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SOUND MEASUREMENTS AND OBSERVATIONS OF THE MOD-OA WIND TURBINE GENERATOR

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by

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INTRODUCTION

Horizontal axis wind turbines having a power rating in the range 100-2000 kW are of widespread interest for generation of electrical power. A number of experimental machines are in operation to demonstrate the state of technology and to gain operational experience in typical utility environments. Noise is of concern for these machines because of the desire to locate them near populated areas. Exploratory noise data are presented in Ref. 1 for a 2-bladed 100 kW machine having both full span and part span wooden blades and an rpm range from 26 to 40. Narrowband and broadband noise data are presented for various azimuth angles and distances.

The purpose of this paper is to present the results of an experimental study of the sound of the MOD-OA wind turbine generator under steady state operating conditions and normal ranges of ambient temperature, wind velocity and output power. These results represent an extension of the MOD-0 data of Ref. 1 to a machine having similar nacelle and tower configurations but with full span fiberglass composite blades, and located at a different operational site.

This effort is part of the Department of Energy Wind Energy Program which is managed by the NASA Lewis Research Center. The MOD-OA machine was built under contract to NASA by the Westinghouse Manufacturing Company and the municipal utility selected to participate in the operational portion of the program is owned by the town of Clayton, New Mexico.

APPARATUS AND METHODS

Description of Site

The MOD-OA machine for which data are presented is located near Clayton in the northeast corner of New Mexico (Figure 1). Clayton is in the high plains region at an elevation of about 1500 m. The terrain is gently rolling grassland with essentially no trees. The wind turbine generator site (see photo insert of Figure 1) is on the outskirts of Clayton near a local park and fair grounds complex, and about 500 m from the nearest residences. A main highway is located about 1500 m north and a heavily traveled single track railroad is about 1000 m to the east. Land to the west and south is sparsely populated.

Description of Wind Turbine Generator

An appreciation for the size and configuration of the MOD-OA machine can be obtained from inspection of the insert photo and sketch of Figures 1 and 2. It has a 38.1 m diameter rotor mounted downwind on a 30.5 m high four legged tower built of pipe trusses. The rotor has two fiberglass blades which rotate at 40 rpm. The tapered blades have a thickness to chord ratio near the root of 30 percent and a thickness to chord ratio at the tip of 12 percent. They have a 10° twist angle and are pitch controlled at the root. The machine is designed to cut-on at a wind speed of about 4.5 m/s and to cut-off at about 15 m/s. At a wind speed of about 6 m/s the rated power output is 200 kW. Output power is fed into the Clayton Electric Power Grid which has about a 3800 kW capacity. The data in this paper were obtained under conditions of 5 m/s wind velocity, an ambient temperature of about 40° F and a power output of about 70 kW.

Sound Measurements and Observations

All sound measurements were made with commercially available battery powered instrumentation. One half inch diameter condenser microphones with a usable frequency range of 3 to 20,000 Hz were used with two different tape recording systems. One of the systems included a two channel direct recording machine which provides a useful dynamic range of about 100 dB in the frequency range from 25 Hz to 20,000 Hz. This system provided the high dynamic range needed for direct playback in subjective listening tests. The other system included an FM four channel recorder having a useful dynamic range of about 40 dB in the frequency range from 0 to 15,000 Hz. This FM system provided the recordings from which the data of this paper were obtained. For some recordings the microphone signals to both recorders were C-weighted in an attempt to more effectively utilize the available dynamic ranges. Sound pressure level measurements were also taken with a precision sound level meter on the linear scale as well as on A-, B- and C-weighting networks.

Data were obtained for distances up to about 122 m (400 ft.) and at various azimuth angles between 0° (on axis upwind) and 315°. The measurement locations for tape recordings are shown in Figure 2. Sound level meter readings were also obtained at all locations shown at distances of 30.5 and 61 m. Sound spectral data were obtained with the aid of one-third octave band and narrow band analyzers, and by means of a recording oscillograph with high frequency galvanometers. To minimize the detrimental effects of wind noise, polyurethane foam microphone wind screens were used and microphones were placed on the ground surface, where wind velocities were relatively low.

Attempts were made to observe the far field radiation patterns and spectra during routine operations in order to define the extent to which the wind turbine noise is detectable above the background noise upwind, downwind and to the side of the machine.

RESULTS AND DISCUSSIONS

Sound pressure data contained herein were obtained from listening observations, from precision sound level meters, and from FM tape recordings. Data are presented in the form of instantaneous pressure time histories, narrowband spectra, one-third octave band frequency spectra and overall linear, A-weighted, B-weighted and C-weighted levels.

Figure 3 contains data obtained by means of sound level meters for an azimuth circle at a distance of 30.5 m and for the linear, A-weighted, B-weighted and C-weighted networks respectively. All of the overall level data are plotted as a function of azimuth angle. Lower levels are seen to be associated with A-scale and B-scale readings. This result indicates that the sound spectra must contain substantial low frequency components. Furthermore, there are dips in all the curves at the 90° and 270° azimuth angles (in the plane of rotation) and peaks at the 0° (360°) and 180° azimuth angles which are in the direction of the axis of rotation. Data obtained at a distance of 61 m show the same trends. These latter results suggest that the sound radiation from the machine is a maximum along the axis of the rotor and is a minimum in the plane of the rotor.

These findings are further illustrated by the one-third octave band spectra of Figure 4. Data are presented at azimuth angles (with respect to the wind) of 90°, 135° and 180°. Also shown is a spectrum of background noise associated with a wind velocity just below the cut-on value. Only small differences are seen between the spectra at 135° and 180°, however they both have consistently higher levels in the audible range of frequencies than does the spectrum at 90°. Of particular interest are the broadband peaks at about 1000 Hz and 10,000 Hz respectively.

The noise at about 10,000 Hz is easily observable while the machine is in normal operation. It has the character of squeaks and is believed to be mechanically generated in the nacelle region. Inspection of the recorded tape signals indicated that these squeak components were amplitude modulated at a frequency corresponding to the rotor rotational speed.

The components at about 1000 Hz are believed to arise from the interactions of the turbulent boundary layers on the blades with their trailing edges. These components are readily audible during normal operations and tend to characterize the acoustic signature of the machine. A distinguishing feature of the sound is that it is amplitude modulated at a frequency corresponding to the blade passage frequency as illustrated in Figure 5.

