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AN EXPLORATORY SURVEY OF NOISE LEVELS ASSOCIATED WITH A 100 kW WIND TURBINE

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ABSTRACT

During performance tests of a 125-foot diameter, 100 kW wind turbine at the NASA Plum Brook Station near Sandusky, Ohio, the opportunity arose to make exploratory noise measurements and results of those surveys are presented. The data include measurements as functions of distance from the turbine, and directivity angle, and cover a frequency range from 1 Hz to several kHz. Potential community impact is discussed in terms of A-weighted noise levels relative to background levels, and the infrasonic spectral content. Finally, the change in the sound power spectrum associated with a change in the rotor speed is described. The acoustic impact of this size wind turbine is judged to be minimal.

INTRODUCTION

Wind turbines have recently attracted considerable interest as a way of generating additional electricity, while avoiding the adverse environmental impact characteristic of conventional power plants. These wind turbines, however, have their own potentially adverse impact on the environment, that of producing noise. In respone to future needs, there is likely to be an increasing use of wind turbines in both larger and more numerous installations. Experience with small wind turbines such as used on farms, indicates that the noise level of these devices is rather low. For larger installations designed for utility use, this may not be true. the evaluation of the possible wind turbine environmental impact is difficult at present since only a small amount of information is available about the level and propagation of wind turbine sound (ref. 1). To predict the sound levels of future wind turbine designs, information describing wind turbine acoustic characteristics is required. This paper presents data and an analysis of the noise associated with a 100 kW wind turbine.

EXPERIMENTAL APPARATUS AND PROCEDURE

Wind Turbine

To determine wind turbine acoustic characteristics, exploratory measurements were made on a 38 m (125 ft) diameter, 100 kW wind turbine (ref. 2), located at NASA's Plum Brook Station near Sandusky, Ohio. For several years this facility has been used to evaluate the operating characteristics of a number of wind turbine configurations. Figures 1 and 2 present views of the two configurations in which the wind turbine was operated during two series of acoustic field surveys.

The first series is associated with the installation shown in figure 1, which used full span airfoil blades. For this test series, the wind turbine was operated at 40 rpm, and with the wind available during the test period, generated 30-40 kW. The second test series is associated with the installation shown in figure 2, which used part span airfoil blades. For this test series, the wind turbine was operated at 33 and 26 rpm, and with the winds available on the two test days it generated abut 60 kW. Regardless of the choice of rotor rpm, by means of a variable gear ratio, the wind turbine generator speed was controlled to generate power at 60 Hz. During both test series, the wind turbine was oriented with the blades downwind of the support tower.

Records of operating conditions from the first test series are shown in figure 3. These records are typical of both test series. Wind speed and direction changed significantly during the testing, making the quoted power levels only nominal. Figure 3 indicates a wind speed variation of 10-30 km/hr mph over a few minutes, and wind direction variation of about 40°. The corresponding power level varied approximately from 0 to 100 kW design value.

Acoustic Measurements

For the first series of acoustic tests, the microphones used to measure the wind turbine noise were located as shown in figure 4. The instrumentation associated with these microphones was mounted in a small van located as shown in this figure. Two microphones were used, Bruel & Kjaer models 4133 of 1.2 cm (0.5 in) diameter and 4161 of 2.5 cm (1 in) diameter. These condenser microphones, both protected by windscreens, had a flat frequency response down to approximately 10 Hz. The low-frequency response corrections that were used were not the same for the two instrumentation channels because of the differences in sensitivity of the two microphones. The applicable corrections are listed in table 1. These tabular values are corrections for all equipment errors, and were determined partially by reference to manufacturers literature and partially by experimental evaluation of these units. For this series, as well as the second test series, the microphones were located about 1.8 m (6 ft) above ground level. For this first test series, the 2.5 cm diameter microphone (M1 in fig. 4) was used as a survey microphone at 30, 61 and 122 m (100, 200, and 400 ft) distances at about 120° from the wind turbine's upwind axis. The 1.2 cm diameter microphone (M2 in fig. 4) was fixed at 61 m (200 ft) from the wind turbine at approximately 40° from the wind turbine upwind axis. These same microphones were also used to record the ambient noise at these locations for comparison with wind turbine sound levels.

For the second series of acoustic tests the measurement locations were as identified in figure 5. For these measurements, two surveys in the azimuthal direction around the wind turbine were made. The first survey was made during operation at 33 rpm, and the second during operation at 26 rpm. Additional acoustic instrumentation was available for this test series. Consequently four microphones were used to obtain data for the 10 positions required. These 10 positions were 61 m (200 ft) from the wind turbine at angles from 0° to 180° in 20° increments. The four instrumentation channels were scheduled so that one was used for 0°, 60°, and 120°, a second for 20°, 80° and 140°, a third for 40°, 100° and 160°, and the fourth for 180_o. In this test series, only model 4133 1.2 cm (0.5 in) diameter microphones were used.

Apparatus inaccuracies, particularly at low frequencies, influence the data accuracy. Most acoustic measuring equipment is designed for the audio range of 20 Hz to 20 kHz. This equipment (microphones, preamplifiers and amplifiers) consequently has a severely degraded accuracy in the 0.1 to 20 Hz infrasonic range. For this program, the decision was made to use conventional acoustic equipment and to attempt to compensate for the reduced frequency response.

In addition to the low frequency inaccuracies, there may also be high frequency limits to spectral accuracy. Limitations in the dynamic range of tape recorders restrict the amplitude range of data that can be recorded for analysis. High frequency amplitude limits occurred because the wind turbine high frequency sound levels, when recorded, were comparable to, or less than, those of the tape recorder noise. For this noise survey, the usable frequency range was limited to approximately 1-3000 Hz. Figure 6 illustrates the characteristics of the tape recorder noise floor.

