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RESPONSE MEASUREMENTS FOR TWO BUILDING STRUCTURES EXCITED BY NOISE FROM A LARGE HORIZONTAL AXIS WIND TURBINE GENERATOR

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INTRODUCTION

The noise from large wind turbine generators may, under some conditions, cause building structures to vibrate. These structural vibrations can be observed by occupants of the buildings and thus may be a factor in community reaction (Ref 1). To date only a few data are available as a basis for evaluating the possible environmental impact of wind turbine noise induced building vibrations (Ref 2). In the present study window and wall acceleration measurements were made on two different building structures during excitation by noise from the WTS-4 wind turbine generator (Ref 3). This paper presents these data and compares the results with similar building response data from aircraft and helicopter flyover noise tests and sonic booms.

This effort is part of the Department of Energy wind energy program which is managed by the NASA-Lewis Research Center. The WTS-4 machine was manufactured by the Hamilton Standard Division of United Technologies and is currently operated by the Department of the Interior, Bureau of Reclamation.

APPARATUS AND METHODS

Description of Test Site

Tests were conducted at the site of the WTS-4 wind turbine generator near Medicine Bow, Wyoming (Figures 1 and 2). The site is located in gently rolling open range territory that has an elevation of about 2075 m (6800 ft) above sea level and is remote from airports and highways. There are no trees and only sparse vegetation.

All data reported herein were recorded during the period October 23-25, 1983, between 1000 and 1600 hours; except for the noise data of Figures 13(b) and 14(b) which were recorded on September 12, 1984, between 1000 and 1100 hours. The wind direction varied from 260° to 290°, the wind velocity ranged from 8 to 12 m/s (18 to 27 mph), and the ambient temperature varied from 40° to 60° F.

Descriptions of Buildings

Two structures for which structural response data were obtained are shown in the sketches of Figure 1 and the photographs of Figure 2. One is the Visitor's Center which is designated structure 1. It is a one-story frame building with floor dimensions of about 7.5 X 18 m (24.5 X 60 ft) and is located about 213 m (700 ft) upwind of the WTS-4 machine. It is partitioned to provide an open area in the front and space for the operations staff and the associated monitoring and control equipment in the back. Wall framing construction is believed to be representative of that found in residences with the exception that the ceiling height is 3m (10 ft) and the exterior surface is metal cladding. The test window is .91m X 1.5m (3' X 5') with a 1.9cm (3/4") air space between double panes.

Structure 2 is a conventional house trailer with approximate floor dimensions 3 X 16 m (10 X 52.5 ft) and is located about 275 m (900 ft) upwind of the machine. It is unfurnished and is used for storage of materials. The test window has a single pane with dimensions .61m X .61m (2' X 2').

Acoustic and Vibration Measurements

All noise and vibration measurements were made with commercially available battery powered instrumentation. One half inch diameter condenser microphones with a useable frequency range 3-20,000 Hz were used with an FM four channel tape recorder having a useful range 0-15,000 Hz. Accelerometers with the same types of signal conditioning and recording equipment were used for acceleration measurements.

Simultaneous measurements on tape were made of exterior noise, interior noise, wall accelerations and window accelerations. The magnetic tape records were analyzed with the aid of conventional one-third octave band and narrow band analyzers.

Wind Turbine Acoustic Excitation

Data were obtained while the WTS-4 wind turbine generator was operating in a normal power generation mode. Example spectra of the noise impinging on the two structures are shown in Figures 3 and 4. Figure 3 shows narrow band spectra for frequencies below 100 Hz. The spectra peak at very low frequencies and generally decrease in amplitude as a function of frequency. Some discrete frequency components are present. The tone at 60 Hz is from the electric power generator and the several peaks at very low frequencies which occur at integral multiples of the blade passage frequency (1 Hz) are identified as loading harmonics (Ref 3). At higher frequencies (Figure 4) no discrete frequencies are seen and the spectra are generally broad band in nature. Note that there is some evidence of destructive interference in the frequency range 100 to 800 Hz due to the 1.5m (5 ft) elevation of the microphone above ground level.

RESULTS AND DISCUSSION

Measured data for wall and window responses are included for two different structures. These response data are correlated with the inside and outside noise spectra and the results are compared with published data from aircraft and helicopter flyover noise tests.

Wall Responses

Figures 5 through 9 present data which characterize the accelerations of the walls of the two buildings. Figures 5 and 6 contain reproductions of oscillograph records of sample time histories of the noise inputs and wall acceleration responses. The top time history trace of Figure 5 shows the impinging wind turbine noise at a location 1.5m (5 ft) away from the east wall of structure 1. The bottom trace in Figure 5 is the simultaneous wall acceleration response, as obtained from an accelerometer 1.5m (5 ft) above floor level and midway between the windows.

The acoustic input is seen to consist of a train of pulses having a period of 1.0 second, corresponding to the blade passage frequency (1.0 Hz) of the wind turbine. The acceleration response is also characterized by a corresponding series of pulses. Each pulse is triggered by a noise input pulse and decays in amplitude before the next one occurs. It can be seen that there is general correlation between the amplitudes of the input pulses and the response pulses. This latter result is expected for this type of structure which usually responds in a linear manner.

The detailed structure of the response pulses is much more uniform than that of the input pulses. This result is illustrated in Figure 6 which has an expanded time scale to emphasize some details of the input and response time histories. Even though the two input pulses vary widely in character, the response pulses are similar. They consist of a transient signal having a strong component near 10 Hz which is believed to correspond to the first bending mode of the vertical wall studs. The narrow band response spectrum of Figure 7 shows evidence of some forced responses at frequencies below 10 Hz, the dominant peak near 10 Hz, and other lesser response peaks at higher frequencies.

A comparison of the one-third octave band spectra of the acceleration responses of the walls of structures 1 and 2 is shown in Figure 8. As indicated in Figure 7, the wall of structure 1 has a dominant resonance near 10 Hz and at higher frequencies its response is considerably weaker. On the other hand, the wall of structure 2 has significant higher frequency responses. The responses of structure 2 are noted to be generally higher than those of structure 1 even though its acoustic inputs are lower as seen in Figures 3 and 4. This increased acceleration response is due at least in part to its less massive wall construction.

The data of Figure 9 give a comparison of the measured acceleration amplitudes with those from other available tests. Two large and comprehensive studies are cited. One of these was conducted at Edwards AFB, CA and involved two different houses heavily instrumented for flyover noise tests of military jet aircraft in both landing and take off configurations and for sonic boom tests involving three different sized supersonic aircraft. These latter data are represented by the open triangle and diamond symbols respectively in Figure 9 and are from the unpublished work of D. S. Findley, V. Huckel, H. H. Hubbard and H. R. Henderson and from Ref 4. The second series of tests involved a number of different residential structures near JFK Airport in New York, Dulles Airport in VA, and at Wallops Station, VA which were instrumented for flyover noise tests of a wide variety of commercial jet and propeller airplanes and helicopters. These results are encompassed by the enclosed area of the figure from unpublished data of R. Deloach, K. P. Shepherd, and E. F. Daniels and from Ref 5. All data of Figure 9 are peak quantities either measured directly or estimated based on other information. The line running from lower left to upper right has been added as a guide to interpreting the results. It is anchored at the low end by the data of the enclosed area and it is extended to higher values based on the assumption that buildings respond linearly to acoustic loads in this amplitude range (Ref 4).

The wind turbine excited peak acceleration responses were derived directly from recordings such as those of Figures 5 and 6. The solid data points from the present wind turbine studies are seen to cluster about this line and to be in general agreement with the data of the closed area. The peak acceleration values measured for structure 2 are generally higher than those for structure 1 because of differences in construction.

Window Responses

During these tests window response data were also obtained in a similar manner to the wall data presented above. The window response results generally parallel those for the walls, as seen in Figures 10, 11 and 12.

Figure 10 shows a narrow band spectrum of the acceleration response of the window in structure 1. The dominant response is near 10 Hz which is apparently the fundamental wall resonance. The window is thus responding mainly as a part of the wall. Its own resonances are superposed and are seen to occur at higher frequencies.

One-third octave band response spectra for both windows are shown in Figure 11 for comparison. The structure 2 window is seen to have the greatest response particularly at the higher frequencies as did the wall of structure 2.

The peak acceleration values as determined from recordings of the type shown in Figure 5, are plotted in Figure 12. The data points are for the windows of structures 1 and 2. The highest responses are for the window of structure 2 and are seen to be generally consistent with those for the commercial aircraft study. The data for the window of structure 1 fall low on the figure. A likely explanation for this latter result is that it is a double pane window with 3/4 inch airspace between panes whereas the other data are for single pane windows.

Inside Noise Levels

Figures 13 and 14 show comparisons of the outside and inside noise spectra for structures 1 and 2. The one-third octave data of Figure 13(a) indicate generally lower band levels inside, particularly at frequencies above 100 Hz. At some lower frequencies, however, the sound level differences between inside and outside are seen to be small. Similar results are shown for different microphone locations in Figure 13(b) for structure 1. Note that somewhat different inside spectra are obtained at floor level for structure 1 depending on whether measurements are made in a corner (position D) or near the center of the wall (position E).

The same data are shown in Figure 14 in narrow band form in order to focus on the lower frequencies. It can be seen that the sound pressure levels for some particular frequencies are higher inside than outside. The frequencies at which this occurs appear to correspond to structural vibration modes and to acoustic modes of the inside space (standing waves). It should be noted that the inside microphones were placed adjacent to one or more inside surfaces, where the sound pressure levels of acoustic modes are a maximum. Space averaged measurements would yield lower inside sound pressure levels at these frequencies.

Measured noise level differences due to a structure, such as may be derived from the data of Figures 13 and 14, are also influenced by the placement of the outside microphone. The presence of the ground surface and the wall of the structure results in interference between the direct and reflected sound fields. Thus destructive (and constructive) interference can occur, the details of which will depend on the location of the microphone relative to the reflecting surfaces.

The results of Figures 13 and 14 are influenced by the relative placements of the inside and outside microphones, and for any given test setup a range of sound pressure level differences can be obtained. It follows that localized regions exist in buildings where sound pressure level enhancement (higher than outside levels) may occur for frequencies corresponding to natural structural vibration modes or room standing waves.