The data of Figures 5 and 6 were obtained at the point nearest to the rotor (Figure 2) as an aid in interpreting the data at the more remote measuring points. The microphone used for these measurements was at ground level in the plane of rotation and within about 11.5 m of the blade tip. Shown in Figure 5 is an instantaneous time history trace of the sound pressures in the one-third octave band having a center frequency of 1250 Hz. The signal is seen to be amplitude modulated at the blade passage frequency (1.33 Hz). It can also be seen that the amplitudes associated with blade A are noticeably higher than those associated with blade B. These differences are observable during tape playback for numerous field points but are most obvious for the points nearest the rotor. This result suggests that the aerodynamic flow conditions near the tips may differ somewhat for the two blades but the cause of the phenomenon has not been identified. The effect is further quantified in Figure 6.

Shown in Figure 6 are two narrowband (5 Hz) spectra derived from analyzing the blade A and blade B pulses of Figure 5. This was accomplished by use of a trigger signal which enabled samples of 0.2 seconds duration to be taken at the maximum amplitude of the signal for each blade (Figure 5). Sixteen blade passages, yielding a total sample time of 3.2 seconds, were used to determine a spectrum for each blade. It can be seen from comparing the two traces that the amplitudes for blade A exceed those for blade B over a wide frequency range. As noted in the discussion for Figures 4 and 6 and from monitoring tape playbacks there is no evidence of the presence of discrete components at frequencies above 100 Hz. A number of discrete components were identified at lower frequencies, however, as indicated in Figure 7.

Results are shown in Figure 7 for narrowband (1 Hz) analyses at the 90° and 180° azimuth angles at a distance of 30.5 m. Discrete frequency components are seen in both spectra. However, the levels are about 5 to 15 dB lower for the 90° (in plane of rotation) location. The spectral peaks at 30,60 and 90 Hz are not very sensitive to changes in direction and are believed to be associated with the electrical power generating equipment. The large number of closely spaced peaks below 30 Hz are the blade loading harmonics which occur at integral multiples of the blade passage frequency. Note that no attempt has been made to compensate for the low frequency roll off of the microphone equipment. The generally lower levels in the plane of rotation correlate well with the data of Figure 3 and with a large number of observations.

During observations, a low frequency thumping (at blade passage frequency) could sometimes be detected. It was most clearly observed close to the machine and on the axis of rotation either upwind or downwind of the tower. This thumping could not be detected in or close to the plane of rotation either during observations of the machine or during playback of the tapes.

COMPARISONS WITH OTHER DATA

The opportunity is taken to compare the measurement results of these tests with the data for a similar machine, MOD-0 (Ref. 1). The MOD-0 machine had wooden blades of slightly different plan form while all other conditions were nearly the same.

Comparisons of measured A-scale levels at three different distances are given in Figure 8. The MOD-0 data points are long term average values obtained from tape playbacks. The MOD-0A data represent short term readings from the fast response mode of the sound level meter for signals of the type illustrated in Figure 5. There is generally good agreement between the two sets of data. The wider variation in levels noted for the MOD-0A data probably results from the different data processing procedure.

Further comparisons of the MOD-0 and MOD-0A results are given in Figure 9. Narrowband (1 Hz) spectra for three distances on the axis of rotation are reproduced from Ref. 1 for the MOD-0 machine. The data points represent spectral levels at selected frequencies for the MOD-0A machine. It can be seen that the data points follow the trends of the solid curves and the levels are in good agreement. There are thus no significant differences in the sounds from the two machines due to differences in the rotor blade geometry.

OBSERVED DETECTION THRESHOLDS

Some observations are summarized herein to indicate the approximate distances at which the wind turbine generator could be detected aurally above the background noise. These results are shown in Figure 10. All of the data relate to a wind velocity of about 5 m/s and to gently rolling terrain with a thin grass cover and no trees. The data points represent individual observations at distances where only intermittent detection was possible. The position of the dashed curve is estimated based on the available observations. Although no frequency analyses were performed for the larger distances it is observed that the broadband sound centered at about 1000 Hz characterizes the acoustic signature.

The detection distances are greater downwind of the machine than upwind even though the close-in measurements of Figure 3 at equal distances indicate nearly equal levels. These results are compatible with fragmentary data in Ref. 2 for a larger machine, and are believed to result from effects of the mean wind gradient.

CONCLUSIONS

Measurements of sound from the MOD-0A wind turbine generator for a wind velocity of about 5 m/s and a power output of about 70 kW suggest the following:

1. Discrete frequency components below 100 Hz have been identified as blade loading harmonics which occur at the blade passage frequency and integral multiples of it; and at the electrical generator shaft speed and integral multiples of it.

2. Broadband components include nacelle mechanical (squeaking) noises centered at about 10,000 Hz and blade aerodynamic noises which peak at about 1000 Hz. The peak at 1000 Hz is easily observed at all azimuth angles and characterizes the acoustic signature of the machine. The broadband aerodynamic noise is amplitude modulated at the blade passage frequency and one of the blades is observed to consistently generate higher amplitudes than the other.

3. Higher levels are measured in the direction of the axis of rotation than in the plane of the blades. A low frequency thumping is observed on the axis both upwind and downwind but not in the plane of the blades.

4. Aural detection distances of about 525 m upwind and 850 m downwind were observed.

REFERENCES

1. Balombin, J. R. An Exploratory Survey of Noise Levels Associated with a 100 kW Wind Turbine. NASA TM-81486, 1980.

2. Hubbard, H. H.; Shepherd, K. P.; and Grosveld, F. W.: Sound Measurements of the MOD-2 Wind Turbine Generator. NASA CR-165752, July 1981.

