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Practical Methods to Obtain Free-Field Sound Pressure Levels from Acoustical Measurements Over Ground Surfaces

RATIONALE

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1. **BACKGROUND:** SAE Aerospace Information Report (AIR) 1327¹ 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) com-

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

2. INTRODUCTION (Cont'd.):

parison 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.

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.

Since the internationally standardized methods of obtaining flight test noise levels suffer from the same ground reflection interference effects as measurements above the ground plane in the vicinity of a test stand, one appendix describes alternative measurement procedures for the overflight case, together with simplified adjustments to obtain approximate free-field sound pressure levels.

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

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

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

3. PRACTICAL ASPECTS OF GROUND REFLECTION EFFECTS (Cont'd.):

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. See p. 2 for Refs. 2,3.

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 metres 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

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.

⁴It 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")

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.

Appendix C describes the method used by Pratt & Whitney Aircraft to adjust full-scale jet-engine sound pressure level measurements to equivalent free-field pressure levels. At the Pratt & Whitney Aircraft test facility, measurements are made over both sealed asphalt and crushed stone surfaces.

Appendix D describes methods evaluated by Rolls-Royce for obtaining approximate free-field sound pressure levels in flyover noise testing of jet-powered aircraft.

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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PREPARED BY

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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. A1. 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.

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

3. PROBLEMS RAISED BY THE APPLICATION OF A THEORETICAL CORRECTION PROCEDURE (Cont'd.):

- (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.

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. A1, 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 theory¹. However, the significant interference amplitude predicted by theory, particularly for the nulls at the cancellation frequencies, do not generally occur in practice.

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. A2. 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. A2 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

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

4.4 Weighting of Reflection-Index Curve (Cont'd.):

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. A2) as a result of the observations described above. The dashed-line curve in Fig. A2 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 3 dB 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:

$$\Delta N_i = \Delta N_{i1} + \delta (\Delta N_i) \xi \quad (A1)$$

where ΔN_{i1} , and $\delta (\Delta N_i)$ are functions of $\Delta r/\lambda_i$ and are defined in Figure A2 and ξ is an empirical adjustment coefficient to the predicted reflection index that accounts for turbulence effects and the use of a

4.4 Weighting of Reflection-Index Curve (Cont'd.):

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

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

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. A3.

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. A3.

Thus, assuming a free-field noise spectrum having a constant slope (Fig. A3 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

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

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

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

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.

4.4 Weighting of Reflection-Index Curve (Cont'd.):

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

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

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

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

and

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

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. A4 through A6, 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 jet noise predominating.

Three spectra are shown on the first of these figures (Fig. A4): 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. A4.

The second example (Fig. A5) 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. A6. For the spectrum illustrated in Fig. A6, the first null occurs near the peak of the spectrum. (Note: the measuring

5. TYPICAL APPLICATIONS OF THE PROCEDURE (Cont'd.):

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. A6.

In fact, however, the spectrum shown in Fig. A6 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. A2) was too pessimistic for correcting the first interference null. The correction of -4.5 dB shown in Fig. A2 probably should have been larger for the test conditions applicable to the spectrum shown in Fig. A6. 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-index curve 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.

f_{th1} : center frequency of the 1/3 octave band containing the theoretical first null