CONCLUDING REMARKS

Wind turbine noise input pulses resulted in acceleration pulses for the wall and window elements of two test buildings. Response spectra suggest that natural vibration modes of the structures are excited. Responses of a house trailer were substantially greater than those for a building of sturdier construction. Peak acceleration values correlate well with similar data for houses excited by flyover noise from commercial and military airplanes and helicopters, and sonic booms from supersonic aircraft. Interior noise spectra have peaks at frequencies corresponding to structural vibration modes and room standing waves; and the levels for particular frequencies and locations can be higher than the outside levels.

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2. Kelly, Neil D.: Acoustic Generation by the DOE/NASA MOD-1 Wind Turbine. NASA CP-2185, February 1981.

3. Shepherd, Kevin P. and Hubbard, Harvey H.: Measurements and Observations of Noise From a 4.2 Megawatt (WTS-4) Wind Turbine Generator. NASA CR 166124, May 1983.

4. Hubbard, Harvey H.: Noise Induced House Vibrations and Human Perception. Noise Control Engineering Journal, September/October 1982.

5. Stephens, D. G. and Mayes, W. H.: Aircraft Noise-Induced Building Vibrations. ASTM Special Technical Publication 692, May 1978.

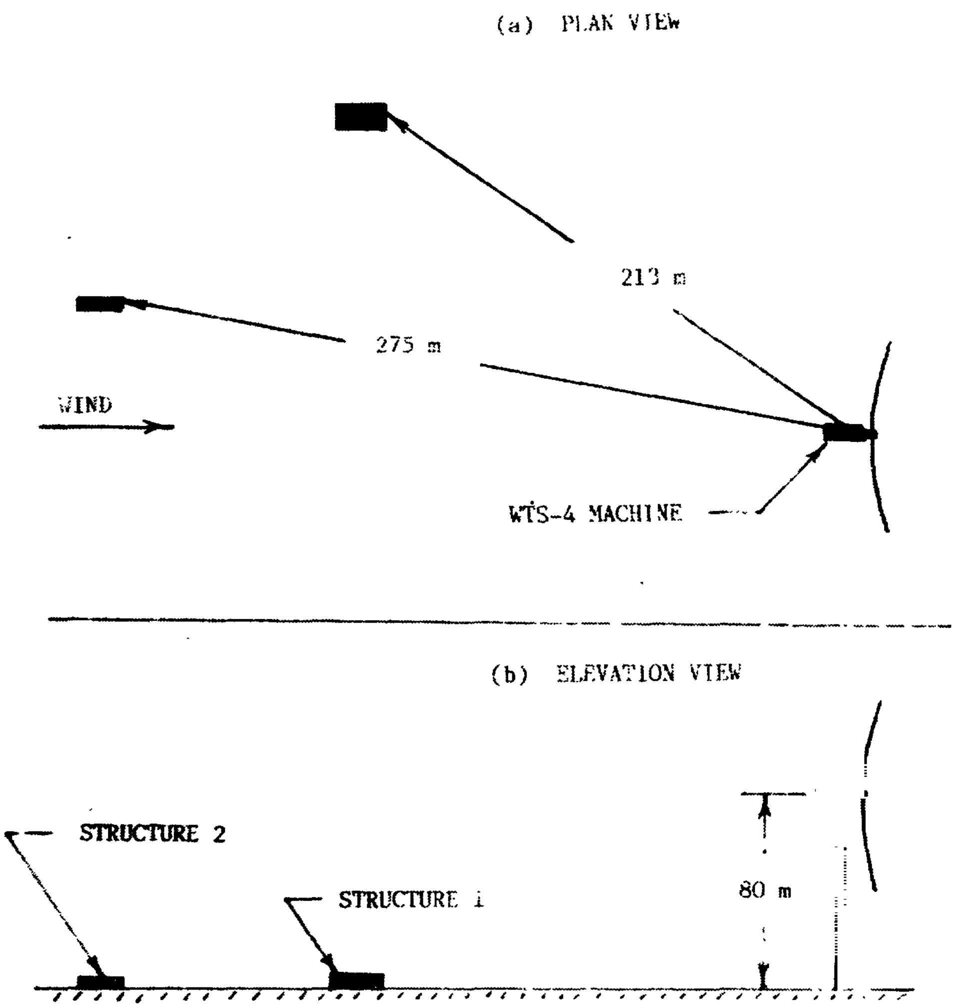
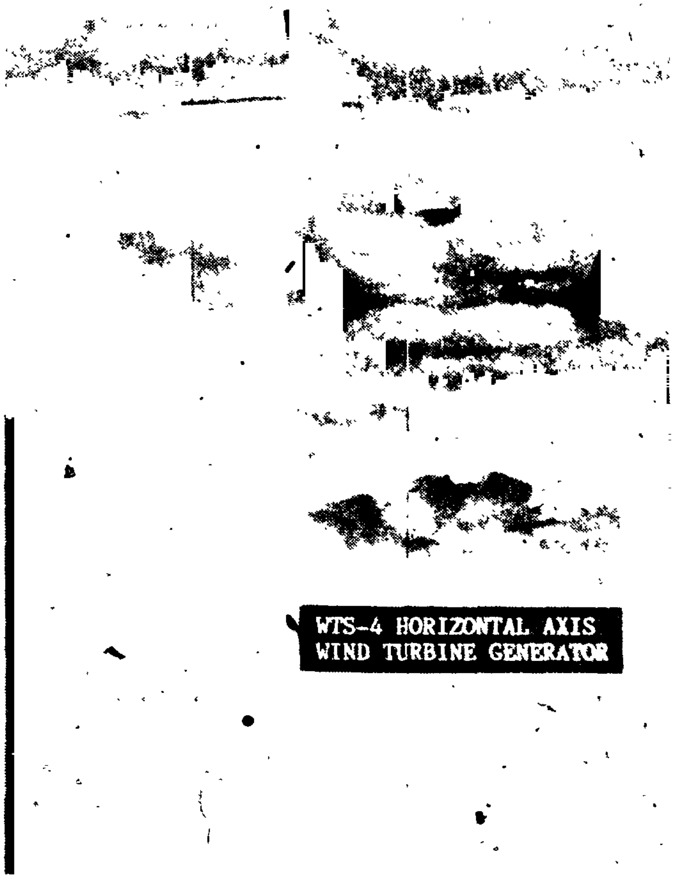


FIGURE 1. LAYOUT OF THE TEST AREA SHOWING RELATIVE POSITIONS OF THE WTS-4 MACHINE AND THE TEST STRUCTURES.



WTS-4 HORIZONTAL AXIS WIND TURBINE GENERATOR

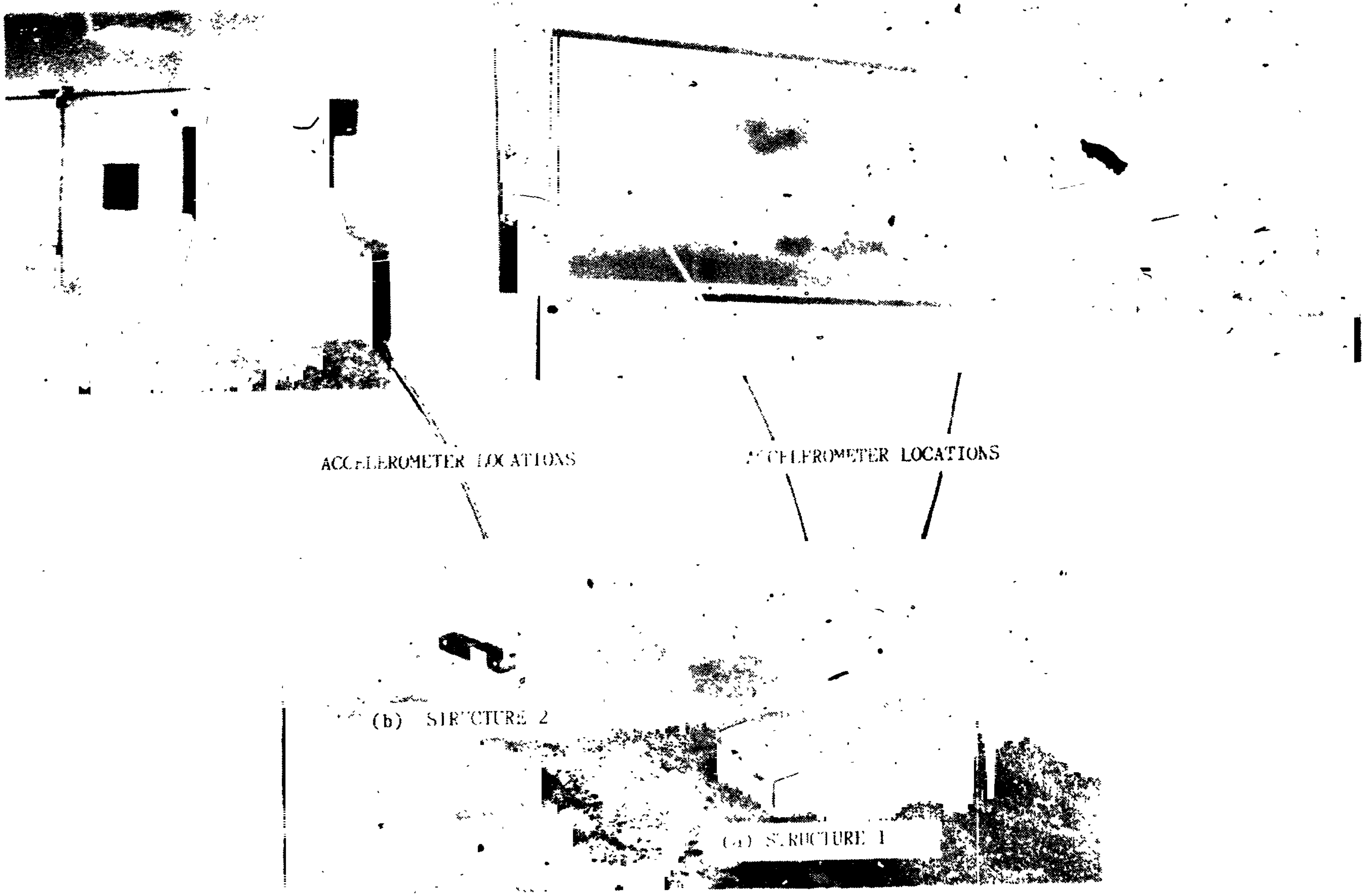


FIGURE 2. PHOTOGRAPHS OF THE TWO STRUCTURES FOR WHICH ACCELERATION RESPONSE DATA WERE OBTAINED.

