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GUIDE TO THE EVALUATION OF HUMAN EXPOSURE TO NOISE FROM LARGE WIND TURBINES

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GUIDE TO THE EVALUATION OF HUMAN EXPOSURE TO NOISE FROM LARGE WIND TURBINES

1.0 ABSTRACT

This document is intended for use in designing and siting future large wind turbine systems as well as for assessing the noise environment of existing wind turbine systems. Guidance for evaluating human exposure to wind turbine noise is provided and includes consideration of the source characteristics, the propagation to the receiver location, and the exposure of the receiver to the noise. The criteria for evaluation of human exposure are based on comparisons of the noise at the receiver location with the human perception thresholds for wind turbine noise and noise-induced building vibrations in the presence of background noise.

2.0 INTRODUCTION

The development of wind turbines which are acoustically acceptable to the community requires an understanding of the human perception of, and response to, wind turbine noise and any noise induced building vibrations resulting from their operation. The factors which are believed to be important in evaluating human exposure to wind turbine noise are shown schematically in figure 1.

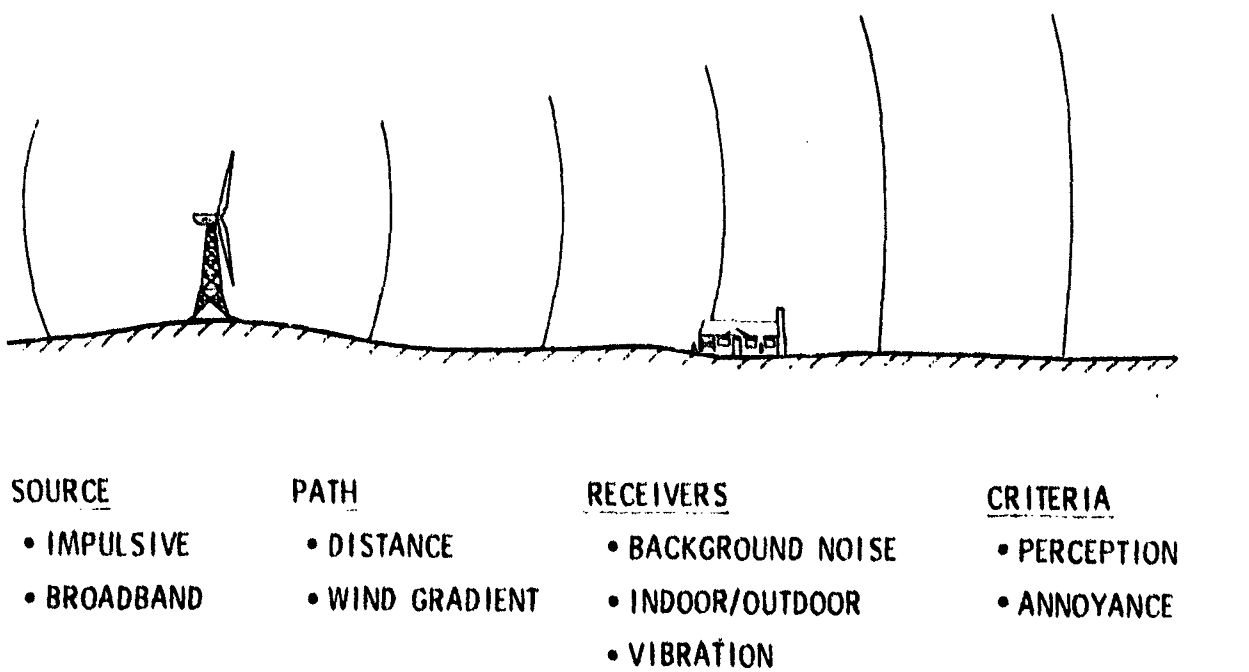

Figure 1.- Wind turbine noise factors.

As indicated, the wind turbine generator may produce noise with both impulsive ("thumping") and broadband ("swishing") characteristics (ref. 1-8). These noise components are modified by atmospheric propagation and terrain effects before reaching the receiver. The effects of wind turbine noise on the receiver may be modified by factors such as the background noise level, location of the receiver (indoors/ outdoors), and the presence of any perceptible house vibrations induced by the noise. To fully assess the impact of the noise, the receiver's perception of, and response to, the acoustical factors (noise level and frequency, for example) and nonacoustical factors (time of day, for example) associated with the operation of the wind turbine should be considered.

This guide presents a procedure for evaluating wind turbine noise with emphasis on the acoustical factors. The guide is based upon results of recent laboratory studies of human response to wind turbine noise as well as information contained in the available literature on noise induced building vibrations, noise propagation in the atmosphere and wind turbine source characteristics. For completeness, the background information used in the development of the guide is presented in Appendices A through E, and is based on experience with horizontal axis machines. The guide is intended for use in the design, siting and assessment of wind turbine systems for community acceptability.

3.0 SCOPE

The evaluation criteria are based upon the noise and noise-induced vibrations at a receiver location. Noise and vibration may be measured at a receiver location if possible or may be inferred from a knowledge of the noise at the turbine site (source noise) along with an estimate of the propagation effects. The data herein are most directly applicable to sites in which the intervening terrain from the noise source to a receiver is relatively flat and treeless, and the receiver is in a rural or suburban neighborhood. The scope of this guide in terms of the source, path and receiver are as follows:

3.1 Source

The wind turbine noise may contain both impulsive characteristics due to blade/tower-wake interactions and broadband noise due to unsteady flow over the blades (Appendix A). A schematic representation of a spectrum containing both of these components is presented in figure 2. Although the details for calculating the source noise characteristics are not included in this document other than by reference (ref. 3), both impulsive and broadband components are considered in the evaluation process. Impulsive noise is an important consideration for those horizontal axis configurations with downwind rotors for which there is the possibility of strong rotor blade/tower-wake interactions. Broadband noise, however, is of concern for all types of machines.

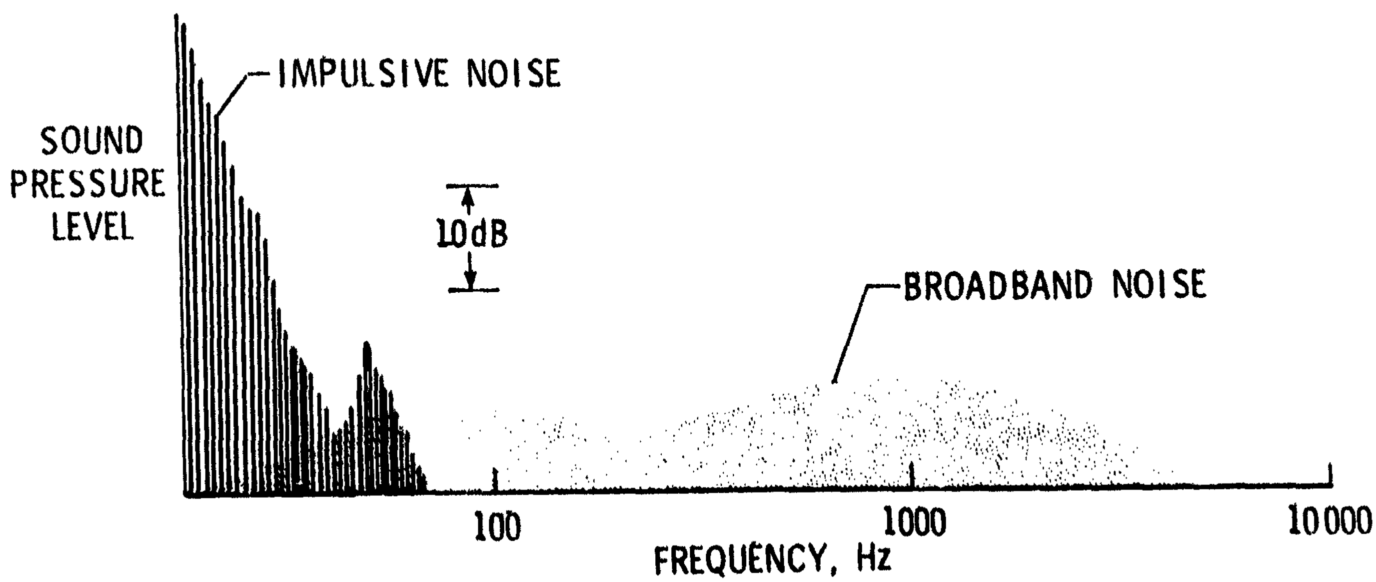

Figure 2.- Schematic diagram of noise spectrum from large wind turbine generator.

3.2 Path

The modification of the sound in propagating from the turbine site to a receiver location is considered to be due to distance, wind, and absorption effects (refs. 9 and 10). These effects are quantified based upon data available in the literature for use in cases where propagation data are not available.

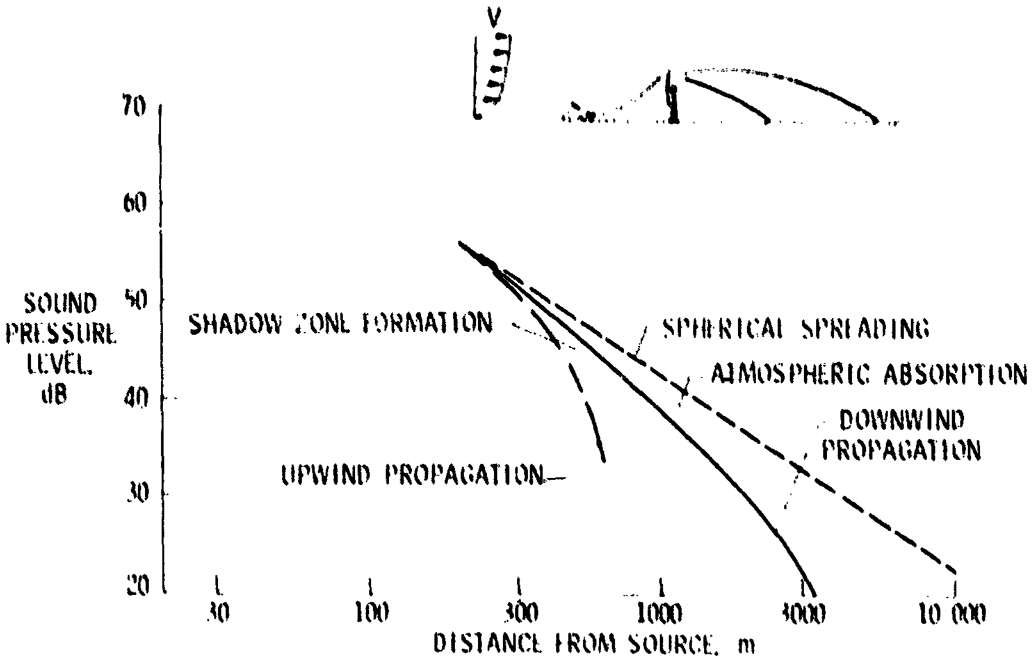

Figure 3.- Schematic illustration of the effects of distance and wind direction on the sound from wind turbine generators.

The prediction of sound pressure levels downwind of a wind turbine is based upon spherical spreading and atmospheric absorption (fig. 3). In the upwind direction an additional factor, shadow zone formation, is included in the prediction method.

3.3 Receiver

The receiver exposure is evaluated both outside and inside the house. Outside, the receiver is considered to experience wind turbine noise in the presence of background noise. Inside, the receiver experiences noise modified by the house structure and may also experience noise-induced building vibration.

In considering the human exposure to noise and vibration, the suggested evaluation criteria are based upon the human perception thresholds for both. The evaluation criteria for the noise are based upon the results of laboratory simulations of wind turbine noise which were conducted in direct support of this effort to develop wind turbine noise guidelines. The details of these tests as well as the results are given in Appendix B. The evaluation criteria for the building vibration are based on building response data (primarily from aircraft flyover tests) and the International Standards Organization guidelines for human response to vibration. The details for determining building vibrations and associated human effects are contained in Appendix C.

