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NOISE MEASUREMENTS FOR SINGLE AND MULTIPLE OPERATION OF 50 KW WIND TURBINE GENERATORS

Harvey H. Hubbard and Kevin P. Shepherd

THE COLLEGE OF WILLIAM AND MARY
Virginia Associated Research Campus
Newport News, Virginia 23606

and

THE BIONETICS CORPORATION
Hampton, Virginia 23666

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Langley Research Center
Hampton, Virginia 23665

INTRODUCTION

Most of the available noise measurements on large wind turbine generators are for single unit operation (See Refs. 1-9). There is a need for information on the noise from multiple unit operations, especially with regard to the temporal quality of the noise and the manner in which it propagates as a function of distance.

The data of this paper provide some needed information in support of the development of criteria for the environmental noise impact on nearby residential communities of wind energy farm operations involving large numbers of machines. Data are provided in the near and far acoustic fields, and for a range of power output conditions, for machines in the 50 kw range (See Fig. 1).

This effort is part of the Department of Energy Wind Energy Program which is managed by the NASA-Lewis Research Center. The installation described herein is owned and operated by U. S. Windpower Inc., and power generated is purchased by the Pacific Gas and Electric Company.

APPARATUS AND METHODS

Description of Site

The wind energy farm site at which noise measurements were made is near Livermore, Ca., (See Fig. 1). The machines are installed in linear arrays along ridge lines which extend roughly in the north-south direction (See Fig. 2), at elevations ranging from about 305 m (1000 ft) to slightly in excess of 366 m (1200 ft). The terrain is rolling as indicated by the contour lines of Figure 2, and is sparsely populated. Prevailing winds are south westerly. For all data reported herein the temperature varied from about 70° to 90°F, the mean wind speed varied from about 11 to 30 mph and the mean wind direction varied from about 213° to 251°. Measurements were made at locations which varied in distance from 30.5 m (100 ft) to 1160 m (3800 ft) and for a range of elevations. The elevation-distance combinations at the measuring stations are shown in Figure 3. All data were recorded on August 27, 28 and 29, 1982, between 0900 and 1900 hours.

Description of Wind Turbines

The U. S. Windpower Inc., wind turbine generator is shown in the inset photograph of Figure 1. It is a downwind machine rated at 50 kw and operates in the wind velocity range of about 12-44 mph. It has a three bladed 17.6 m (57.7 ft) diameter rotor mounted on an 18.3 m (60 ft) high three legged tower, the legs of which are circular (10 cm diameter) in cross section. The tower is not guyed and supports a free yawing Nacelle. Rotational speed range for synchronized operation is 72 to 73.7 rpm.

Two experimental tower modifications designed to alleviate the low frequency noise associated with tower wake-blade interactions were evaluated. These modifications are shown in the photographs of Figure 4. Figure 4(a) illustrates the helical strakes (1.7 cm thick rope) which were applied to each of the three tower legs in the vicinity of the outer 20 percent of the span of the blades. Figure 4(b) illustrates the approach of attaching a streamlined fairing to each leg. The objective of both treatments was to beneficially affect the tower wake.

Two different blade configurations are in use and attempts were made to obtain acoustic data for each. Standard blades have a trailing edge with a bluntness dimension of about .64 cm. Some blades were modified to essentially eliminate the bluntness along the outer 7 percent of the radius. This was done by filing of the low pressure side of the blade until a sharp trailing edge was obtained. The treated blades referred to are those with sharp trailing edges.

Noise Measurements and Observations

All noise measurements were made with commercially available battery powered instrumentation. One half inch (1.27 cm) diameter condenser microphones with a useable frequency range 3-20,000 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 of 25 Hz to 20,000 Hz. This system provided high dynamic range recordings 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 of 0 Hz to 15,000 Hz. For some recordings the microphone signals were C-weighted in attempts to more effectively utilize the available dynamic ranges. Sound pressure level measurements were also taken with a precision sound level meter. Sound spectral data were obtained with the aid of conventional one-third octave band and narrow band analyzers.

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 of multiple machines in order to define the extent to which the wind turbine noise is detectable above the background noise in the downwind direction.

MEASUREMENT RESULTS AND DISCUSSION

Acoustic 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 sound pressure time histories, narrow band spectra, one-third octave band frequency spectra and overall A-weighted levels. In addition some observations are summarized to indicate the approximate distances at which the wind turbine generator noise can be detected above the background noise.

Single Machine Data

A representative time history trace of instantaneous sound pressure for the standard machine is given in Figure 5 along with a shaft position indicator signal. These data are for a distance of 30.5 m (100 ft) downwind of the machine (180° azimuth angle) and for wind conditions near the cut-in value. Note that for each shaft revolution there are three blade passages. Each blade passage consists of three strong pressure peaks, thus suggesting that each of the three tower legs generates a wake which is significant in noise generation.

Comparisons of representative noise time histories of the standard machine and those modified as illustrated in Figure 4 are shown in Figure 6. The rope strake treatment causes reductions in the peak pressure amplitude but all three tower leg related peaks are evident for each blade passage. The fairing treatment causes an additional peak amplitude reduction, plus some modification of the orderly peak structure. A significant feature of the time history data of Figure 6 is that there is variability of the peak amplitudes with time for all three configurations. Observed variability was greatest, however, for the fairing treatment. A varying wind velocity and direction is believed to cause a varying tower wake structure to be ingested by the rotor. Since the fairings of Figure 4(b) were fixed to the legs, that configuration is believed to be particularly susceptible to inflow misalignments.

Further effects of the tower leg treatments are shown in the comparisons of narrow band spectral data of Figures 7 and 8 and of corresponding one-third octave band spectra in Figures 9 and 10 respectively. The narrow band spectra for a wind condition near cut-in and for relatively low power outputs are given in Figure 7. Note that narrow band components can be identified within the frequency range starting from the fundamental blade passage frequency (3.6 Hz) up to about 120 Hz. Such a well structured pattern of frequency components, which are harmonically related to the blade passage frequency, suggests that significant tower wake effects are present. Such wake effects may be altered somewhat by the addition of tower leg treatments but are still present and easily observed. Note that the data of Figure 7 represent rms values averaged over a period of 64 seconds. This long term averaging time was used in an attempt to compensate for observed short term variability in the recorded sound pressure time history signals.

The corresponding one-third octave band data obtained using a 64 second averaging time, (Figure 9) are entirely consistent with the narrow band data of Figure 7. The data of Figures 7 and 9 suggest that the tower leg treatments evaluated do not provide the hoped for noise reductions over a wide frequency range at the low power output condition. The data of Figures 8 and 10 which relate to the high power output condition, also support the general conclusion that the tower leg treatments are relatively ineffective.

Multiple Machines

The opportunity was taken to operate some of the machines selectively in order to determine the manner in which their sound fields interacted. The results of these tests are presented in Figures 11-14.

Figure 11 contains instantaneous sound pressure time histories at a distance of about 91 m for one, two and three machines for comparison. The data for one machine indicates a rather orderly time sequence of blade passage peaks but with considerable variation in the peak pressure values. As more machines are added the pressure peaks become more numerous and less orderly and their maximum value increases. Based on theoretical considerations the maximum value for simultaneous operation of identical machines would vary from one to three times that for one machine, depending on their instantaneous phase relationships. The data of Figure 11 (c) are for example conditions intermediate between the extremes noted above and show a peak value increase of about 50 percent.

Corresponding one-third octave band data are given in Figure 12. It can be seen that the band levels increase generally as the number of machines increases. The increases are larger, however, at the lower frequencies for which constructive interference seems to occur.

Spectral data for larger groups of machines are presented in Figures 13 and 14. The data of Figure 13 show differences in the spectra for two groups of machines having different blade configurations. The most pronounced difference is in the broad band noise peak near 2000 Hz. Both spectra have peaks but the lower peak is associated with the treated blades. These results suggest that sharpening the outer portions of the blades to minimize the bluntness is very beneficial in reducing the radiated high frequency "whistling" noise.

Figure 14 shows narrow band spectra for the two operating conditions of Figure 13. Note that blade passage related components are present at frequencies from about 20 Hz to 120 Hz as seen in Figures 7 and 8 for measurements close to single machines. Those components below about 20 Hz are apparently masked by wind noise in Figure 14. Although some differences are noted in comparing Figure 14 (a) and (b) they are not believed to be significant. Thus treating the blades by sharpening the trailing edges does not seem to have a beneficial effect for that portion of the spectrum containing components related to blade passage.

NOISE ESTIMATES

Based on the measured data described above, estimates have been made of the sound pressure levels as a function of distance from the U. S. Windpower Inc. machines, as they are presently configured. The results are shown in Figures 15 through 17.

Figure 15 presents the measured sound pressure levels in the one-third octave band centered at 31 Hz for various numbers of machines. This band was chosen because it seems to represent the peak in the low frequency portion of the spectrum and it is in the range where buildings have structural resonances. The curves represent estimated values as a function of distance, for a single machine generating 60 dB band pressure level at 30 m and for other number combinations of similar machines in linear arrays. The assumptions are that the sources are non-directional, spacing along the array is 24.4 m (80 ft), distance is measured perpendicular to the array, there is random phase operation (doubling the number of sources increases the sound pressure level by 3 dB at the same distance), and there is no atmospheric attenuation. Although the measurements indicate variability, these data follow the general trends of the predictions. Band levels ranging from about 60 dB down to 34 dB are expected as distances increase from 30 to 3000 meters from a multiple array.

Similar estimates have been made in Figure 16 for A-scale values which are believed to be significant from the stand point of community response. The curves in this case are based on an A-scale level of 55 dB at 30 m and an atmospheric attenuation of 4.5 dB per 1000 meters. These levels vary from about 55 dB down to 30 dB(A) in the range of distances from 30 m to 1500 m respectively.