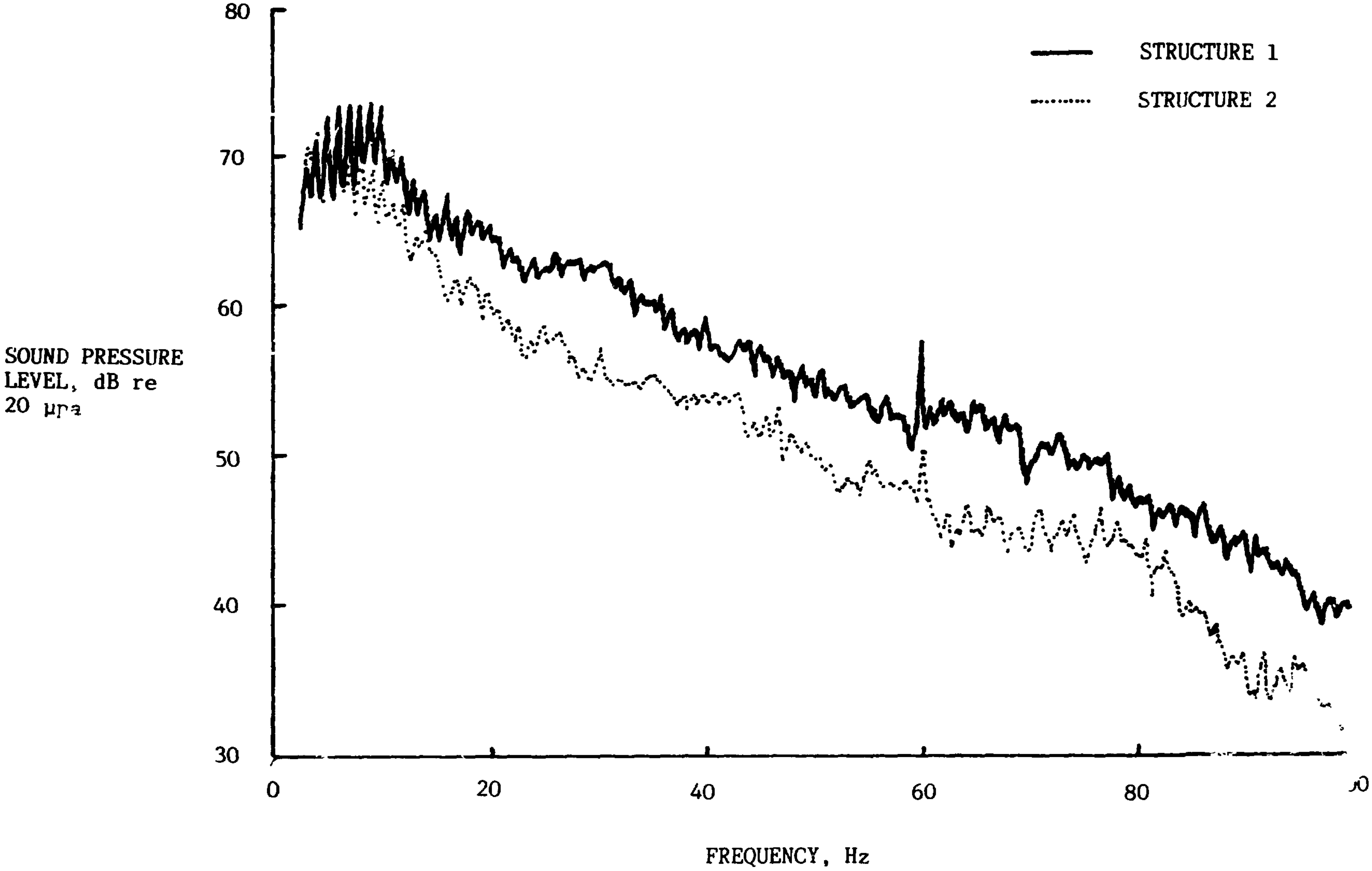


FIGURE 3. NARROW BAND (Δf = 0.25 Hz) ACOUSTIC INPUT SPECTRA FOR THE TWO TFST STRUCTURES.

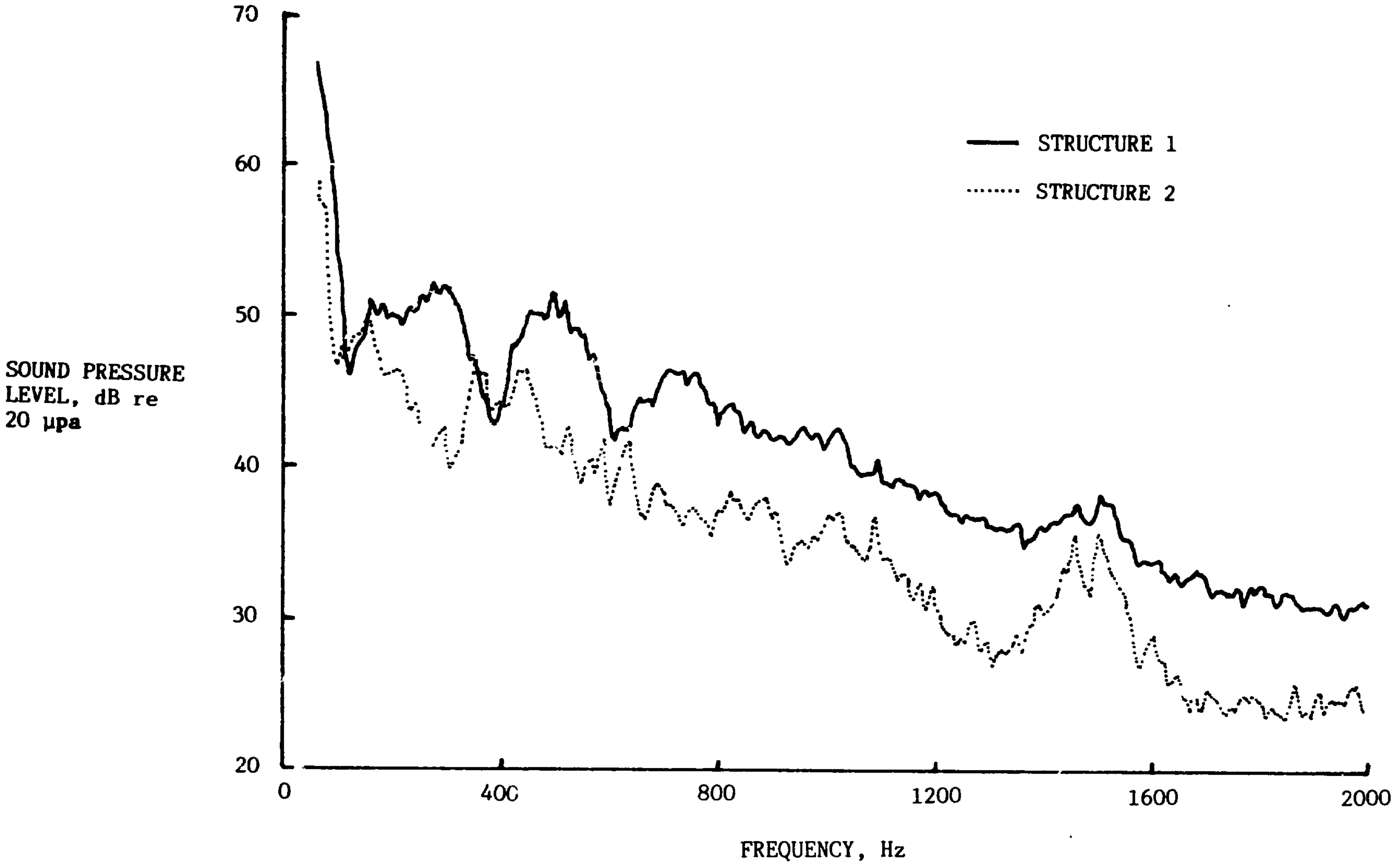
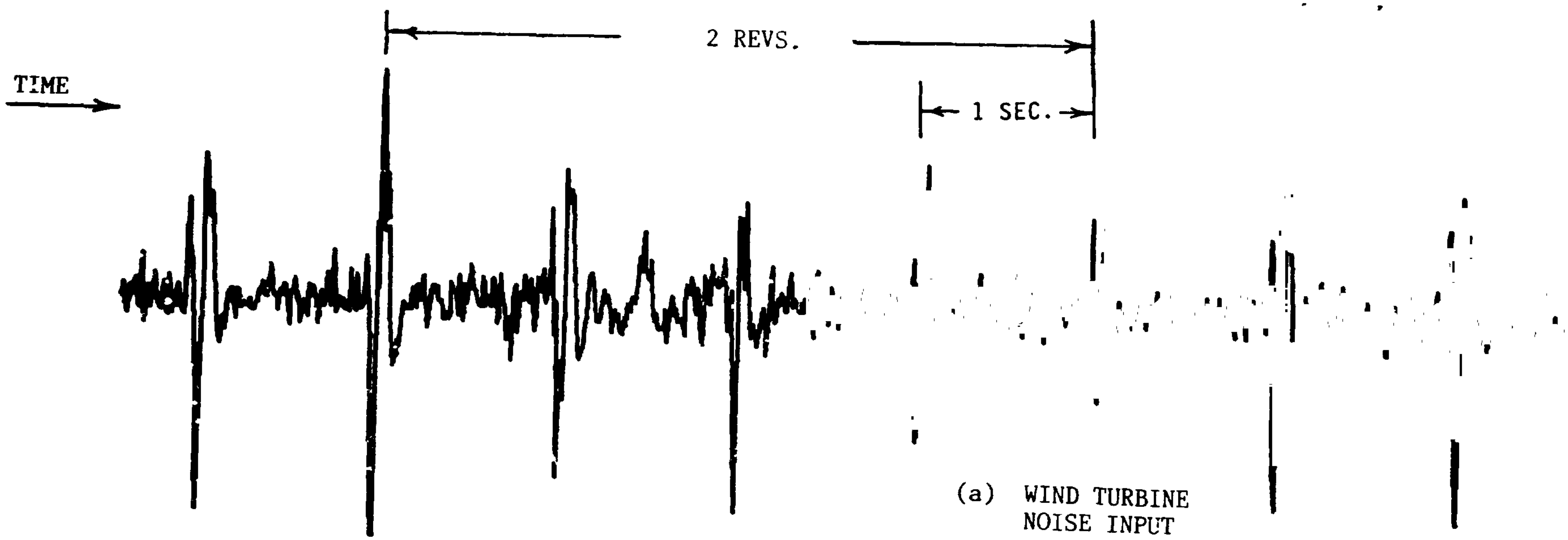
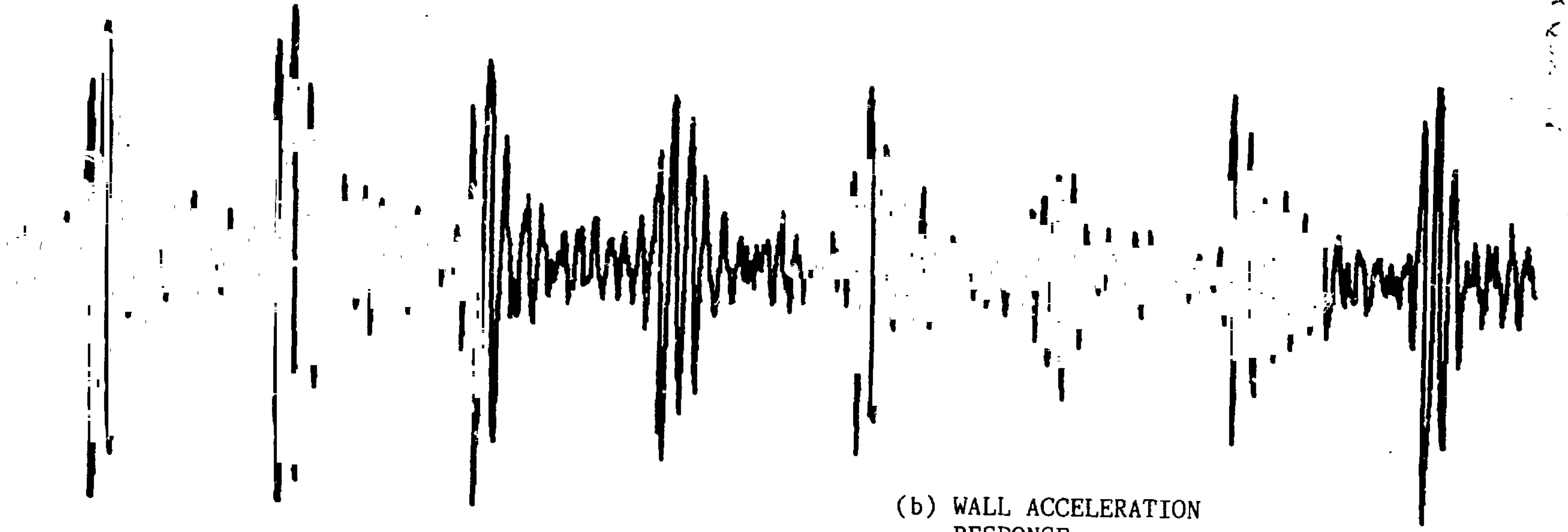