Data Presentation

The bulk of the acoustic data presented was produced by analyzing the recorded data using constant bandwidth filters. The resulting presentation is that of sound pressure level as a function of the log of frequency, with a nominally 1 Hz (actually about 1.3 Hz) bandwidth. To obtain this frequency resolution, each data sample was analyzed over 0 - 130 Hz, 0 - 1300 Hz and 0 - 13 000 Hz ranges, and then portions of each of the three plotted analyses combined to form plots over four decades of frequency, 1-10 000 Hz. This involved combination of spectra was done in an attempt to maximize resolution and normalize spectra to a 1 Hz bandwidth.

The final sound pressure level figures combine the 1 - 10 Hz decade of the first range, 10 - 100 and 100 - 1000 Hz decades of the second range, and the 1000 - 10 000 Hz decade of the third range. The final resolution was made the same as that of the original 10 - 1000 Hz decades. To make the levels of the 1 - 10 Hz and 1000 - 10 000 Hz decades compatible with the 10 - 1000 Hz decades, a change is required. The factor of 10 times the log of the ratio of frequency resolutions was used to correct the broadband spectrum levels for the change in display bandwidth. Use of this factor results in adding 10 db to the levels of the 1 - 10 Hz portion, and in subtracting 10 db from the levels of the 1000 - 10 000 Hz decade. The tone levels, when initially clearly resolved, are unaffected by analysis bandwidth and consequently remain at their original amplitudes.

Test Limitations

Several limitations are present in making meaningful and accurate noise measurements on wind turbines. One limitation may be simply the relatively close microphone locations that were used in comparison with the size of the noise source. In general, at distances which are relatively small the sound level will not decrease with the inverse square of the distance. If the diameter of the wind turbine, 38 m (125 ft), is used as the size of the noise source, then the microphones should be much farther than 38 m (125 ft) for the wind turbine to act as point source with the microphone in the geometric far field. Another limitation arises from the low frequency nature of the wind turbine noise. At the measurement points, the microphones were less than one wavelength away for frequencies less than 5-10 Hz, which have wavelengths of 30-60 m. At frequencies or distances greater than this (acoustic far field) the sound pressure characteristics of the wind turbine are more fully developed.

There are other limitations, particularly at low frequencies. As is true for most turbomachinery, the highest spectral levels are at the blade passage frequency; the wind turbine's low speed of rotation and small number of blades result in a blade passage frequency near 1 Hz. Pressure levels at these low frequencies could be subject to errors either from wind effects or from the equipment limitations previously discussed. The noise or turbulence due to the wind blowing over obstacles in the vicinity would be expected to be predominantly at low frequency. In addition, wind blowing over the microphones themselves can create noise at low frequence, and there may be aerodynamic pressure fluctuations or pseudo sound generated. Each of these wind noise sources may vary in intensity with the wind speed and direction.

RESULTS AND DISCUSSION

First Test Series

The results of the radial survey of wind turbine noise levels will be presented first followed by the results of the azimuthal surveys.

The radial survey measurements offer potential answers to several questions. One question is how much noise is generated by the wind turbine. Since the degree to which a wind turbine may affect a community's environment is a consideration, the annoyance reponse A-weighting scale was used in evaluating sound level. This scale weights most heavily the levels at frequencies near 1000 Hz for which hearing response is most sensitive. Figure 7 presents A-weighted sound levels measured by the fixed microphone 61 m (200 ft) from the wind turbine. To produce this figure, six data samples, approximately 6 minutes long, were recorded and analyzed into several 30 second averages. The upper three clusters of points result from A-weighting the noise of the wind turbine while operating at about a third of its design power. The lower three clusters of point result from A-weighting the background noise at the same location. At 61 m (200 ft), the wind turbine sound level was 60 dBA, with approximately 1 db scatter. At the same location, the background level was approximately 48 dBA, with a scatter between 2 and 10 db between 30 second periods. For comparison, 50 dBA is the sound level in a typical residential area, while 60 dBA is representative of levels inside large retail stores.

Another question of interest about wind turbine noise is how the sound level changes with distance. Figure 8 presents the A-weighted sound levels from the survey microphone (designated M1 on fig. 4). Since the survey and fixed microphone data were taken simultaneously, the three background noise points at 30, 61 and 122 m (100, 200 and 400 ft) distances were taken during the background test points of figure 7, respectively, and the corresponding wind turbine data points were taken in similar fashion. As was the case for the fixed microphone (M2) data, there is about a 1 db scatter in the 30 sec. averages of wind turbine sound levels, but a decrease in level clearly exists. The level changes from 63 dBA at 30 m (100 ft) to 60 dBA at 61 m (200 ft) and then to 54 dBA at 122 m (400 ft). The attenuation slope changes at 61 m (200 ft) from about 3 db per doubling of distance at closer locations to 6 db per doubling of distance at farther locations. This decrease of the A-weighted level indicates that by 60 meters (200 ft) far field distances have been reached for audio frequencies. In considering community response to the noise propagated from this wind turbine, it should be noted that the data at 122 m (400 ft) distance indicate a wind turbine sound level nearly equal to the background sound level. Figure 9 presents averages of the previous survey microphone data, and more clearly shows the decrease of wind turbine noise with distance. When these microphone data were extrapolated to greater distances, the wind turbine and background levels became equal at about 183 m (600 ft).

Thus far, the results of the radial survey of wind turbine noise have been presented in terms of A-weighting which emphasizes the impact of audio frequencies near 1000 Hz. Further results will be presented as unweighted spectra from 1 Hz to slightly over 2 kHz. The associated pressure has rather coarse resolution because of the large range of amplitudes that are displayed. Figure 10, which displays wind turbine noise spectra at three distances and the background noise, shows a decrease with distance for frequencies greater than about 100 Hz.