The recommended goal for designing and siting future machines is that the noise and vibration levels at the receiver location be below the respective perception threshold values when considered along with the background noise.

4.0 EVALUATION PROCEDURE

This section describes the recommended procedures for acquiring, analyzing and interpreting the data required in each of the steps of the evaluation procedure which is illustrated schematically in figure 4.

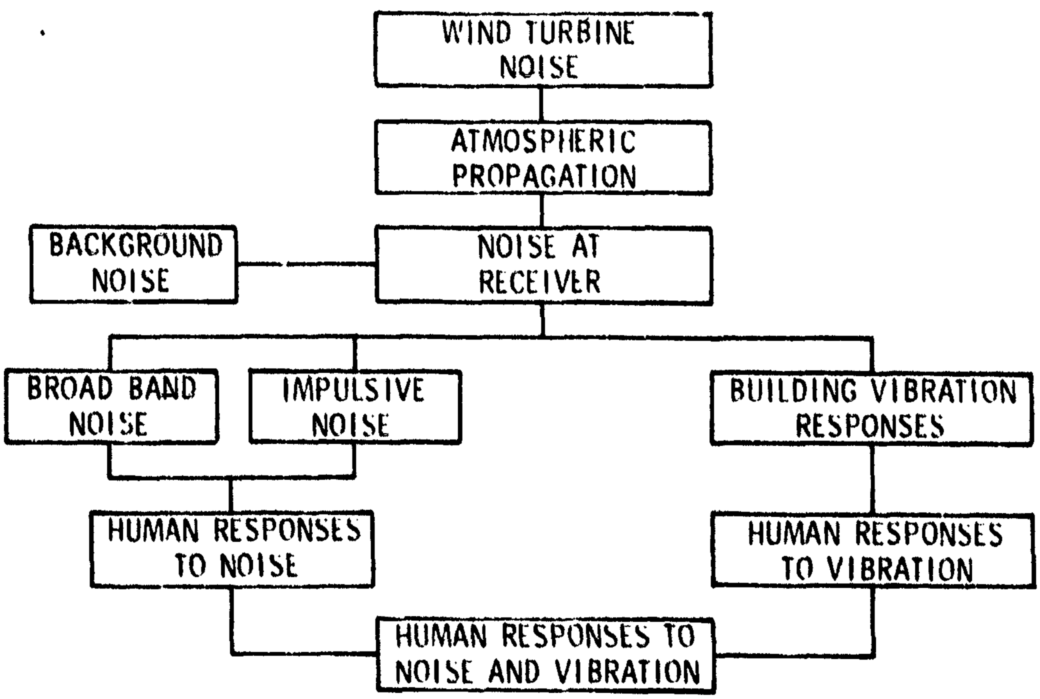

Figure 4.- Evaluation of human exposure to wind turbine noise.

4.1 Source Description

The source noise should be predicted or measured at a reference location near the machine. A distance of 200 meters downwind of the machine is recommended and will be referred to as the "reference distance." The spectrum should be presented in terms of one-third octave bands covering a frequency range from 20 to at least 2000 Hertz. If the machine has impulsive (thumping) characteristics, a narrow band spectrum should be determined in addition to the one-third octave band spectrum. The narrow band spectrum should have a bandwidth resolution narrower than the blade passage frequency and should cover a frequency range from blade passage to at least 100 Hertz. Spectral components which occur below 3 Hertz may be difficult to measure without the aid of special low frequency microphones. However, it is believed that these very low frequency blade passage harmonics will not be significant in most cases.

The noise spectra are dependent upon operating conditions at the site such as the velocity and direction of the wind, and hence are time dependent. It is recommended that spectra be selected for evaluation which are representative of those which would be experienced for sustained periods of time (greater than 30 minutes) during operations which produce the highest levels of noise.

4.1.1 Measurement Considerations.- The measurement of wind turbine generator noise may be difficult because of the adverse effects of the wind. Background noise levels due to wind blowing over the microphone tend to be highest at very low frequencies, decrease rapidly as frequency increases, and at frequencies above a few hundred Hertz cease to be a significant problem. Several procedures are recommended for minimizing the wind noise effects such as: the use of a windscreen, location of the microphone near the ground surface where wind velocities are relatively low, and the choice of a reference location close to the machine to maximize the signal to background noise level. The use of low frequency filtering can also be very useful as a means of minimizing the effects of wind noise.

4.2 Atmospheric Propagation

When available, propagation data acquired at the test site should be used in estimating the noise at the receiver location. In the absence of such data, procedures are recommended (Appendix D) for estimating the noise upwind, downwind and crosswind (90° to the wind direction) of the machine. The measured or predicted sound pressure level spectrum should first be corrected to the reference distance of 200 meters by the following:

$$SPL_2 = SPL_1 + 20 \log_{10} \frac{r}{200}$$

SPL_2 = Sound pressure level at 200 meters
SPL_1 = Sound pressure level at r meters
r = Distance from machine at which measurement or prediction was made.

4.2.1 Downwind.- The attenuation downwind is estimated based only on spherical spreading and atmospheric absorption. Figure 5 gives the sound pressure level reduction as a function of frequency and distance from the wind turbine.

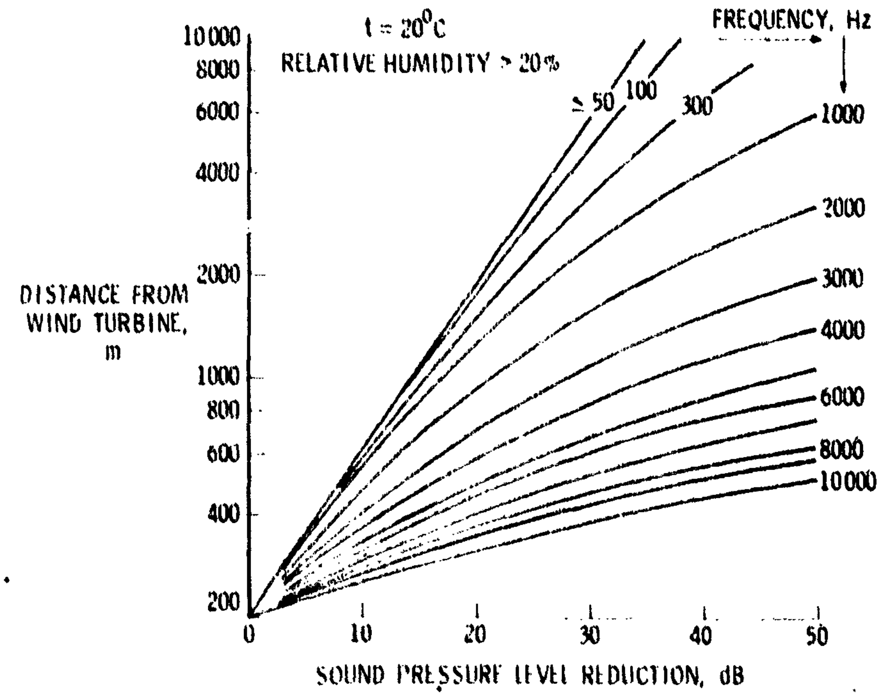

Figure 5.- Sound pressure level reductions due to spherical spreading and atmospheric absorption for various frequencies as a function of distance from wind turbine.

4.2.2 Crosswind.- Attenuation cross~~wind~~ is estimated in the same manner as downwind propagation using figure 5.

4.2.3 Upwind.- Sound propagating upwind results in the formation of a shadow zone in which rapid sound attenuation takes place. The distance from the machine to the edge of the shadow ~~zone is~~ dependent on both the ~~wind speed~~ and the height of the noise source above the ground. Figure 6 may be used to determine this distance. It is suggested that the lowest operating wind speed be used (low speed cut-out) and the source height be the top of the rotor disc for broadband sound and the bottom of the rotor disc for impulsive sound.

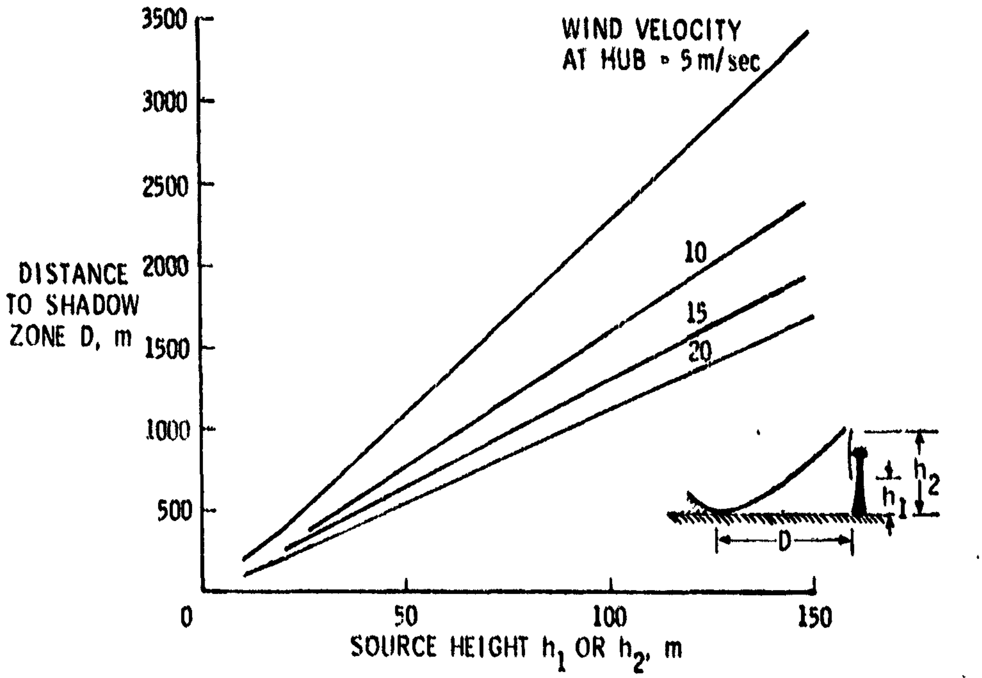

Figure 6.- Distance to the edge of shadow zone as a function of source height and wind velocity.

Sound pressure levels at distances between the machine and the edge of the shadow zone may be estimated based on spherical spreading and atmospheric absorption. Figure 5 specifies the reduction in noise level to be applied to the reference sound pressure level (SPL_2) as a function of frequency and distance from the wind turbine.

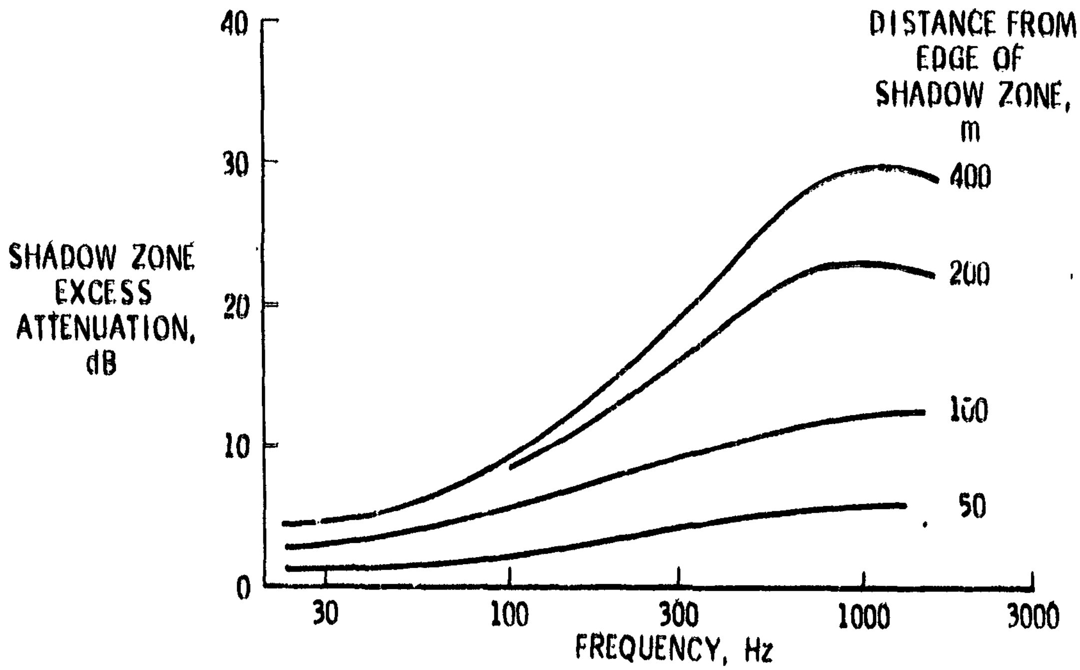

Figure 7.- Excess sound attenuation in the shadow zone as a function of frequency and distance.