FIGURE 4. NARROW BAND ($\Delta f = 2.5$ Hz) ACOUSTIC INPUT SPECTRA FOR THE TWO TEST STRUCTURES.

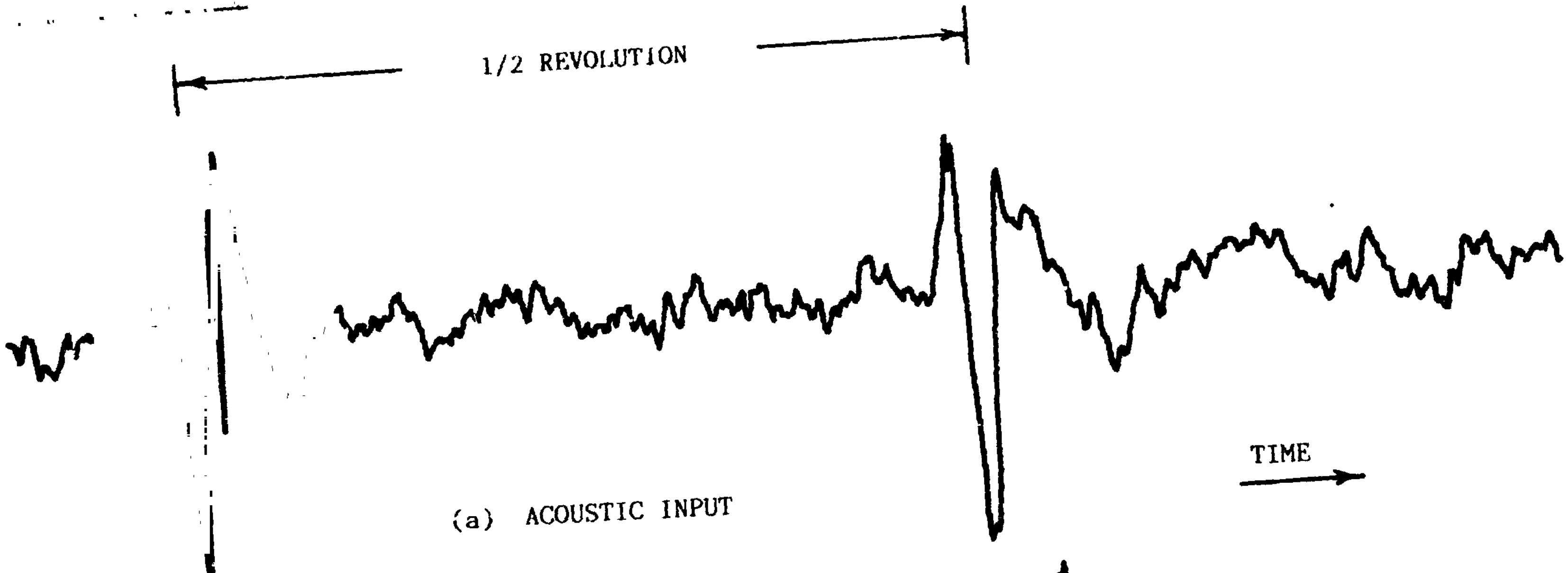


(a) WIND TURBINE NOISE INPUT

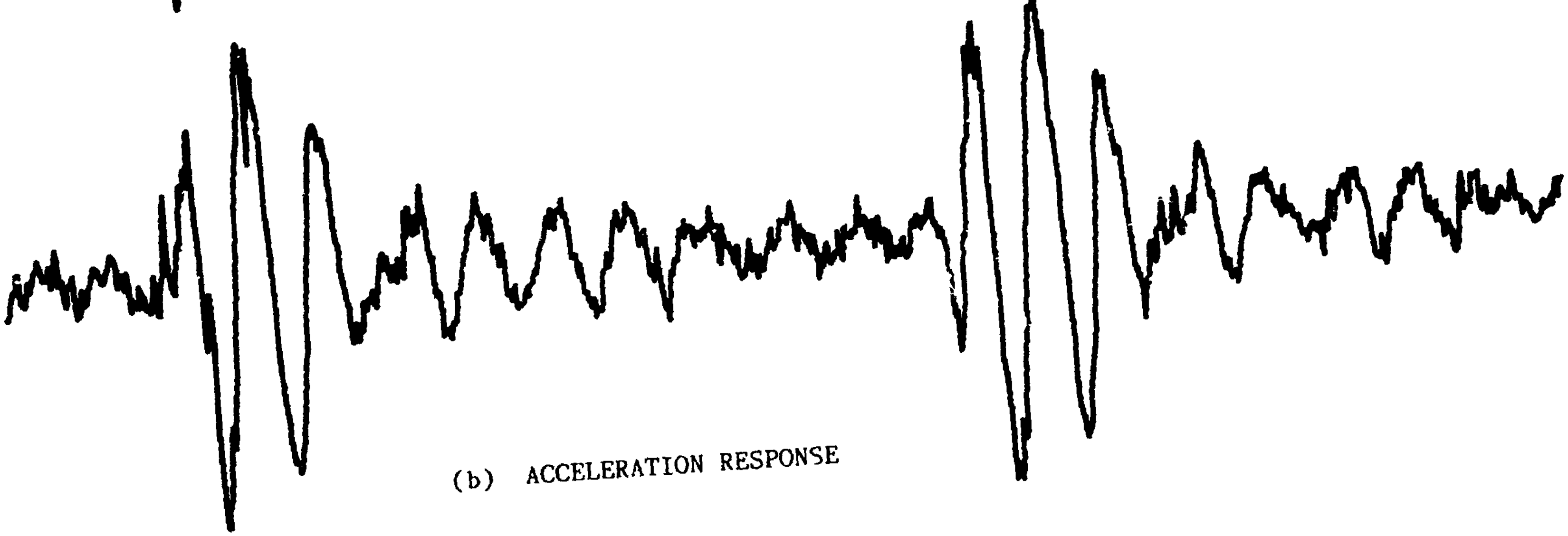


(b) WALL ACCELERATION RESPONSE

FIGURE 5. SIMULTANEOUS OSCILLOGRAPH RECORDINGS OF THE WIND TURBINE NOISE INPUT AND THE ACCELERATION RESPONSES OF THE WALL OF STRUCTURE 1.