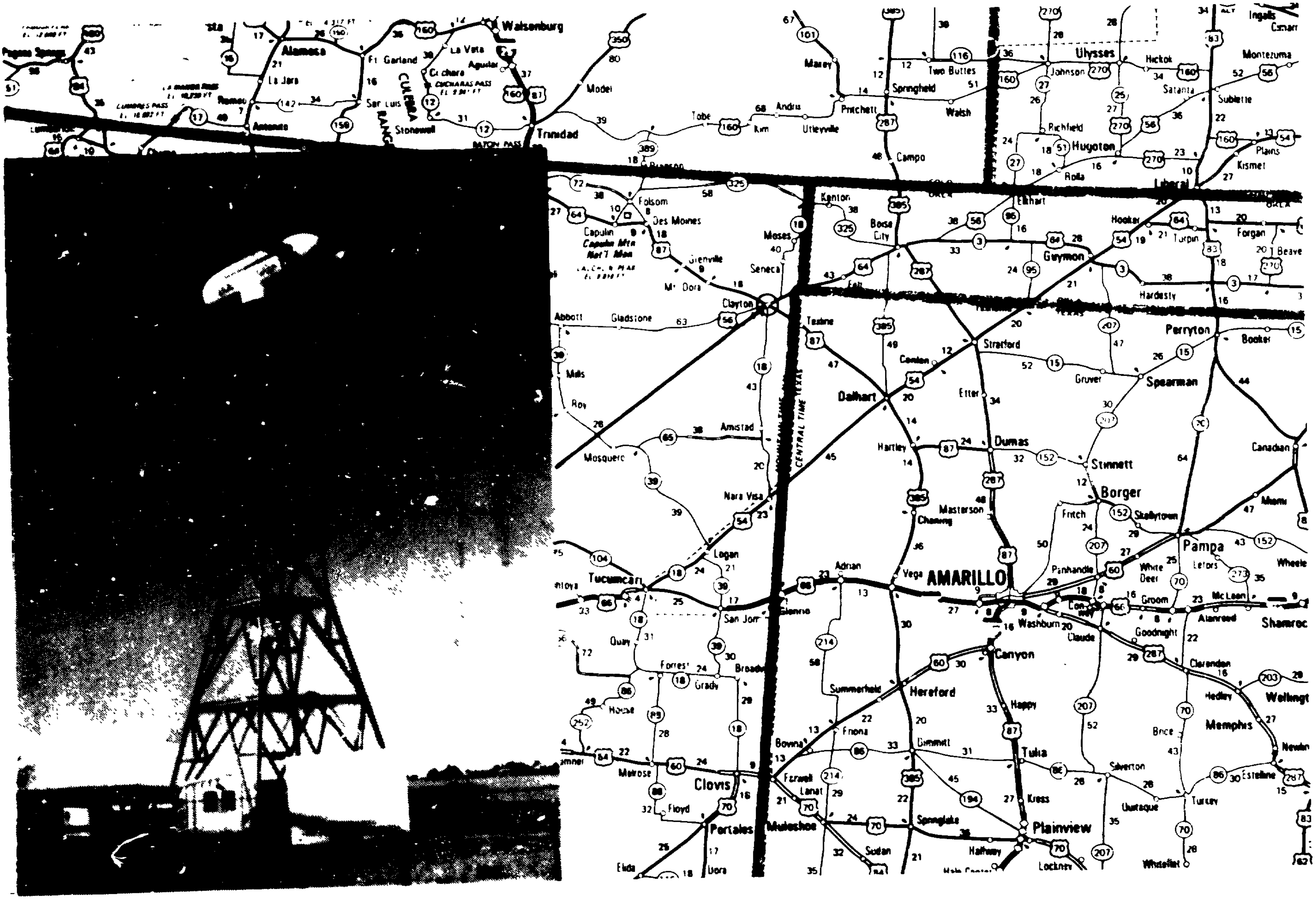

Figure 1. - General location and photograph of the MOD-0A wind turbine generator site.

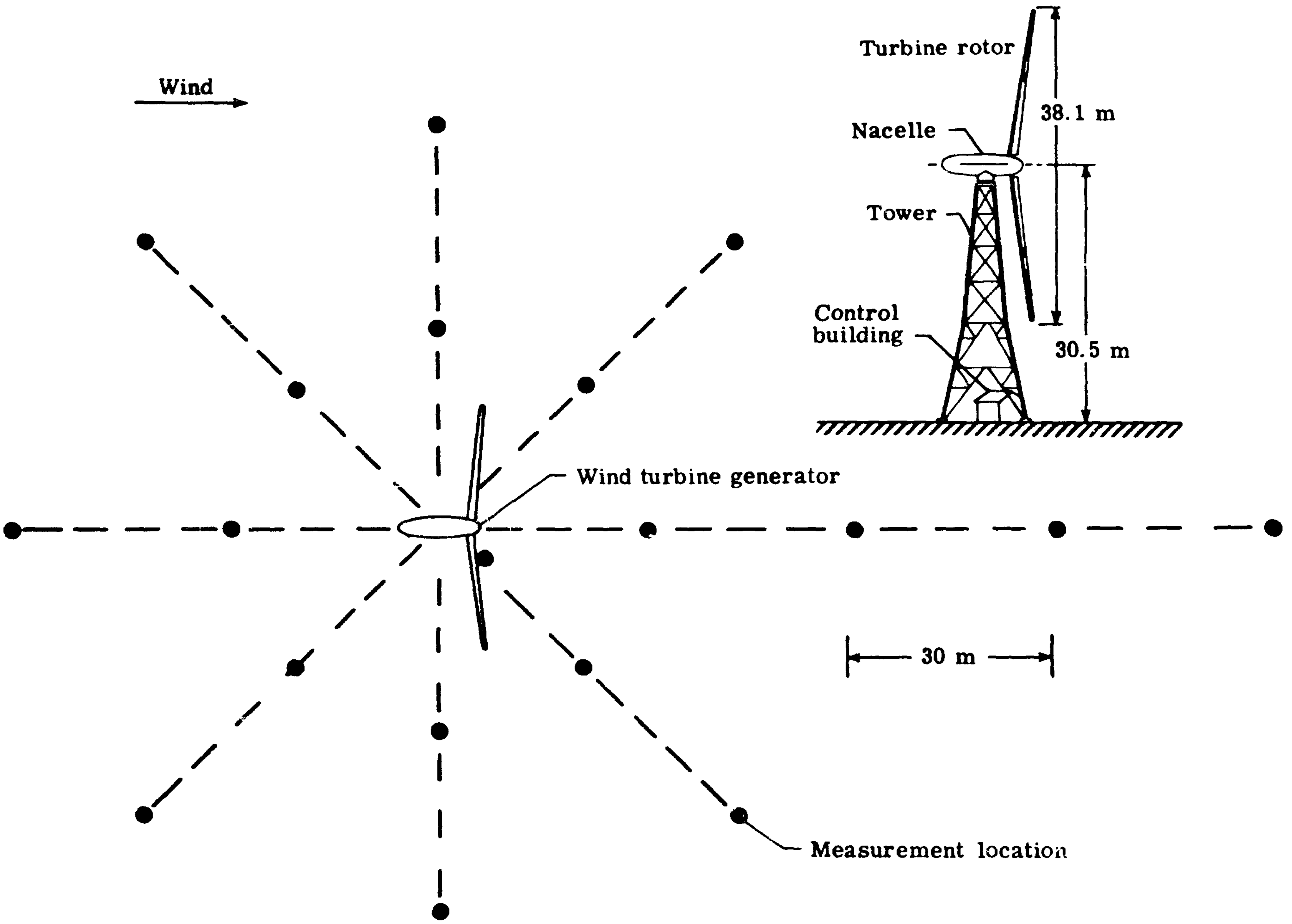

Figure 2. - Plan view sketch showing locations for which data were taken.

