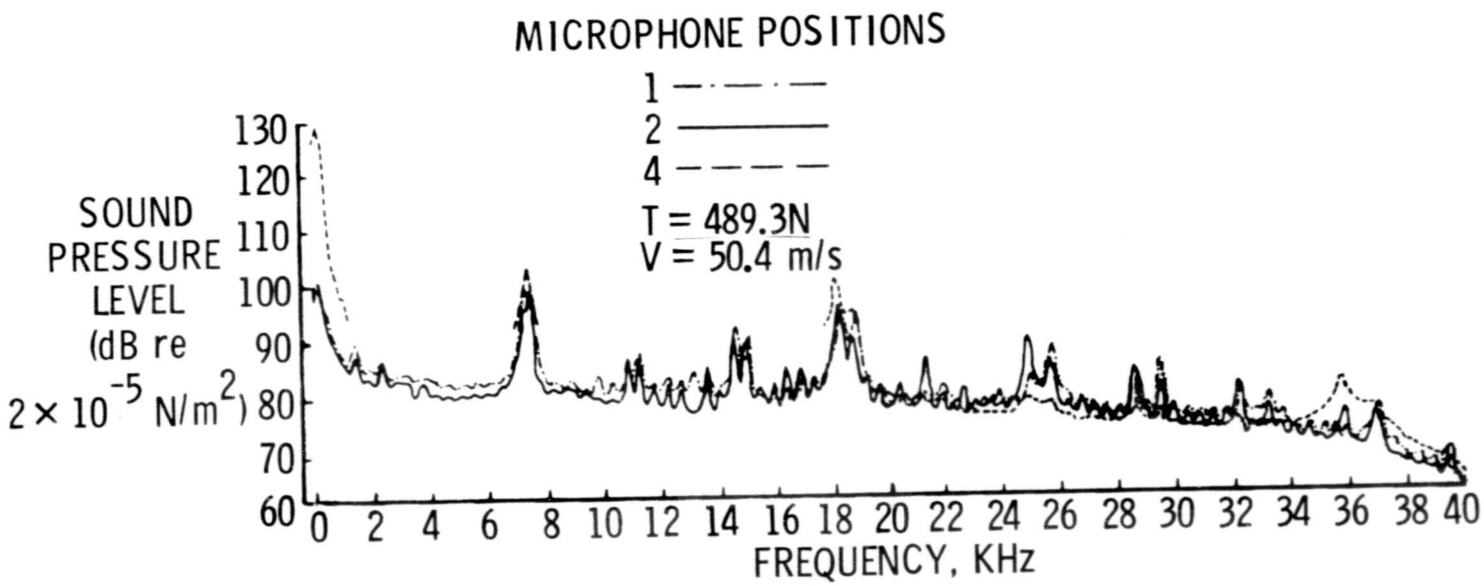

Figure 10.- Sound pressure level spectra produced by engine simulators for three microphone positions. (Closed configuration) The tunnel velocity and engine thrust were 50.4 m/s and 498.3N, respectively.