Based on the results of Figure 16, a family of "A"-weighted sound pressure level contours has been estimated for the U. S. Windpower Inc. site near Livermore, Ca., and these are superposed on the site map in Figure 17. Contour lines are shown for 50, 40 and 30 dB(A) levels. For conditions of wind velocity of 13 - 20 mph and an array of 14 machines, the observed detection threshold was at a distance of 1160 meters, and was located between the 40 dB(A) and the 30 dB(A) contours. For these listening conditions, the machine noise levels are comparable to the ambient noise levels with minimum wind at the observer, and the observer senses the machine noise only intermittently.

CONCLUDING REMARKS

The noise characteristics of the U. S. Windpower Inc., 50 kw wind turbine generator have been measured at various distances from 30 m to 1100 m and for a range of output power. The generated noise is affected by the aerodynamic wakes of the tower legs at frequencies below about 120 Hz and the blade trailing edge thickness at frequencies of about 2 kHz. Rope strakes and airfoil fairings on the legs did not result in significant noise reductions. Sharpening the blade trailing edges near the tip was effective in reducing broad band noise near 2 kHz.

For multiple machines the sound fields are superposed. A three-fold increase in the number of machines (from 1 to 3) results in a predicted increase in the sound pressure level of about 5 dB. The detection threshold for 14 machines operating in a 13 - 20 mph wind is observed to be at approximately 1160 m in the downwind direction.

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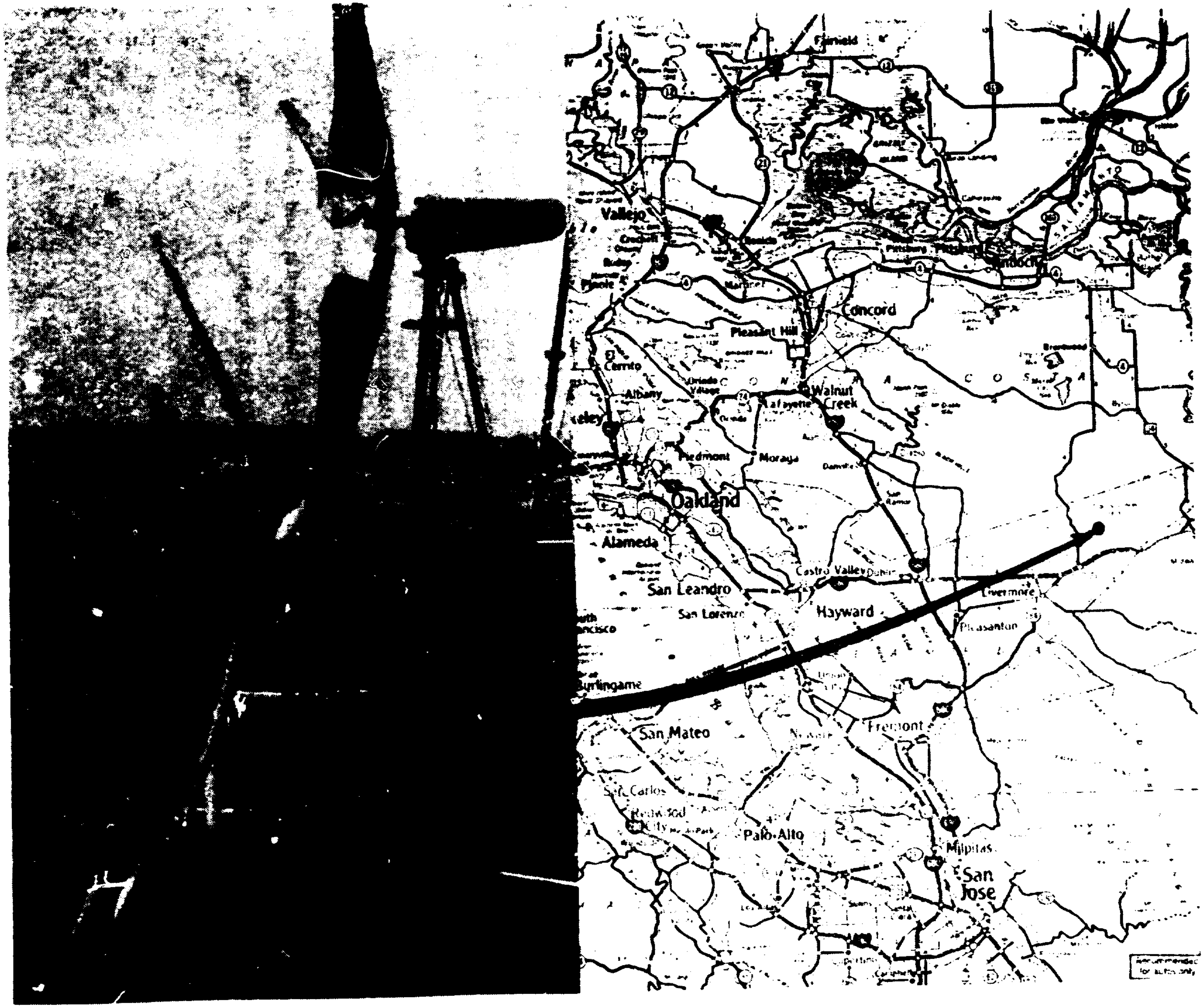


Figure 1.- Location of Test Site with Inset Photograph of a Portion of Wind Turbine Arrays.

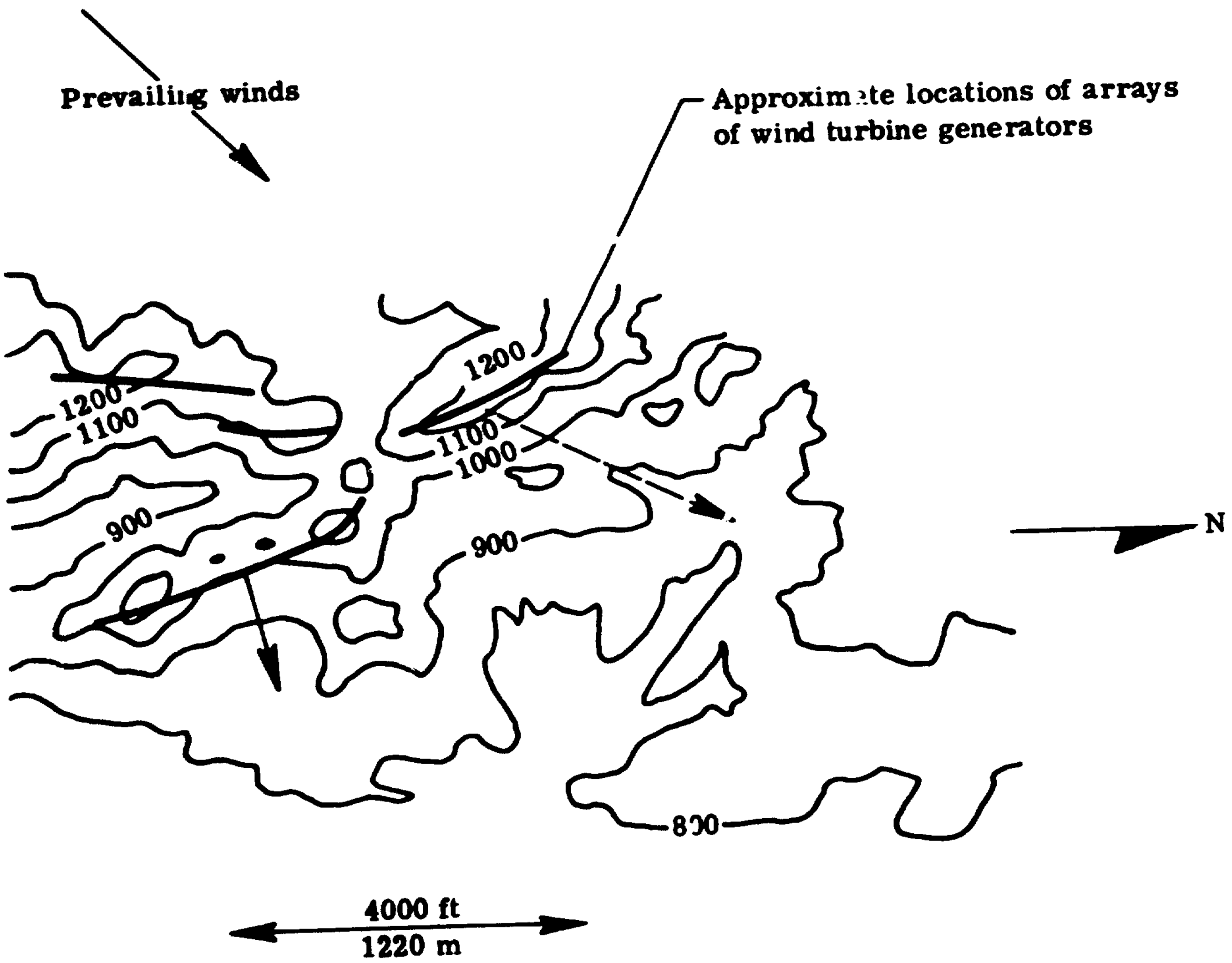


Figure 2.- Elevation Contours in the Acoustic Measurement Area Downwind of the Test Site. Dashed Lines Indicated Directions for which most of the Far Field Data were Obtained. Contour Numbers are in Feet.