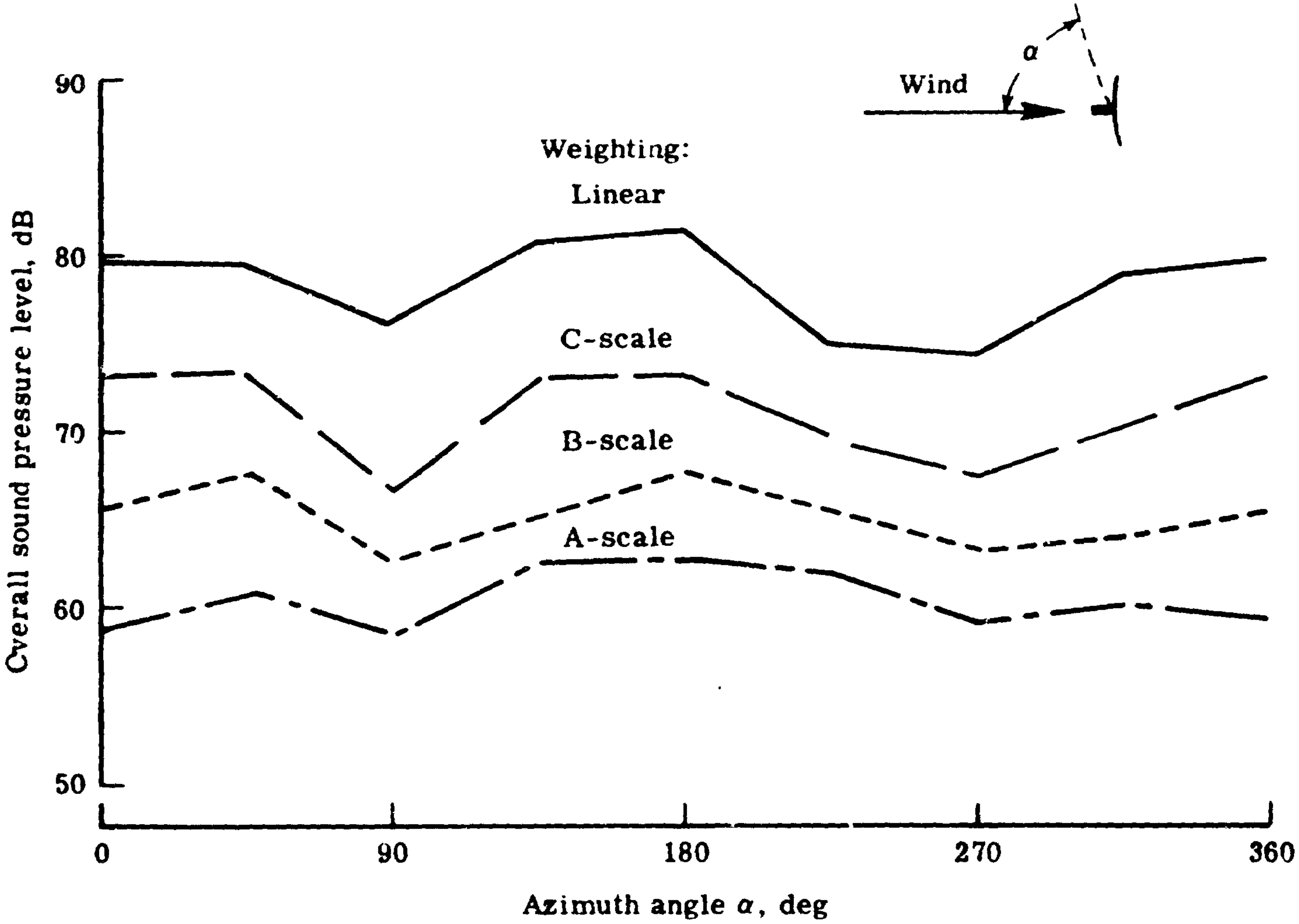

Figure 3. - Overall sound pressure level as a function of azimuth angle at a distance of 30.5 m for four different weighting scales.

