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PRACTICAL METHODS TO OBTAIN FREE-FIELD SOUND PRESSURE LEVELS FROM ACOUSTICAL MEASUREMENTS OVER GROUND SURFACES

1. BACKGROUND

SAE Aerospace Information Report (AIR) 1327[1] was prepared as a review of theoretical descriptions of constructive and destructive interference effects on sound pressure level spectra measured above a reflecting ground plane. The reflecting plane could have either infinite acoustic impedance (a perfect acoustic reflector) or finite acoustic impedance.

The purposes of AIR 1327 were to provide a review of the analytical basis for ground reflection effects and to present some practical methods for obtaining free-field sound pressure level spectra from measurements containing spectral irregularities caused by ground-plane reflections. Results from some model-scale jet-noise experiments and full-scale jet-engine tests were included in AIR 1327 to validate the procedures for removing reflection effects to obtain free-field spectra. Recommendations were also given for determining free-field sound pressure levels from flyover noise tests.

The recommendations in AIR 1327 for removing ground reflection effects are intentionally general in scope. It is not the purpose of AIR 1327 to provide methods of obtaining free-field sound pressure levels that could cover all test situations. Each measurement situation is unique because of unique test geometry, ground-surface acoustic impedance, and noise-source acoustic characteristics. This AIR, therefore, was prepared to go beyond the general recommendations in AIR 1327 and to present descriptions of specific practical methods developed by various organizations for obtaining free-field sound pressure level spectra.

2. INTRODUCTION

Acquisition of free-field data is of practical significance in the field of aeronautical acoustics. The need for free-field data includes (but is not restricted to) the following: (1) comparison of acoustical data obtained from the same engine under various measurement conditions, (2) comparison of the results obtained from models with those from an engine on a test stand, (3) comparison of noise measurements made on the same engine under static and in-flight conditions, (4) design of test facilities, (5) standardization of techniques for "in situ" acoustical measurements, (6) spectral decomposition to isolate the contribution of different sources to the total noise, and (7) prediction of aircraft noise on the basis of methods which, generally, provide free-field data.

[1] SAE Committee A-21, "Acoustic Effects Produced by a Reflecting Plane," SAE Aerospace Information Report 1327, 15 January 1976.

2. INTRODUCTION (Cont'd.)

There is an increasing tendency to test full-scale engine components and scale models in anechoic test facilities that provide free-field conditions. This AIR complements this work by identifying those methods in current use which provide free-field acoustic data for measurements on engines under static conditions in the presence of a ground surface.

Separate Appendices to this AIR describe different methods for noise measurement in the field that conform with the state-of-the-art to a certain extent. That is, each method has generally been systematically used by at least one organization and has been substantiated by data obtained from at least one test site.

Each Appendix is dated, is subject to later modifications when additional data become available, and provides an approach to a particular technique presented by a member of the A-21 Committee.

The following section discusses certain practical aspects of ground reflection effects.

3. PRACTICAL ASPECTS OF GROUND REFLECTION EFFECTS

A simple geometrical acoustics description of the noise measurement situation when both the source and microphone are positioned above a reflecting plane assumes that sound waves travel from the source to the microphone along two different paths: the direct path (line-of-sight), and an indirect path corresponding to the reflected waves which can be partially absorbed (with a change of phase) by the surface. The two waves combine at the microphone to produce an interference pattern which modifies the observed sound pressure levels from those which would be observed if there were no surface present, i.e., the free-field sound pressure levels. The interference pattern strongly depends upon the geometry, i.e., on the heights of the source and the microphone above the surface, the horizontal separation distance, and the acoustical impedance of the ground. A complete description of these phenomena is given in AIR 1327 for the case of a quiescent, homogeneous atmosphere, neglecting the complex phenomena associated with sound propagation at a near-grazing incidence over an absorbing ground plane.[2,3] Under ideal conditions, experimental determinations of ground reflection effects were shown to be generally in good agreement with the theory.

In practice, however, a statistical analysis of the results from the same installation (i.e., one with a good approximation to an acoustically ideal reflective surface), with source and microphones located a few meters above the surface, showed consistent evidence of discrepancies. The discrepancies fell into two categories:

- in certain measurement conditions, the frequencies where the interference extrema occurred did not correspond with the theoretical frequencies. Variations as much as two to three 1/3-octave bands have been noted.

- the magnitude of the interference effect was less than calculated, particularly at low angles to the jet axis. In most cases, a more or less extensive "filling up" of the interference nulls was observed, especially the null at the first cancellation frequency.

The consequence of these discrepancies is that the systematic adjustment of measured spectra to equivalent free-field values using the geometry and theoretical methods without empirical factors often results in an incorrect estimate of the equivalent free-field sound pressure levels.[4]

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[2] J.E. Piercy, et al, "Review of Noise Propagation in the Atmosphere," J. Acoust. Soc. Am. 61, 1403-1418 (1977).

[3] C. I. Chessel, "Propagation of Noise Along a Finite Impedance Boundary," J. Acoust. Soc. Am. 62, 825-834 (1977).

[4] It should be pointed out that specific values of spectral adjustment factors developed by the procedures presented in the Appendices to this document may, in some cases, be dependent on the nominal frequency response characteristics of the spectral analysis filters employed and hence must be qualified accordingly. (See, for example, American National Standard S1.11-1966 (R1971), "Specifications for Octave, Half-Octave, and Third-Octave Band Filter Sets")

3. (Continued)

Numerous studies have shown that the discrepancies described above are due, in part, to the use of a theoretical model which does not include the phenomena associated with near-grazing-incidence waves and, in part, to the fact that actual atmospheric conditions are never ideal. Wind and temperature gradients (which can be especially high near the ground surface) and atmospheric turbulence and gustiness are sufficient to provoke the above mentioned effects in sound pressure level measurements above a ground plane.

Thus, a practical method to account for ground reflection effects should not only account for the specific features of the acoustical test facility (features that are determined by calibration), but also for random factors which are introduced by uncontrollable atmospheric conditions.

4. SUMMARY OF APPENDICES

Appendix A describes the measurement technique applicable to the SNECMA static full-scale engine acoustic-measurement facility and the procedure developed by SNECMA to remove the effects of ground reflections from measured pressure level spectra.

Appendix B describes the method used by Boeing for obtaining acoustical data free from ground-plane anomalies during static, full-scale engine testing. The method requires an acoustically hard and smooth test surface and the placement of microphone diaphragms within one microphone diaphragm diameter of that surface.

NOTE: A number of terms and concepts used in this report are unusual in routine acoustic work. For definitions and further background material, AIR 1327 (referenced on page 1) is recommended.

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APPENDIX A

PROCEDURE DEVELOPED BY SNECMA TO REMOVE GROUND REFLECTION EFFECTS FROM SOUND PRESSURE LEVELS MEASURED BY MICROPHONES LOCATED ABOVE A HARD SURFACE

March 1979

This Appendix describes the noise measurement technique applicable to the SNECMA full-scale-engine acoustic-test facility and the procedure developed by SNECMA to eliminate the effects of ground reflections from the measured sound pressure level spectra. The procedure was developed for systematic and automatic data processing by a digital computer.

1. INTRODUCTION

Development of a procedure to adjust measured spectra, particularly 1/3-octave-band analyses, to yield equivalent free-field sound pressure levels by eliminating the effects of interferences caused by reflection from a concrete surface, was initiated during the design of SNECMA's jet engine test facility. A practical procedure was developed by combining the results of an extensive theoretical analysis with the results of numerous tests both in an anechoic chamber and on the test site itself. The adjustment procedure established on the basis of the investigations is described below.

2. DESCRIPTION OF THE TEST FACILITY

SNECMA has a specific jet engine test stand that is used to obtain measurements of farfield noise levels under static operating conditions. Measurements are made by microphones mounted on poles above a smooth concrete surface which is considered to be a perfect reflector for sound waves in the frequency region of interest. The height of the engine centerline is generally between 9.8 ft (3 m) and 14.8 ft (4.50 m). The sound field is measured along a semicircle of 196.8 ft (60 m) radius, centered on the engine exhaust plane using either a series of fixed microphones located every 5° or movable microphones. The height of the fixed or movable microphones ranges between 6.6 ft (2 m) and 14.8 ft (4.50 m).