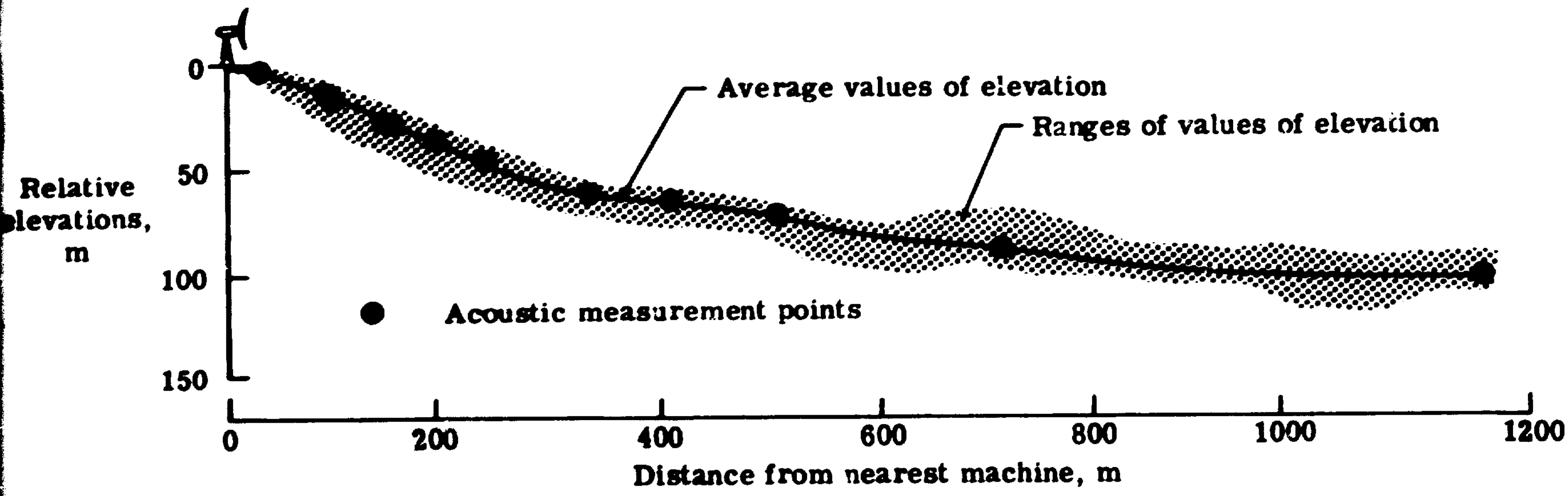
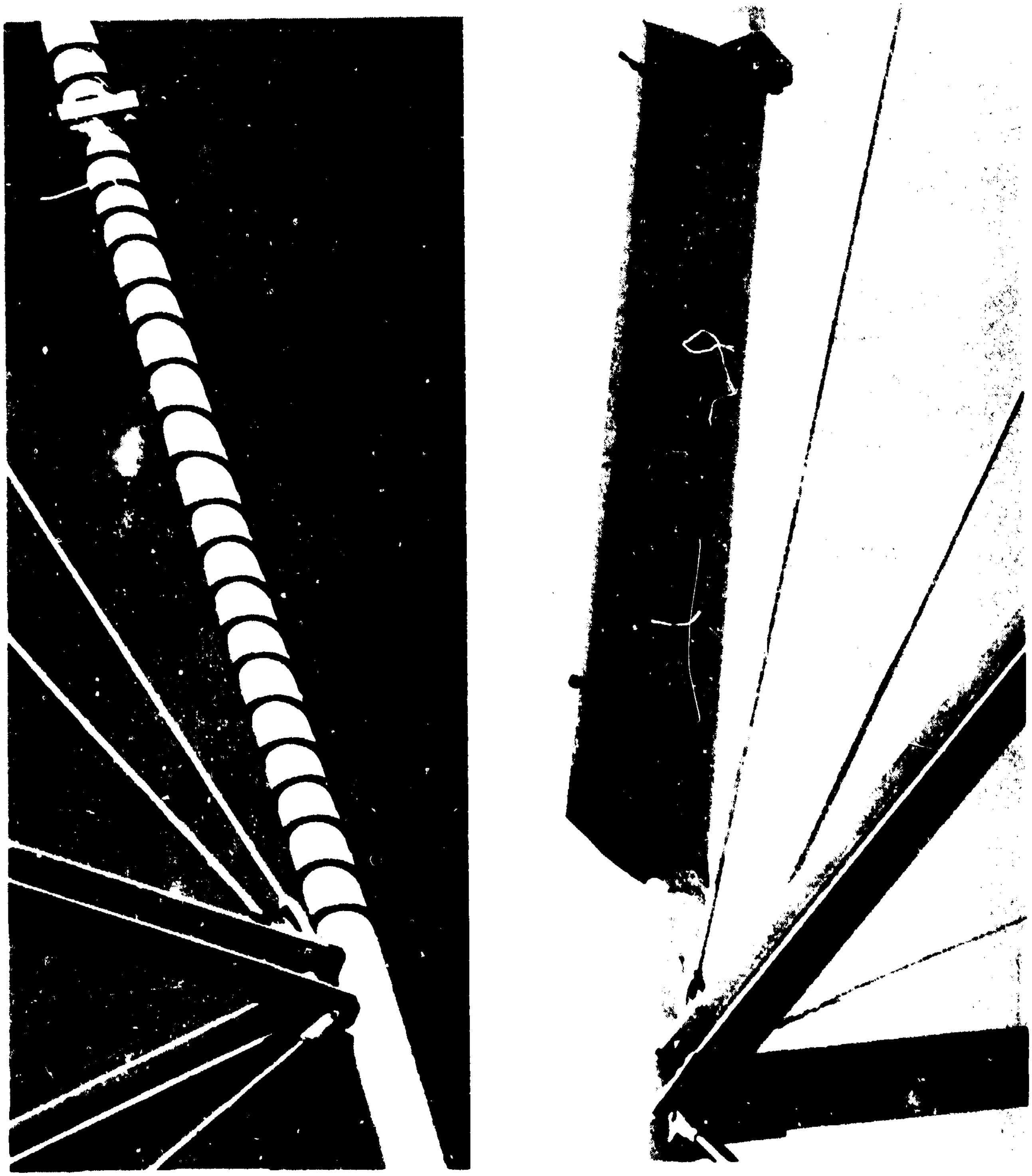


Figure 3.- Relative Elevations as a Function of Distance in the Areas in which Measurements were made.



(a) Rope Strakes

(b) Airfoil Shaped Fairings

Figure 4.- Photographs of Two Different Tower Leg Treatments.

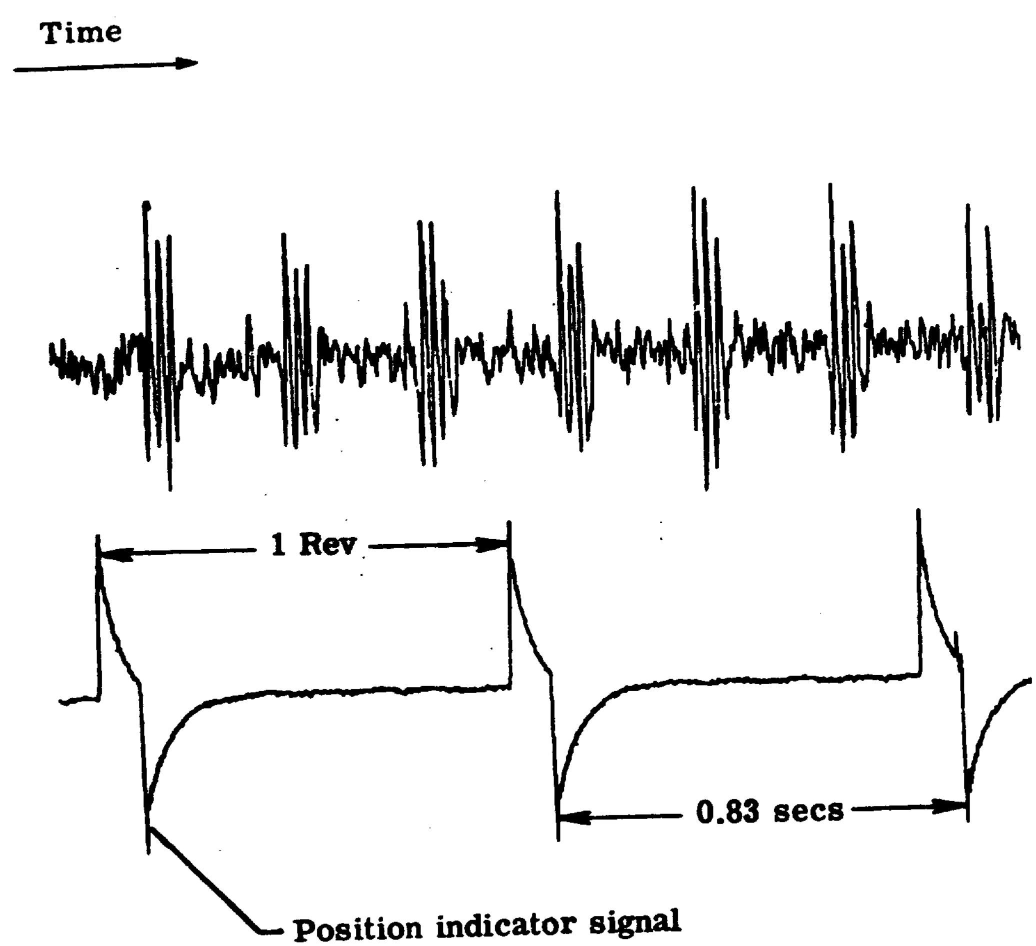


Figure 5.- Instantaneous Sound Pressure Time History for a Standard Machine at a Distance of 30.5 m and an azimuth angle of 180°. Data are for cut-in wind velocity and power output of 5 kw.