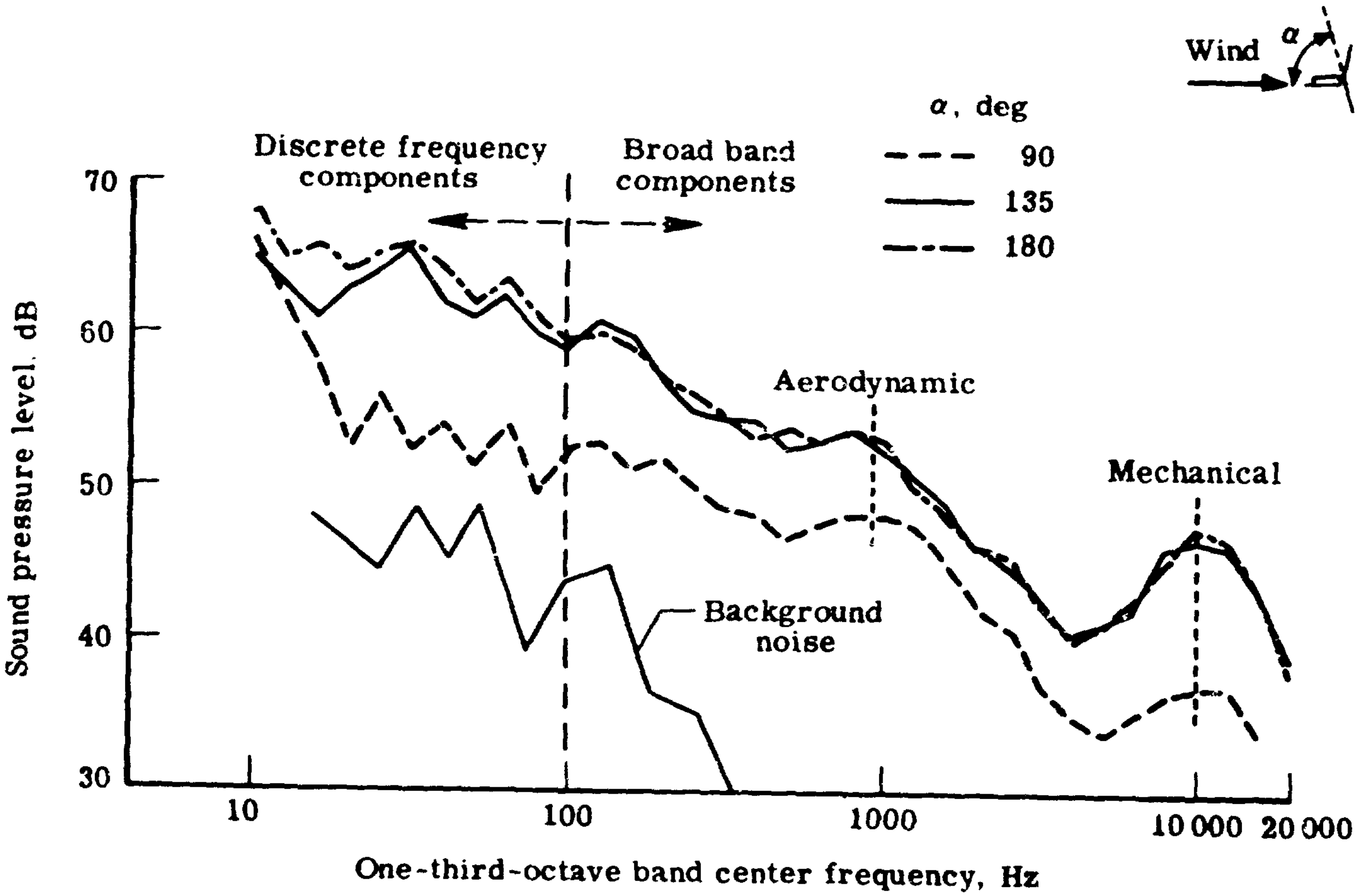

Figure 4. - Effects of azimuth angle on one third octave band spectra at a distance of 61 m.

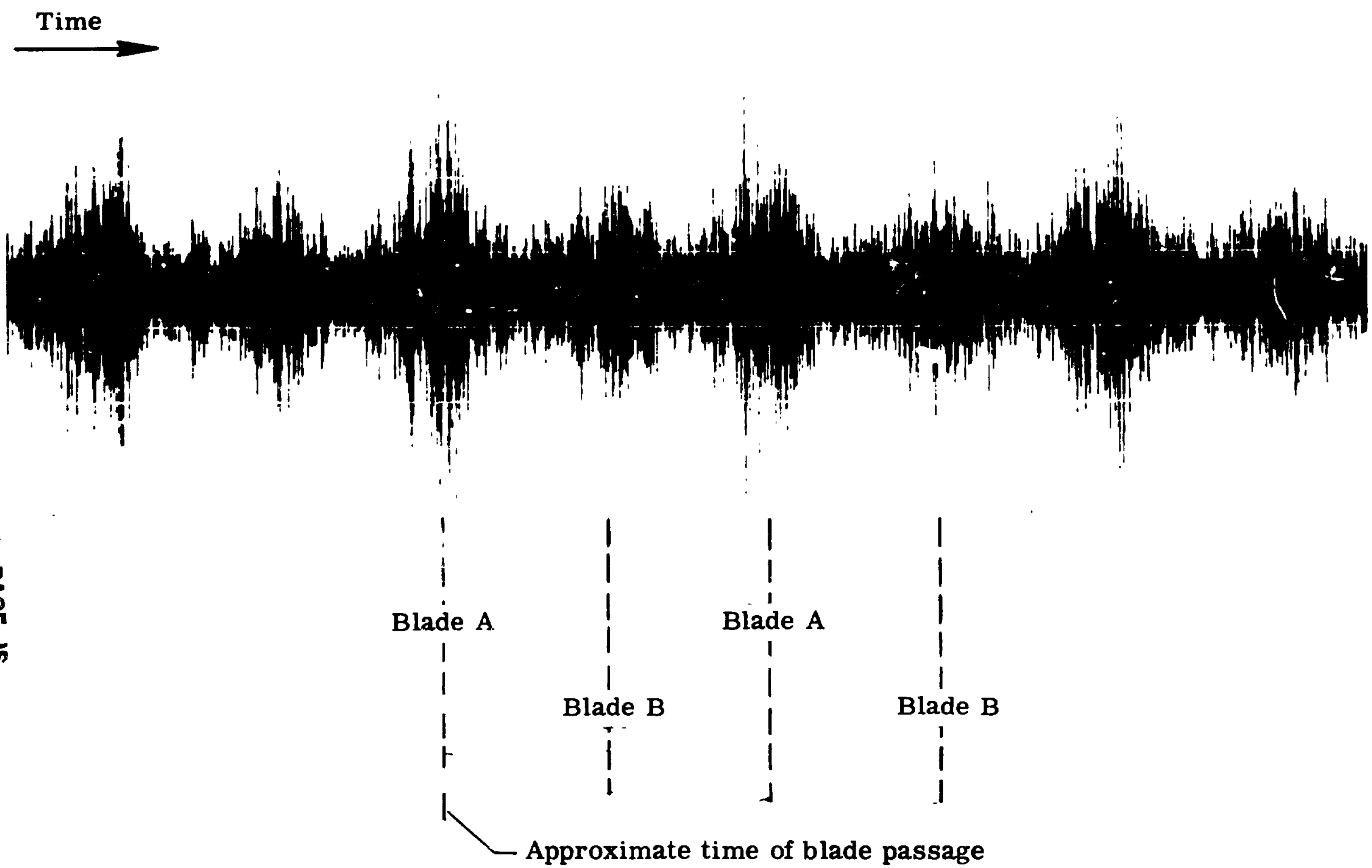

Figure 5. - Sound pressure time history of one third octave band having center frequency of 1250 Hz.