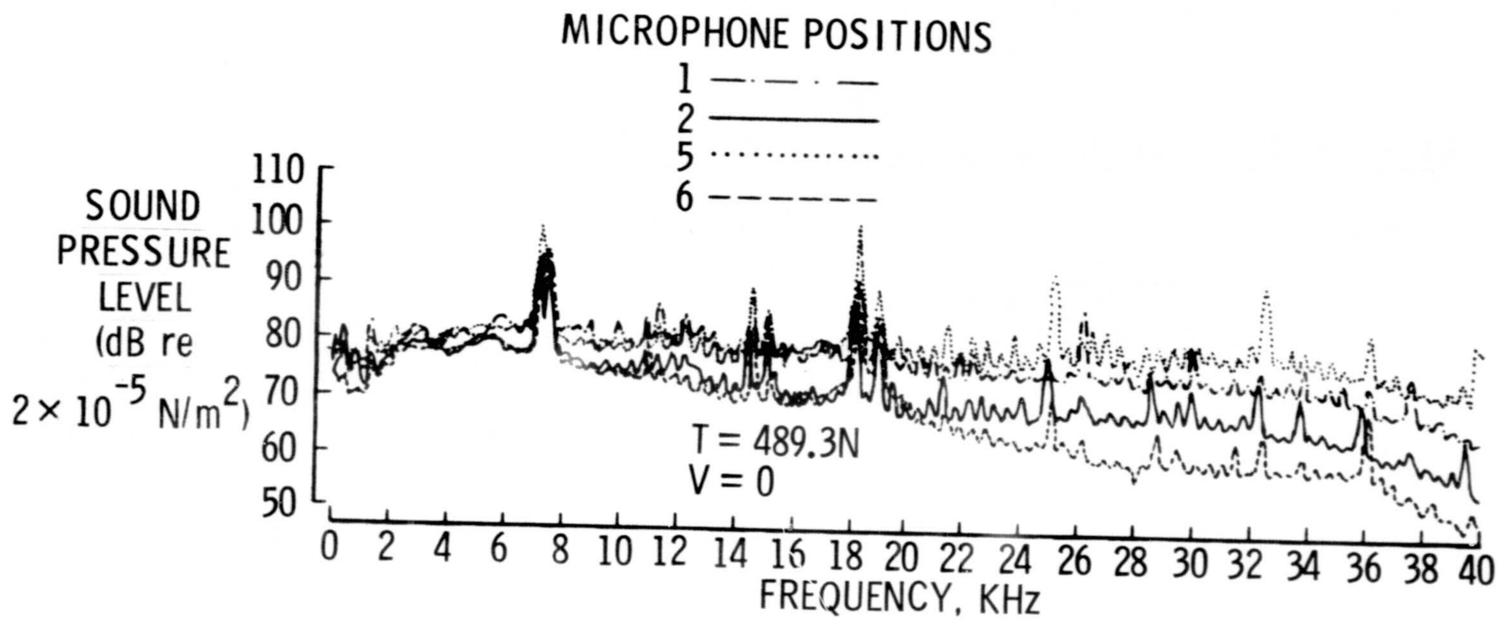

Figure 11.- Sound pressure level spectra produced by engine simulators for four microphone positions. (Open configuration) The tunnel velocity and engine thrust were 0 and 489.3N, respectively.

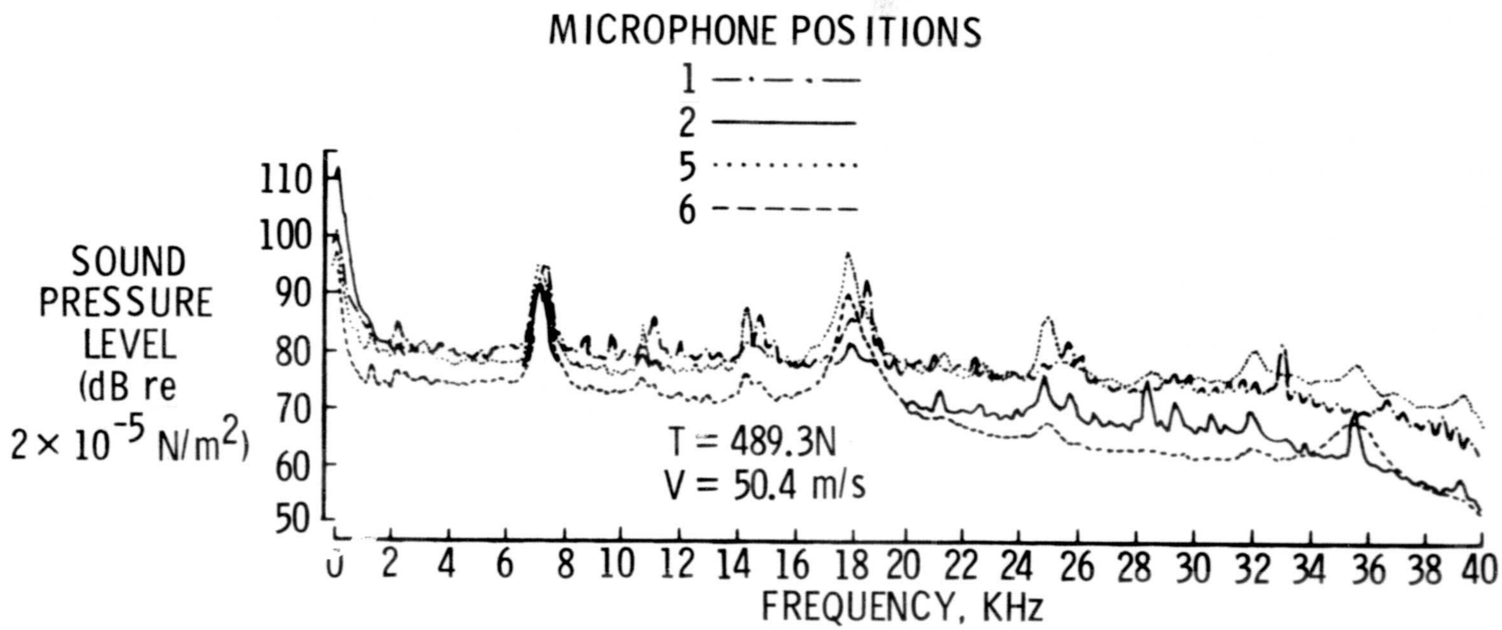

Figure 12.- Sound pressure level spectra produced by engine simulators for four microphone positions. (Open configuration) The tunnel velocity and engine thrust were 50.4 m/s and 489.3N, respectively.