A rapid drop in sound pressure level, which is frequency dependent, occurs during the first 400 m inside the shadow zone as given by figure 7. This figure also displays the reduction in sound pressure level which occurs at intermediate distances between the edge of the shadow zone and 400 m. Sound pressure levels beyond this distance are again based on spherical spreading and atmospheric absorption (fig. 5). A numerical example of this calculation procedure is presented in Appendix E.

4.3 Receiver Exposure

As indicated by the flow chart of figure 4, the evaluation of the noise exposure at the receiver location consists of two parts: an evaluation of the noise effects on the receiver and an evaluation of the noise-induced building vibration effects on the receiver. It is recommended that the goal for design and siting of machines be such that the levels of noise and vibration at the receiver location be below the perception thresholds when considered along with the background noise levels associated with the periods of high turbine noise. The evaluation of the noise and the vibration are considered separately as follows.

4.3.1 Outside Noise Evaluation.- The evaluation of wind turbine generator noise outside buildings involves the temporal and spatial characteristics of the machine, the pertinent atmospheric propagation phenomena, and the background noise at the receiver location. Both the broadband noise components and the narrow band impulsive noise components should be considered.

4.3.1.1 Background Noise.- The hearing perception threshold data contained herein were determined for background noise spectra having shapes similar to those of figure 8 which apply to rural/suburban settings. For other situations such as in urban or industrial settings background noise spectra should be measured on a one-third octave band basis or estimated from reference 11.

4.3.1.2 Broadband Noise.- A one-third octave band spectrum of the wind turbine noise should be compared to the one-third octave band spectrum of the background noise. The procedure is illustrated in figure 8, as an example. To be below the perception threshold, the noise level at a receiver location should be below the noise level of the background noise for all one-third octave bands. No adverse human response is predicted for cases where the levels of the turbine noise are equal to or below the background levels. If the levels exceed the background noise, Table I (modified from ref. 12) indicates the potential human response.

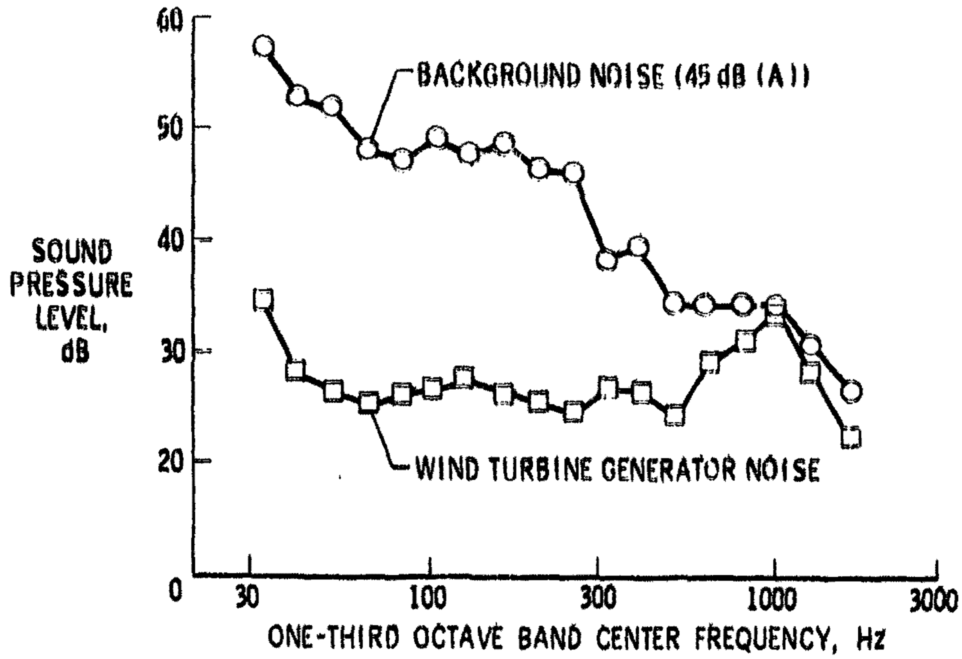

Figure 8.- Example of broadband noise that would be just perceptible in the presence of the assumed background noise.

TABLE I.- ESTIMATED COMMUNITY RESPONSE TO WIND TURBINE GENERATOR NOISE

AMOUNT IN DECIBELS BY WHICH THE RATED NOISE EXCEEDS THRESHOLD LEVEL	ESTIMATED COMMUNITY RESPONSE	
	CATEGORY	DESCRIPTION
0	NONE	NO OBSERVED REACTION
5	LITTLE	SPORADIC COMPLAINTS
10	MEDIUM	WIDESPREAD COMPLAINTS
15	STRONG	THREATS OF COMMUNITY ACTION
20	VERY STRONG	VIGOROUS COMMUNITY ACTION

4.3.1.3 Impulsive Noise.- A narrow band spectrum of the wind turbine should be compared with the curves of figure 9, which are for a machine having a fundamental blade passage frequency of 1 Hz. Adjustments should be made for other frequencies according to:

$$\Delta SPL = 10 \log_{10}(\text{blade passage frequency})$$

Thus, the curves for 0.5 Hz fundamental would be 3 dB lower and the curves for a 2 Hz fundamental would be 3 dB higher than those presented in figure 9.

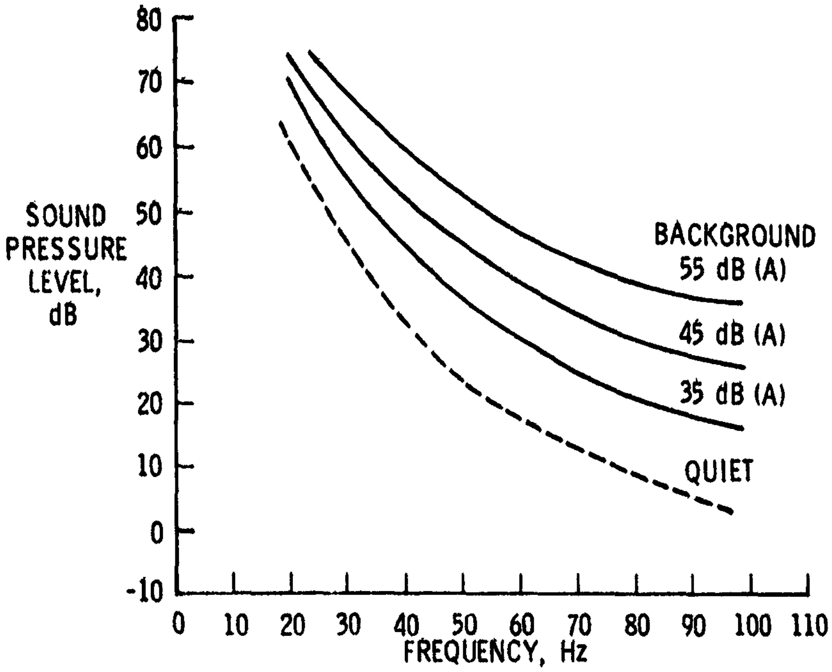

Figure 9.- Thresholds of perception for impulsive noise for different background noise levels (1.0 Hz fundamental).

To be below the perception threshold, the sound pressure levels of turbine noise spectra should be below the threshold curves throughout the frequency range presented. If the sound pressure levels exceed those of the curves, human response as given in Table I may result.

One may interpolate between the curves of figure 9 if the background noise levels are different than those presented. However, the usefulness of figure 9 is limited to situations in which the shape of the background noise spectrum does not differ significantly from those used in the study of Appendix B.

4.3.2 Inside Noise Evaluation.- The evaluation of inside noise involves the additional factors of noise reduction loss from outside to inside, the dimensions and layout of the rooms and the inside background noise. For frequencies above 50 Hz the house noise reduction data of figure 10 apply directly and permit the estimation of inside noise levels (Appendix C).

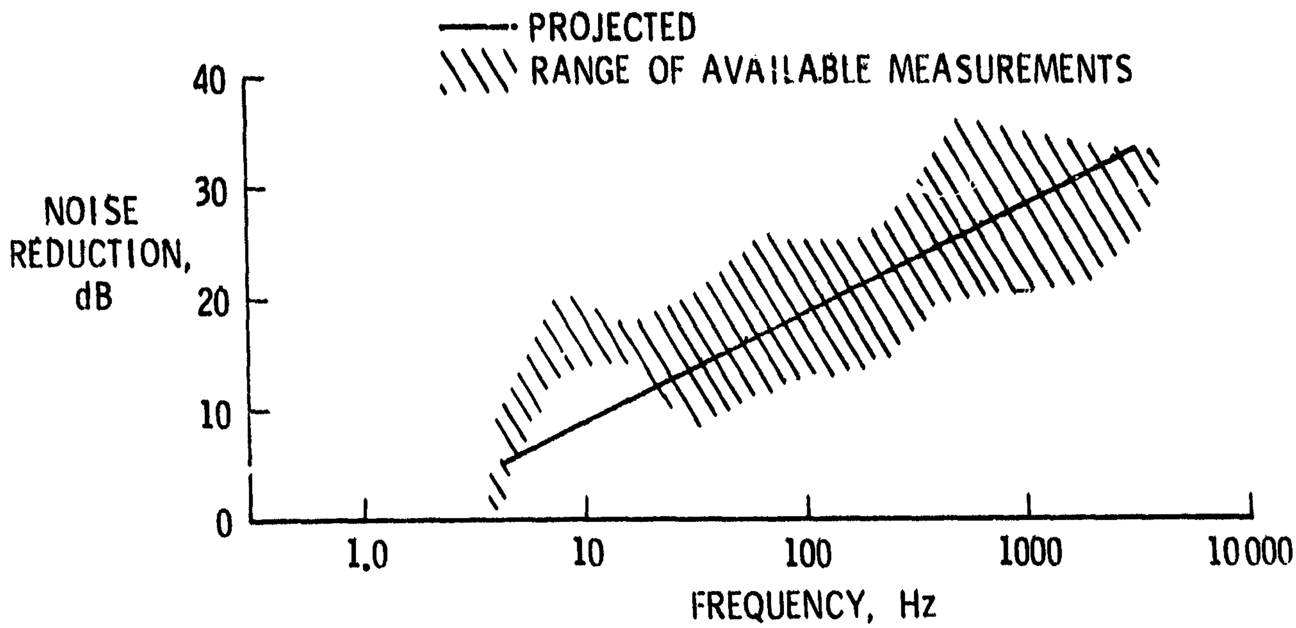

Figure 10.- House noise reduction as a function of frequency for the windows closed condition.

At frequencies below 50 Hz very few data are available to indicate how the inside and outside acoustic fields are related and hence zero noise reduction is assumed. Once the transmitted noise and house ambient noise are determined, the same evaluation procedures are followed as for the outside noise situation.