(a) ACOUSTIC INPUT



(b) ACCELERATION RESPONSE

FIGURE 6. ACCELFRATION RESPONSE OF THE EAST WALL OF STRUCTURE 1 DUE TO ACOUSTIC EXCITATION BY THE WTS-4 WIND TURBINE GENERATOR.

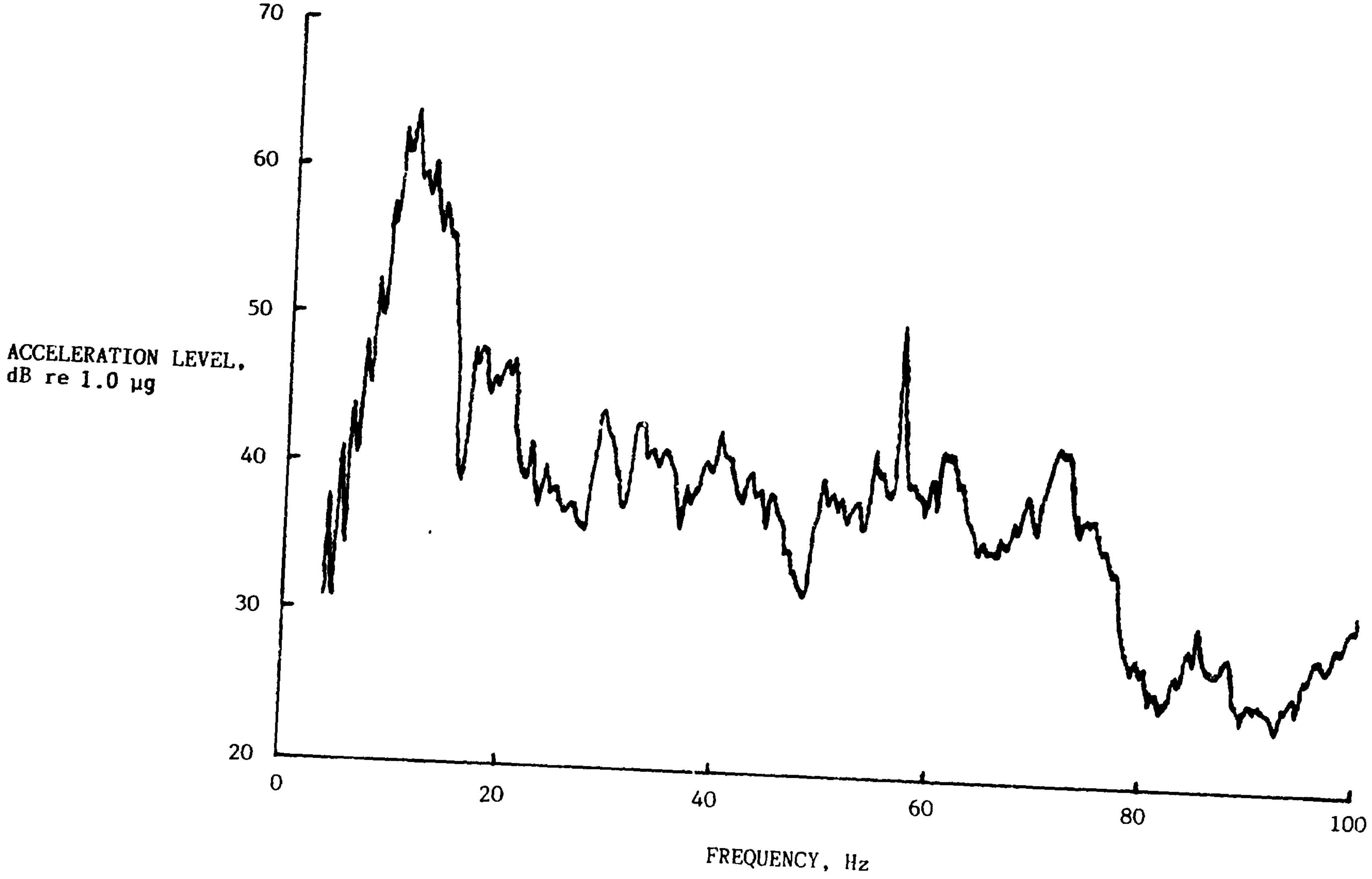


FIGURE 7. NARROW BAND ($\Delta f = 0.25$ Hz) WALL ACCELERATION RESPONSE SPECTRUM FOR STRUCTURE 1 DUE TO ACOUSTIC EXCITATION FROM THE WTS-4 WIND TURBINE GENERATOR.

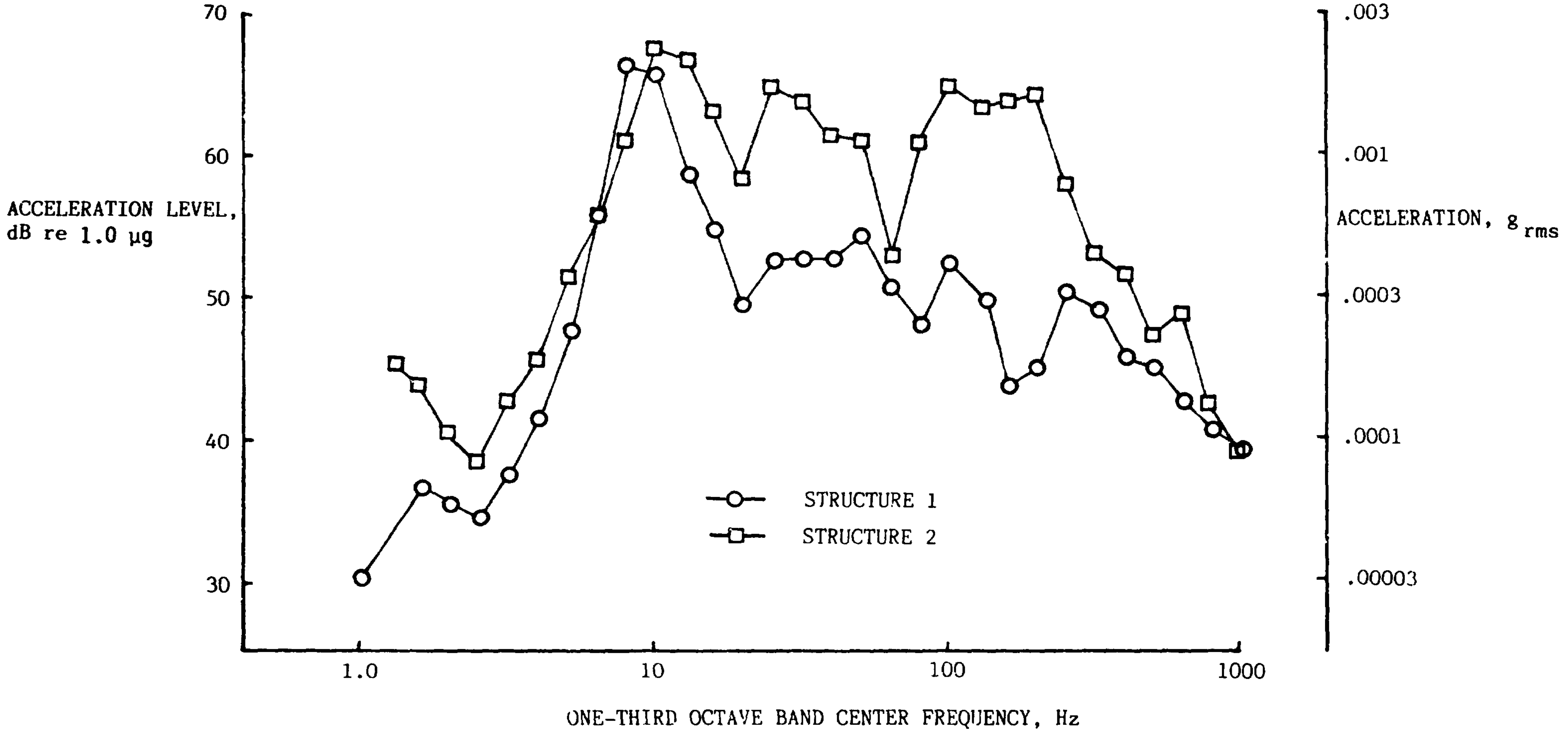


FIGURE 8. ONE-THIRD OCTAVE BAND SPECTRA OF THE ACCELERATION RESPONSES OF THE WALLS OF STRUCTURES 1 AND 2.