3. PROBLEMS RAISED BY THE APPLICATION OF A THEORETICAL CORRECTION PROCEDURE

Although a clearly defined boundary condition is provided by the concrete surface, resulting in interferences which should easily be treated by analysis,[1] practical experience has shown that application of theoretical formulae do not provide consistent indications of the measured interference effects. (See also Appendix B). The basic reason for the inapplicability of the theory lies in the measurement geometry which causes a wave to impinge on the concrete surface with a grazing angle less than 10°, resulting in the corresponding reflected wave being propagated over a long distance at a shallow angle through the atmospheric layer adjacent to the ground. The boundary layer near the concrete surface often contains high temperature and wind gradients and a significant degree of atmospheric turbulence.

These conditions of propagation result in two effects:

(a) the temperature and wind gradients, through refraction phenomena, produce path length differences between the direct and the reflected rays which can be much different from those determined by geometrical acoustics and which vary from one test to another and with farfield microphone location. As an example, the probability distribution of the center frequency of the third octave band containing the first interference null (as observed during a statistical survey covering 200 spectral analyses) is shown in Fig. 1. Note that the actual frequency of the first cancellation was often as much as ± 2 1/3-octave bands away from the theoretical value of the first cancellation frequency.

(b) turbulence present in the ground shear layer introduces variations in the phase relations between the direct wave and the reflected wave and, consequently, in the interference extrema if the length scales of the turbulence are on the order of, or greater than, the wavelength of the sound waves.

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[1] SAE Committee A-21, "Acoustic Effects Produced by a Reflecting Plane", SAE Aerospace Information Report 1327, 15 January 1976.

3. (Continued)

It was therefore not feasible to define an adjustment method for ground-reflection-phenomena purely on the basis of the theoretical considerations employed in Reference 1, because it is at present impossible to analytically evaluate the effects of local atmospheric characteristics such as turbulence and gradients in temperature and wind, even if these local characteristics could be easily measured "in situ" during noise testing. A practical adjustment procedure therefore required development of the empirical method described in the following sections.

4. PRACTICAL ADJUSTMENT PROCEDURE

4.1 Principle of the Method: It is generally necessary to analyze a large number of spectra when defining the noise characteristics of an engine in its various configurations. A ground-reflection adjustment procedure should therefore be suitable for computerized data processing techniques. In addition, considering the comments of the previous section, the adjustment procedure should be suited to the particular location of each microphone at the specific test site.

To comply with these two requirements, the method developed - which is applicable to 1/3-octave-band analyses only - is based on an "examination" of each measured spectrum. The examination includes:

(a) a search for interference nulls in order to fit the selected, and empirically determined, reflection-index curve to the measured spectral data; and

(b) the determination of the final reflection-index curve to be applied to eliminate the interference effects and yield the free-field spectrum.

The spectral examination method is appropriate only to the extent that the pressure spectrum of the noise emitted from the source does not contain irregularities, especially in the frequency band where the first interference null is expected to occur. The spectrum of jet noise usually meets this requirement. The method is specifically not applicable without special care for engine noise spectra containing discrete frequency components from low-frequency sources such as multiple-pure-tone or "buzzsaw" sounds.

4.2 Search for Interference Nulls: The measurement geometry [relative positions of the source (assumed for the purpose of this method to be at the center of the nozzle exit), the microphone, and the reflection plane] usually permits calculation of the theoretical path length difference and the theoretical frequencies at which the interference nulls should occur and, hence, the center frequencies of the 1/3-octave bands containing the theoretical cancellation frequencies. However, as mentioned in section 3, because of variations in path length differences, the frequencies of interfering extrema are highly dependent on the local atmospheric conditions existing during the test. The method used, therefore, is based on finding the first null frequency within a frequency range covering six 1/3-octave bands, distributed as shown in Fig. 1, i.e.: f_{thi-3} through f_{thi+2} (f_{thi} being the center frequency of the 1/3-octave band containing the theoretical frequency of the first null). If the cancellation effect is not sufficient to produce a significant null at the first cancellation frequency, a search for the second null frequency may be made.

4.3 Empirical Reflection-Index Curve: Having determined which 1/3-octave band contains the first interference null, it is now possible to fit a reflection-index curve that is appropriate to the measured spectrum. This operation is done individually for each spectrum in order to make interference effects agree with those effectively encountered under various test conditions.

A reflection-index curve is known from theory[1]. However, the significant interference amplitude predicted by theory, particularly for the nulls at the cancellation frequencies, do not generally occur in practice.

[1] SAE Committee A-21, "Acoustic Effects Produced by a Reflecting Plane," SAE Aerospace Information Report 1327, 15 January 1976.

4.3 (Continued)

Considering the cancellation at the first null frequency as an example, the value of the difference between the measured and the free-field sound pressure levels given by theory, for a 1/3-octave-band analysis (with a perfect filter) is -13.6 dB. Values in the vicinity of -8 dB were found during anechoic chamber experiments on noise from model-scale jets. Results from examination of spectra measured around the SNECMA test site in nearly ideal atmospheric conditions ranged from -4 dB to -6 dB. The analysis of a large number of results from tests conducted either in an anechoic chamber with a measurement geometry similar to that used at the SNECMA full-scale test facility, or on the test site itself, was the basis for establishing the empirical reflection-index curve shown as the solid-line curve in Fig. 2. This curve is applicable to propagation under conditions when there is negligible atmospheric turbulence near the ground plane.

4.4 Weighting of Reflection-Index Curve: The empirical reflection-index curve defined by the solid line in Fig. 2 is satisfactory in many measurement cases, provided it is fitted against the actual cancellation and reinforcement frequencies by the method described in 4.2. There may be cases, however, where phase relations and the corresponding interference extremum amplitudes are degraded by the effect of atmospheric turbulence in the propagation paths. In the particular case of noise measurements at the SNECMA engine test facility, sound waves can propagate through a turbulent boundary layer, adjacent to the concrete surface, that is approximately 1.65 ft to 3.3 ft (0.5 m to 1 m) thick. The usual measurement geometry [r = 196.8 ft (60 m), h = h' = 11.5 ft (3.50 m)] results in an approximate geometrical path length difference of 1.31 ft (0.4 m), and, consequently the first null occurs at a wavelength of 2.6 ft (0.8 m) on the average. Assuming the maximum length scale of turbulence within the boundary layer to be approximately equal to the boundary layer thickness, interferences are affected by turbulence at frequencies corresponding to the first two or three interference nulls.

A modified empirical reflection-index curve applicable to measurements made in conditions of turbulence was defined (dashed line in Fig. 2) as a result of the observations described above. The dashed-line curve in Fig. 2 was developed on the basis of the following considerations:

- In the usual geometrical conditions for tests at the SNECMA test site, the theoretical path length difference Δr is generally always the same, and the above wavelength considerations apply also to the variable $\Delta r/\lambda i$.

- At low values of $\Delta r/\lambda_i$, wavelengths are large compared to the turbulence length scale, and the direct and reflected waves should be in phase as though the turbulence were negligible. Thus, a pressure doubling should occur and the theoretical increase of +6 dB should be maintained.

- At high values of $\Delta r/\lambda_i$, because of the turbulence, direct and reflected sound waves should be uncorrelated, so that the intensity is doubled, and the corresponding 3 dB increase should also be maintained.

The sensitive part of the reflection-index curve (corresponding to intermediate values of $\Delta r/\lambda_i$) was faired in to provide a smooth transition between reflection-indices of 6 dB and 3dB for the low-frequency and high-frequency asymptotes.