4.3.3 Building Vibration Evaluation.- The evaluation of the response to noise-induced building vibration is determined from figure 11, which uses an assumed one-third octave band wind turbine noise spectrum for illustrative purposes. The outside noise spectrum associated with the turbine operations can induce vibrations of the windows, walls and floors (Appendix C and refs. 13 and 14) as illustrated. The recommended design goal is that the response of the walls be below the human perception threshold, or below the ambient perceptible vibration.

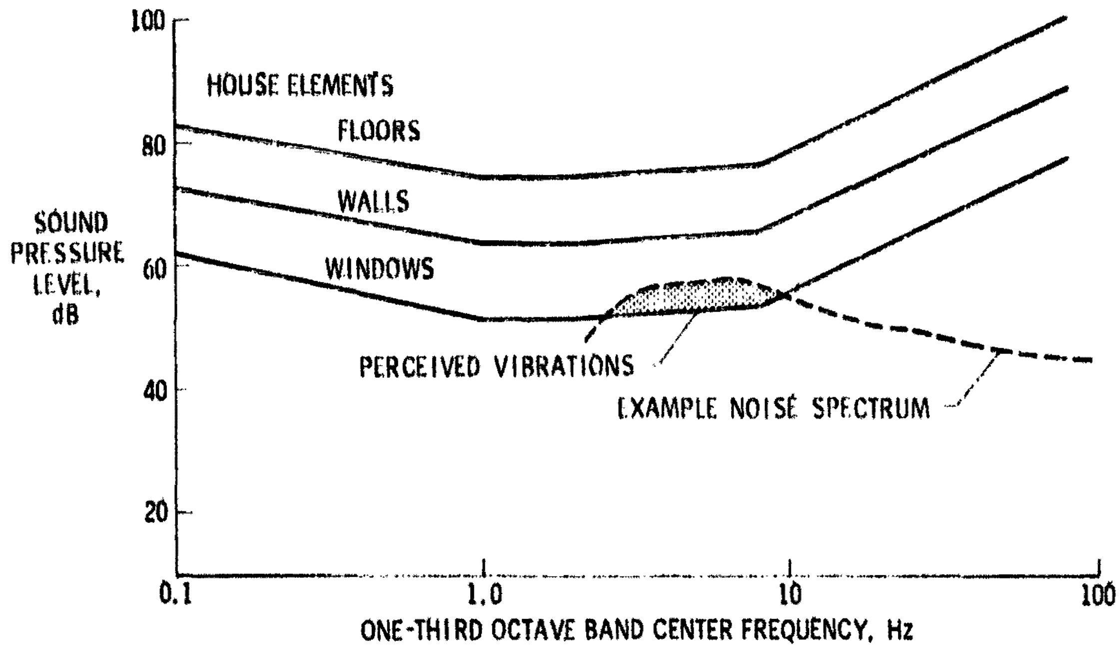

Figure 11.- Sound pressure levels sufficient to cause perceptible vibrations of house structure elements over a range of frequencies.

It is believed that in a residential environment human perception (wholebody) of the floor vibration would be unacceptable. Although the effects of noise on building response and building damage are discussed in Appendix C, it is believed that the levels of turbine noise will generally be well below those required for building damage.

4.3.4 Combined Noise and Vibration Evaluation.- Perception threshold criteria for noise (4.3.1 and 4.3.2) and vibrations (4.3.3) are derived separately and there are no provisions for combined environment effects. If both noise and vibration thresholds are exceeded, it is recommended that a 5 dB increment be added to the higher of the two levels for entry into the left hand column of Table I to estimate the resulting reaction.

5.0 SUMMARY AND RECOMMENDATIONS

This guide has been prepared for use in the design, siting and assessment of wind turbine systems for community acceptability. The evaluation is based on the noise at the receiver location which may be measured directly or inferred from a knowledge of the noise at the turbine site along with an estimate of the atmospheric propagation effects. The evaluation criteria for human exposure involves a comparison of the noise at a receiver location and any noise-induced building vibration with the human perception thresholds for wind turbine noise and building vibration. The effects of background noise are included in the evaluation. The recommended design/siting goal is that the levels of noise and vibration at the receiver location be below the perception thresholds at the appropriate background noise conditions.

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APPENDIX A

RADIATION OF AERODYNAMIC SOUND FROM LARGE WIND TURBINE GENERATORS

To assess the acoustical impact of large wind turbine generators, which may operate singly or in multiple units, an understanding of the basic sound generating mechanisms is required. The purpose of this Appendix is to characterize and assess the importance of the sources of aerodynamic sound from various types of wind turbine generators.

TYPES OF WIND TURBINE GENERATORS

Wind turbine generators, which cover a wide range of power ratings from kilowatts to megawatts, can be categorized as vertical axis or horizontal axis machines as indicated in figure A-1. Vertical axis machines include the Darrieus and Gyromill types. They typically have 2 to 4 blades which rotate about a vertical axis; they are nondirectional with respect to the wind and require power input for starting.

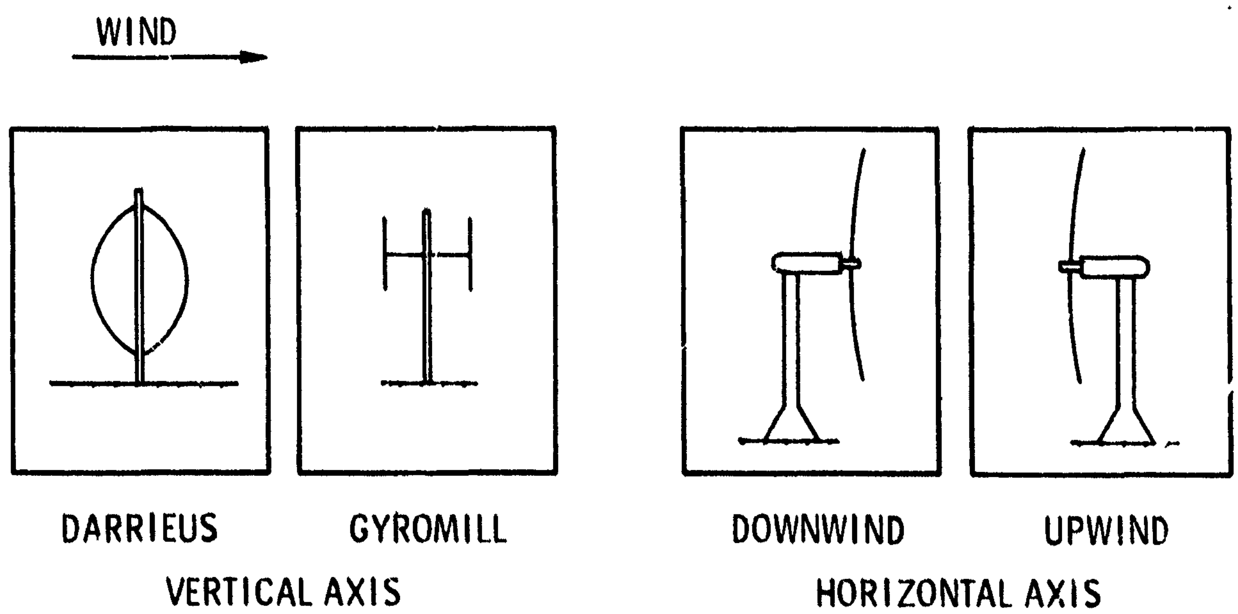

Figure A-1.- Types of large wind turbine generators.

Horizontal axis machines are self starting, have 1 or more blades, and operate in the range 17-40 rpm. Their design incorporates automatic pitch control for constant rotational speed and other control and safety systems directed by microprocessor units. They are referred to as either upwind or downwind machines depending on the location of the rotor with respect to the supporting tower. They operate most efficiently when aligned with the wind vector.

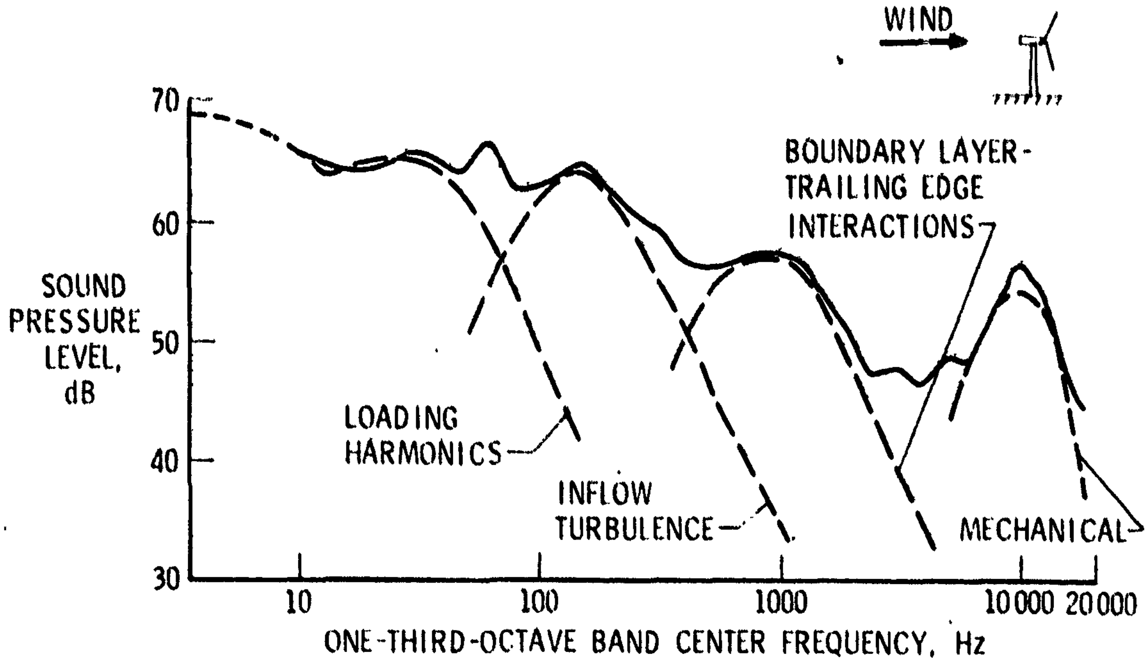

Figure A-2.- Acoustic sources for a downwind horizontal axis wind turbine generator

ACOUSTIC SOURCES

Acoustic sources associated with vertical axis and downwind horizontal axis machines are illustrated in figure A-2 which contains an example frequency spectrum of a downwind horizontal axis wind turbine. The spectrum can be divided into discrete frequency harmonics and broadband components. Loading harmonics associated with both steady and fluctuating blade loads are at multiples of the blade passage frequency and hence occur at very low frequencies. The discrete frequency components caused by steady aerodynamic loading are dominated by the loading harmonics which arise from the interaction of the rotor with the turbulent wake behind the tower. Discrete tones around 10,000 Hz are caused by a mechanical "squeak" which occurs once per revolution.