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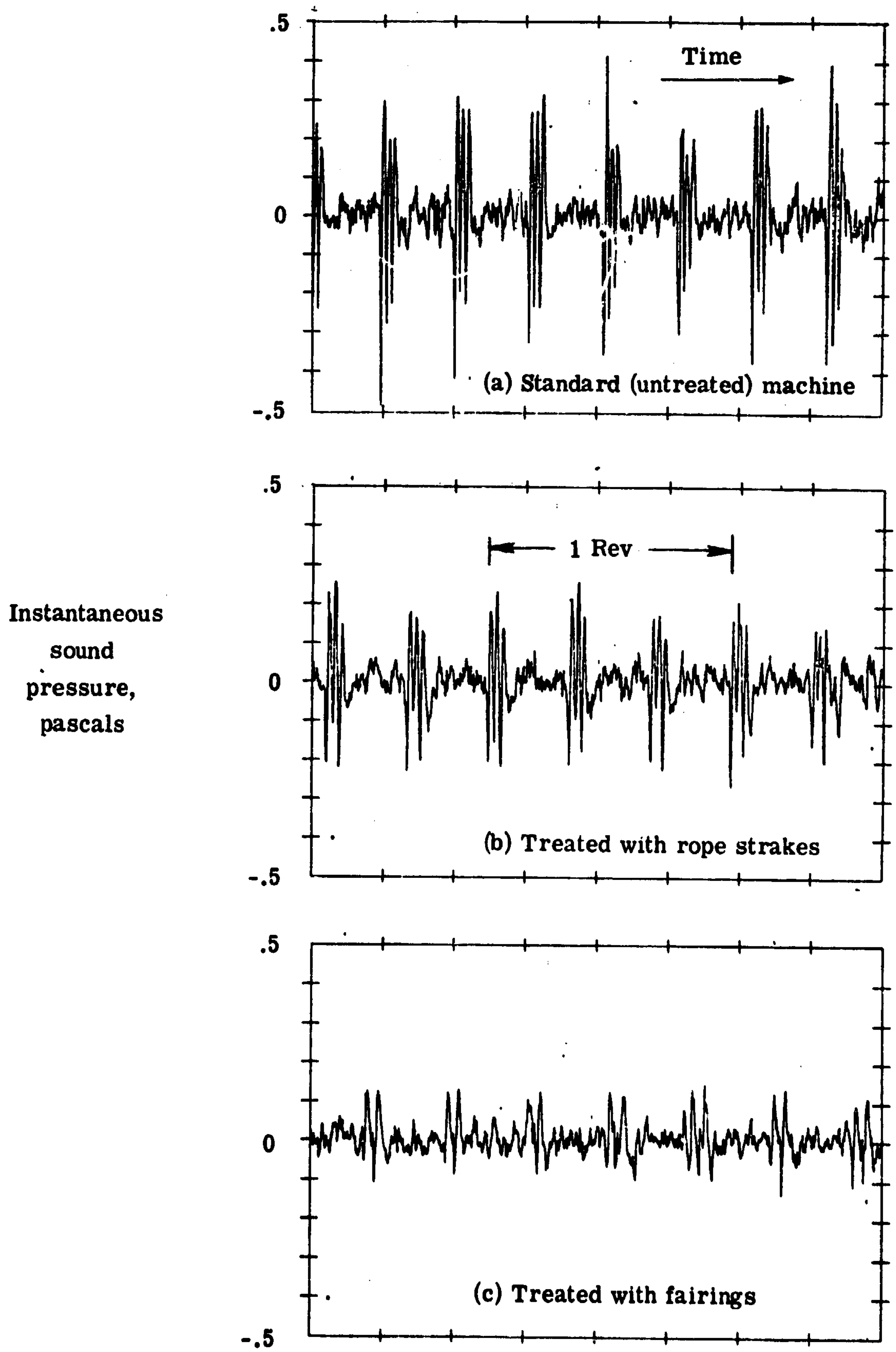

Figure 6.- Comparisons of the Instantaneous Sound Pressure Time Histories at a Distance of 30.5 m Downwind of Treated and Untreated Machines for a Power Output of about 5 kw.

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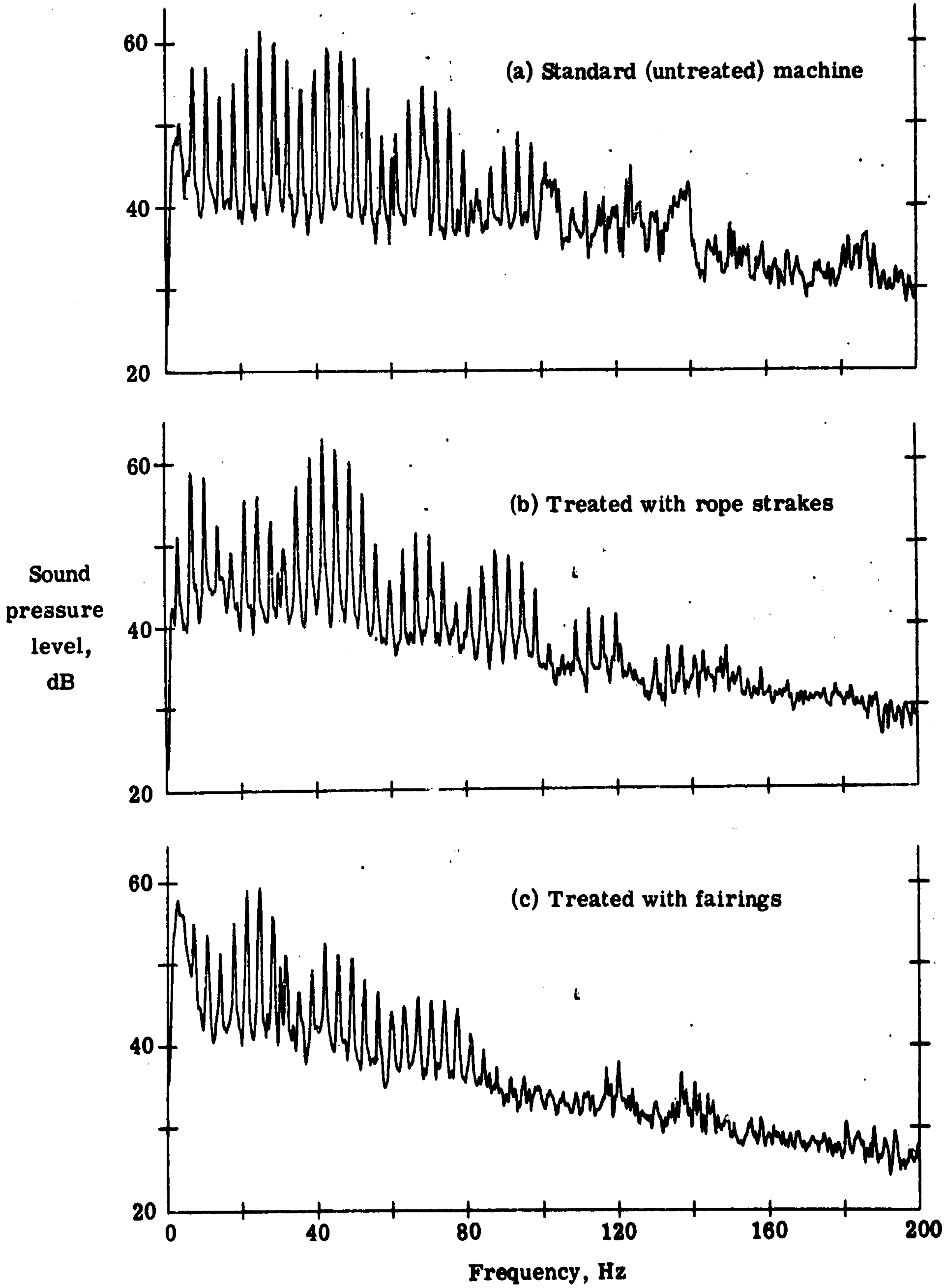

Figure 7.- Comparison of Sound Spectra (0.25 Hz Bandwidth) at a Distance of 30.5 m Downwind for Low Wind Conditions and a Nominal Power Output of 5 kw.