Thus, for a 1/3-octave-band center frequency f_i, the reflection-index to be applied to measured spectra may be written:

$$\Delta N_i = \Delta N_{i1} + \delta\left[(\Delta N_i)\right] \xi \qquad \text{(A1)}$$

4.4 (Continued)

where ΔN_{i1}, and $\delta(\Delta N_i)$ are functions of $\Delta r/\lambda_i$ and are defined in Figure 2 and ξ is an empirical adjustment coefficient to the predicted reflection index that accounts for turbulence effects and the use of a simplified theoretical model. Because of the difficulty of obtaining a quantitative assessment of the effect of atmospheric turbulence, and the lack of an applicable theory, the value of ξ has to be derived from the shape of the measured spectrum around the frequency of the first interference null. To obtain values for ξ, it was assumed that, in a frequency range extending two octave bands on each side of the measured null frequency, the free-field spectrum would have a continuous and constant slope. With this assumption, reflection interferences produce amplitude oscillations in the measured 1/3-octave-band spectrum which are evaluated by a parameter γ.

The parameter γ was defined by the sum of differences in the measured 1/3-octave-band sound pressure levels as

$$\gamma = (N_{e-3} - N_e) + (N_{e+3} - N_e) \qquad \text{(A2)}$$

where N_e is the sound pressure level of the band containing the first cancellation frequency and with band center frequency f_e and where N_{e-3} and N_{e+3} are the sound pressure levels of the bands with center frequencies f_{e-3} and f_{e+3} below and above f_e as indicated in Fig. 3.

In the absence of turbulence, the values of the differences in the sound pressure levels measured by a microphone above a reflecting surface, relative to a corresponding free-field spectrum, have the typical values shown in Fig. 3.

Thus, assuming a free-field noise spectrum having a constant slope (Fig. 3 shows a positive slope as often found for jet noise at low frequencies) and, in the absence of turbulence effects on the reflected waves, the parameter γ has the approximate maximum value of

$$\begin{aligned} \gamma_{max} &= \left[3.4 - (-4.5)\right] + \left[5.7 - (-4.5)\right] \\ &\simeq 18 \text{ dB} \end{aligned} \qquad \text{(A3)}$$

Assuming a scatter of $\pm$ 1 dB in the sound pressure level measurements, the minimum value of γ, in the absence of turbulence, will be

$$\begin{aligned} \gamma_{min} &= \left[(3.4 - 1) - (-4.5 + 1)\right] + \left[(5.7 - 1) - (-4.5 + 1)\right] \\ &\simeq 14 \text{ dB} \end{aligned} \qquad \text{(A4)}$$

For the case when the interference phenomena are disturbed by turbulence, the value of γ will be less than 14 dB. The amount by which γ is less than 14 dB was taken as a quantitative representation of the effect of turbulence.

The empirical adjustment coefficient to account for turbulence effects on interference phenomena was then defined as

$$\begin{aligned} \xi = \gamma/\gamma_{min} &= \left[(N_{e-3} - N_e) + (N_{e+3} - N_e)\right]/\gamma_{min} \\ &= \left[(N_{e-3} - N_e) + (N_{e+3} - N_e)\right]/14 \end{aligned} \qquad \text{(A5)}$$

4.4 (Continued)

The coefficient ξ was assigned limiting values of 0 and 1 defined as

$$\xi = 0 \text{ when } (N_{e-3} - N_e) + (N_{e+3} - N_e) \leqslant 0 \qquad \text{(A6)}$$

and

$$\xi = 1 \text{ when } (N_{e-3} - N_e) + (N_{e+3} - N_e) \geqslant 14 \qquad \text{(A7)}$$

The limiting values were defined in this way to allow for cases when the differences in the 1/3-octave-band sound pressure levels were less than zero and for cases when the sound pressure level differences exceed the typical minimum value of 14 dB determined in the absence of turbulence.

5. TYPICAL APPLICATIONS OF THE PROCEDURE

The above described procedure was used as a basis for a computer program that generates free-field spectra from engine noise measurements made at the SNECMA test facility.

Examples of results obtained with this procedure are given in Figs. 4 through 6, showing measured spectra and spectra adjusted to free-field sound pressure levels. Three examples are shown which comply with the main assumption made when defining the method, i.e., they do not show any significant spectral irregularities within the "examined" frequency range of the spectrum (i.e., two octave bands located each side of the first null frequency). The spectra represent turbojet noise measurements with net noise predominating.

Three spectra are shown on the first of these figures (Fig. 4): the as-measured spectrum, the spectrum adjusted to free-field using the theoretical reflection-index curve from AIR 1327, and the spectrum adjusted to free-field using the method described herein. The advantage of the proposed method and the disadvantage of using the theoretical method (which may result in significant distortions near the interference nulls) are readily observable in Fig. 4.

The second example (Fig. 5) shows that, even in the case of a spectrum with comparatively steep low-and high-frequency slopes, the method presented in this Appendix is satisfactory.

There are measurement cases, however, where the use of the method is not satisfactory, as shown in Fig. 6. For the spectrum illustrated in Fig. 6, the first null occurs near the peak of the spectrum. (Note: the measuring distance was, in this case, 98.4 ft (30 m) instead of 196.8 ft (60 m). The proposed spectral adjustment method does not work well when the first null is located near the peak of the spectrum because the assumption of a constant slope between the 1/3-octave bands f_{e-3} and f_{e+3} is not complied with. The calculated value of the parameter ξ will be too small and the weighting of the empirical reflection-index curve will therefore be excessive with the result that the spectrum is not properly adjusted as shown by the low levels in the 160-Hz and 200-Hz bands in Fig. 6.

In fact, however, the spectrum shown in Fig. 6 was measured under exceptionally good propagation conditions. For the wavelengths associated with the first null, there probably was a negligible effect of turbulence on the phase of the reflected wave and the maximum value of ξ was therefore obtained.

The insufficient correction of the first interference null (in the 160-and 200-Hz bands), therefore, probably results from the fact that the empirically derived "ideal" reflection-index curve which was used in this case (the solid line of Fig. 2) was too pessimistic for correcting the first interference null. The correction of -4.5 dB shown in Fig. 2 probably should have been larger for the test conditions applicable to the spectrum shown in Fig. 6. Additional investigations would be required to develop curves applicable to all test conditions.

6. CONCLUDING REMARKS

The method for adjusting 1/3-octave band spectra, as described in this Appendix, was established to generate free-field spectra from measurements made around a static noise test facility. While it is satisfactory in most cases, the empirical reflection-indexcurve must be modified for specific application to each particular test facility. For the measurement of any broadband noise spectrum (e.g., jet noise), however, the principle of weighting the empirical reflection-index curve after "examination" of the spectrum to be adjusted to free-field conditions appears attractive and should generally be satisfactory, provided the measurement geometry is carefully chosen so that the first interference extrema do not occur within a frequency range where the spectrum displays a rapid variation in slope.