The sources of broadband sound, which are important for all wind turbine generators, are spread over a very wide frequency range from subaudible into the normal range of hearing. At low frequencies (20-150 Hz) the mechanism for airfoil generated sound is the phenomenon of fluctuating lift due to the interactions of the inflow turbulence in the atmosphere with the blade leading edge. The random vertical and horizontal velocity fluctuations cause effective angle of attack changes which in turn result in unsteady airfoil loads and associated sound radiation. Another mechanism for generation of sound by an airfoil in motion is the convection of the turbulent boundary layer past the trailing edge of the airfoil. It is best represented by an edge dipole which radiates mainly forward and to the sides. The radiated sound can be characterized by a broad spectral peak at frequencies between 800 and 2500 Hz. These broadband sounds are clearly present in the frequency spectrum depicted in figure A-3 which was obtained for an upwind horizontal axis machine. No intense discrete low-frequency

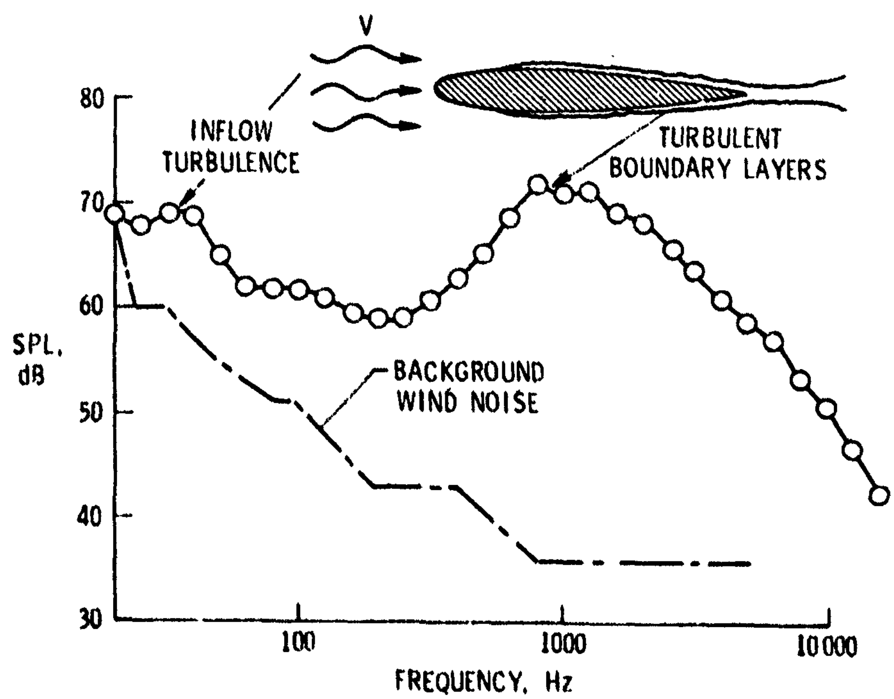

Figure A-3.- Acoustic sources for an upwind horizontal axis wind turbine generator.

components are present. Other broadband sources such as direct radiation from the turbulent boundary layers and the aerodynamic wakes from the blades, vortex shedding, separated flows due to localized stalling and the interacting of the aerodynamic flow with surface roughness, proturbances, cavities and slots are found not to be important for the machines discussed in references 1 and 2.

NOISE PREDICTIONS

There are no known methods for noise prediction which are well established and validated for large wind turbine generators. Data which relate to noise prediction are included in references 1-8. References 2 and 3 contain procedures for predicting some features of the broadband noise, and reference 4 contains methodology for predicting the narrow band (impulsive) noise.

CONCLUDING REMARKS

Radiated aerodynamic sound from wind turbine generators consists of broadband components for all machines while, in addition, rotors operating in the turbulent wake of their supporting tower display intense low frequency harmonics. The important broadband sources are due to turbulent inflow and interaction between the turbulent boundary layers and the blade trailing edge.

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APPENDIX B

HUMAN PERCEPTION THRESHOLDS FOR WIND TURBINE NOISE

INTRODUCTION

The purpose of this appendix is to present the results of experiments conducted to determine the perception thresholds for wind turbine spectra covering the range of existing and future machine designs and operating conditions. Thresholds of detection for a range of impulsive stimuli associated with blade/tower-wake interactions and for broadband sounds associated with trailing edge noise are presented for different levels of background (ambient) noise. These results have been presented previously (ref. 1).

APPARATUS AND PROCEDURES

Tests were conducted to determined the threshold of detection for the impulsive "thumping" sounds which result from blade/tower-wake interactions. This stimulus is believed to be the dominant source of annoyance in large downwind machines such as the MOD-1 configuration. Although the thump resulting from a blade passing through the wake of the tower is uniquely defined by the time history of the pressure pulse, it is more common to define the noise by a frequency spectrum which, with information on the phase relationship between harmonic components, completely describes the noise signature. Since phase information is not always available from measurements or calculations, a preliminary study was conducted to examine the importance of phase to the subjective detection of the noise. Four phase conditions were examined; three having coherent phase relationships and one being random. For the first three (nonrandom) conditions, the threshold of detection was found to be independent of phase and lower in level (7-10 dB) than that found for the random phase condition. For this reason, the impulsive sounds used in this study had a coherent phase relationship between harmonic components.

Wind turbine test stimuli were computer generated and consisted of a fundamental frequency (blade passage) and up to 250 harmonics for which amplitude and phase were defined. A typical wind turbine sound spectrum and time history used in the test are presented in figure B-1. Since the sound amplification/reproduction system introduces phase and amplitude distortion, the transfer function between the output from the computer and a microphone placed at the location of the test subject's ear was calculated. This transfer function was incorporated in the noise generation software, enabling the desired spectra and time histories to be produced in the anechoic test facility (fig. B-2). This facility has dimensions of 4 m x 2.5 m x 2.5 m (cutoff frequency of 150 Hz) and is equipped with two loudspeakers having a frequency response of 5 Hz to 20 kHz.

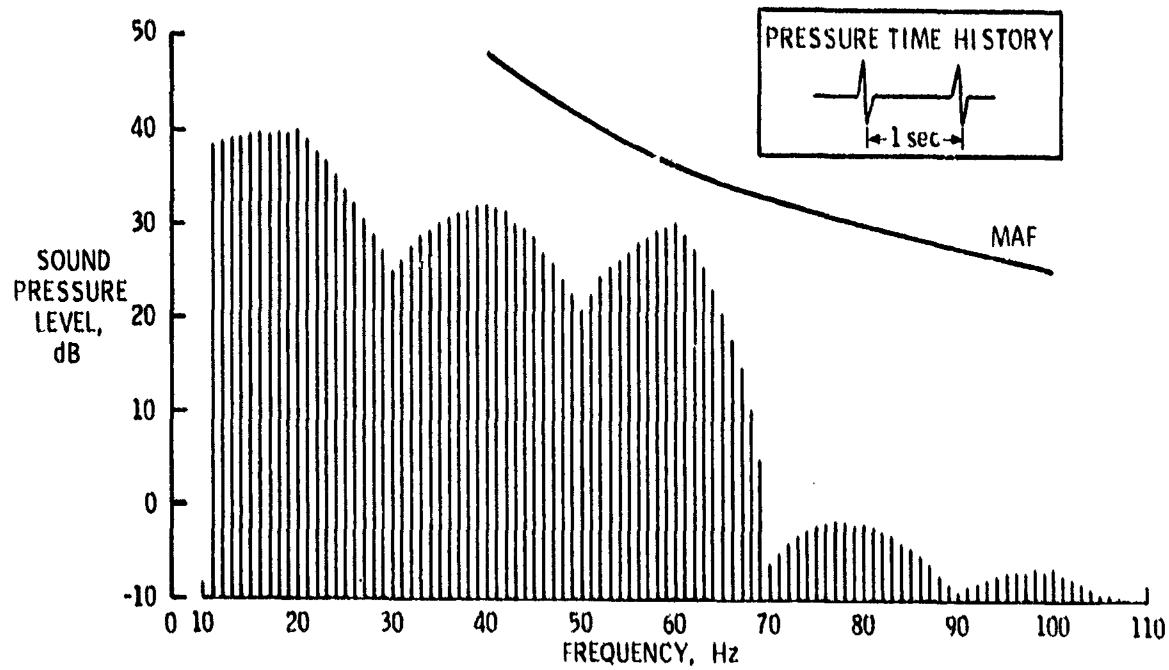

Figure B-1.- Schematic representations of wind turbine impulsive noise spectrum and time history.

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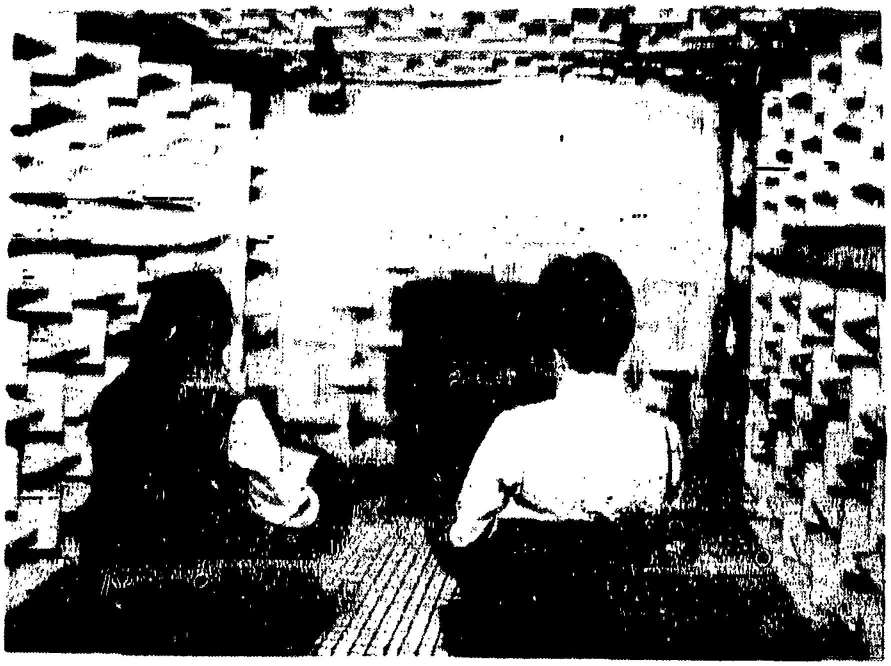


Figure B-2.- Anechoic test facility.

As a result of measurements of the MOD-2 wind turbine (ref. 2) it was determined that the subjectively dominant sound was characterized by a broad spectral peak occurring in the 800-1000 Hz range. This is associated with the interaction between the blade boundary layer and its trailing edge and is predictable based upon blade geometry and tip speed. It is believed that this may be an important noise generation mechanism for both "upwind" and "downwind" machines. In order to encompass a range of present and future designs of large wind turbines, broadband sounds having peak frequencies of 500, 1000, and 2000 Hz were synthesized by shaping white noise. These three sounds and a recording of MOD-2 made 76 m (250 ft) directly upwind were used in the laboratory to determine thresholds of detection.

In order to examine the effects of background noise, tape recordings were made at night in a suburban/rural location for use in the laboratory. A short section of tape, having a constant sound pressure level and no identifiable events such as automobile passbys, was selected and a tape loop constructed. This background noise was played continuously during which time thresholds of detection of wind turbine sounds were determined.

In conducting a test, a single subject was seated in front of the loudspeakers and instructed to press a hand-held switch when the wind turbine sound was heard (fig. B-3). This switch activated a light which was monitored by the test conductor. The sound pressure level of the sound was slowly reduced until no longer detectable and then slowly raised until detectable again. This process was repeated until consistent ascending and descending thresholds were achieved. The mean of these two values was considered to be the threshold of detection.

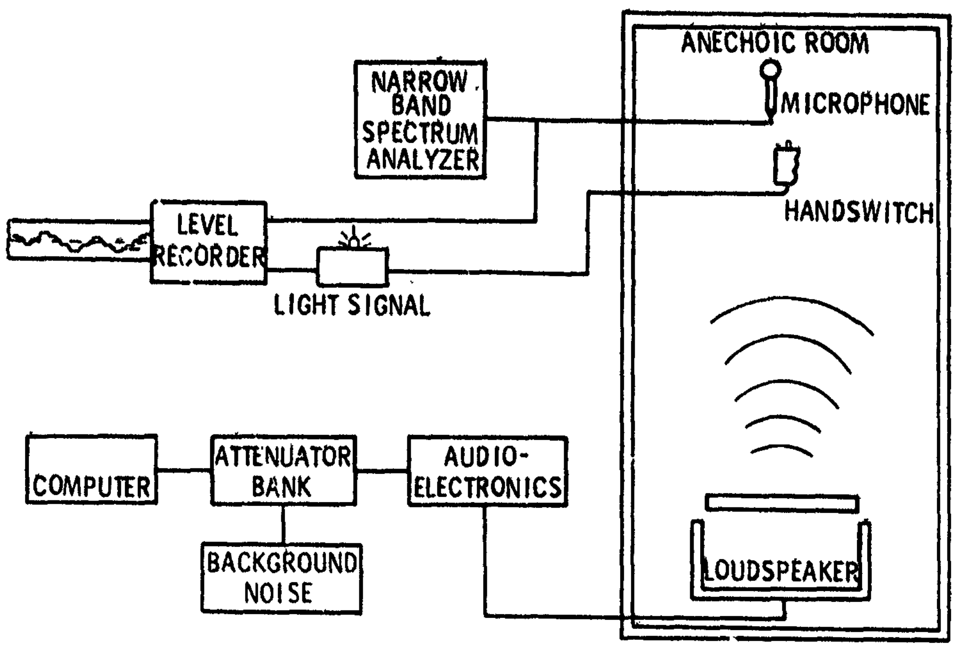


Figure B-3.- Stimuli presentation and subjective response system.