The large number of tones in the wind turbine noise spectra at frequencies greater than 100 Hz were not identified as to origin, but are presumably associated with mechanical components of the wind turbine power train. Those tone frequencies which are common with the background are most likely due to extraneous noise sources at the test site or in the instrumentation.

There is some evidence of tones at multiples of blade passage frequency, at approximately the background level. It was expected that the noise characteristics of the wind turbine would include these low frequency tones because in typical turbomachinery spectra, blade passage frequency harmonics are very obvious and influential components. It was expected that despite the smaller number of blades and lower speed of a wind turbine, compared with more conventional turbomachinery, these discrete frequency tones would still appear. These tones do appear, but at relatively low levels. Somewhat unexpected is the appearance of an amplitude envelope around these tones (fig. 11) which is a pattern characteristic of a repeated impulse rather than of a sinusoidal disturbance. In this test series, the blades were located downwind of the turbine tower, so a likely source of this periodic impulse noise is the interference of the tower wake with the blades. This source identification seems likely for the following reason. The time period of this disturbance may be estimated as the inverse of the interval of the tone envelope (10 Hz). Therefore, the period of time that a wake interferes with the blades would be approximately 0.1 second for this first test series (for which the wind turbine speed was 40 rpm). At an effective point of 70% of the blade span, this 0.1 second period corresponds to the time required for a blade to pass through a wake as wide as the tower. Consequently, it is likely that the source of the low frequency tones is the interference of the support tower wake with the blades.

The low-frequency spectrum levels are nearly the same at each measurement point. One possible reason for this is the fact that the microphone locations are in the acoustic near field. Another possibility is that the blade passage frequency interaction tone may be so low in amplitude that the background noise predominates. Figure 11 presents spectral data from 1-20 Hz for wind turbine sound at 30 m (100 ft) and 122 m (400 ft) and also the background level. A C.03 Hz bandwidth was used to better resolve the tones, and the curves were offset by 10 db to avoid confusion. Apparently, while the tones decrease an average of 9-10 db between the two locations, the broadband level is independent of location. The broadband level is essentially the background level. A further comment can be made about the levels in this frequency range. These low frequencies are outside the audio range, but pressures at these frequencies may be sensed if the levels are high enough. The threshold of human annoyance, or even psychological damage is not well defined, but one reported threshold of annoyance to infrasound is a sound pressure level of 120 db at frequencies less than 5 Hz, decreasing to 90 db at 20 Hz (ref. 3). These particular levels were not exceeded or even approached during the reported wind turbine testing.

Second Test Series

The second test series explored the effects of speed on the wind turbine sound level and surveyed the sound field as a function of angle. These measurements of wind turbine noise were made on a 61 m (200 ft) radius at 26 and 33 rpm, using the configuration shown in figure 2, with microphones located as shown in figure 5. The results, as displayed in figure 12 as individual microphone location spectra, are generally higher in amplitude than the data from the first series. Several differences exist between the two test series; among them are blade shape, turbine power level and wind speed. The specific reason for the data difference is not known, and no further comparison with the radial survey data will be made.

The wind turbine noise level differences between operation at 26 rpm and 33 rpm are mainly at the upwind angles, 0° - 40°. These differences, shown for 0° though 180° in 20° increments, increase with frequency, independent of angle. This difference as a function of frequency is seen more clearly in figure 13, which presents estimates of the wind turbine sound power levels at 61m for the two speeds. These data, like the sound pressure level data, are presented on a log frequency scale with a frequency bandwidth of 1 Hz. The difference in estimated wind turbine sound power between opration at 26 rpm and 33 rpm increased from about 3 db at 1 Hz to 16 db at 1000 Hz. A prediction of the amount of the increase, based on a 6th power dependency of noise level on speed, would be 6 db. If the differences in power level of figure 13 are integrated over the frequency range, the mean difference between total power levels is slightly over 5 db -- fair agreement with a 6th power relationship.

To some extent, the power level data at frequencies less than about 100 Hz are only estimates. The true power level should be independent of distance from the wind turbine. Since these low frequency pressures do not decrease with the square of distance (fig. 10), the computed power levels will be a function of distance. The power level values presented here are determined from the measurements at 61 m (200 ft).

In addition to the exploration of noise trends with speed, the variation of wind turbine sound pressure level with angle was explored. To do this, the spectral data of figure 12 were plotted against angle in figures 14 and 15 for 26 and 33 rpm, respectively. Results are shown for 2, 10, 100, 200 and 500 Hz. The 2 and 10 Hz frequency levels show high amplitudes with nearly omnidirectional characteristics except for a 5 - 10 db lobe in the downwind quadrant. The 2 and 10 Hz data are probably near-field data, while the pressures at higher frequencies have the more lobular far-field propagation characteristics. The 100 and 200 Hz levels show directivity peaks in both upwind and downwind quadrants. The 500 Hz pressure has the more pronounced lobes characteristic of high frequencies. The 33 rpm data, figure 15, show characteristics similar to those of the 26 rpm data.

CONCLUDING REMARKS

Evaluation of the results of this exploratory survey yields an appreciation of the basically low-frequency nature of wind turbine noise. Acoustic levels for this wind turbine are relatively low and at moderate distances - 150 to 180 m (500 - 600 ft) comparable in level to the background wind noise. Infrasonic levels are dominated by background noise although some periodic tones exist.

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TABLE I - MICROPHONE RESPONSE CORRECTIONS (LOW FREQUENCY)

Frequency (Hz)	2.5 cm Diameter Microphone M1 Correction (dB)	1.2 cm Diameter Microphone M2 Correction (dB)
0.6	19.0	29.0
0.8	16.0	20.0
1.0	11.5	13.5
1.5	6.0	9.0
2.0	4.0	6.0
3.0	1.8	3.0
4.0	1.0	2.0
6.0	.5	1.5
8.0	.2	1.0
10.0	0	.6
20.0	0	0

Figure 1. - View of wind turbine with full-span blades.