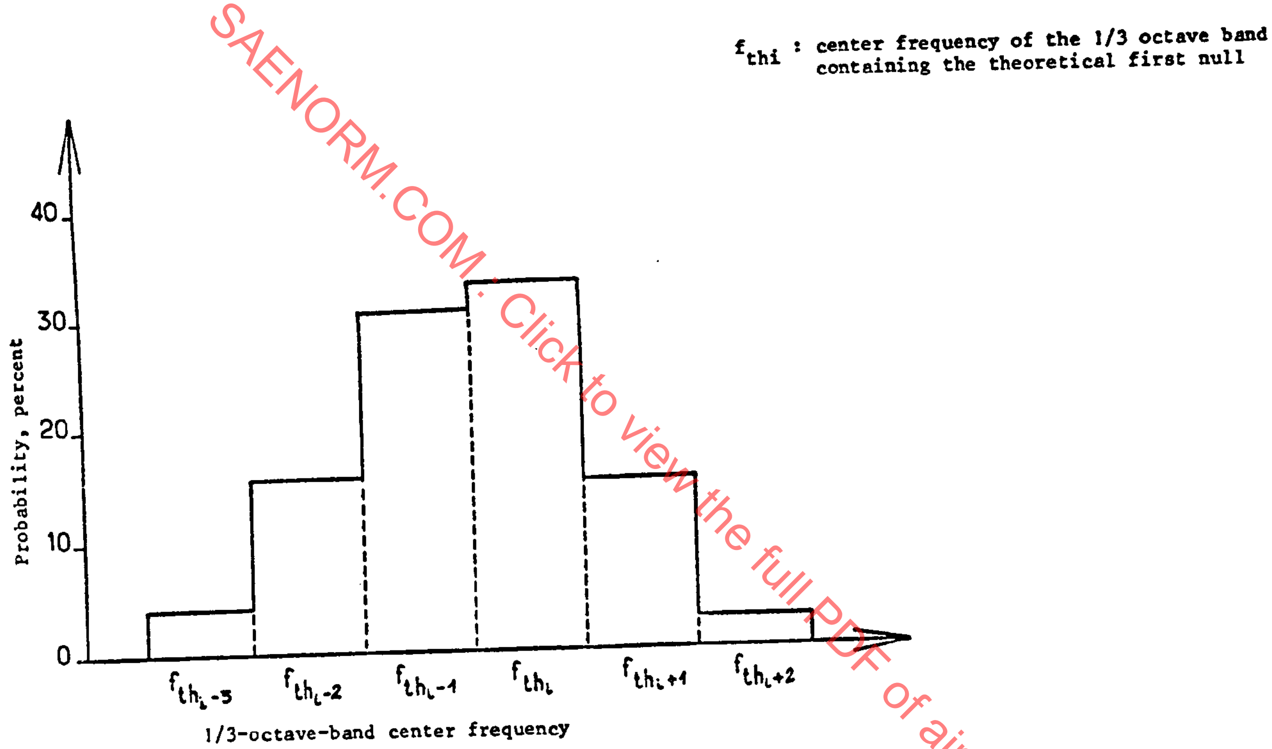

Figure 1. PROBABILITY DISTRIBUTION OF THE FREQUENCY OF THE FIRST NULL AS MEASURED AT THE SNECMA TEST SITE.

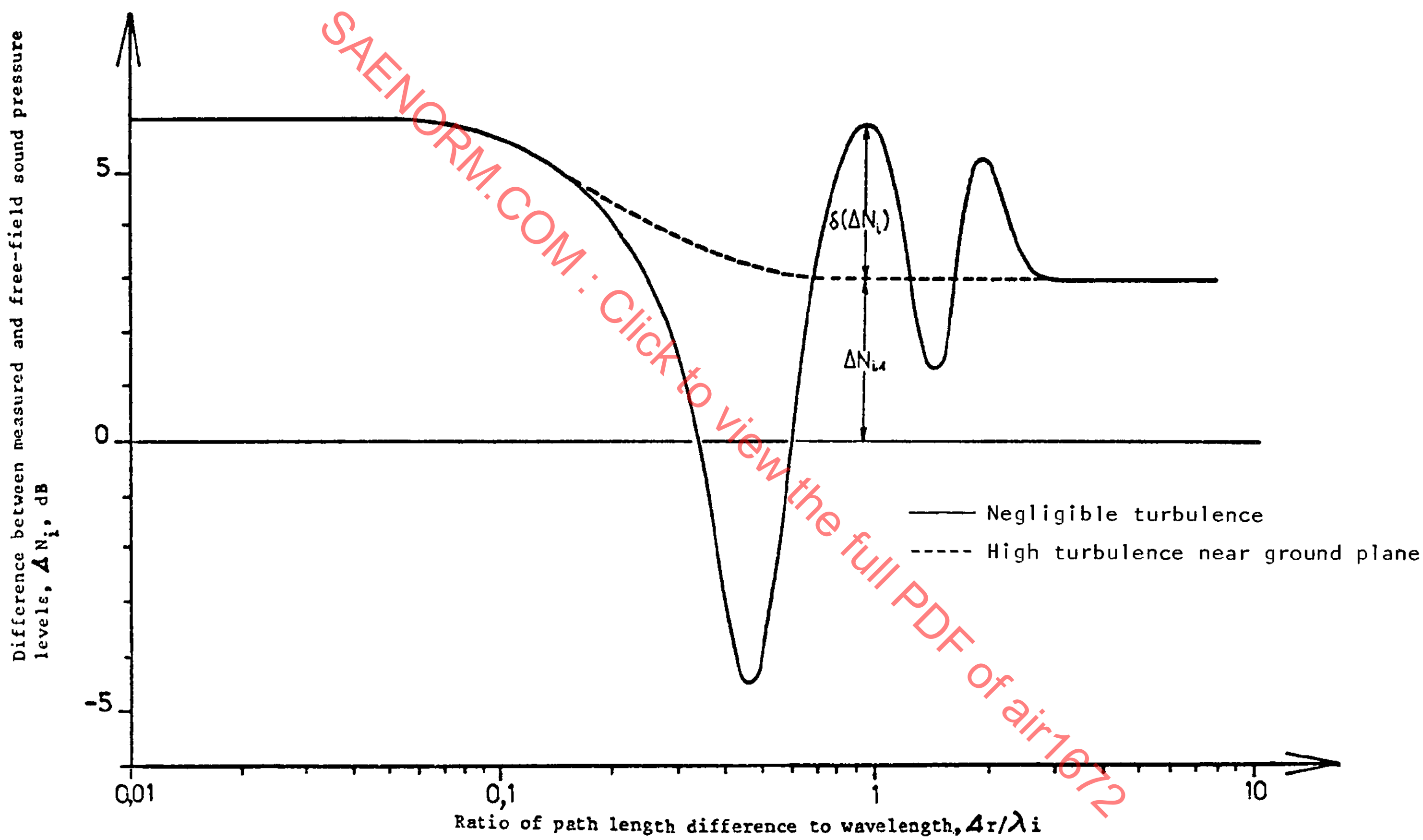

Figure 2. EMPIRICAL REFLECTION INDEX CURVES TO BE FITTED TO 1/3-OCTAVE-BAND SOUND PRESSURE LEVELS.