RESULTS AND DISCUSSION

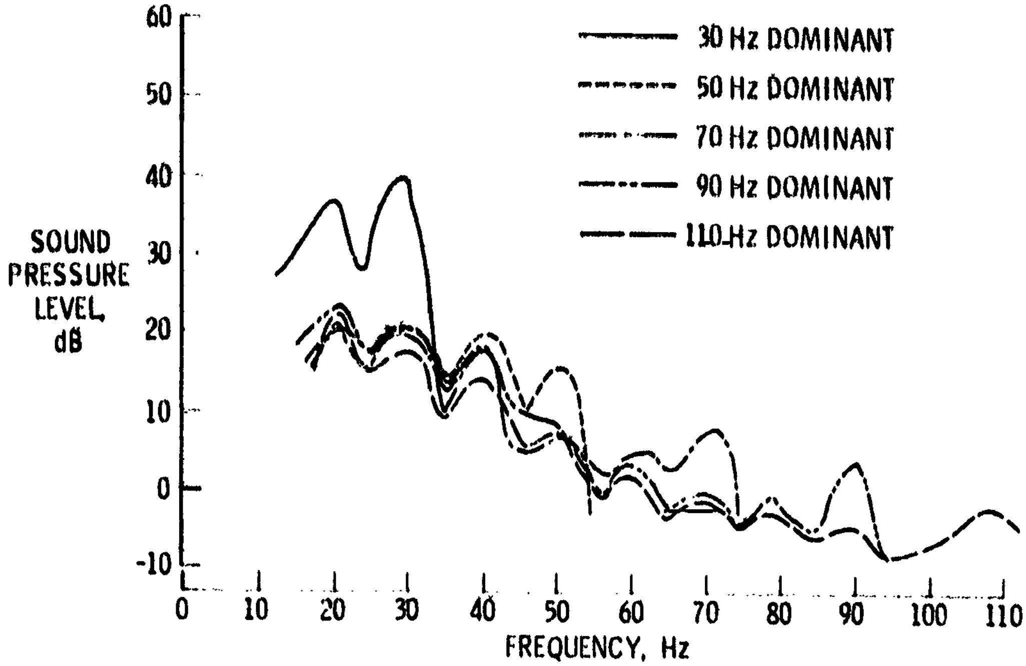
Impulsive Sounds

The primary objective of this part of the study was the determination of the threshold of detection for impulsive turbine noise having a variety of spectra in the frequency range from 20 to 110 Hz. Frequencies below 20 Hz, were considered to be unimportant for listening tests due to the extreme insensitivity of the ear to wind turbine noise levels in this low frequency region.

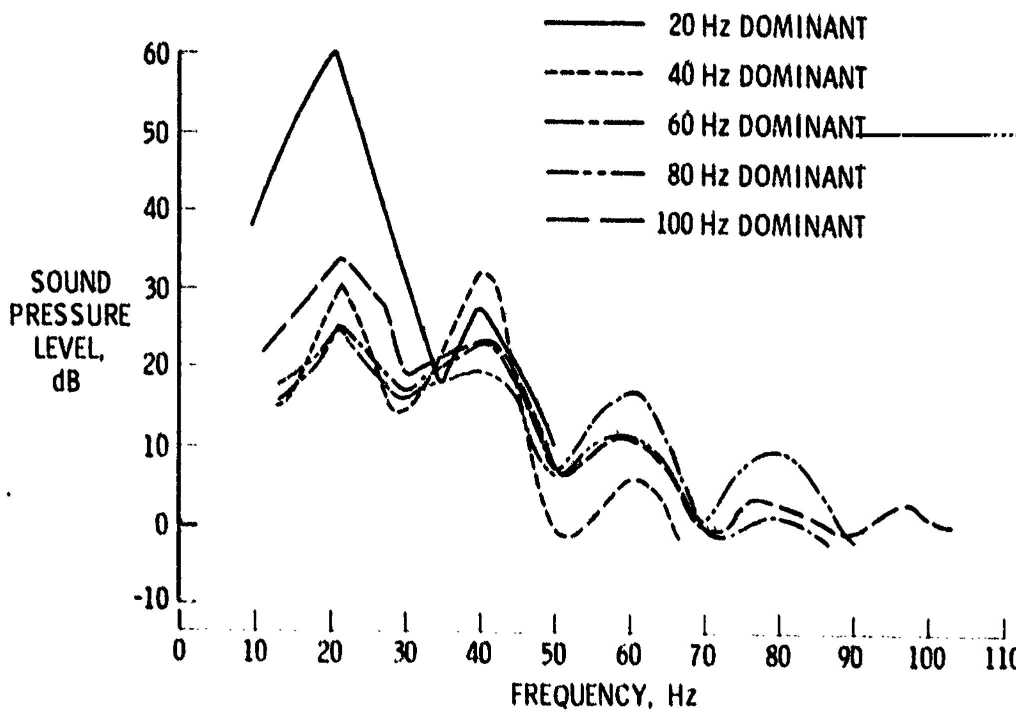
These spectra were synthesized based on measured data from the MOD-1 site as well as calculations of the spectra resulting from blade/tower-wake interactions (refs. 3 and 4).

The spectra were designed such that detection would be achieved over a narrow frequency range. This was accomplished by comparing spectrum levels with the ISO pure tone threshold (or minimum audible field--MAF) (ref. 5). For example, if the level of the spectrum in figure B-1 is raised, the frequency components near 60 Hz will be the first to intersect the MAF curve, and hence this frequency region is considered dominant. A total of 10 spectra, having a fundamental "blade passage" frequency of either 0.5 Hz or 1.0 Hz were designed to be dominated, subjectively, by harmonics at different frequencies as shown in figure B-4. Those having a 1.0 Hz fundamental were dominated by components at 20, 40, 60, 80 and 100 Hz and those having a 0.5 Hz fundamental were dominated by components at 30, 50, 70, 90 and 110 Hz. For the purpose of clarity figure B-4 presents spectral "envelopes" rather than showing the spectrum levels of the individual harmonics. Detection thresholds were determined for each of the 10 sounds using nine test subjects, none of whom had significant hearing loss. The standard deviations of the threshold measurements were found to be typically 2.5 dB, with a tendency for the spectra having 0.5 Hz fundamental to have the higher standard deviations.

The narrow band spectra as presented in figure B-4 are at the mean of the threshold levels measured for each subject. Tangential curves were fitted to the spectral peaks and are presented in figure B-5 for comparison. Due to the higher harmonic density, the curve for the spectra having 0.5 Hz fundamental is lower than the 1.0 Hz case. Also shown is the ISO pure tone or minimum audible field (MAF) threshold (ref. 5) which has the same general shape. The difference in level between the wind turbine curves and the MAF curve may be attributed to the integration time and to the critical bandwidth of the human ear (ref. 6) which is far greater than the bandwidth used in the spectral analysis.



(a) 0.5 Hz Fundamental.



(b) 1.0 Hz Fundamental.

Figure B-4.- Narrow band spectra at the mean threshold level.

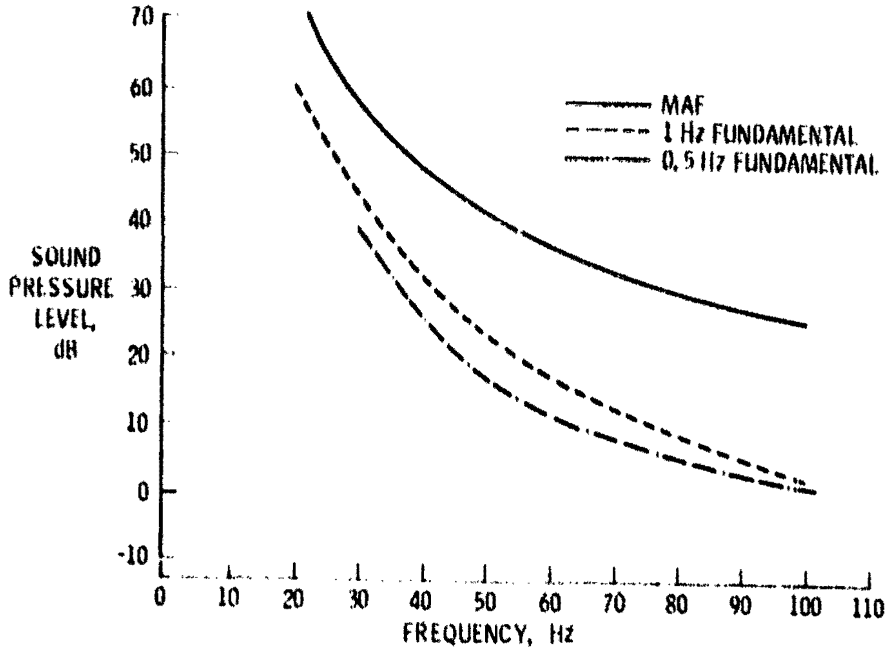


Figure B-5.- Detection thresholds.

Detection thresholds were also determined for some of the wind turbine sounds in the presence of background noise. All five sounds having a 1.0 Hz fundamental and two having a 0.5 Hz fundamental were presented to eight test subjects. Detection thresholds were determined in two levels of background noise (35 and 45 dB(A)), having spectra as shown in figure B-6.

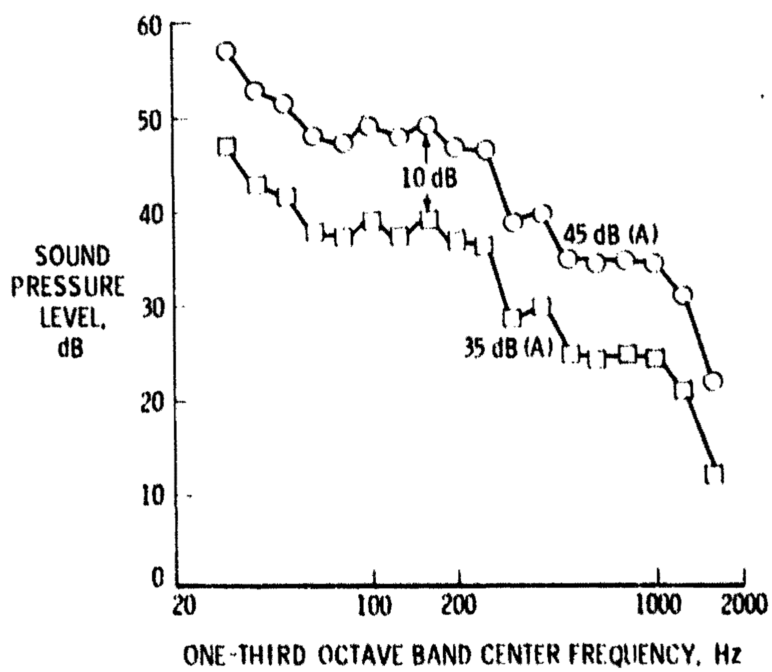


Figure B-6.- Background noise spectra at 35 and 45 dB(A).