Figure 2. - View of wind turbine with part-span blades.

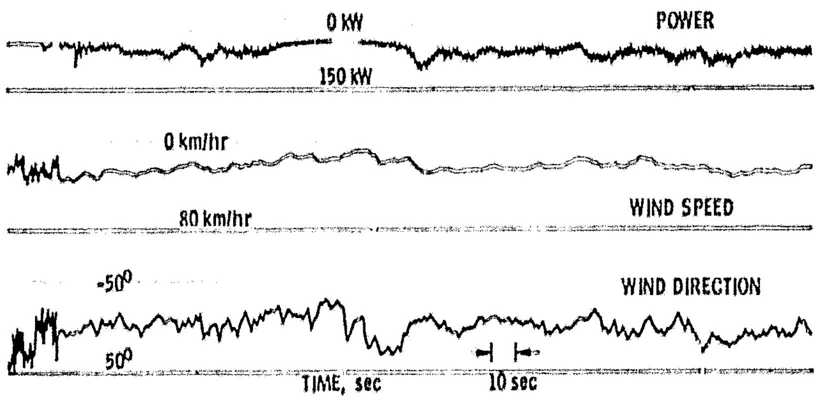

Figure 3. - Wind turbine operating parameters during noise measurements (first test series).

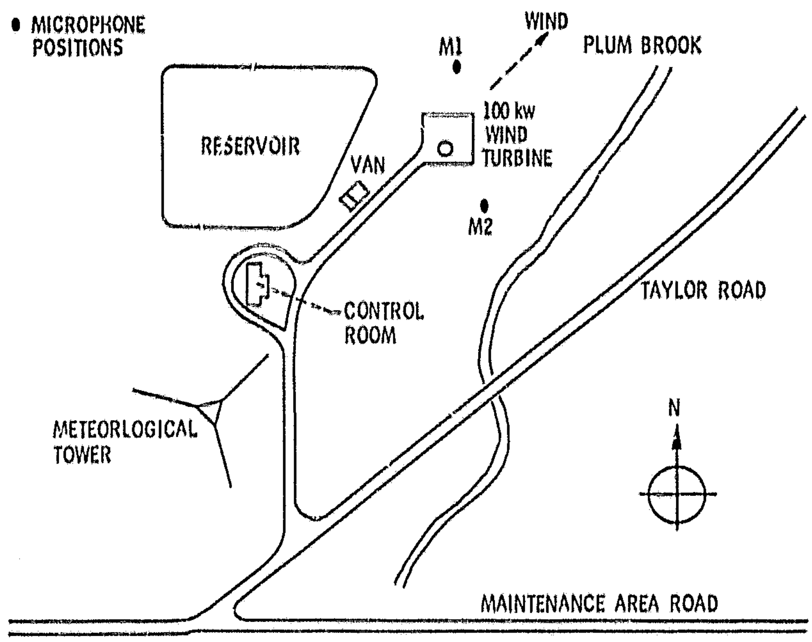

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Figure 4. - Plan view of wind turbine site showing microphone locations for first test series.

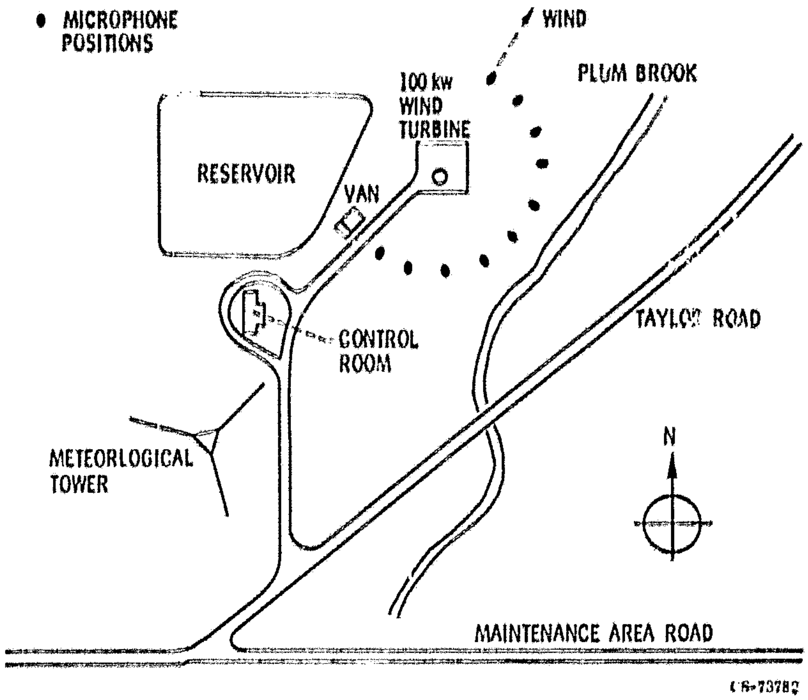

Figure 5. - Plan view of wind turbine site showing microphone locations for second test series.

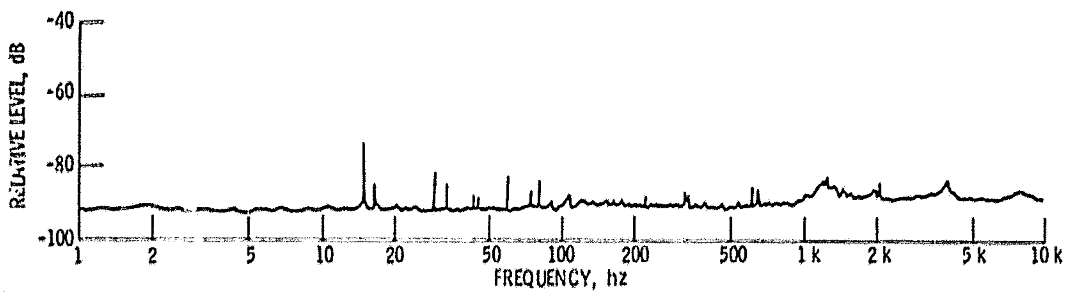

Figure 6. - Tape recorder noise spectrum.