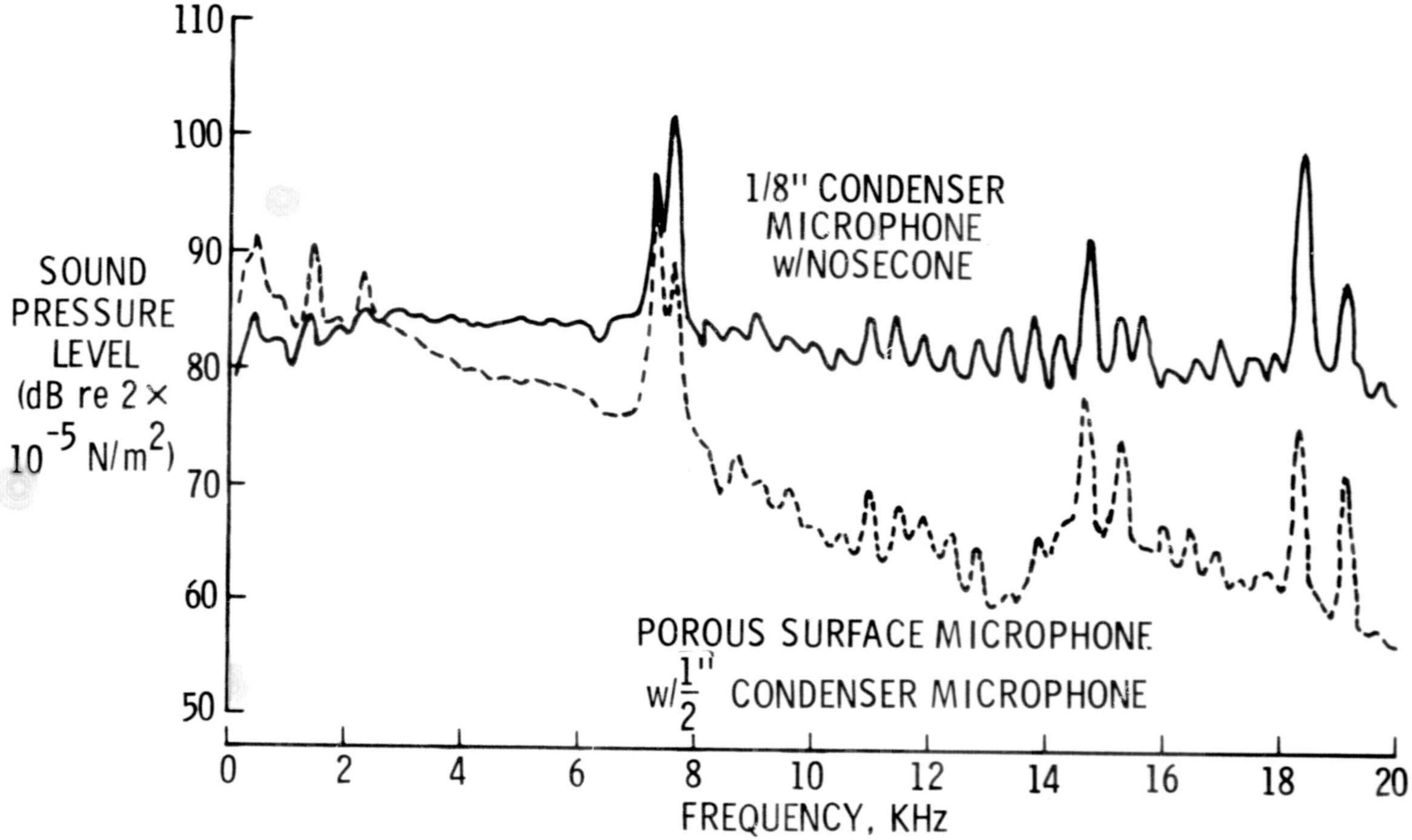

Figure 13.- Comparison of sound pressure level spectra of porous surface microphone at position 2 and standard 1/8 in. condenser microphone, also at position 2