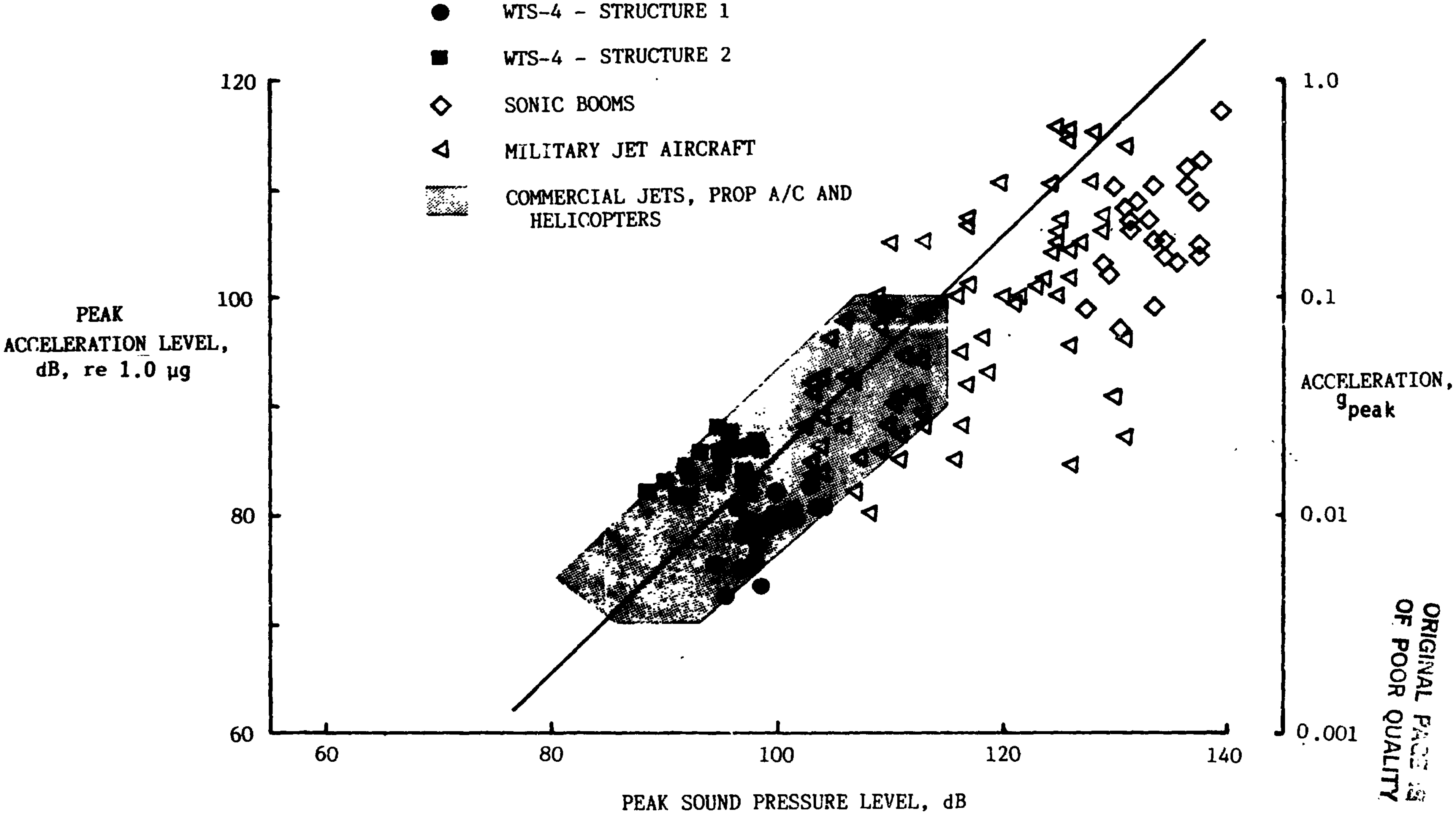


FIGURE 9. PEAK WALL ACCELERATION RESPONSES AS A FUNCTION OF PEAK SOUND PRESSURE LEVEL OF THE OUTSIDE NOISE EXCITATION.

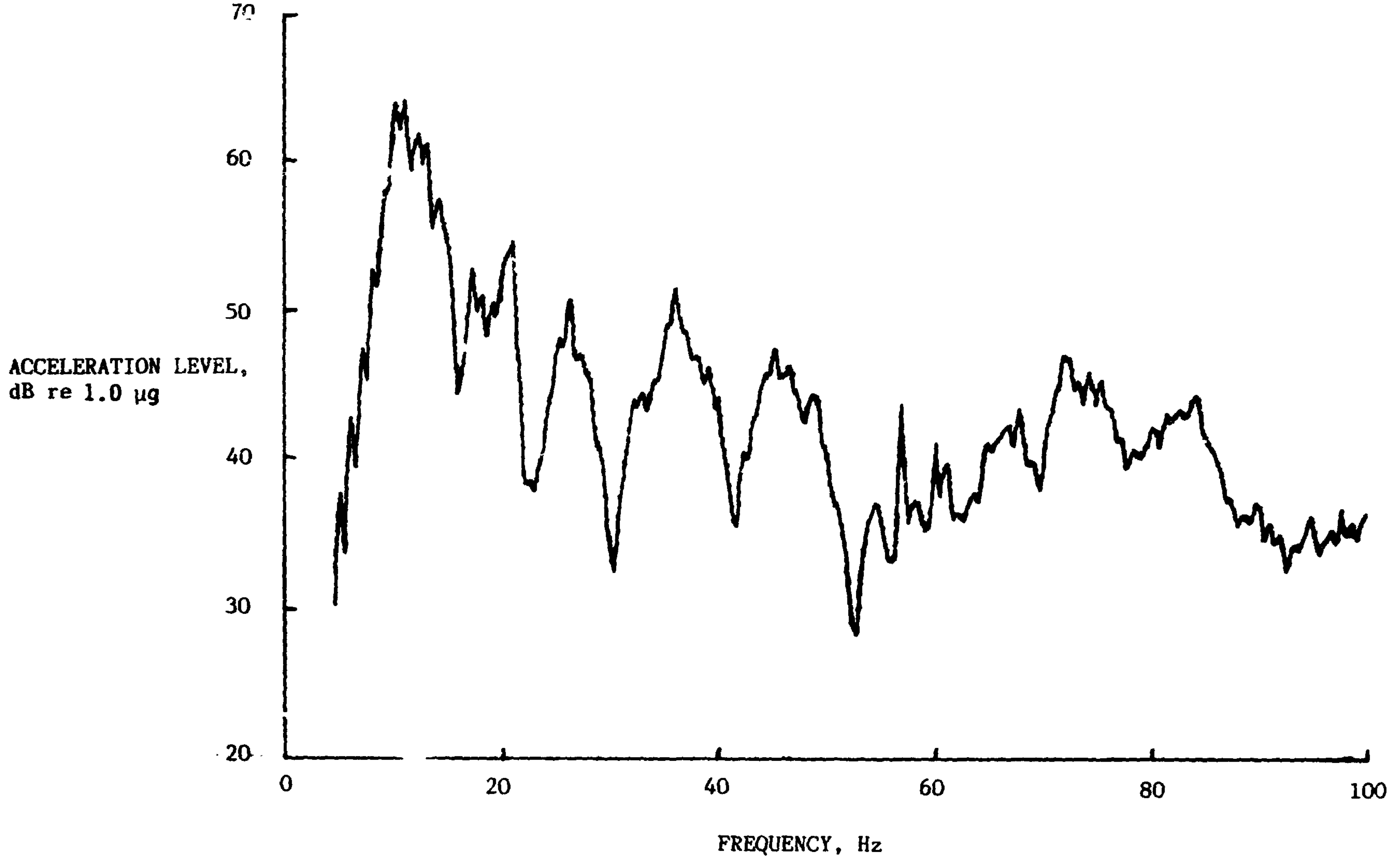


FIGURE 10. NARROW BAND (Δf = 0.25 Hz) WINDOW ACCELERATION RESPONSE SPECTRUM FOR STRUCTURE 1 DUE TO ACOUSTIC EXCITATION FROM THE WTS-4 WIND TURBINE GENERATOR.

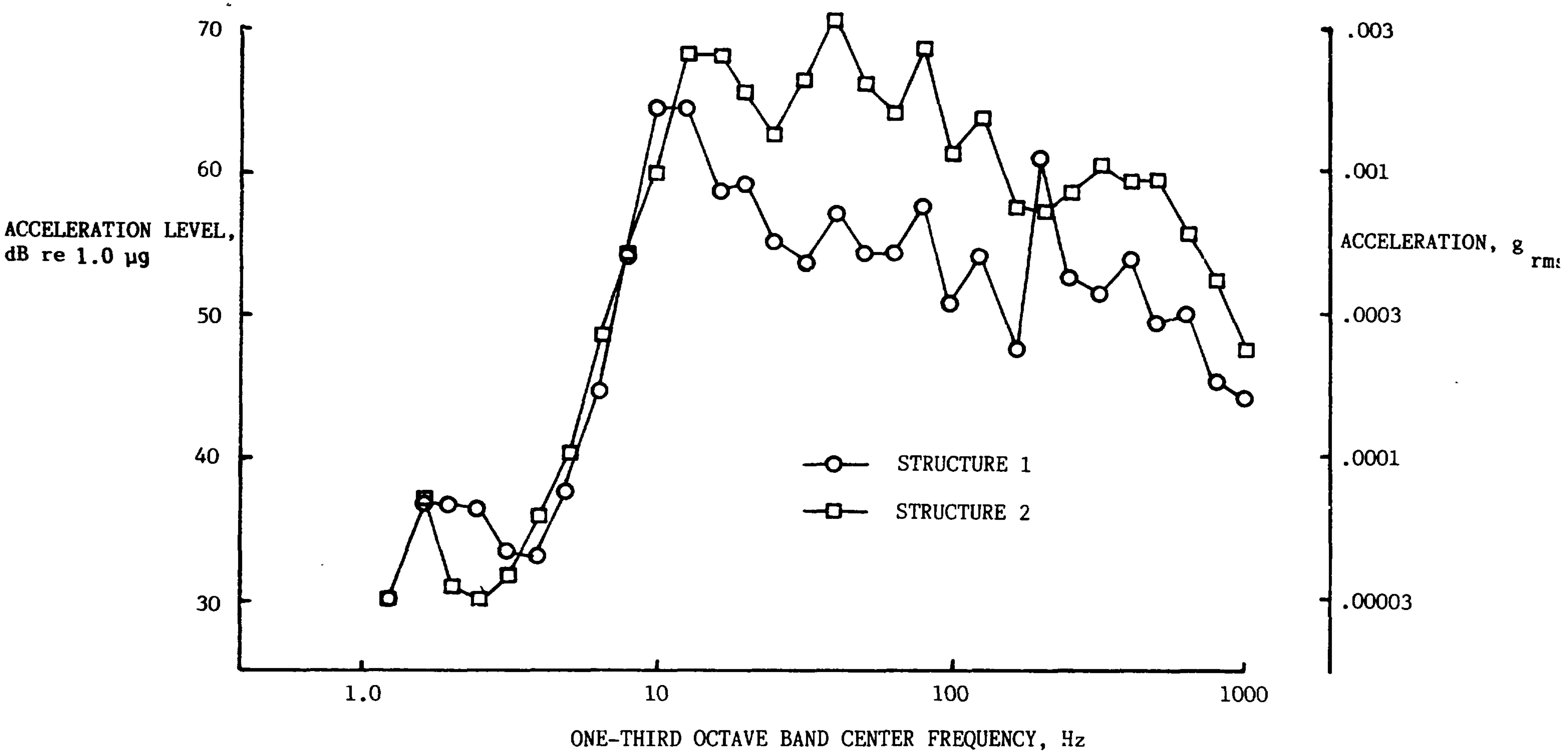


FIGURE 11. ONE-THIRD OCTAVE BAND SPECTRA OF THE ACCELERATION RESPONSES OF THE WINDOWS OF STRUCTURES 1 AND 2.