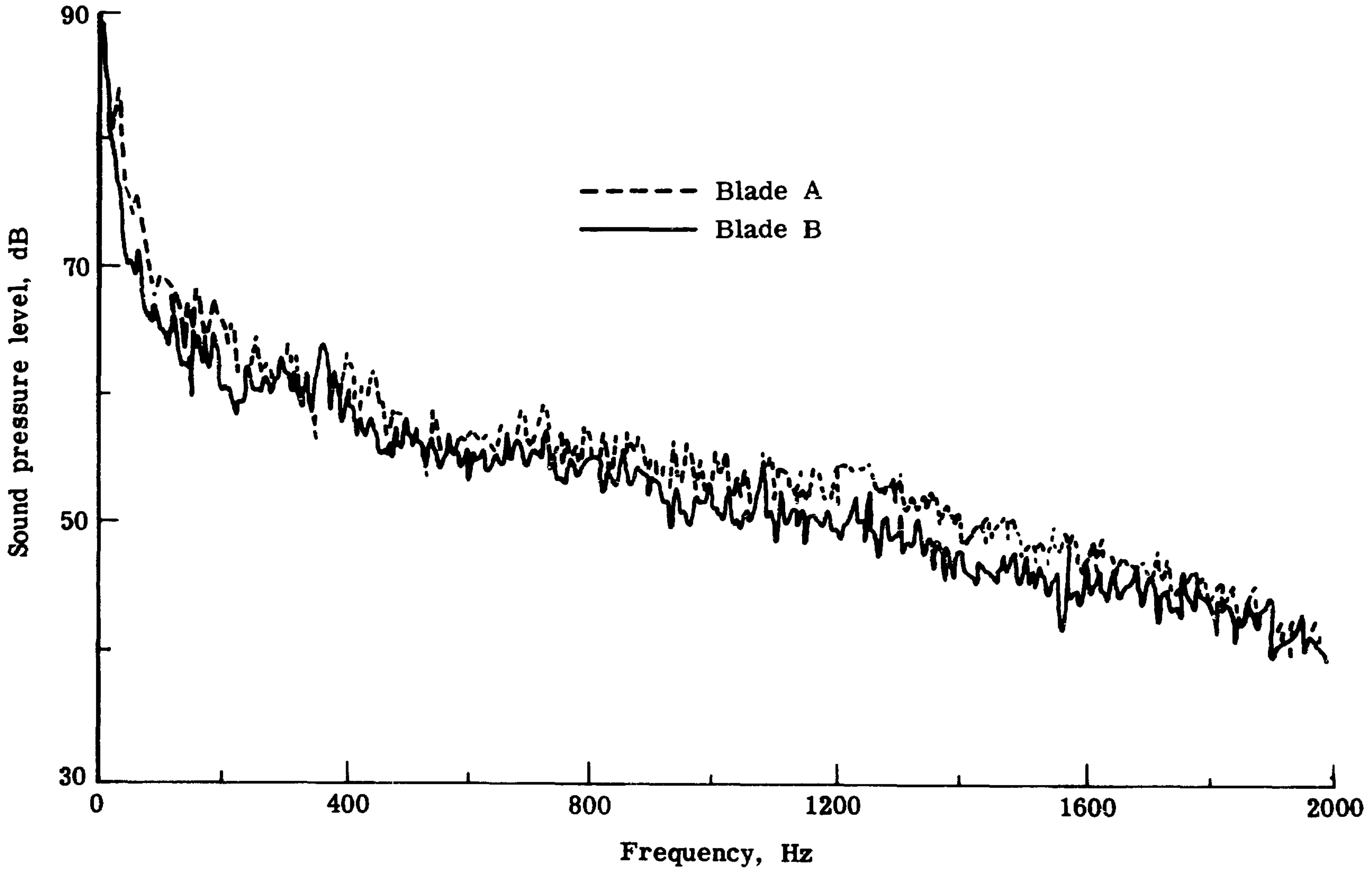

Figure 6. - Comparison of narrowband spectra of the near field noise pulses associated with blades A and B. $\Delta f = 5$ Hz.