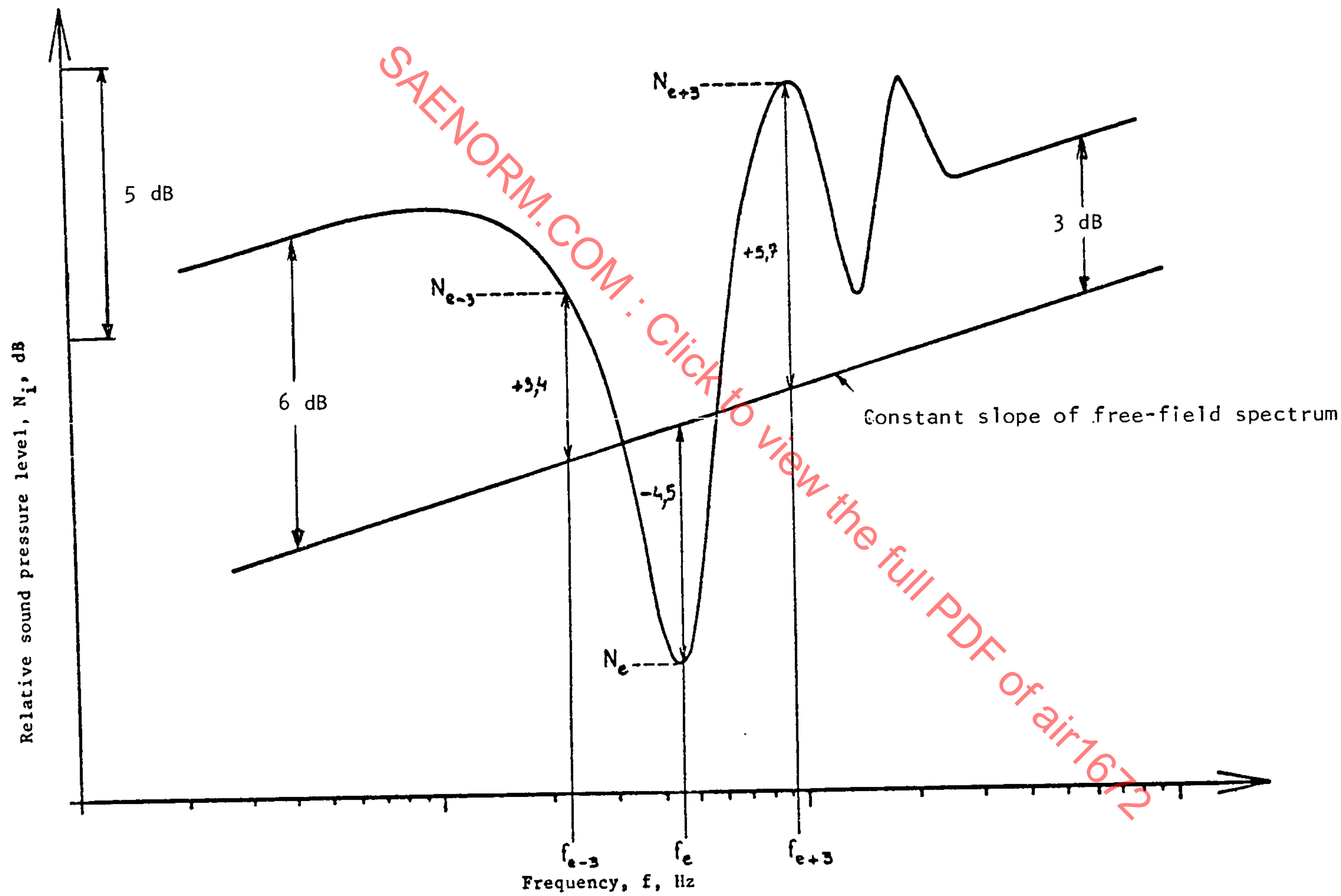

Figure 3. ILLUSTRATION OF EFFECT OF OSCILLATIONS CAUSED BY GROUND REFLECTIONS ON A FREE-FIELD NOISE SPECTRUM HAVING A CONSTANT SLOPE.

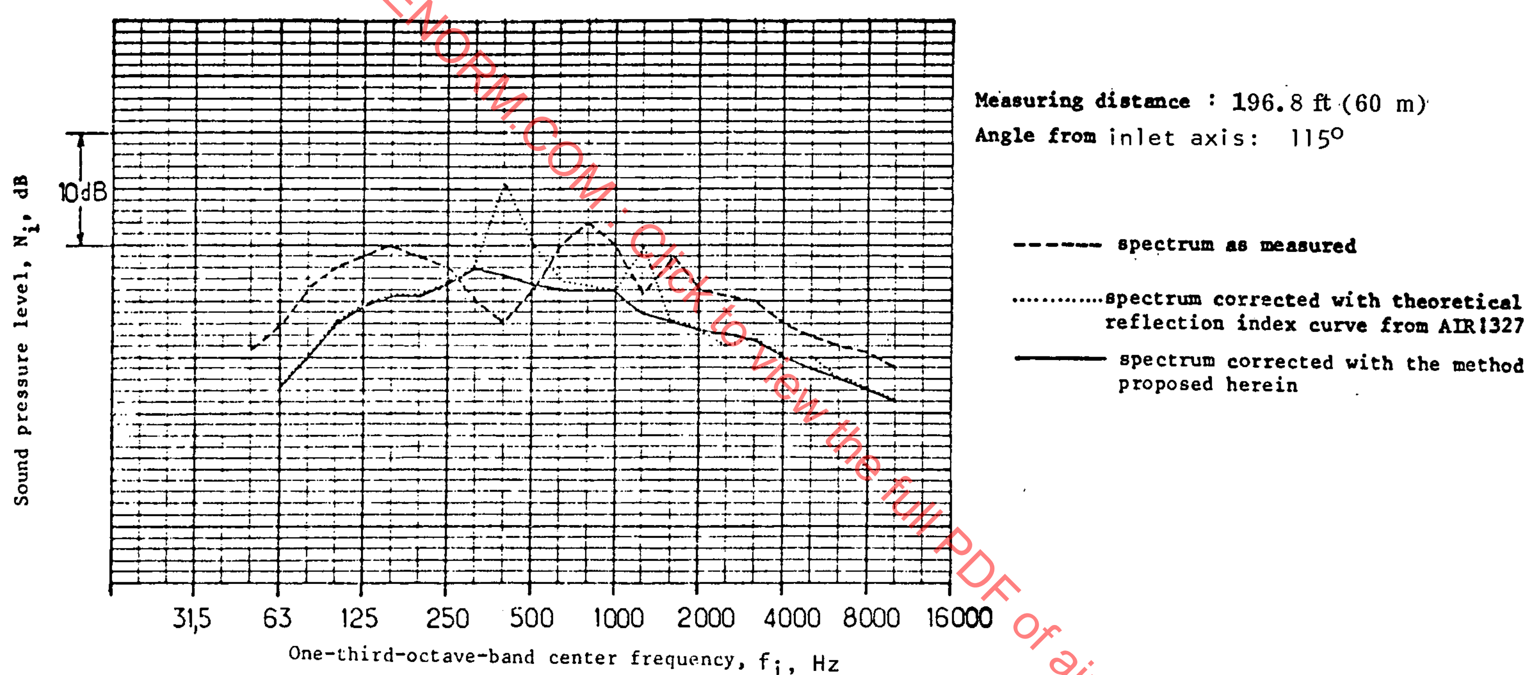

Figure 4. COMPARISON OF SPECTRA CORRECTED ACCORDING TO THEORY AND THE PROPOSED METHOD.

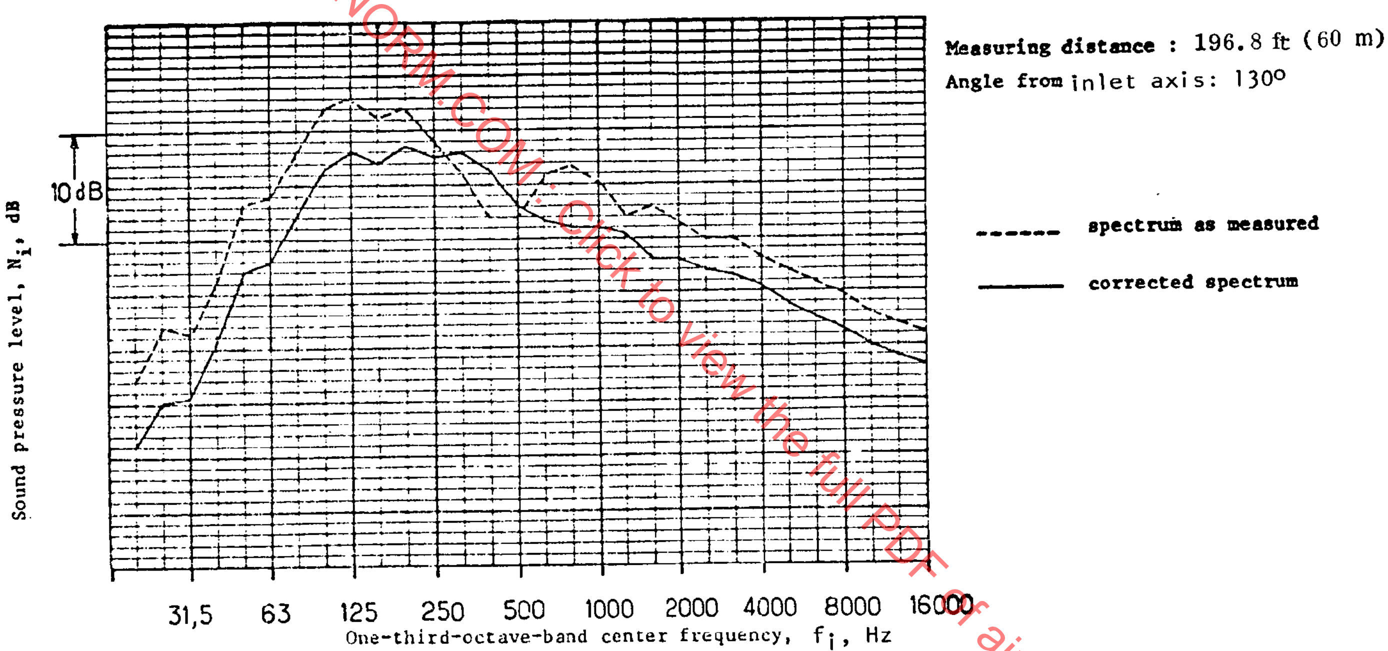

Figure 5. EXAMPLE OF APPLICATION OF THE SNECMA METHOD TO A SPECTRUM HAVING STEEP SLOPES AT LOW AND HIGH FREQUENCIES.