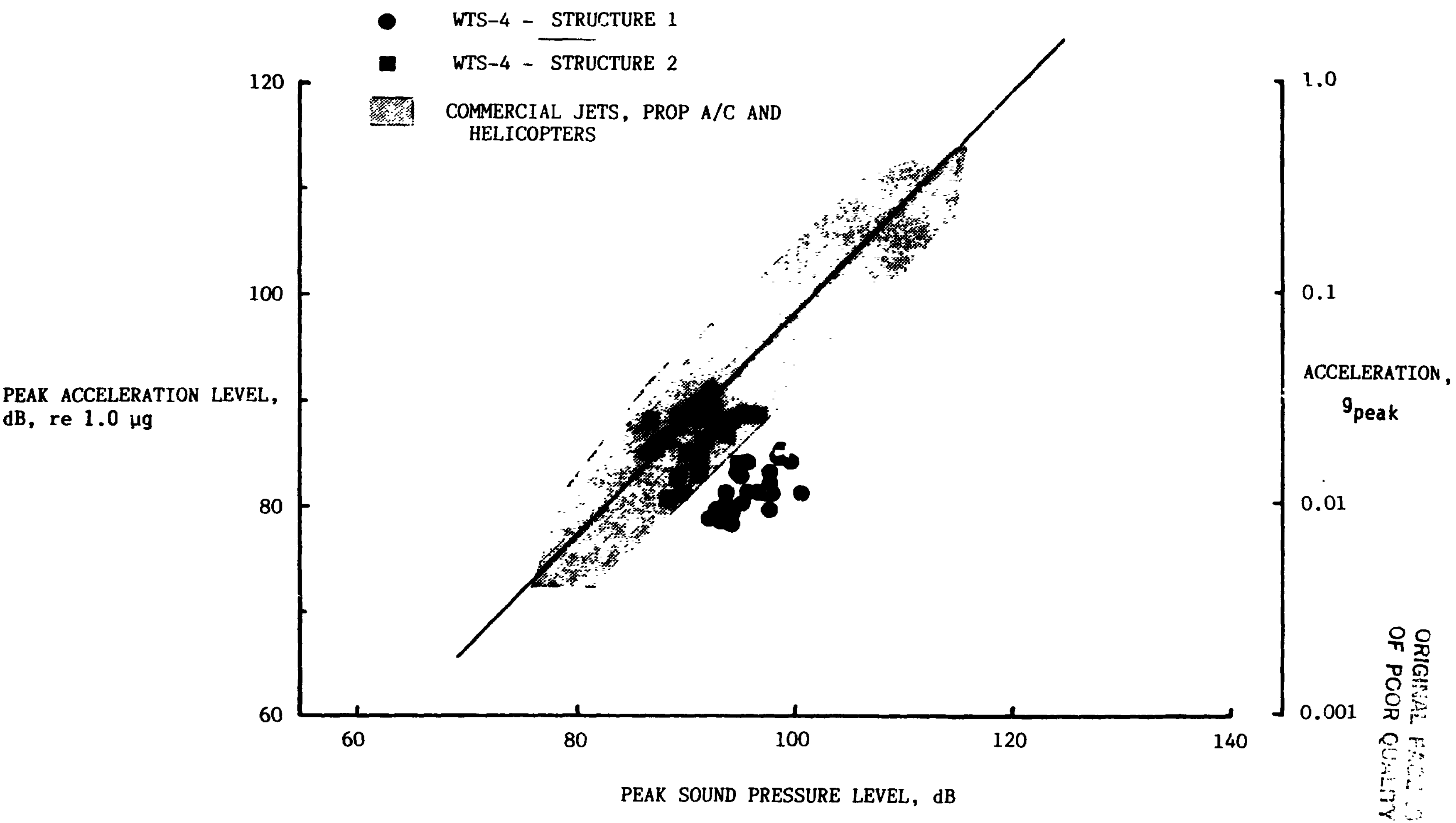


FIGURE 12. PEAK WINDOW ACCELERATION RESPONSES AS A FUNCTION OF PEAK SOUND PRESSURE LEVEL OF THE OUTSIDE NOISE EXCITATION.

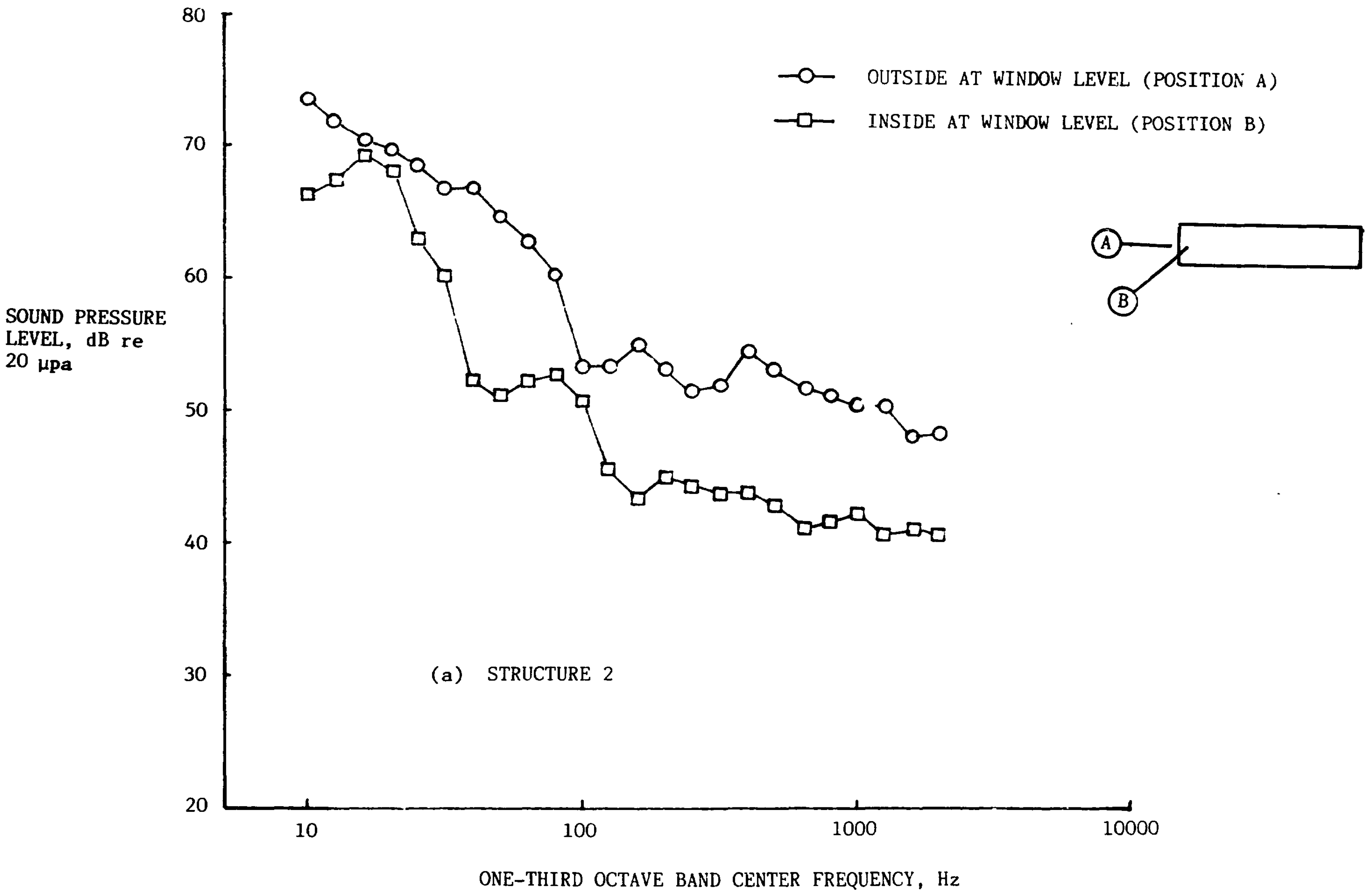


FIGURE 13. MEASURED ONE-THIRD OCTAVE BAND NOISE SPECTRA OUTSIDE AND INSIDE OF TWO TEST STRUCTURES DUE TO WIND TURBINE OPERATIONS.