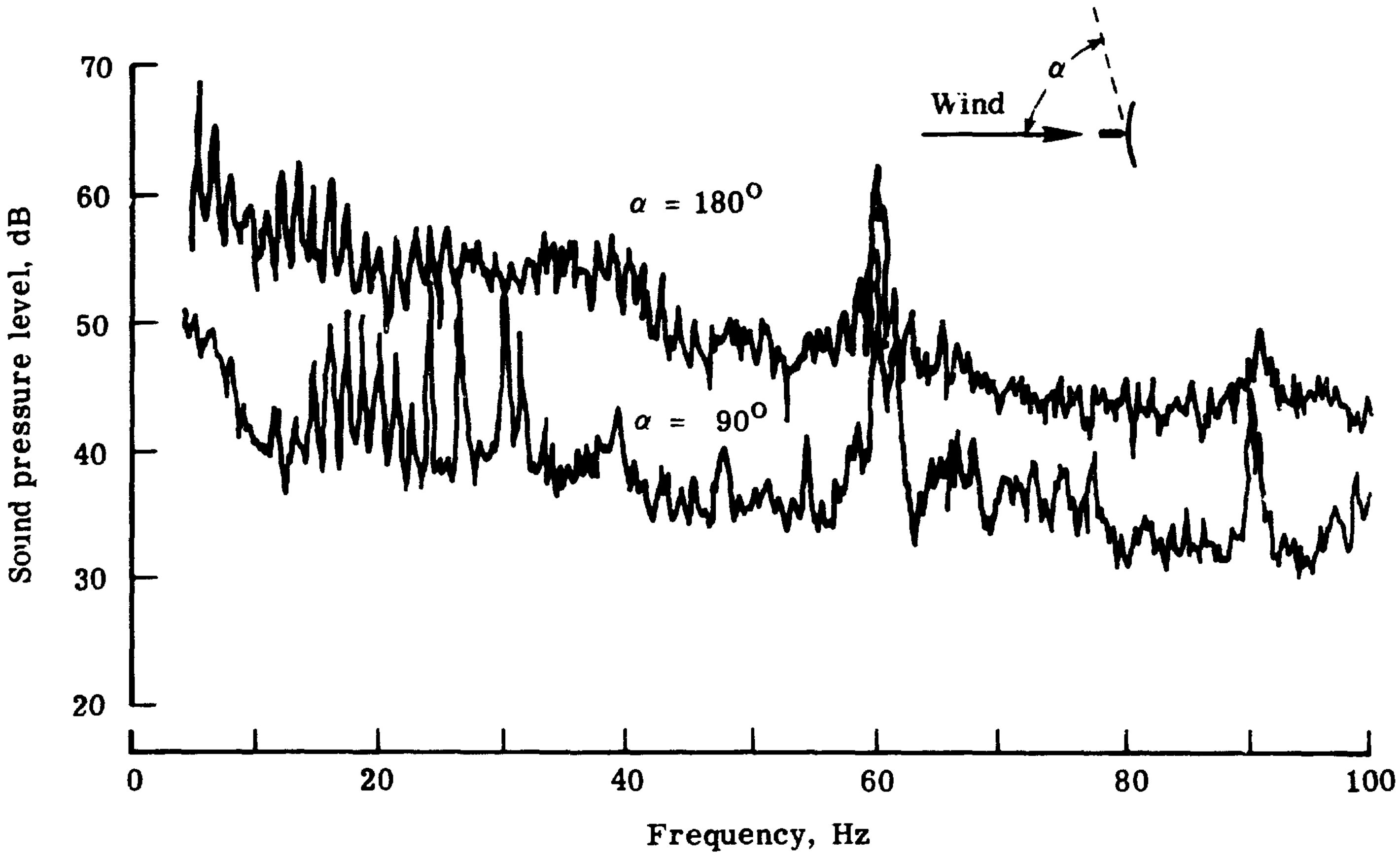

Figure 7. - Narrowband (1 Hz) spectra at a distance of 30.5 m.

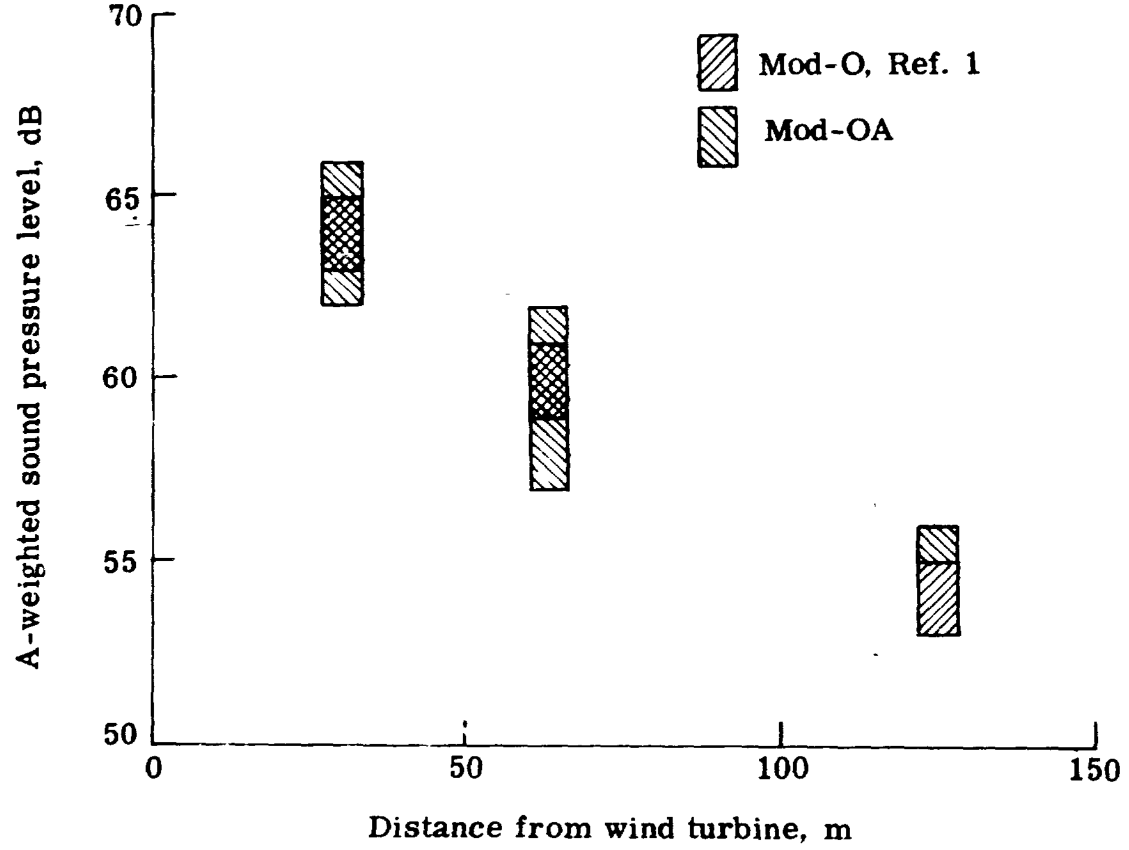

Figure 8. - A comparison of A-weighted sound pressure levels for the MOD-0 and MOD-0A wind turbine generators.