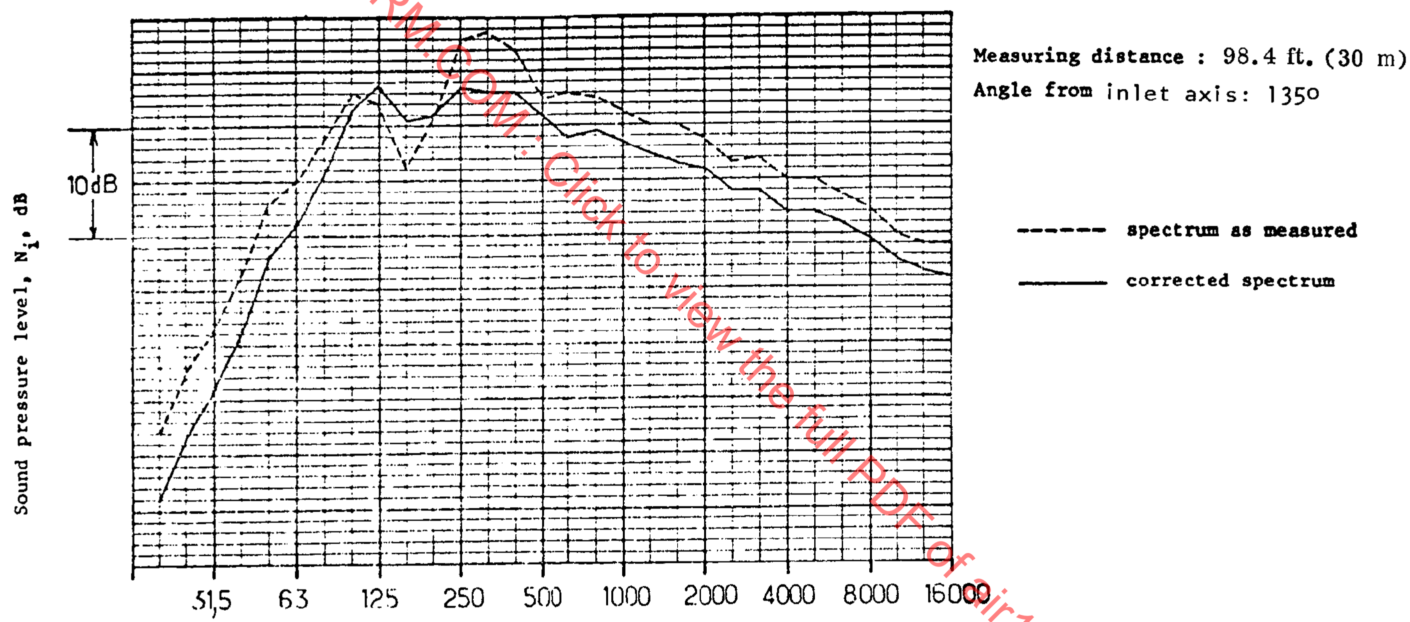

Figure 6. EXAMPLE OF SPECTRUM INSUFFICIENTLY CORRECTED BY THE SNECMA METHOD.

APPENDIX B

PROCEDURE DEVELOPED BY THE BOEING COMPANY TO DETERMINE EQUIVALENT FREE-FIELD SOUND PRESSURE LEVELS AROUND AN ENGINE TEST STAND

January 1979

This appendix describes the method used by Boeing to obtain acoustic data free of destructive interference effects caused by ground-plane reflection. The method has been successfully used to make noise measurements of: a jet engine on a static test stand, model-scale jets and aircraft during flight. The method requires a test surface that is acoustically hard and smooth. Measurements around a jet engine are made with a condenser microphone placed above the test surface with its diaphragm within 0.5 in (1.27 cm) of the surface. By testing over an acoustically hard surface with the microphone placed near the test surface, interference effects between direct and reflected sound waves, over the frequency range extending to 10,000 Hz, are essentially reduced to a single reinforcement (pressure doubling); i.e., the measured sound pressure levels are 6 dB higher than those in an acoustic free field. Valid results have been obtained at microphone-to-engine distances as large as 213.3 ft (65 m). Amplitude and phase distortions may be introduced when sound waves travel a relatively long distance at a shallow elevation (near grazing) angle through an atmosphere containing wind and temperature inhomogeneities. Therefore, to ensure reliable measurements it is recommended that: (1) the elevation angle to the engine at the microphone location be at least 4 degrees, (2) the ground-plane surface between the microphone and the engine be uniformly smooth and acoustically reflective (e.g., concrete), and (3) to be certain of acquiring valid measurements (not unduly influenced by propagation anomalies) tests should not be performed when there are strong thermal gradients (from solar heating) near the ground plane nor when the winds exceed approximately 7 knots (3.6 m/s) from any direction. Sufficient testing has not yet been accomplished to accurately define a test envelope outside which anomalous measurements will occur. The suggested test envelope is based on known conditions that will provide reliable results.

1. INTRODUCTION

Sound pressure measurements above a reflecting surface such as a ground plane are always affected by interference between the sound propagated directly from a source to a microphone and the sound reflected from the surface (see Reference 1). Practical experience has shown that the effects of these interferences are not easily predictable in both amplitude and frequency, and are therefore not always possible to remove with any certainty. The desire to obtain noise measurements of a jet engine during test stand operations free of such effects led Boeing to investigate the use of microphones placed so near the reflecting surface (ground plane) as to be virtually flush mounted. The result was the development of a technique which reduces interference effects to the single effect of reinforcement (pressure doubling) at all frequencies of practical interest for jet engine noise measurements.

Although this Appendix is confined to a discussion of the use of ground-plane microphones for full-scale static engine operations, the method is also applicable to model-scale noise measurements, and a similar technique has been shown to provide aircraft flyover noise data that are free of the variable cancellation and reinforcement effects inherent in data acquired by microphones located a few feet above the ground surface.

2. DESCRIPTION OF BOEING TEST FACILITIES

Boeing currently has two test facilities that are used to obtain far-field acoustical data during static engine operations. One facility is located near Boardman, Oregon and has a single engine test stand with a concrete pad. The other facility is located at Tulalip, Washington and consists of two test stands, one with a concrete pad and the other with a crushed rock pad. This section describes the development of the essential acoustical features of the two test stands with the concrete pads.

Development of procedures for measuring the sound field near the ground-plane surface began at the Tulalip test facility when it had a gravel surface between the engine and the far-field microphones. Sheets of plywood were laid on the gravel and the microphones were installed in a flush-mounted arrangement near the center of the sheet. The results were not satisfactory and ground-plane measurements were abandoned because the spectrum of the measured sound pressure was not as free of spectral irregularities as desired.

After a period of time, the Boardman facility became available for engine noise testing. This facility had a smoothly trowelled, uniformly reflective concrete test pad larger than the original Tulalip gravel test area. The surface of the concrete was large enough to permit measurements 250 ft (76.2 m) from the engine in one aft quadrant as shown in Fig. 7. A second section of concrete was added later to provide for 100 ft (30.48 m) radius testing in the forward quadrant.

With this later facility an attempt was again made to obtain accurate ground-plane sound pressure level measurements. Initially, microphones were merely laid on the concrete surface pointing in the general direction of the engine. The resulting spectral data, even with the simple arrangement for the microphones, were essentially free of the peaks and nulls caused by interference between direct and reflected waves found when using microphones located above the surface.