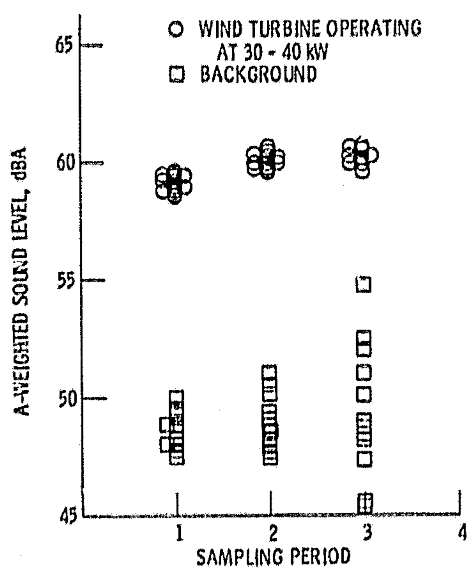

Figure 7. - A-weighted sound levels measured by reference microphone at 200 feet (microphone M2, first series, 30 sec average).

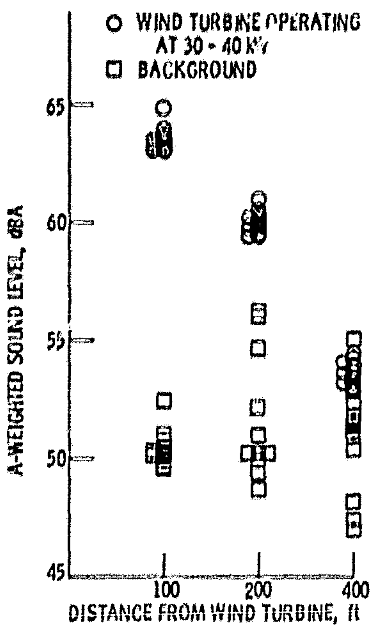

Figure 8. - A-weighted sound levels as a function of distance from wind turbine (microphone M1, first series, 30 sec average).

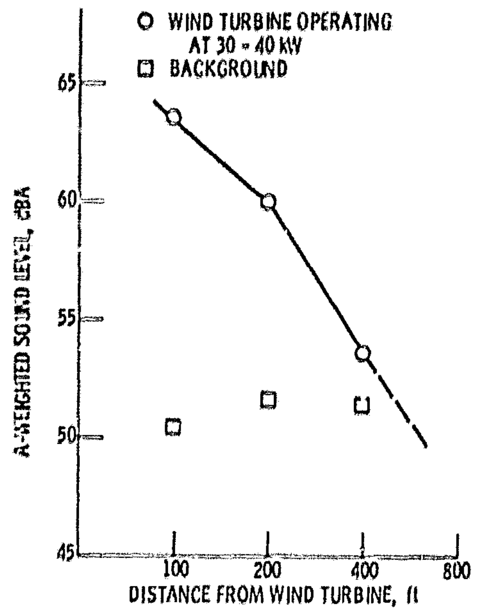

Figure 9. - A-weighted average sound levels as a function of distance from wind turbine (microphone M1, first series, 6 min. average).

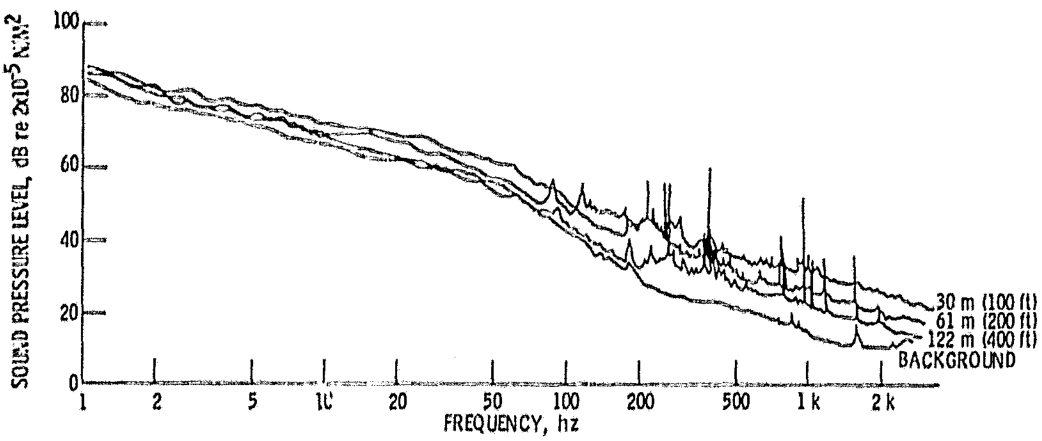

Figure 10. - Wind turbine sound pressure level spectra (1 hz bandwidth, first test series, 40 rpm).