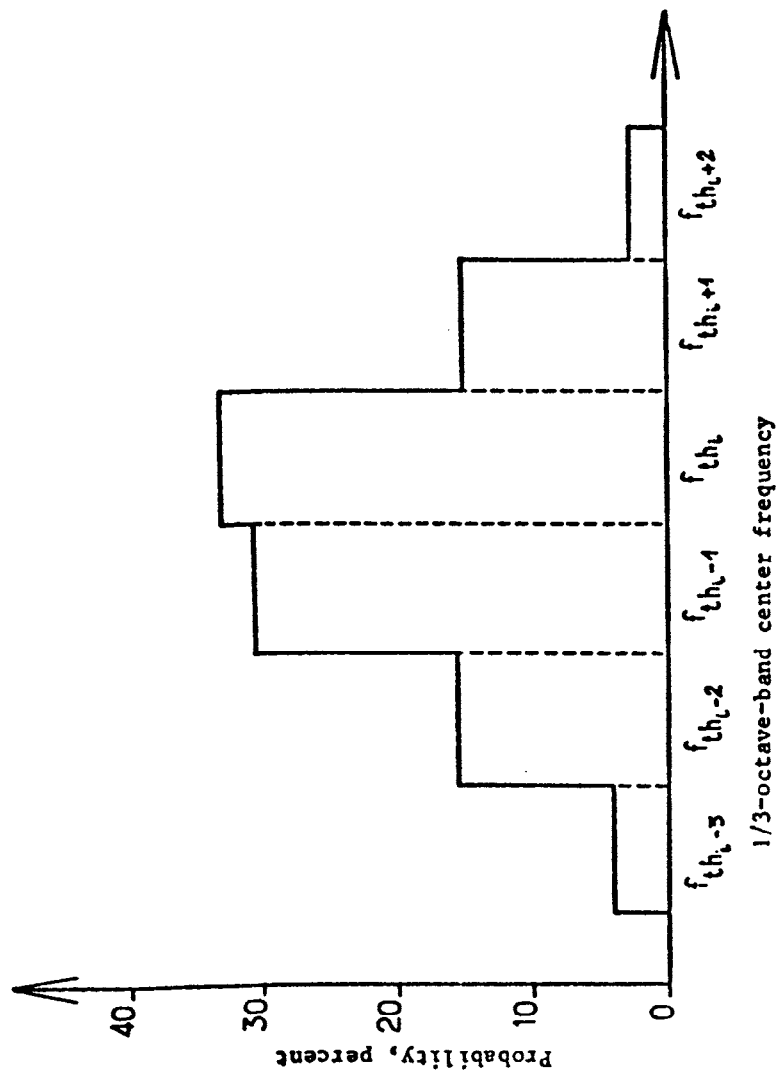


Figure A1. PROBABILITY DISTRIBUTION OF THE FREQUENCY OF THE FIRST NULL AS MEASURED AT THE SNECMA TEST SITE.