There was some concern that the microphones' directional characteristics might deter from measuring the "correct" levels due to the widely distributed sources of the engine, and as a result of this concern a more sophisticated mounting system was considered: namely, true flush mounting in the concrete. However, because flush mountings are costly to install, time consuming to set up, and inflexible in layout, an alternative arrangement was conceived and developed. This alternative arrangement utilizes an inverted microphone to measure the sound pressure field at a very small distance above the ground plane.

1. SAE Committee A-21, "Acoustic Effects Produced by a Reflecting Plane." SAE Aerospace Information Report 1327, 15 January 1976.

2. (Continued)

Subsequent to successful testing at the Boardman facility using microphones at ground level, a concrete test area considerably larger than at the Boardman test site was installed at the Tulalip test site (Fig. 8). This larger test area was designed to facilitate acquisition of data at small angles relative to the jet exhaust on a 150 ft (45.7 m) "sideline" type layout as well as a 150 ft (45.7 m) polar layout in both the forward and aft quadrants. The inverted microphone arrangement is currently used at both sites to acquire quasi-free-field sound pressure levels.

The current implementation of the inverted microphone arrangement consists of an aluminum microphone holder welded to a 0.04 in. (1 mm) thick aluminum plate. The microphone, with its diaphragm grid cover, is inserted inside the holder so that the diaphragm is 0.5 in. (1.27 mm) above the aluminum plate (see Fig. 2). (NOTE: This microphone arrangement is applicable for tests where the direct sound wave is within approximately 25 degrees of grazing incidence relative to the microphone diaphragm.) A positive stop is provided on the microphone cathode follower to ensure proper positioning of the microphone. An air-dielectric condenser microphone with a 0.5 in (1.27 cm) diaphragm is commonly used. The selected aluminum plate, purposely thin to avoid an impedance change (edge effects), is glued with a medium-tack adhesive to the concrete surface to prevent acoustically induced vibration of the plate and microphone. No microphone diffraction corrections are applied to the data because the microphone is assumed to be in a small cavity and hence only the pressure field frequency response need be considered. Since Boeing normally specifies a test window including wind speeds of less than 7 knots (3.6 m/s) as measured at the engine centerline height, wind speeds at the microphone diaphragm will be somewhat below 7 knots (3.6 m/s), thus eliminating the need for a wind screen.

The data presented in this Appendix were all obtained from tests conducted at the Boardman test site. The engine from which the presented data were taken was mounted with the engine centerline 13 ft (3.96 m) above a concrete pad. Considering the 13 ft (3.96 m) height to be the height of the noise source above the ground plane, and at a sideline distance of 100 ft (30.48 m), the approximate difference in path length between the direct ray from the source which just grazes the edge of the microphone diaphragm and the sound ray reflected from the smooth aluminum plate to a corresponding point on the diaphragm is of the order of 1/8 in (3 mm). The wave-length at the frequency of the first cancellation ($\lambda c = 2 \Delta r$; Reference 1) is thus approximately 1/4 in (6 mm). The 1/4 in (6 mm) wave-length corresponds to a frequency of approximately 57 kHz for sound propagation at normal air temperature.

Theoretically, the difference between a 6 dB pressure reinforcement and the reflection index at the highest frequency of practical interest for full-scale engine tests (i.e., approximately 10 kHz) is about 0.5 dB, according to Reference 1. At lower frequencies, i.e., longer wavelengths, the difference is even smaller - at 5 kHz it is approximately 0.1 dB. Thus, for all practical purposes, the direct and reflected waves are in phase and the sound pressure levels measured by the inverted microphone method can be considered to be just 6 dB higher than those that would be measured in a free field. Note that at greater distances from the source the path length differences would be even less than calculated in the above example and the 6 dB pressure doubling assumption would result in even less error. At distances shorter than 100 ft (30.48 m), the accuracy of the 6 dB correction would, of course, be good over a somewhat smaller range of frequencies, although not enough smaller to be of concern for most engine noise sources. If desired, improved accuracy at the higher frequencies can be achieved by reducing the separation distance between the ground surface and the microphone diaphragm. Tests conducted by Boeing with the microphone diaphragm 0.25 in (0.63 cm) above the aluminum plate indicate no reduction in data quality from the 0.5 in (1.27 cm) installation, thus indicating a simple remedy for the potential discrepancy in the higher frequency range.

3. APPLICATION OF THE INVERTED GROUND-LEVEL MICROPHONE TECHNIQUE

The inverted ground-level microphone technique has been in use by The Boeing Company since 1971. Since that time numerous acoustical measurements have been made at both the Boardman and Tulalip test sites using this type microphone installation. Initial concerns with the technique were the possible amplitude variations that might be introduced as a result of (1) the direct and reflected sound waves propagating long

3. (Continued)

distances at shallow grazing angles through a turbulent atmosphere above the concrete surfaces, and (2) variations in the meteorological conditions of the atmosphere along the sound propagation paths. Subsequent experience amply demonstrated that for tests conducted under ordinary conditions of wind and temperature (current experience covers winds up to about 10 knots (5.1 m/s) and temperatures between 32° and 81°F [0° and 27° C]). no special problems are introduced and a very high order of data repeatability can be expected.

Acoustical data presented in this Appendix correspond to a single test series and were selected to illustrate (1) the differences between noise levels measured by ground microphones and by microphones mounted on poles at engine centerline height, (2) the need for an area near the microphones free of obstructions, and (3) the accuracy of the determination of free-field spectra that can be expected even at low elevation angles.

The microphone test layout used to acquire the acoustic data presented herein is shown in Figure 3. Ground level microphones were located along 50 ft (15.24 m) and 100 ft (30.48 m) sidelines and on a 200 ft (60.96 m) polar arc at angles of 110°, 120°, 130°, 140°, and 150° relative to the engine inlet axis. All distances were measured relative to a point on the concrete directly below the center of the engine exhaust nozzle. Four pole-mounted microphones were positioned at engine centerline height along the 100 ft (30.48 m) sideline at angles of 120°, 130°, 140°, and 150°. Atmospheric conditions during the test were: ambient temperature 57.9°F (14.4°C); relative humidity 61%, wind 7 knots (3.6 m/s) blowing almost directly into the engine inlet. At these distances and with a 13 ft (3.96 m) engine centerline height the differences between the radial and the angular coordinates of corresponding ground and pole-mounted microphones are negligible.

3.1 <u>Comparison of Centerline-Height and Surface Microphone Data</u>: Comparisons were made at three different engine power settings of the noise spectra measured by pole-mounted and ground-level microphones located along the 100 ft (30.48 m) sideline. Spectral comparisons of data recorded by the pole-mounted and ground microphones at 120° and 150° are presented in Figs. 11(a) and 11(b). Data analysis was performed using a constant 18.75 Hz bandwidth filter. This type of analysis, rather than 1/3 octave band analysis, was selected to better illustrate the cyclic and regular spacing of reflection effects and the fairly close matching of the pole-mounted microphone first-reflection peaks with the pressure-doubled sound pressure levels measured by the inverted ground microphone. Results shown are typical of the data recorded at all power settings. An examination of the data for all power settings indicated no appreciable engine power setting effect on the ground-level versus pole-mounted microphone differences.

The problem of reinforcement/cancellation of sound energy inherent in a pole-mounted microphone installation is evident. The data recorded by the inverted ground microphones were completely free of spectral irregularities at frequencies up to 10 kHz except for those locations having pole-mounted microphones adjacent to the ground level microphones. The undulations evident in the ground level microphone data shown in Fig. 11 were determined to be a result of reflections from the base of the microphone stand holding the pole microphone. At 110°, where no pole microphone stand was present, very smooth spectra were recorded [Fig. 12(a)]. This result points out the necessity for an obstruction-free area near any microphone if precise acoustical information is desired. After smoothing out the reflections resulting from the microphone stand base, good agreement was obtained between the recorded data in the mid-frequency range, after pressure doubling for the ground microphone (+ 6 dB) and intensity doubling for the pole microphone (+ 3 dB) were accounted for. This result was expected since reinforcement/cancellation effects were calculated to be greatly diminished above 1000 Hz for the geometric conditions of the test set-up. However, starting at approximately 7 kHz, the expected 3 dB difference between the sound pressure levels measured by the ground and pole-mounted microphones gradually decreases with increasing frequency. The explanation for this result is not known at present: either the spectra at the pole-mounted microphones could be too high or the ground microphone spectra could be too low. Resolution of this discrepancy will require further investigation.