Tangential curves were fitted to those spectra having a 1 Hz fundamental at their mean threshold level. These curves are presented in figure B-7 and are compared with the threshold measured in "quiet." Figure B-7 shows that an increase in background noise of 10 dB raises the detection threshold of the wind turbine sounds 10 dB at the higher frequencies but only 3 dB at the lower frequencies. The fact that it is not 10 dB at all frequencies may be attributed to the shape of the background noise spectrum, which masks the higher frequencies much more than the lower ones. The threshold change observed at the lower frequencies is due to the downward spread of masking caused by the higher frequencies present in the background noise rather than due to masking by the lower frequencies in the background noise. Consequently, the usefulness of figure B-7 is limited to situations in which background noise spectra do not differ significantly from those used in this study (fig. B-6).

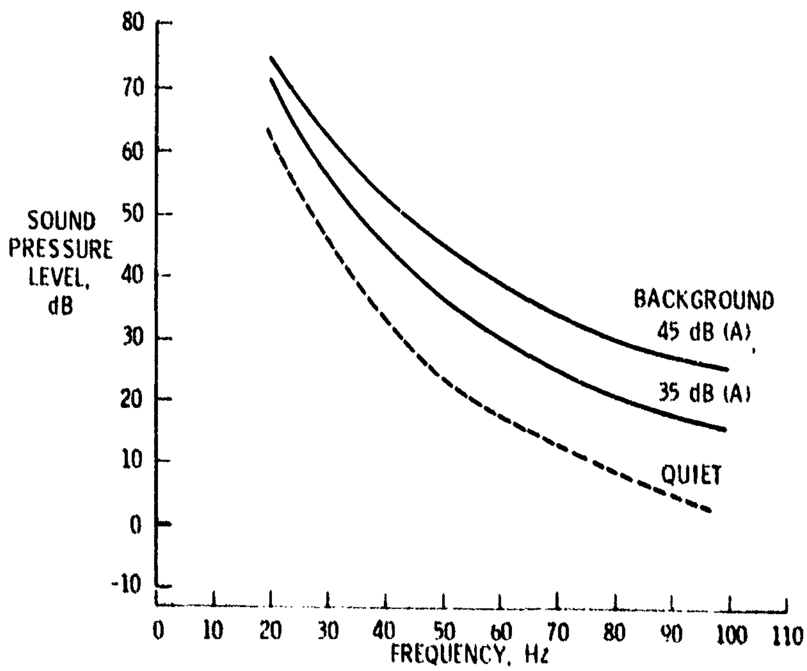


Figure B-7.- Detection thresholds for different background noise levels (1.0 Hz fundamental).

Both detection experiments indicate that the frequency of the fundamental is a significant variable (fig. B-6). However, it is possible to use the 1.0 Hz fundamental curves as a reference and make adjustments on a logarithmic (energy) basis for the actual blade passage frequency. Thus, the curve for a 0.5 Hz fundamental would be 3 dB lower and the curve for 2.0 Hz would be 3 dB higher than the 1.0 Hz fundamental curve. Furthermore, the frequency analysis bandwidth should be less than the fundamental frequency. The use of one-third and octave band analysis is not recommended due to the steep slope of the threshold curves.

Certain limitations of the preceding results need to be considered. Mean threshold data have been presented and consequently some people will be able to detect sound at lower levels. Also, the spectra used to generate the threshold curves were specifically designed such that detection was achieved over a narrow frequency range. The threshold level of sounds which have components at or near the threshold curve over a wider frequency range is unknown at this time but may be presumed to be somewhat lower than the values determined in the present study.

Broadband Sounds

Detection thresholds were determined using three synthesized sounds having peak frequencies of 500, 1000 and 2000 Hz and a recording of MOD-2. Eight subjects took part, none of whom had significant hearing loss.

Figure B-8 displays the one-third octave band spectra of the sounds at the mean threshold level and the ISO pure tone threshold (ref. 5). The peak one-third octave band sound pressure levels are in good agreement with the pure tone threshold at the same frequency, which is to be expected since the critical bandwidth of the human ear is approximately one-third of an octave in this frequency range (ref. 6). It is noteworthy that the detection threshold of the MOD-2 recording is indistinguishable from that of the synthesized sound having the same peak frequency.

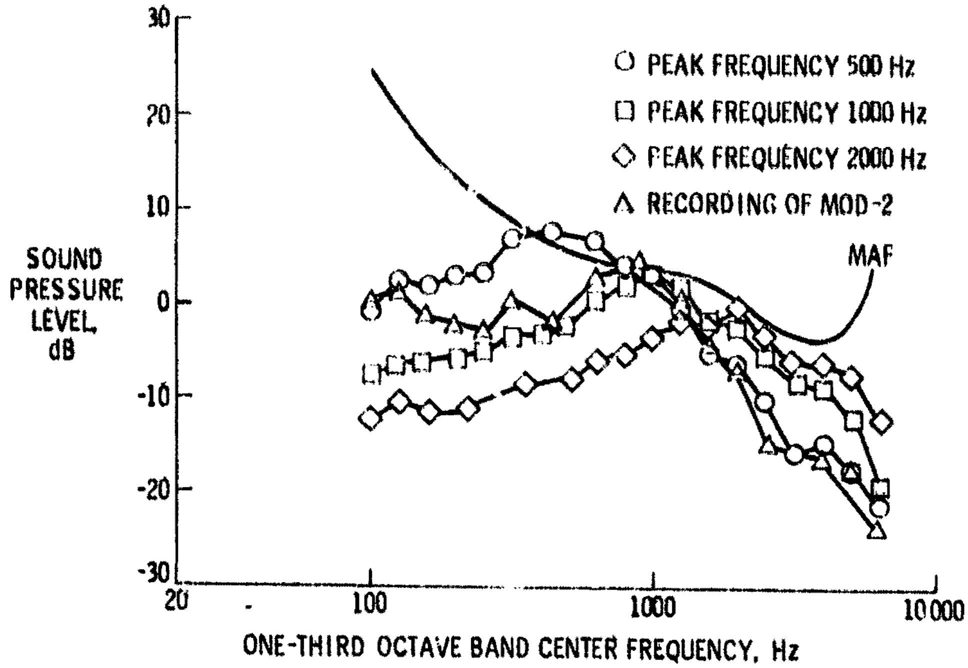


Figure B-8.- Spectra at mean threshold level.

Attempts were made to determine thresholds in the presence of background noise (fig. B-6). This proved to be possible for the MOD-2 recording which had periodic amplitude modulation, but impossible for the synthesized sounds which displayed no such modulation. The spectra at mean threshold level in the presence of background noise at 35 and 45 dB(A) are shown in figure B-9. It was

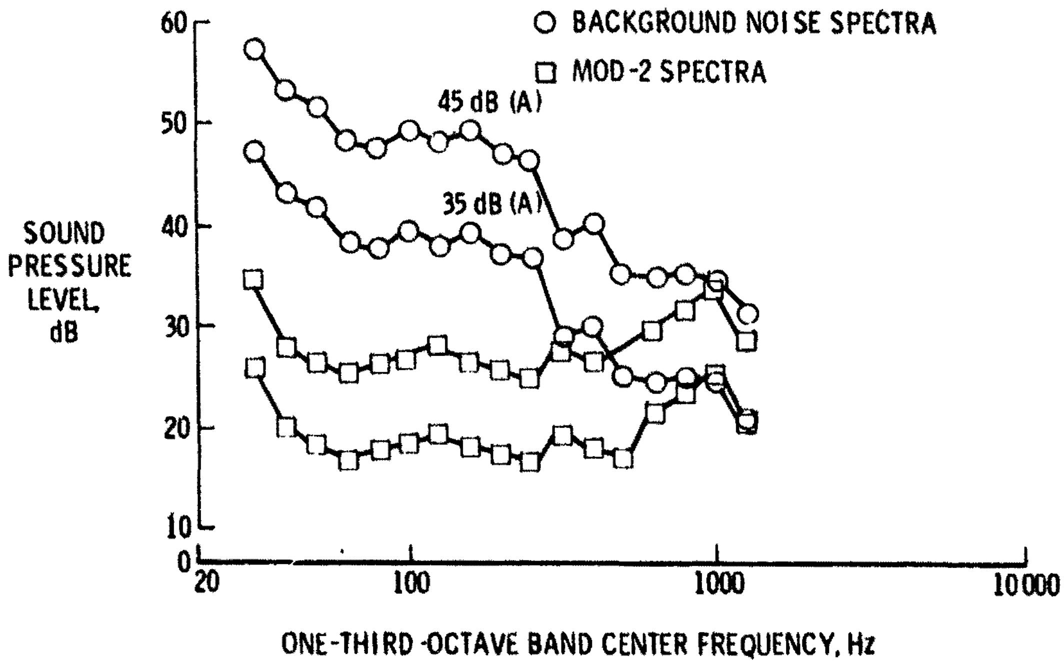


Figure B-9.- Threshold levels for different background noise levels.

concluded that a signal to noise ratio of 0 dB in any one-third octave band is sufficient for detection. It should be noted that detection cannot be predicted on the basis of overall measures such as dB(A).

CONCLUDING REMARKS

Thresholds of detection have been determined for two wind turbine noise components, namely low frequency impulsive sound associated with blade/tower-wake interactions and broadband sound associated with blade boundary layer/trailing edge interactions. The thresholds were measured in "quiet" and in the presence of background (ambient) noise and will enable assessment of the detection of a predicted or measured noise condition at a receiver location.

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APPENDIX C

RESPONSE OF BUILDINGS TO NOISE EXCITATION

INTRODUCTION

One aspect of community response to noise involves people inside houses. Since house structures have many components which are readily excited by noise and which can be coupled, they respond as complex vibrating systems. These dynamic responses are significant because they affect the environment of the observers inside the house. The nature of this noise induced house excitation problem is illustrated in figure C-1.

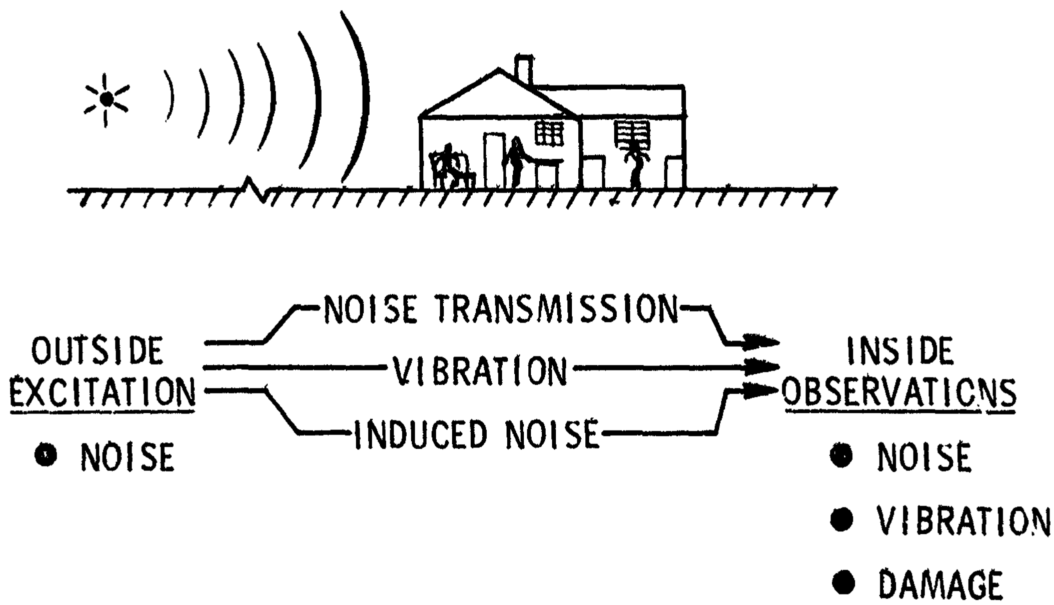

Figure C-1.- Nature of noise-induced house structure responses (ref. 3).