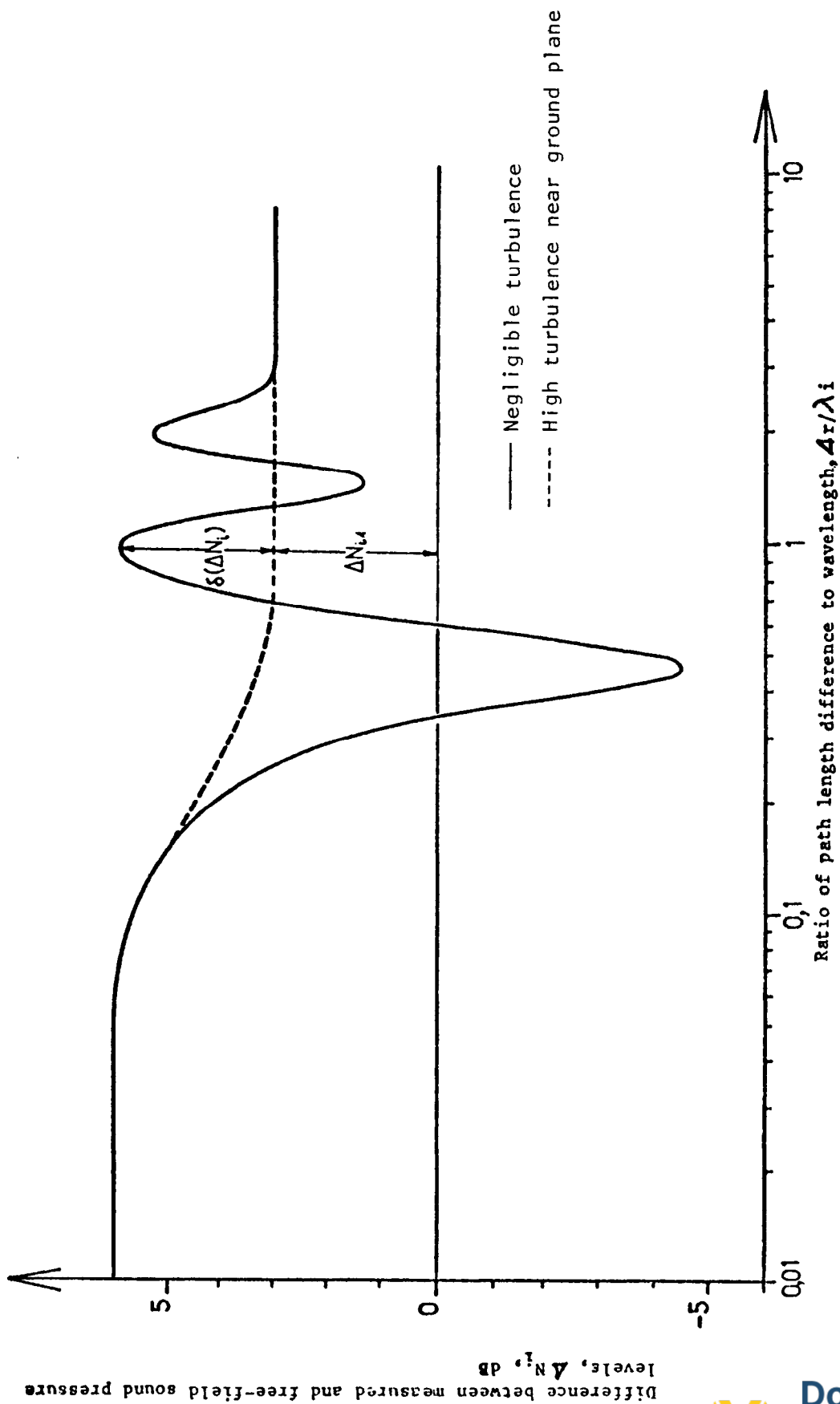


Figure A2. EMPIRICAL REFLECTION INDEX CURVES TO BE FITTED TO 1/3-OCTAVE-BAND SOUND PRESSURE LEVELS.