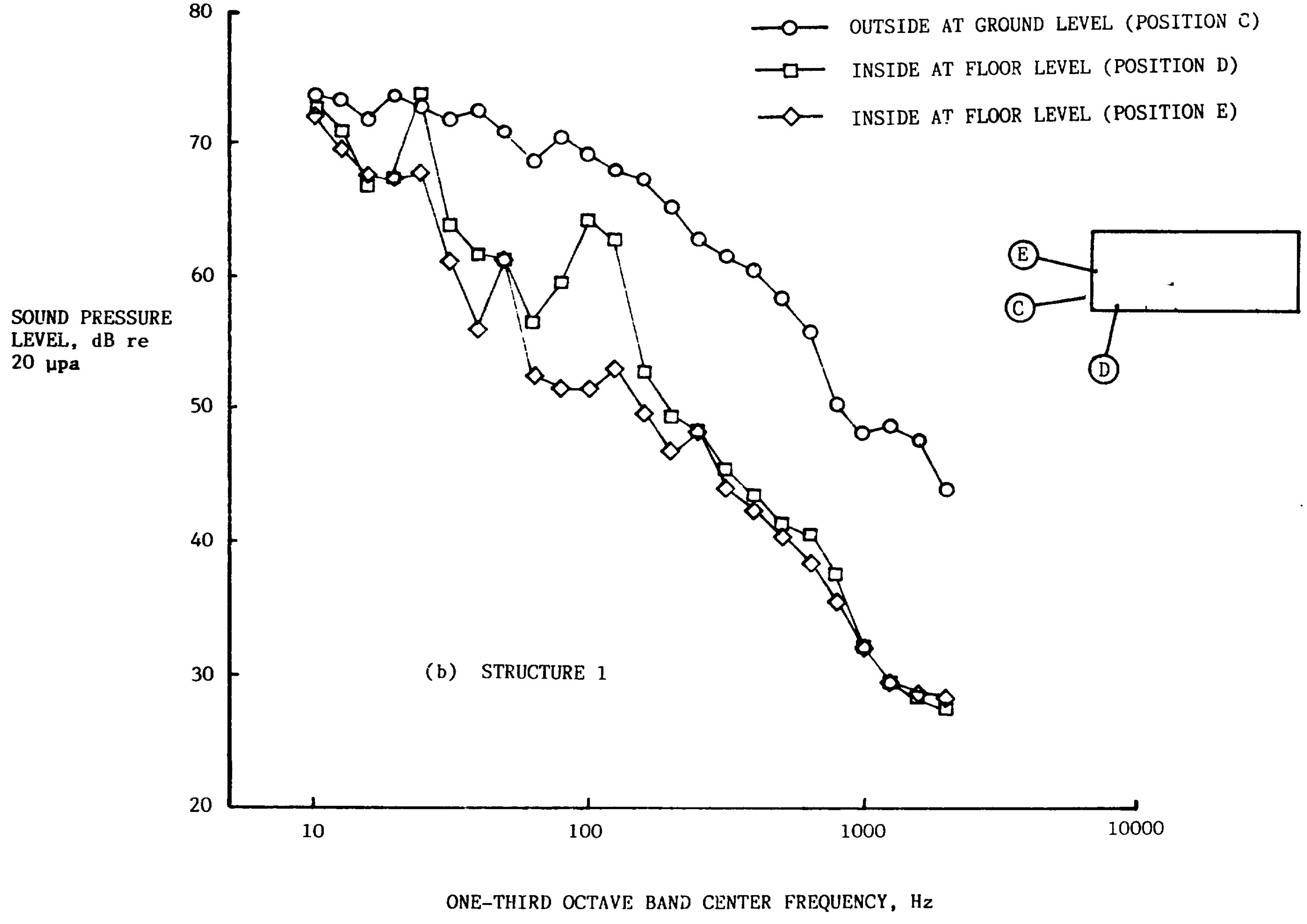


FIGURE 13. (CONCLUDED).

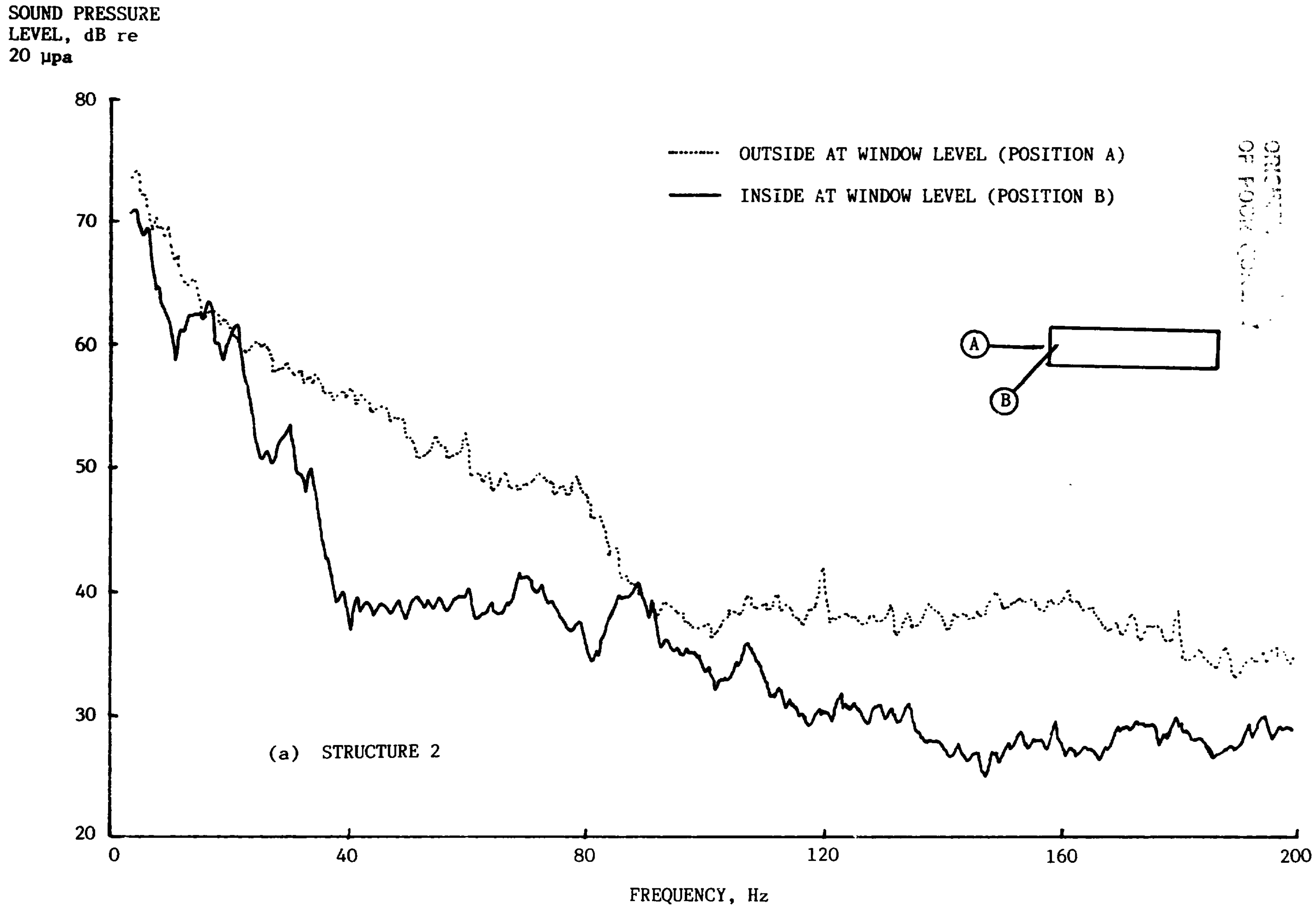


FIGURE 14. MEASURED NARROW BAND (f = 0.5 Hz) NOISE SPECTRA OUTSIDE AND INSIDE OF TWO TEST STRUCTURES DUE TO WIND TURBINE OPERATION.

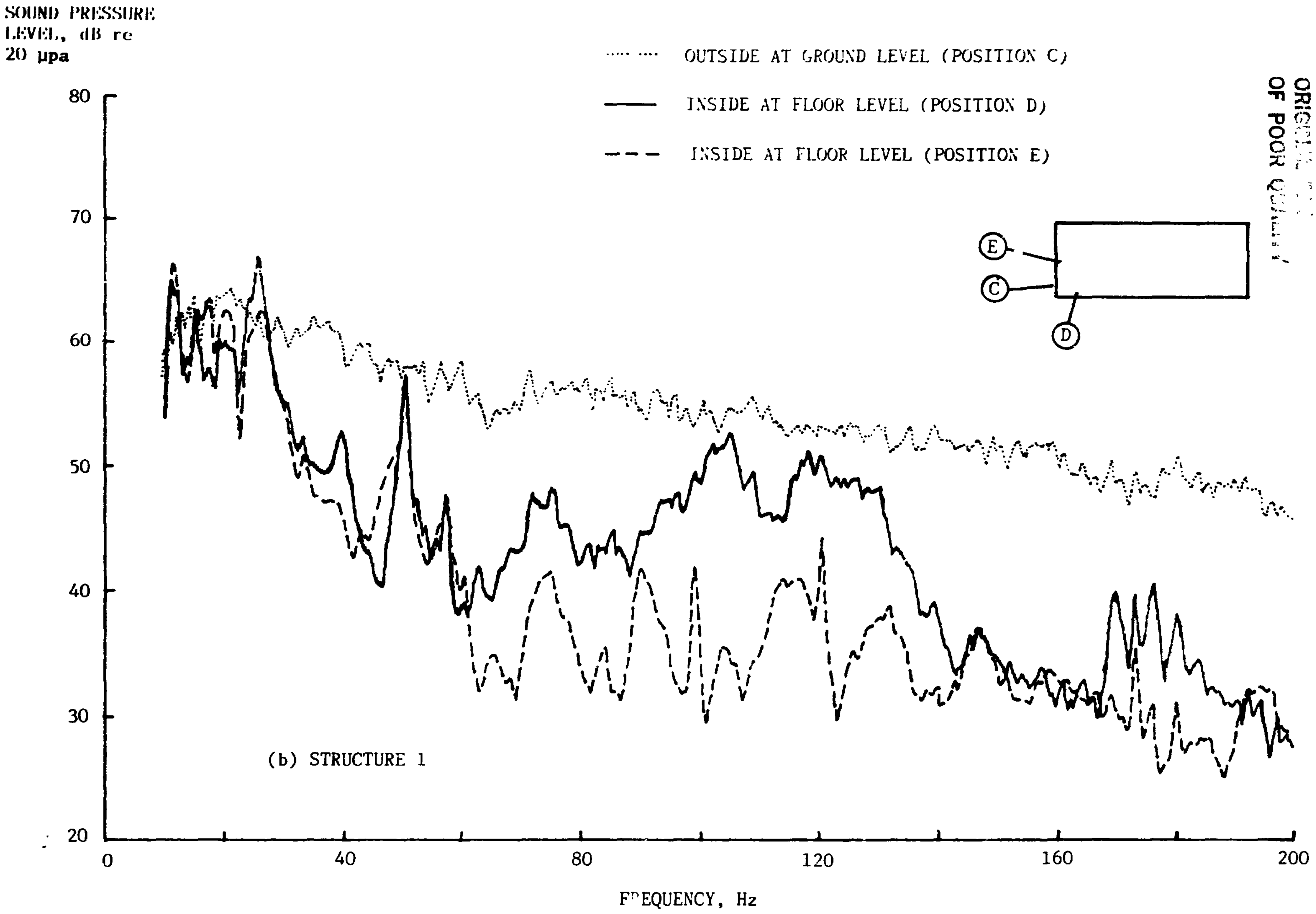


FIGURE 14. (CONCLUDED)