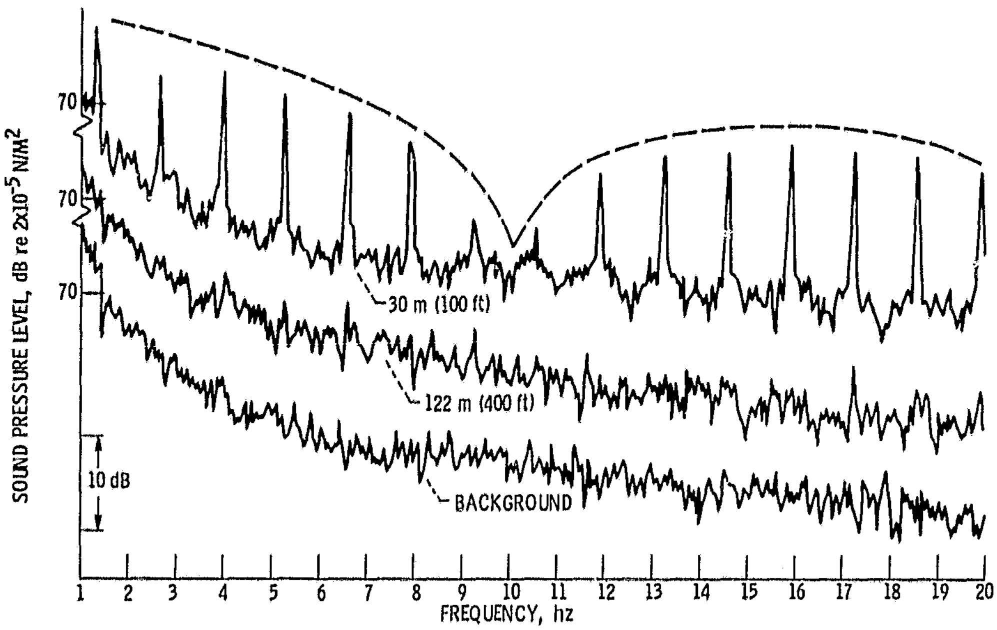

Figure 11. - Wind turbine sound levels at 30 m (100 ft) and 122 m (400 ft) at 40 rpm and background level (0.03 hz bandwidth).

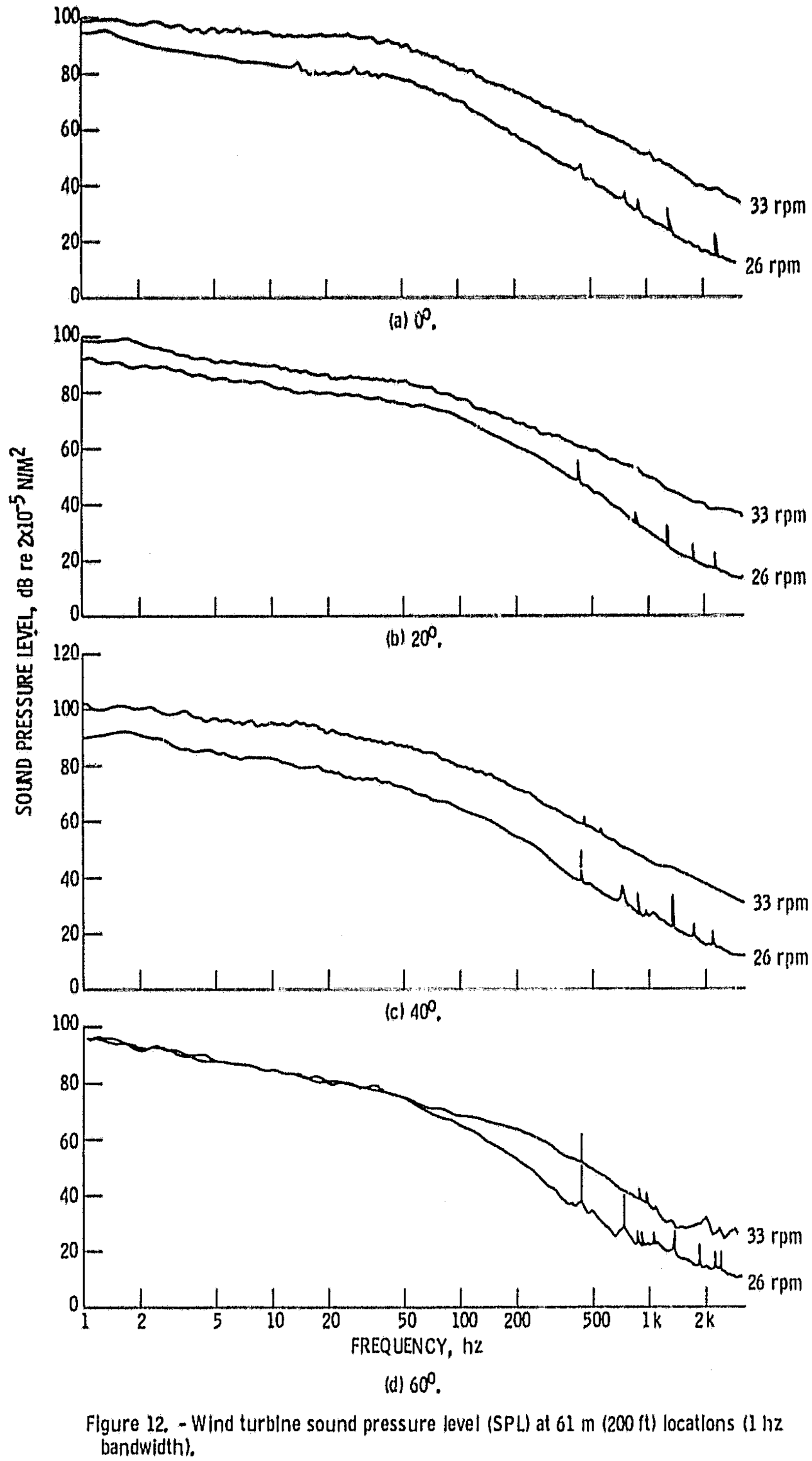

Figure 12. - Wind turbine sound pressure level (SPL) at 61 m (200 ft) locations (1 hz bandwidth).