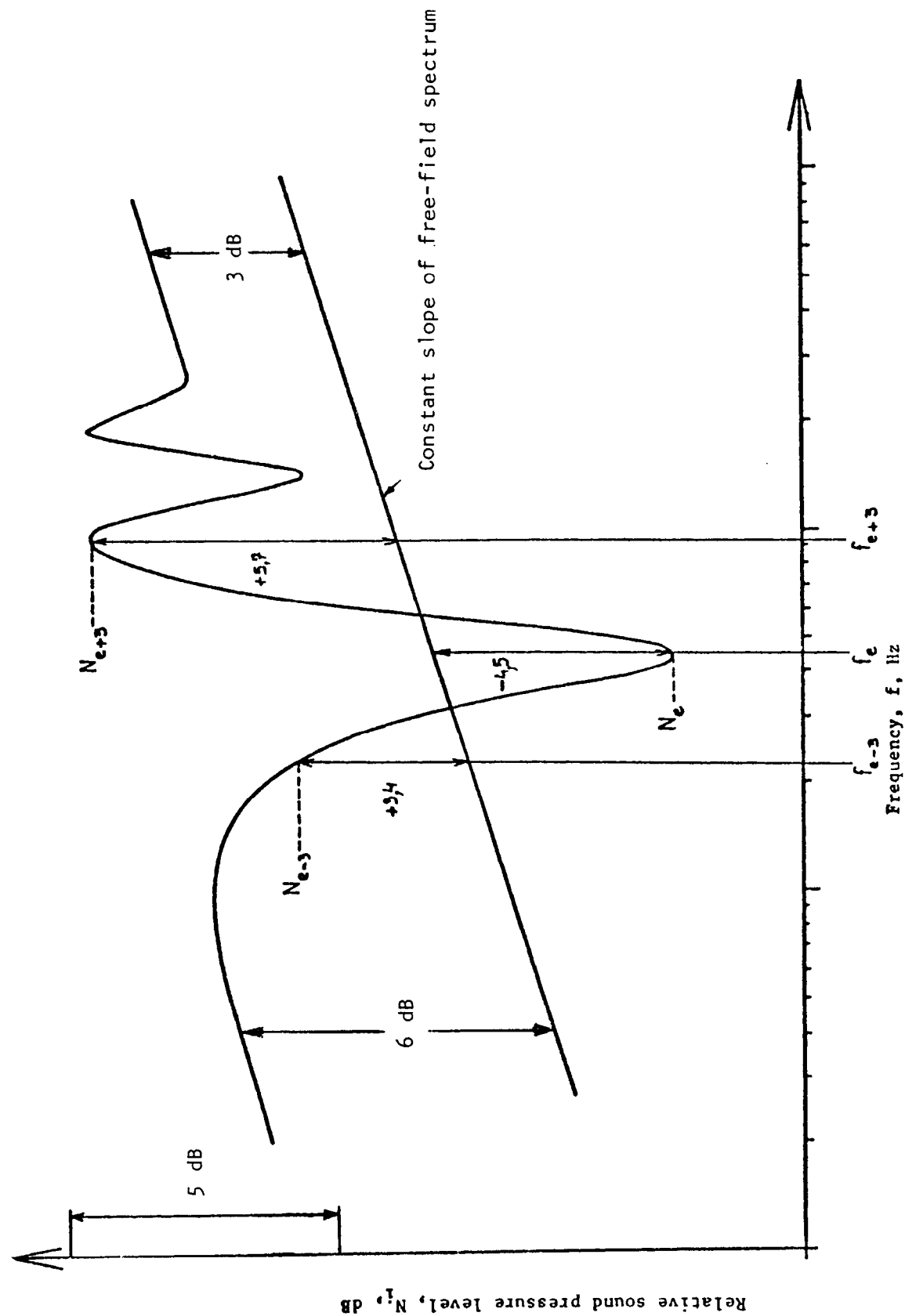


Figure A3. ILLUSTRATION OF EFFECT OF OSCILLATIONS CAUSED BY GROUND REFLECTIONS ON A FREE-FIELD NOISE SPECTRUM HAVING A CONSTANT SLOPE.