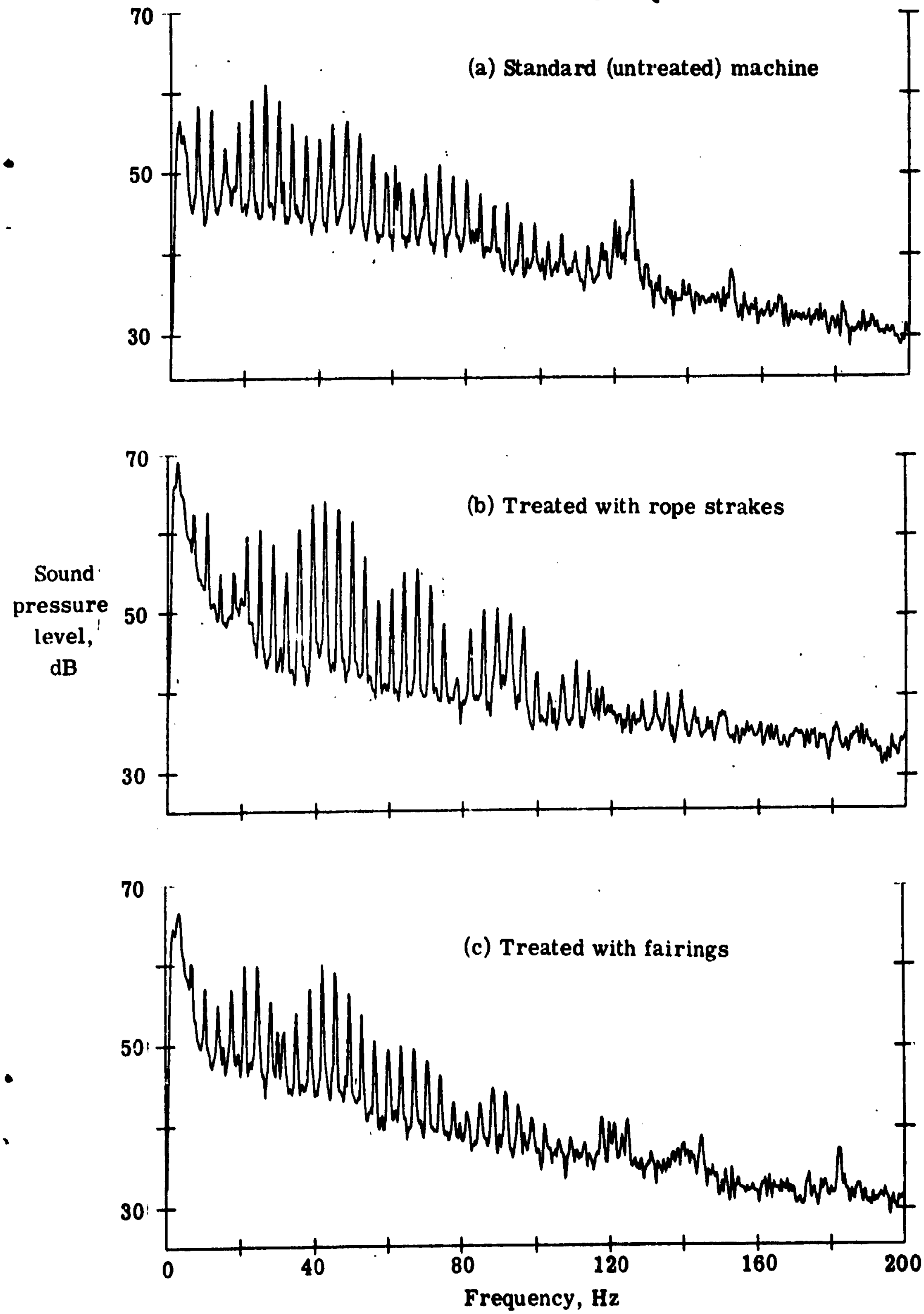

Figure 8.- Comparison of Sound Spectra (0.25 Hz Bandwidth) at a Distance of 30.5 m Downwind for High Wind Conditions and a Nominal Power Output of 55 kw.

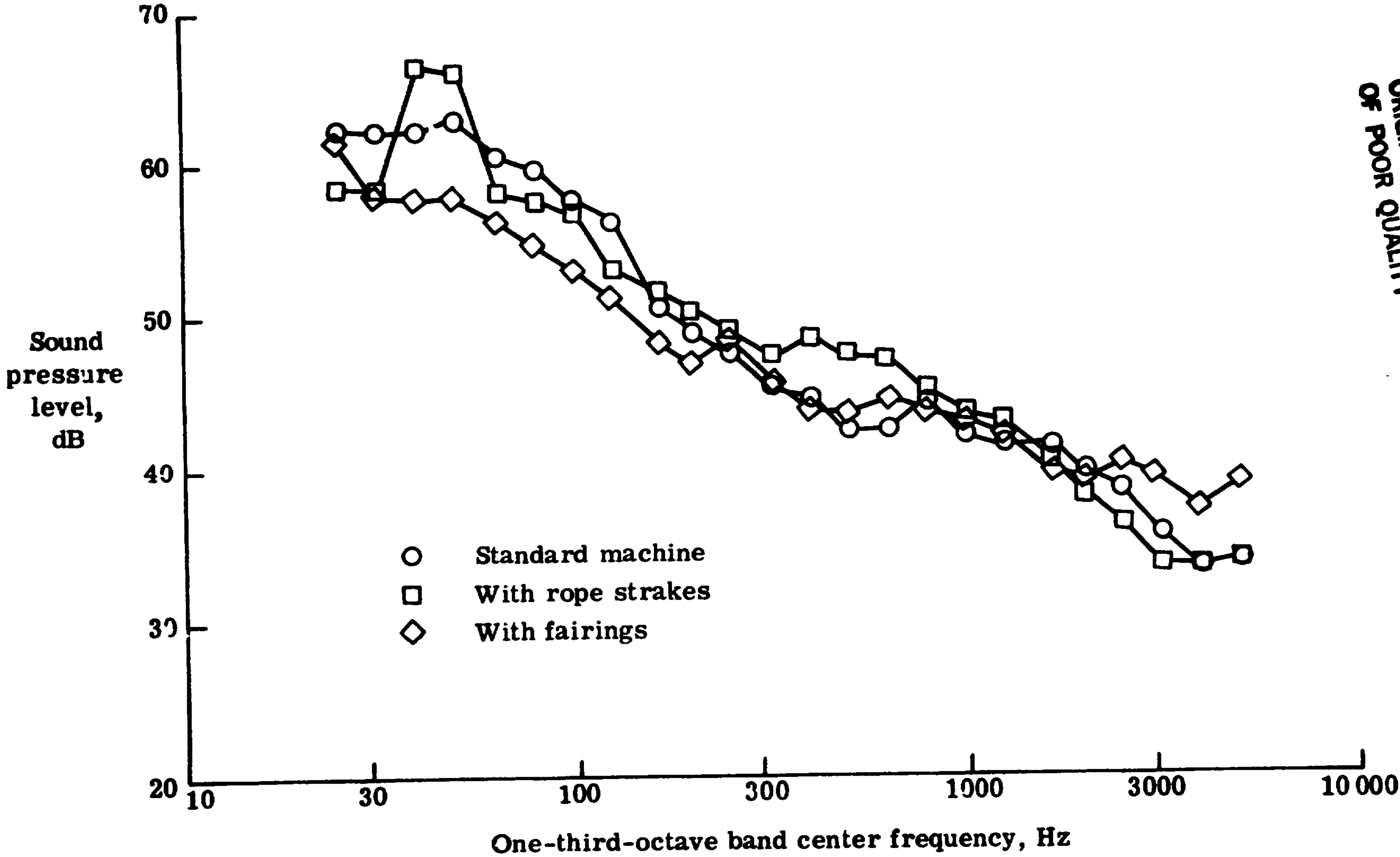

Figure 9.- Comparisons of the One-Third Octave Band Sound Spectra for Modified and Unmodified Machines at a Distance of 30.5 m Downwind for Power Outputs of about 5 kw.

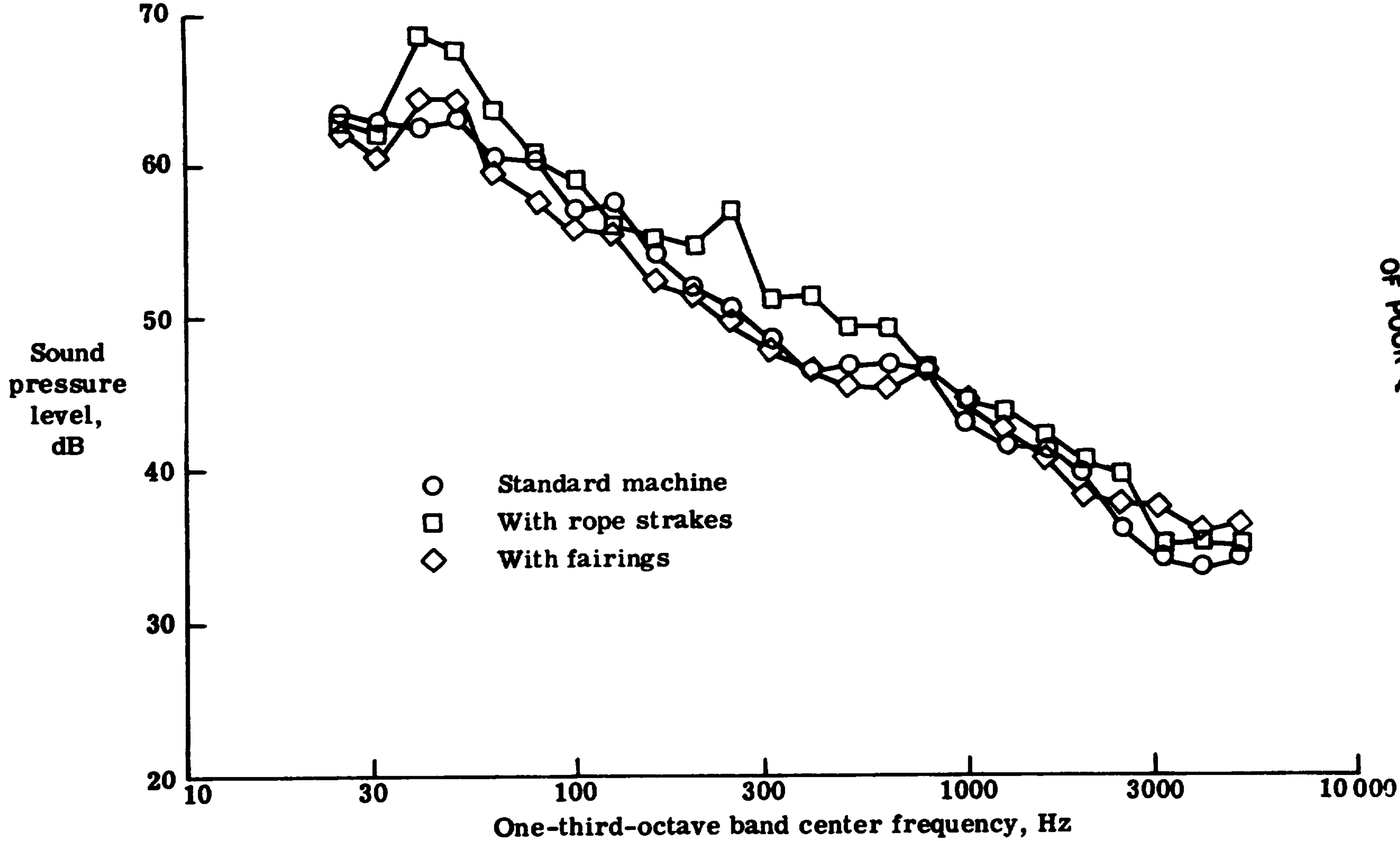

Figure 10.- Comparisons of the One-Third Octave Band Sound Spectra for Modified and Unmodified Machines at a Distance of 30.5 m Downwind for Power Outputs of about 50 kw.