3.1 (Continued)

Acoustic data taken at the Tulalip site subsequent to the herein reported Boardman test series shows negligible, and in many instances essentially zero differences above 1000 Hz between inverted ground microphones and the pole-mounted microphones after applying the 3 dB adjustment. The Tulalip test included ground and pole microphone comparisons at three different angles around the engine on a 150 ft (45.7 m) radius. Microphone to engine elevation angle for these tests was approximately 5°. These tests were conducted under a wide variety of wind conditions including speeds from 0 to approximately 8 knots (4.1 m/s) and directions from 0° to 360° to the inlet axis. Analysis of the data showed that subsequent to applying the 3 dB adjustment in the frequency range of 1-10 kHz the data spread relative to the expected noise level never exceeded 2 dB and generally was less than 1 dB. A limited amount of data obtained at an elevation angle of approximately 4° yielded similar results. Wind direction appeared to have little if any effect on the differences in high frequency noise measured at ground level or at the pole microphone installation.

3.2 Comparison of Surface Microphone Data Recorded at Different Elevation Angles: The effects resulting from changes in elevation angle are of particular interest when the noise source is near the ground and the distance to the microphone is large. Since most jet engine test stands do not provide for engine centerline heights much above 16 ft (4.9 m) and since far field measurements are sometimes taken at distances up to 328.1 ft (100 meters), the angle of elevation will, in some cases, be less than 3°. For the test setup shown in Fig. 10, the elevation angles at the ground plane microphones range from 13.7° to 3.7°. Comparisons of ground microphone spectra were made for 50 ft (15.24 m) sideline, 100 ft (30.48 m) sideline, and 200 ft (60.96 m) polar arc for each of the directivity angles and at three engine power settings. Typical test results are presented in Fig. 12(a) and 12(b) for directivity angles of 110° and 120° respectively.

The results in Fig. 12(a) and 12(b) show that equivalent free-field sound pressure level data can be obtained from ground-plane noise measurements at different distances and elevation angles. The shaded regions for the data on the 100 ft (30.48 m) sideline and 200 ft (60.96 m) polar arc indicate the magnitude of the atmospheric absorption loss calculated (by the method of SAE ARP 866A) using the radial distance to the 50 ft (15.24 m) sideline microphones as a reference. The difference beween the 50 ft (15.24 m) sideline spectra and the adjusted spectra at shallower elevation angles was generally equal to the inverse-square law propagation factor at all frequencies [See Fig. 12(a)].

In some cases, however, the differences at high frequencies between the reference and the adjusted spectral levels were slightly more than the inverse-square law factor. This result indicated that an attenuation mechanism greater than the combination of inverse-square law and atmospheric absorption might be present [see Fig. 12(a)]. Results of spectral comparisons at other angles and engine power settings indicated that this extra loss mechanism never resulted in more than about 2 dB at 10 kHz at the 3.7° elevation angle, for the weather conditions encountered during this test period. Although previous experience showed that very small elevation angles (1-1/2°) sometimes produced greater losses than indicated above, Boeing experience with elevation angles near 4° and greater indicates that elevation angles encountered in most test installations would have little effect on the ground plane noise measurements.

3.3 Limitations on Atmospheric Conditions: Detailed tests necessary to evaluate local atmospheric effects on noise propagation and to accurately define an operational test window have not been performed. Results from tests that have been conducted show that wind speeds up to at least 10 knots (5.1 m/s) are acceptable for measurements made in the aft quadrant when the wind is steady and blowing more or less directly into the engine inlet (positive wind velocities). Negative wind velocities (i.e., a wind direction opposite the direction of noise propagation as in the case of microphones in the forward quadrant with the wind blowing into the engine inlet) have shown no adverse effects up to about 7 knots (3.6 m/s).

3.3 (Continued)

Ray theory analysis indicates that a shadow zone can be produced at ground level when the wind velocity has a component in the direction opposite the direction of sound propagation because of the adverse gradient generated by surface friction. A similar result occurs when high temperature lapse rates exist near the surface. Therefore, the possibility of measuring erroneous sound pressure levels should be recognized when testing on high temperature days in still, or near still, air conditions or days in which the wind directions and/or speeds are outside the experience envelope.

One method for ensuring that no anomalous atmospheric conditions exist during a noise test is to obtain measurements with a microphone at engine centerline heights, or greater, adjacent to a ground level microphone. The measured 1/3 octave band noise level differences for these two microphones should be on the order of 3 dB at frequencies greater than 2000 Hz. Noise level differences greater than expected would suggest the existence of adverse atmospheric conditions for conducting acoustic tests.

4. CONCLUDING REMARKS

a. Results from the use of ground microphones to measure jet engine noise under static (test stand) type operations indicate that, with minor limitations on the test setup and on atmospheric conditions, the inverted-microphone technique for ground-plane measurements can provide a direct and reliable measure of free-field sound pressure levels without having to resort to spectral adjustments of data measured by pole-mounted microphones.

b. When the microphone-to-source elevation angle was 4 degrees or greater, no consistent effect was noticed on the amplitude or frequency distribution of the sound pressure levels measured by inverted microphones near the concrete ground plane as a result of sound waves propagating over the concrete surface at shallow grazing angles. Data measured by microphones at various distances were well correlated, considering only the propagation losses caused by inverse-square geometric spreading and atmospheric absorption.

c. Although theory and practical experience indicate that sound pressure levels measured by ground-plane microphones should be 3 dB higher (at frequencies above approximately 2000 Hz for the typical test geometries considered here for jet engine noise tests) than those measured by microphones above the ground plane (at the same radial distance and azimuth), there were one or two occasions when the levels from the ground-plane microphones were as much as 2 dB lower at 10 kHz than the data from corresponding pole-mounted microphones. This unexplained discrepancy is not regarded as a serious limitation to the inverted microphone method since, even if the free-field sound pressure levels determined by the inverted microphones were lower than the "true" free-field sound pressure levels by 3 dB at 10 kHz (and by a smaller amount at lower frequencies), the impact of the discrepancy on a psychoacoustic noise measure, such as perceived noise level or A-weighted sound level, would be negligible for sources of noise typical of full-scale jet engines.

d. The ability to provide a good measure of the free-field sound pressure level spectrum by eliminating cancellation effects in the frequency range of interest is a strong reason in itself for using an arrangement like the inverted microphone technique to obtain noise measurements during outdoor engine testing. Additional advantages of an inverted microphone arrangement over pole-mounted microphones that have not been addressed herein, but which should be considered in assessing the overall value of using inverted microphones, include: (1) elimination of of discrepancies between calculated and measured frequencies for the cancellations and reinforcements in the spectra measured by pole-mounted microphones; (2) improved resolution of the amplitude and frequency of pure-tone or narrowband random noise that might be difficult to evaluate properly in a frequency region subject to varying interference effects [multiple-pure-tone ("buzzsaw") noise is a commonly encountered example of an engine noise that is more readily measured by ground-plane microphones]; and (3) improved compatibility and consistency in noise measurements made at different test sites. Variations in the interference effects in the spectral data obtained from pole-mounted microphones are associated more with differences in test site than with differences in the engine noise sources.

4. (Continued)

e. Boeing experience to date using surface microphones is primarily over concrete-surfaced test areas. Other "acoustically hard" surfaces should provide results similar to the results reported herein. It would appear, however, that testing over any acoustically hard surface that might tend to generate local high temperature gradients on hot, windless days should be avoided when possible. Dark asphalt, for instance, might best be treated with a light-colored surface material to alleviate possible problems of this nature. Night or early morning testing might also provide a better test "window". The direction of the wind should be more or less directly into the engine inlet during acoustical testing, particularly for winds in excess of about 7 knots (3.6 m/s). Reliable data have been obtained during wind speeds up to approximately 10 knots (5.1 m/s).