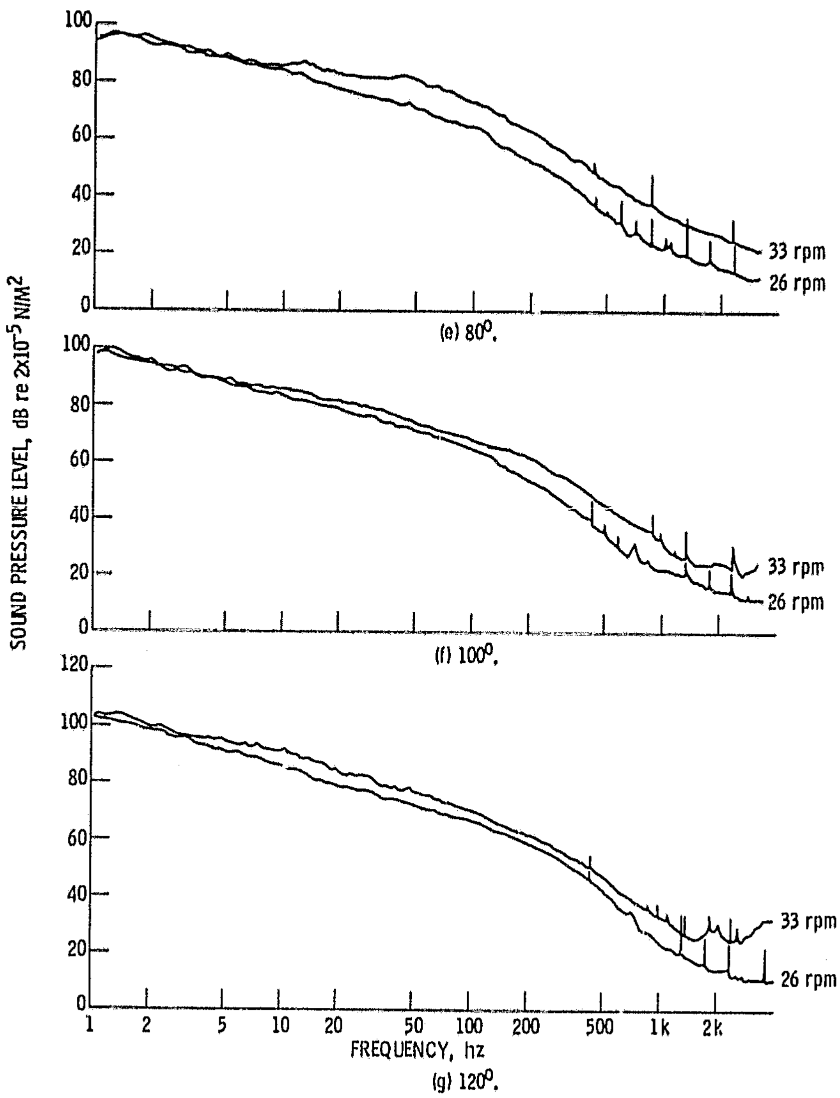

Figure 12. - Continued.

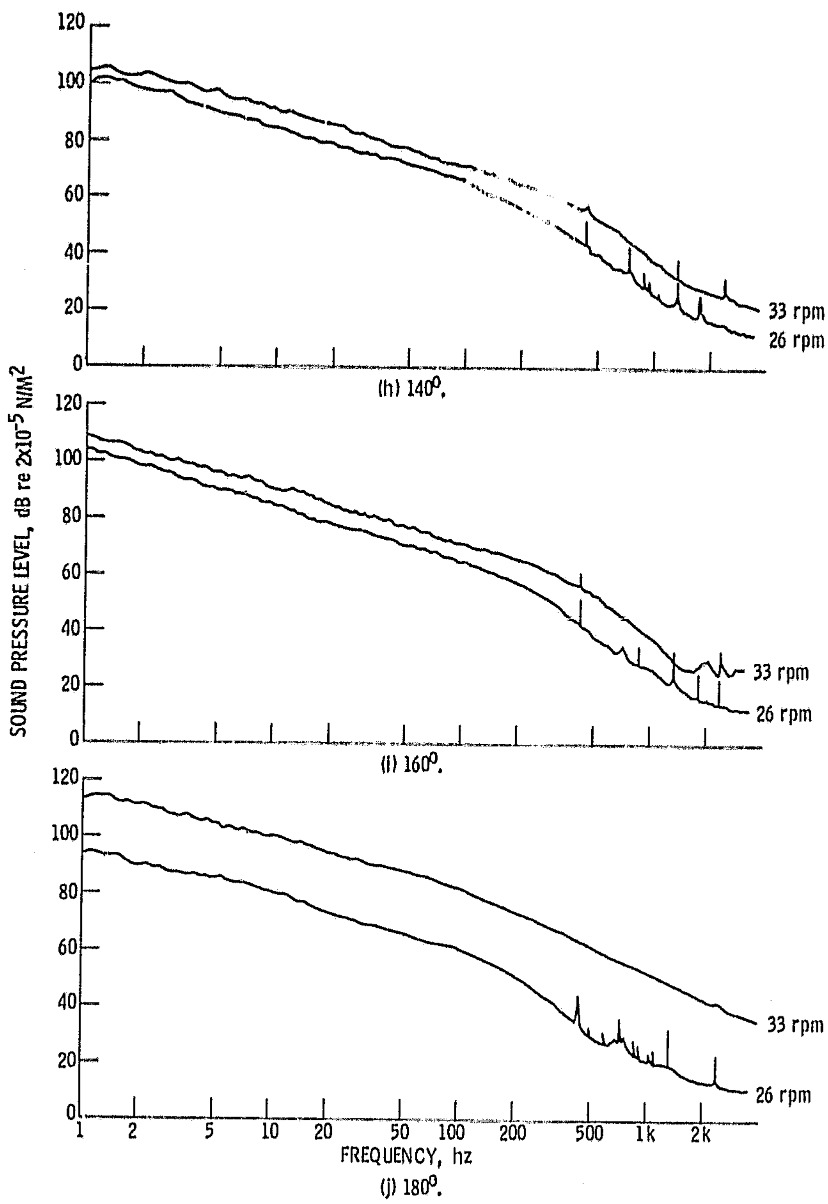

Figure 12. - Concluded.