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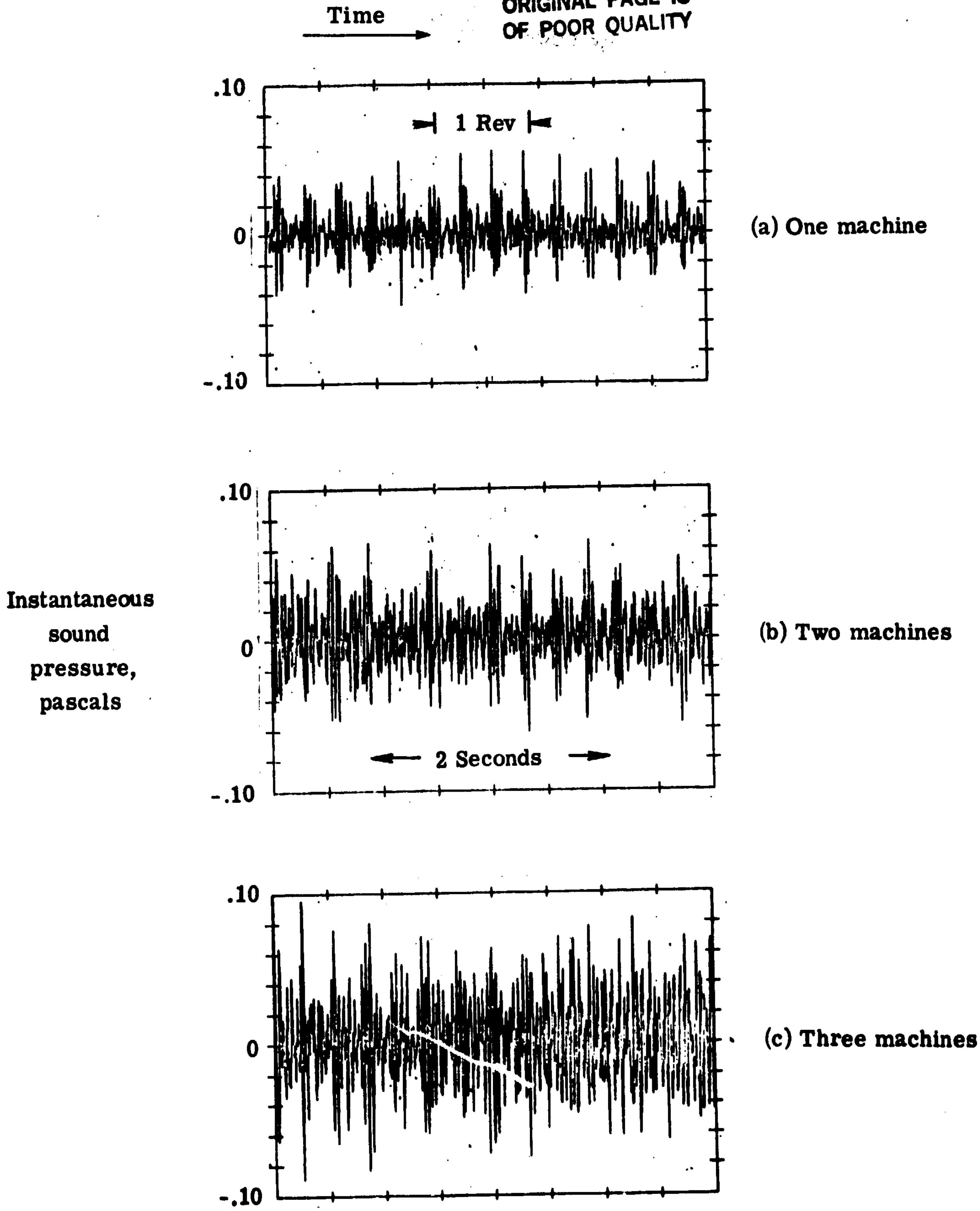

Figure 11.- Comparisons of the Instantaneous Sound Pressure Time Histories at a Distance of 91.4 m for One, Two and Three Machines at a Nominal Power Output of 25 kw per Machine.

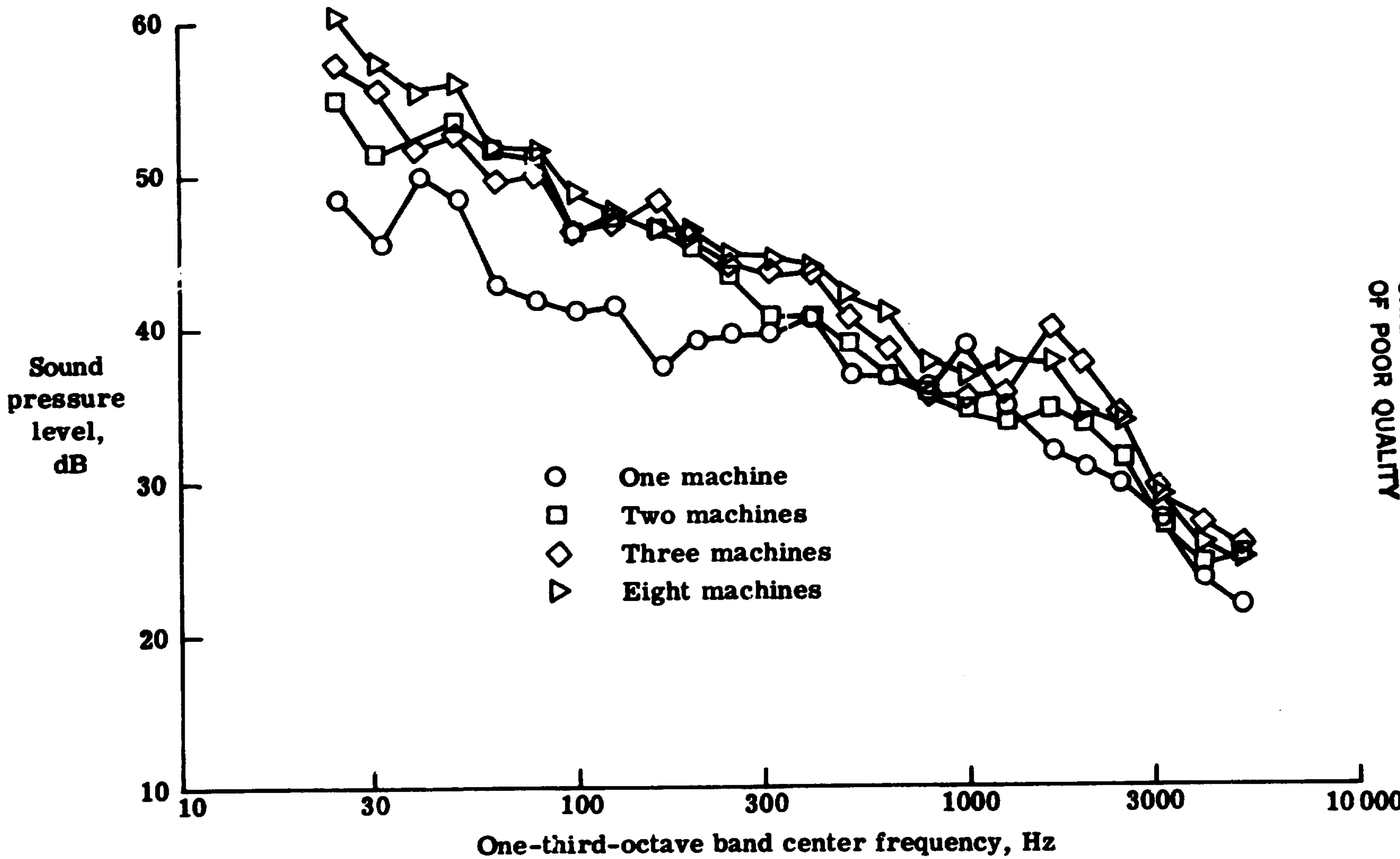

Figure 12.- Comparisons of the One-Third Octave Band Sound Spectra for Multiple Machines at a Distance of 91.4 m Downwind for Power Outputs of about 25 kw per Machine.