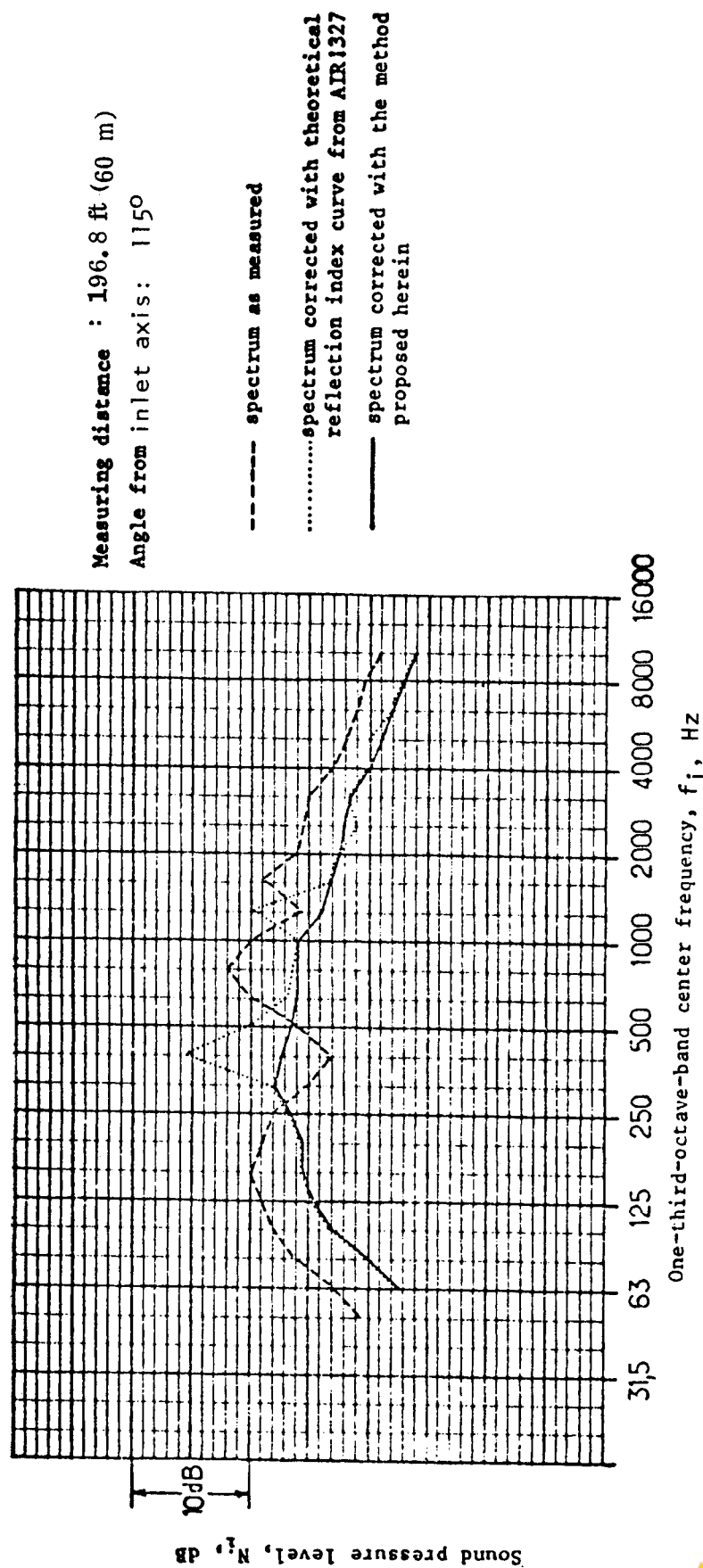


FIGURE A4. COMPARISON OF SPECTRA CORRECTED ACCORDING TO THEORY AND THE PROPOSED METHOD.

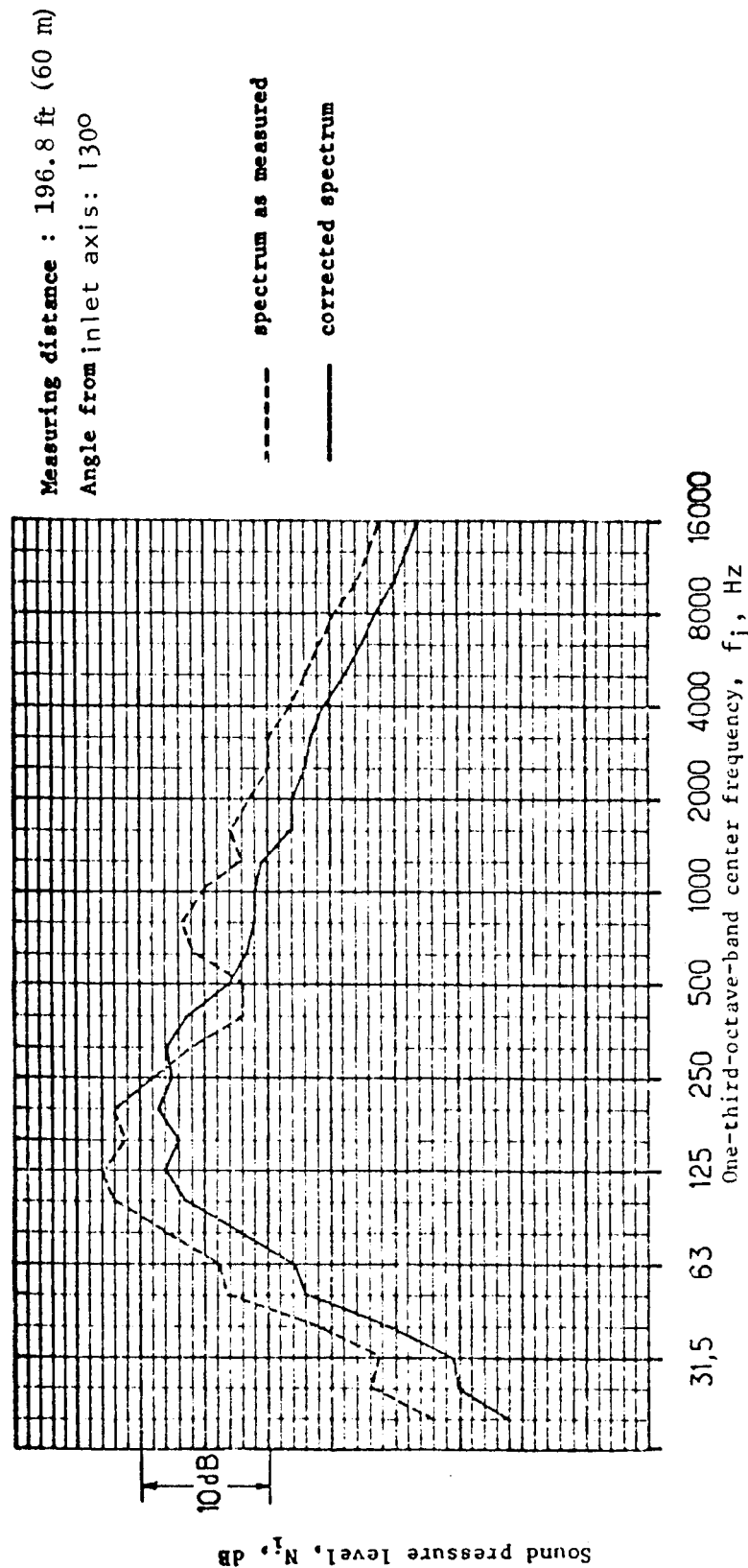


Figure A5. EXAMPLE OF APPLICATION OF THE SNECMA METHOD TO A SPECTRUM HAVING STEEP SLOPES AT LOW AND HIGH FREQUENCIES.