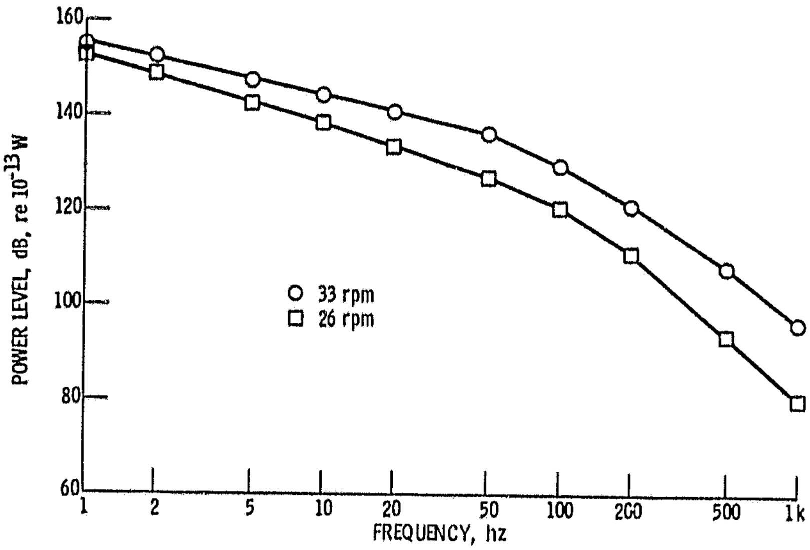

Figure 13. - Wind turbine sound power level at two speeds.

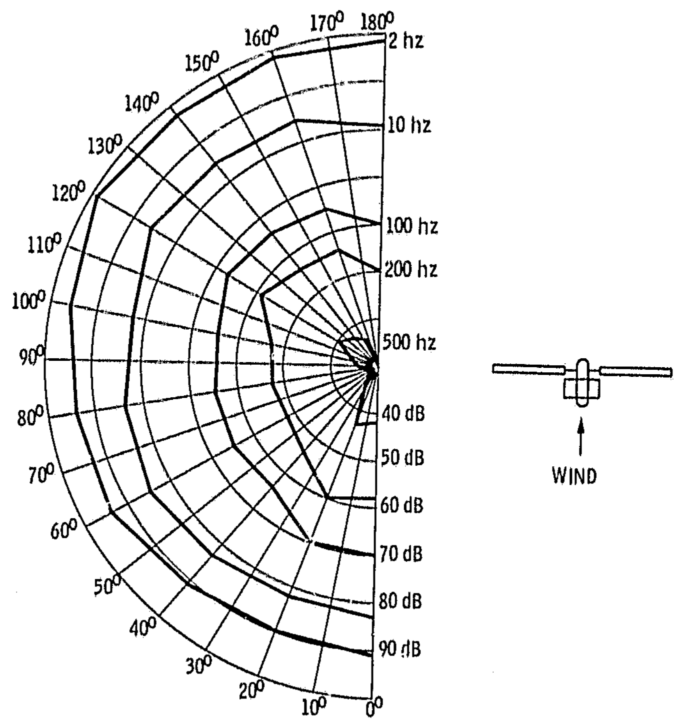

Figure 14. - Wind turbine noise directivity at 26 rpm.

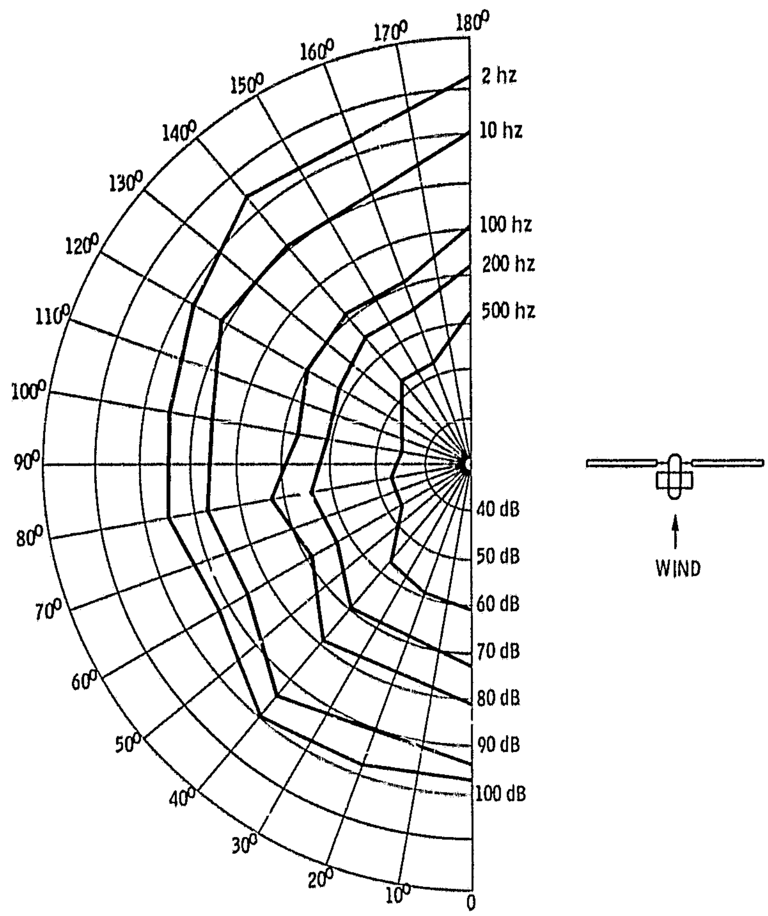

Figure 15. - Wind turbine noise directivity at 33 rpm.

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16. Abstract

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