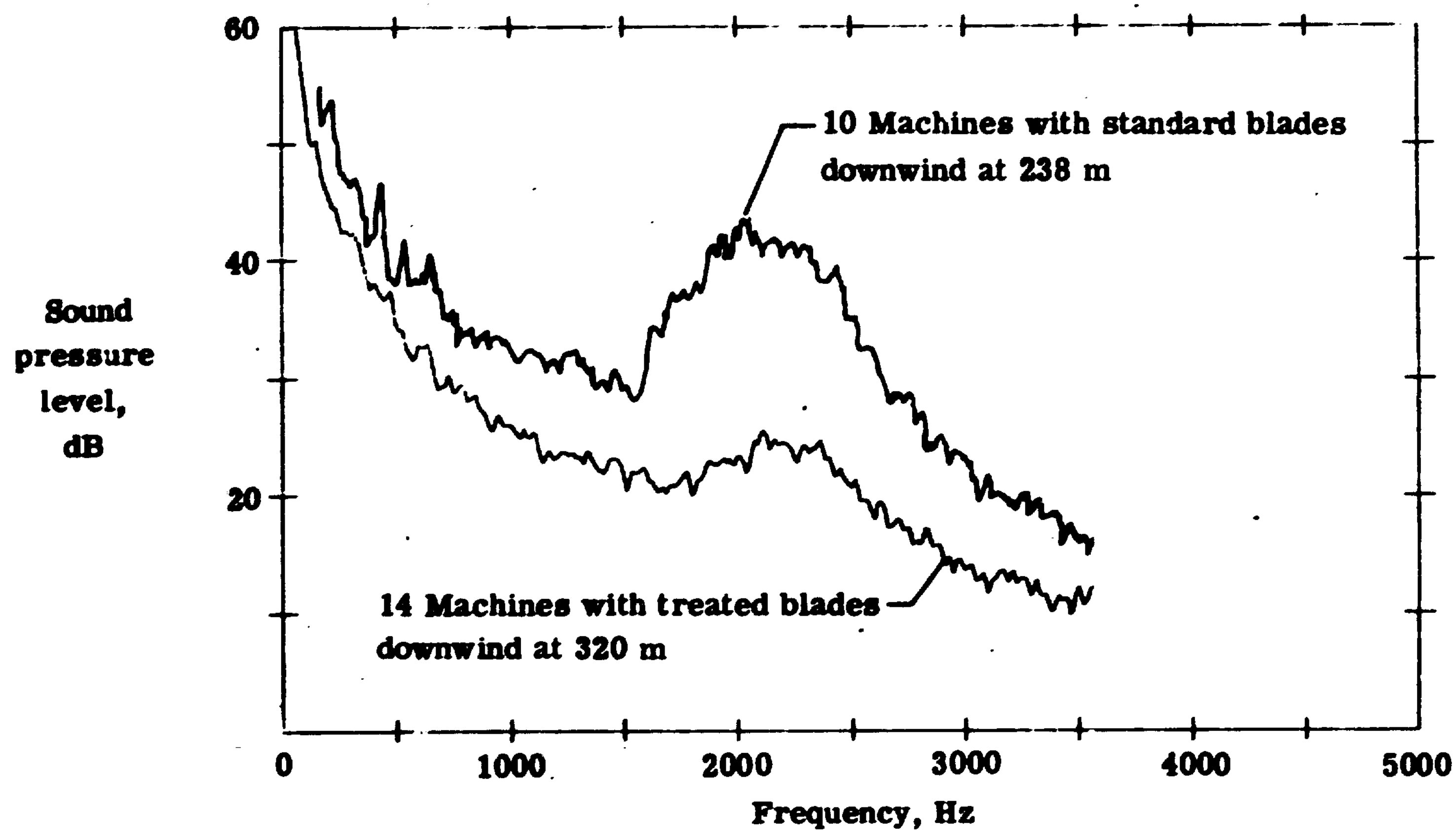

Figure 13.- Example Narrow Band (12.5 Hz) Spectra for Multiple Machines at Two Locations in the Far Acoustic Field. Data are for a Nominal Power Output of 25 kw per Machine.

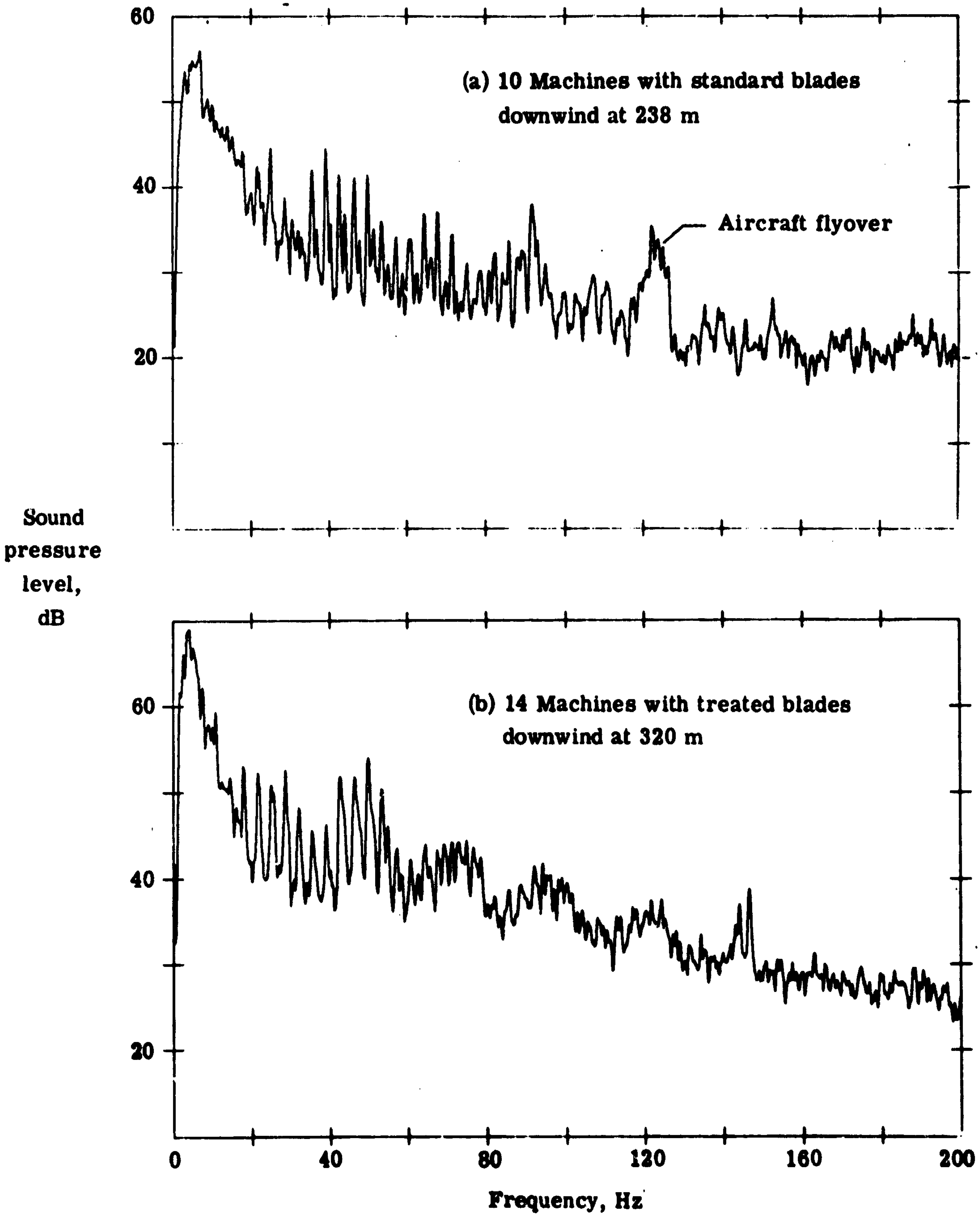

Figure 14.- Narrow Band Spectra (0.25 Hz) for Multiple Machines in the Far Acoustic Field. Data are for a Nominal Power Output of 25 kw per Machine.