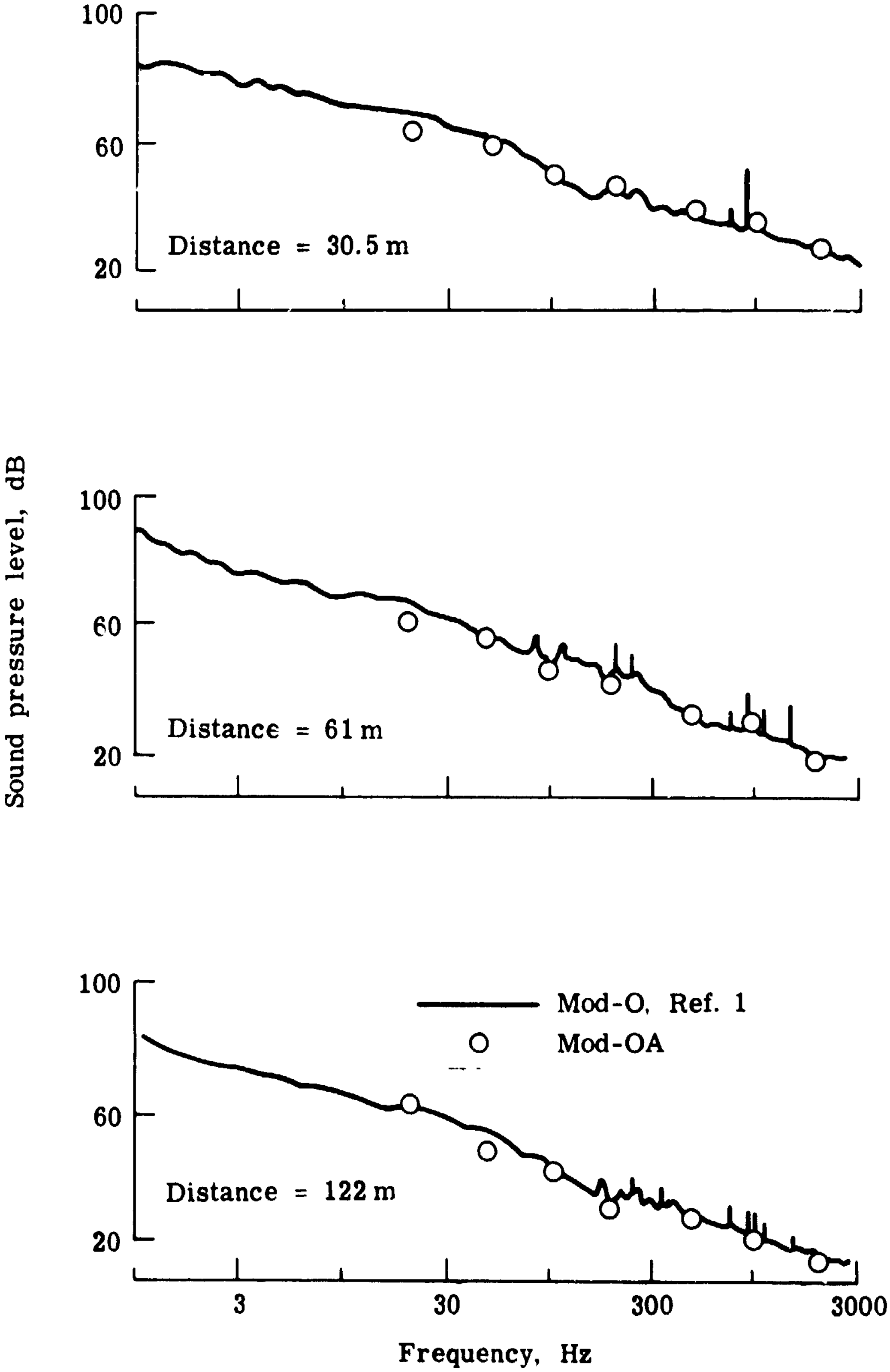

Figure 9. - Comparisons of narrowband (1 Hz) spectra for the MOD-0 and MOD-0A wind turbine generators at three different distances.

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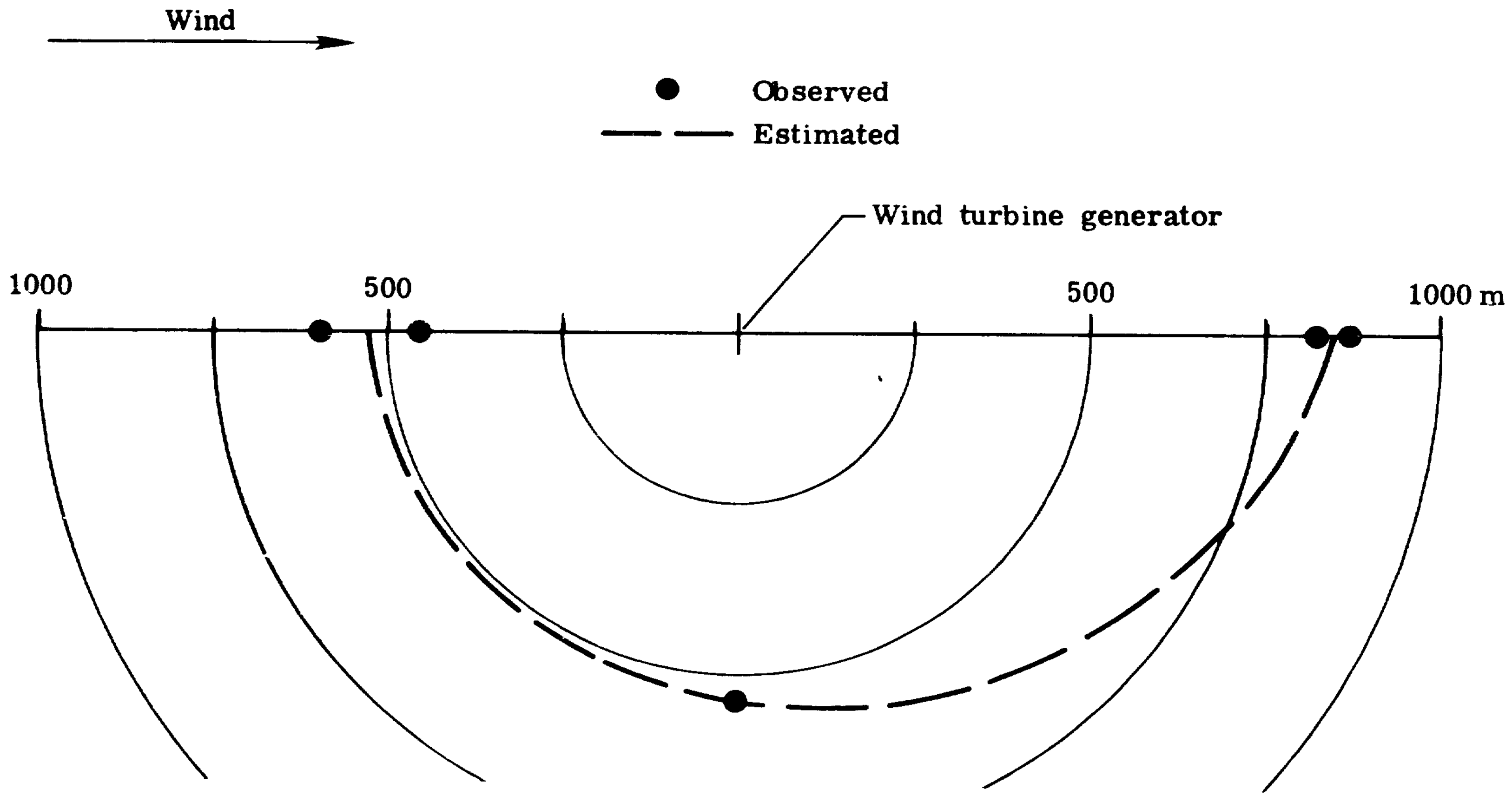

Figure 10. - MOD-OA wind turbine generator aural detection thresholds for a wind velocity of 5 m/s.