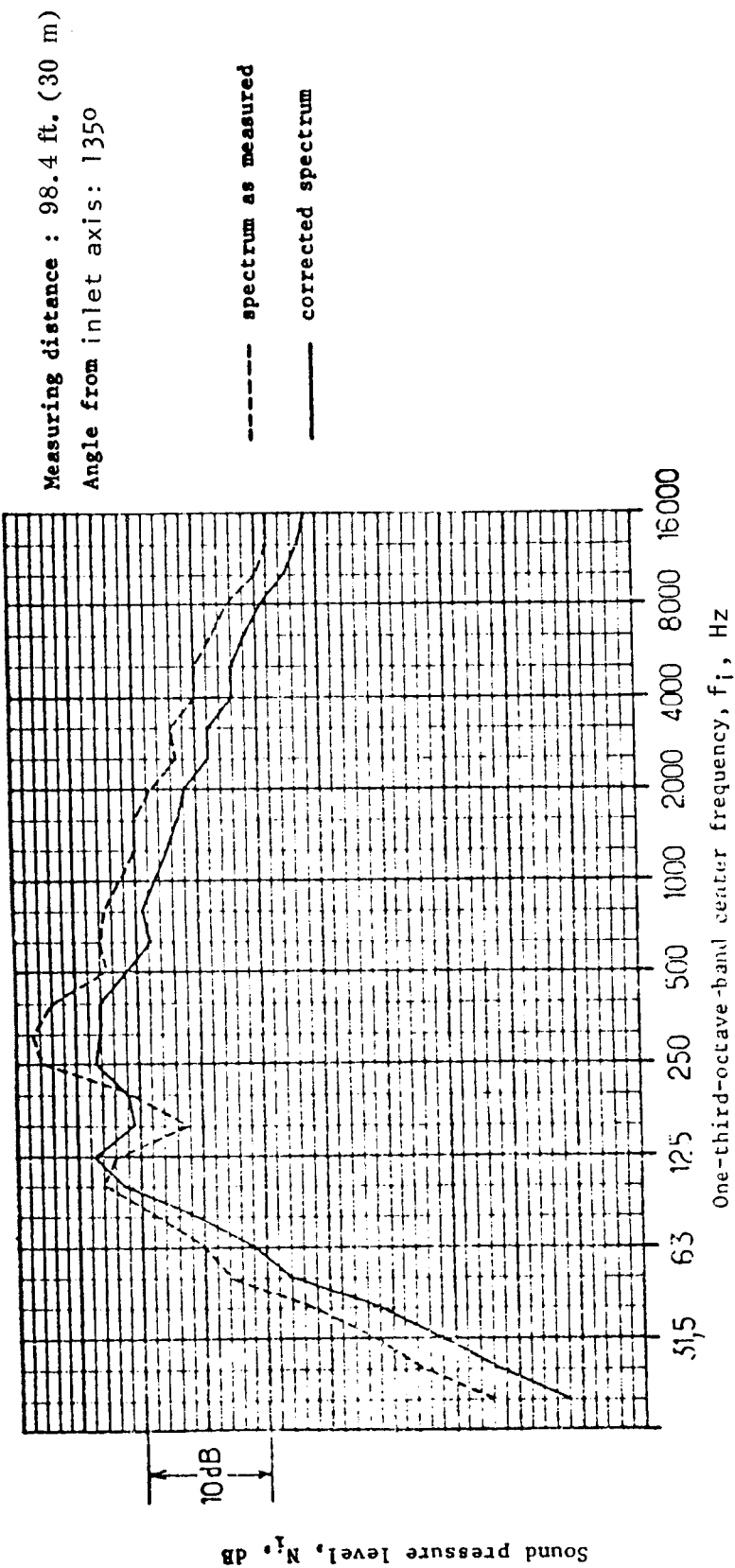


FIGURE A6. EXAMPLE OF SPECTRUM INSUFFICIENTLY CORRECTED BY THE SNECMA METHOD.

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. B1. A second section of concrete was added later to provide for 100 ft (30.48 m) radius testing in the forward quadrant.

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