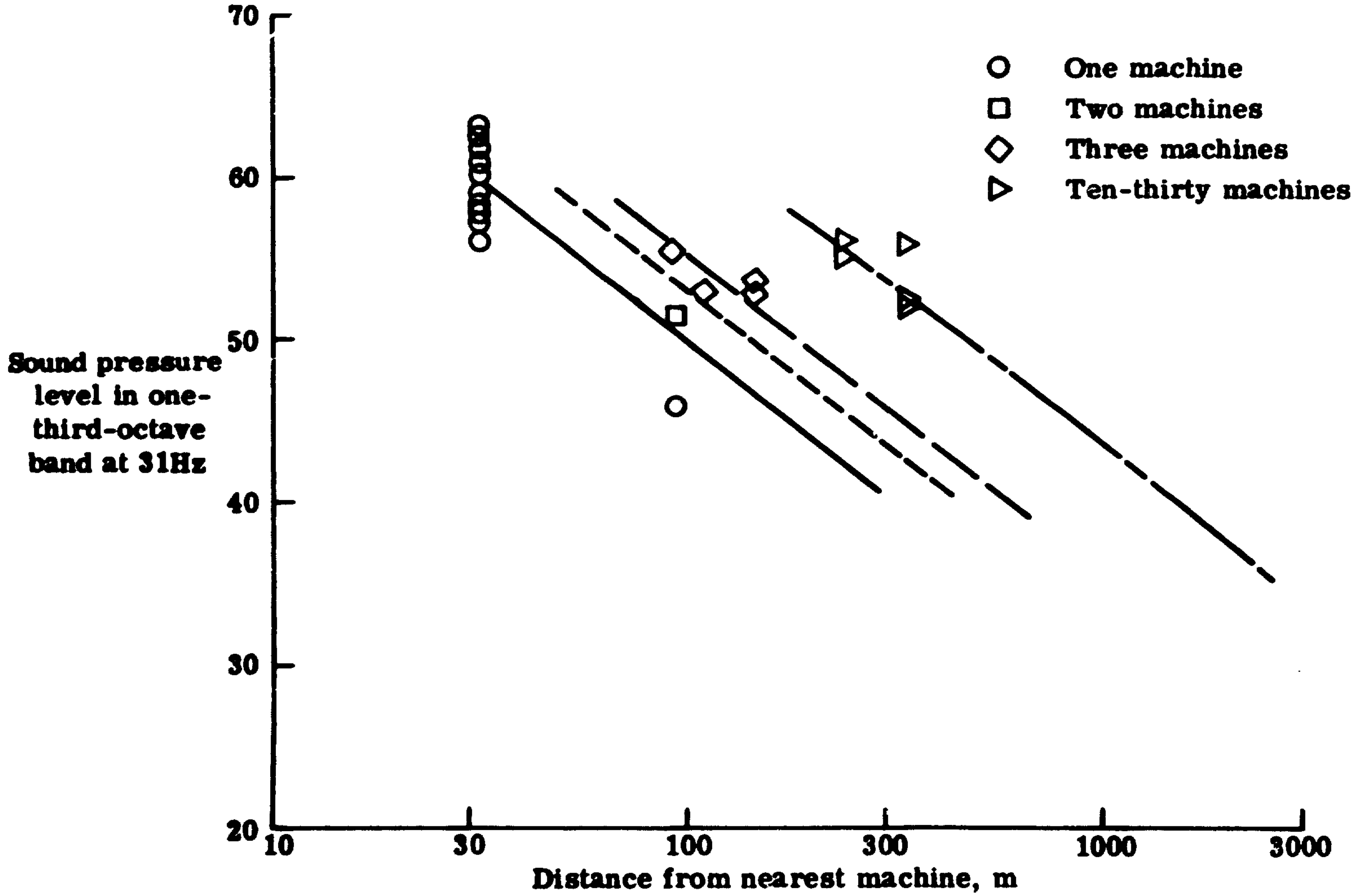

Figure 15.- One-Third Octave Band Levels at 31 Hz as a Function of Distance for Various Numbers of Machines.

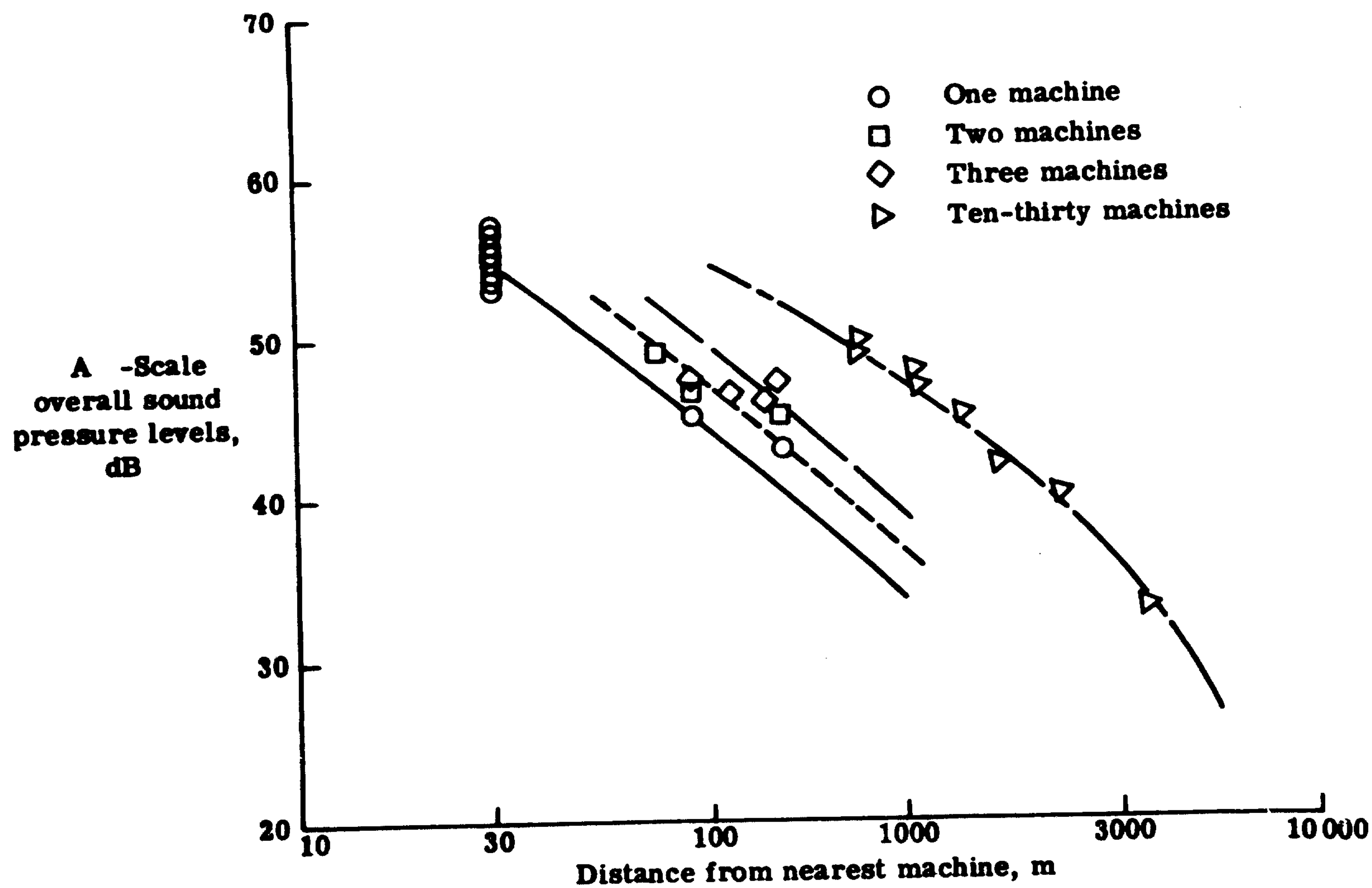

Figure 16.- A -Scale Overall Sound Pressure Levels as a Function of Distance for Various Numbers of Machines.

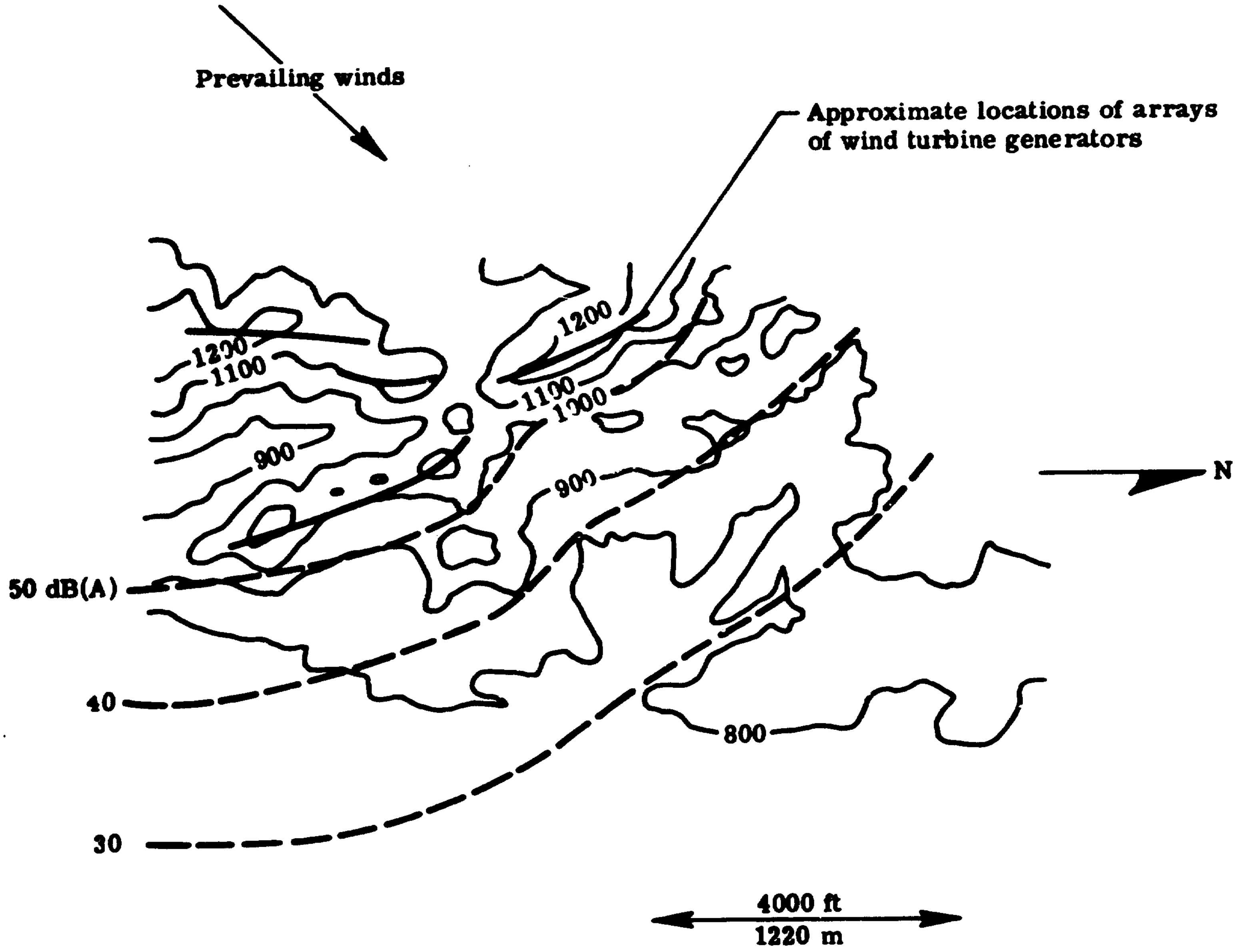

Figure 17.- Estimated A-Level Noise Contours for U. S. Windpower Inc., Wind Energy Farm Near Livermore, Ca. Contour Numbers are in ft.