A person inside the house can sense the inpingement of noise on the external surfaces of the house by means of the following phenomena: noise transmitted through the structure from outside to inside (refs. 1-6); the vibrations of the primary components of the building such as the floors, walls and windows (refs. 2, 3, 7 and 8); the rattling of objects such as dishes, ornaments and shelves which are set in motion by the vibration of the primary components (refs. 2, 3 and 9); and in the extreme cases damage to the secondary structure such as plaster and tile and/or furnishings (refs. 7 and 10).

The purpose of this appendix is to summarize available data on house responses to noise excitation and thus to define the role of house responses in the problem of community reaction to environmental noise.

VIBRATIONS OF HOUSE MAIN STRUCTURE COMPONENTS

Data on the vibration responses of houses is derived from several different sources. Some measurements are available from buildings instrumented with accelerometers, deflection gauges and/or strain gauges on walls, floors, ceilings and windows to record transient responses due to flyovers of subsonic jet and propeller aircraft and helicopters; and the sonic booms of supersonic aircraft (refs. 2 and 11-15). In addition a number of experiments have been conducted in which mechanical shakers have been used to excite and measure the responses of houses and house components (refs. 2 and 8). Results of the flyover and mechanical vibration tests are consistent and tend to characterize the manner in which house structures respond to acoustic loadings.

Frequencies and Mode Shapes

Example mode shapes and frequencies for a one-story test house are given in figures C-2 and C-3. The data of figure C-2 were obtained by means of a frequency sweep for a constant input vibratory force and at a given point of excitation on the wall of bedroom number 1 (see insert sketch). The excited wall had a fundamental resonance at 16.6 Hz. The other wall of the room and its floor had resonances at 21.4 and 26 Hz respectively. Data for a number of different house structures indicate frequency values from about 12 to 30 Hz. The above results are representative of typical house structure responses in the first resonance or "oil canning" modes of the type illustrated in figure C-2. Note that there is evidence of structural and/or air cavity coupling. It can be seen that preferred phase relationships exist as a result of the manner in which the floor and wall structures are arranged.

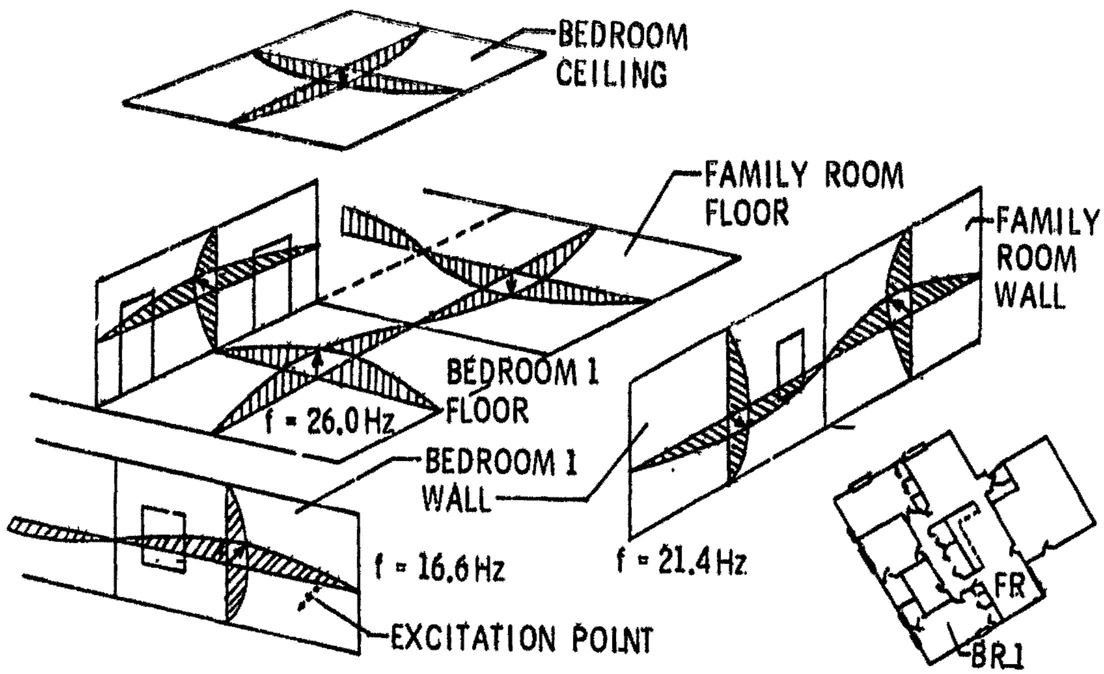

Figure C-2.- Example frequencies and mode shapes for a one-story house excited by a mechanical shaker. Force input = 35.6 Newtons (ref. 2).

Higher order modes may in some cases be excited for preferred loadings or for more complex structural configurations. Examples of such higher order modes are shown in figure C-3 which relates to one of the test structures of ref. 2. Note that resonant frequencies up to 72 Hz and more complex mode shapes are identified for a wall having window and door cutouts.

Building structures are characterized by nonhomogeneous elements. Walls, floors and ceilings are built up from an array of evenly spaced beams with sheathing on one or both sides. The sheathing is typically attached to the beams at discrete points by means of nails. The resulting structure of beams and panels tends to respond as dynamically coupled elements but this behavior is much different at low frequencies than at high frequencies (ref. 8). At low frequencies (below 100 Hz) the response is dominated by the behavior of the

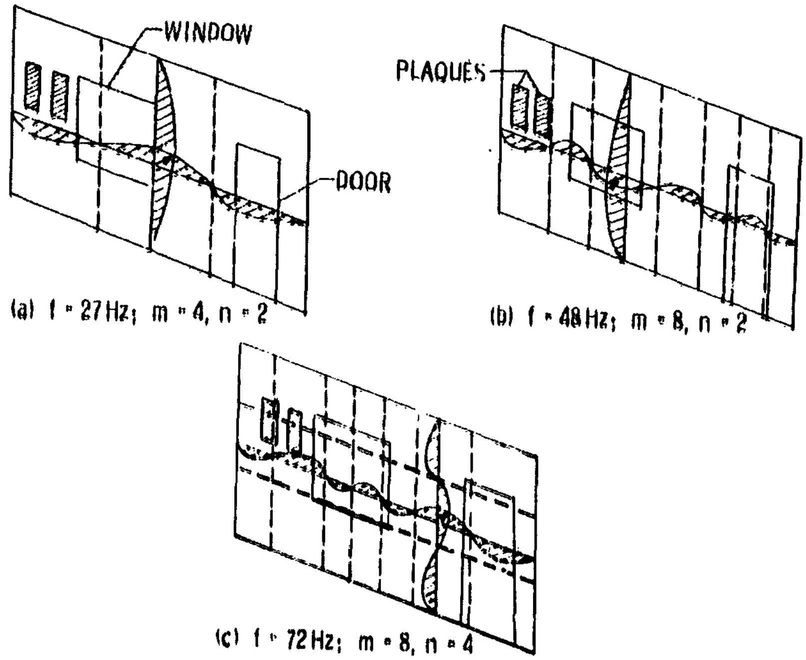

Figure C-3.- Example higher mode responses of a house wall having door and window openings (ref. 2).

beams, as suggested by the mode shapes of figure C-2, and the sheathing panels play only a minor role. On the other hand, higher order modal responses (above 300 Hz) tend to be dominated by the sheathing panels. At intermediate frequencies (100 to 300 Hz) the panels behave as if they were simply supported while for the higher frequencies the panels behave as though their edges were fixed.

Experience has shown that house structures respond in a linear manner to forced excitation (ref. 2). For cases where the accelerations have been measured for a forced excitation at a given frequency, the acceleration amplitudes are a direct linear function of the input force. Likewise, the measured accelerations increase as a function of frequency for a given input force, and they generally occur about a straight line having a positive slope of 6 dB per octave up to frequencies of about 1000 Hz, the limit of measurements.

Windows vary in size from the plate glass type which can be several meters in dimension to conventional double hung designs having much smaller sash elements. All windows are similar in that the major element(s) is a relatively thin glass plate simply supported along its edges. A plate glass test specimen of ref. 8 had natural resonances of 9, 18, 48, and 70 Hz for dimensions of 1.22 m by 1.84 m. Smaller sash windows of conventional houses are noted to have resonant responses in the range of several hundred Hertz. Thus, the range of response frequencies for window components of houses is consistent with those for other structural components. Evidence of window motion may be observed by sight, by feeling, or by the rattling of loose elements.

Acceleration Levels

A large number of measurements are available for the noise induced accelerations and stresses in house structures. These data have come from a wide range of exposure conditions and rather detailed measurements were obtained for a number of different house structures (refs. 11-15) and from unpublished data by R. DeLoach, K. P. Shepherd, and E. F. Daniels. The above studies relate to the problem of community response to subsonic aircraft, supersonic aircraft and helicopters; and specifically provide data relative to house vibrations and possible damage. Accelerations of the various building components such as windows, walls and floors are available and example values are given in figures C-4, C-5

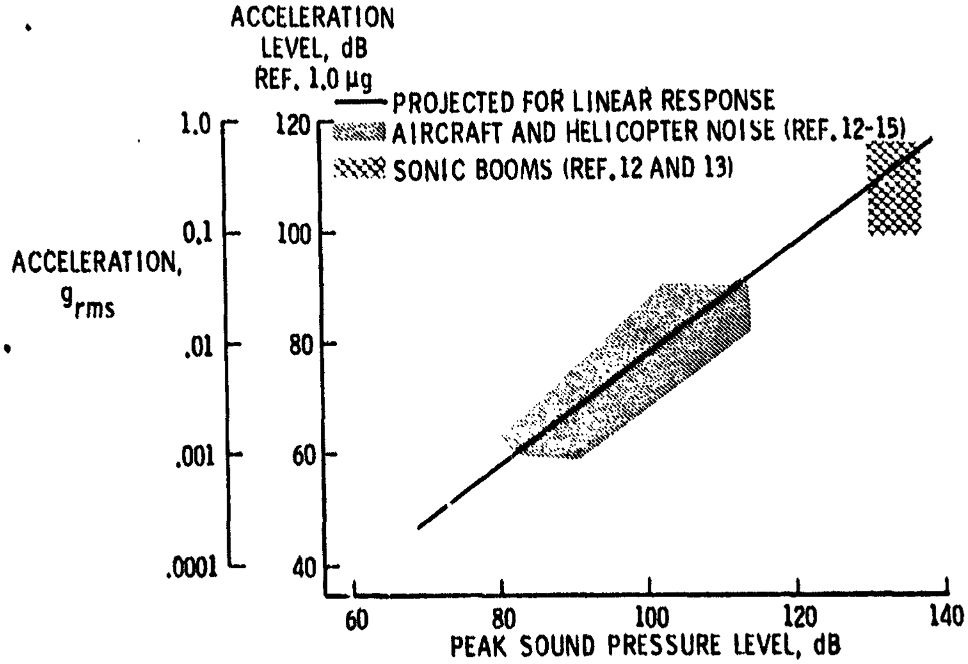

Figure C-4.- Measured house wall acceleration responses due to noise excitation.

and C-6. In each case the measured accelerations are plotted as a function of the peak sound pressure levels measured outside of the house. Acceleration levels are defined as 20 $\text{Log}_{10}(g/g_0)$ where $g_0 = 1.0\ \mu g$.

Data for wall acceleration responses are presented in figure C-4 for houses exposed to noise from commercial and military jet aircraft; helicopters and propeller aircraft; and sonic booms. The large amount of data for aircraft and helicopter noise are encompassed by the lower hatched area and the available sonic boom related data fit within the upper cross hatched area. These data which are associated with a wide variety of input spectra seem to correlate satisfactorily on the basis of peak sound pressure level. It can be seen that the acceleration responses increase generally as the noise levels increase and seem to follow a straight line relationship based on the assumption of linear behavior of the structure.

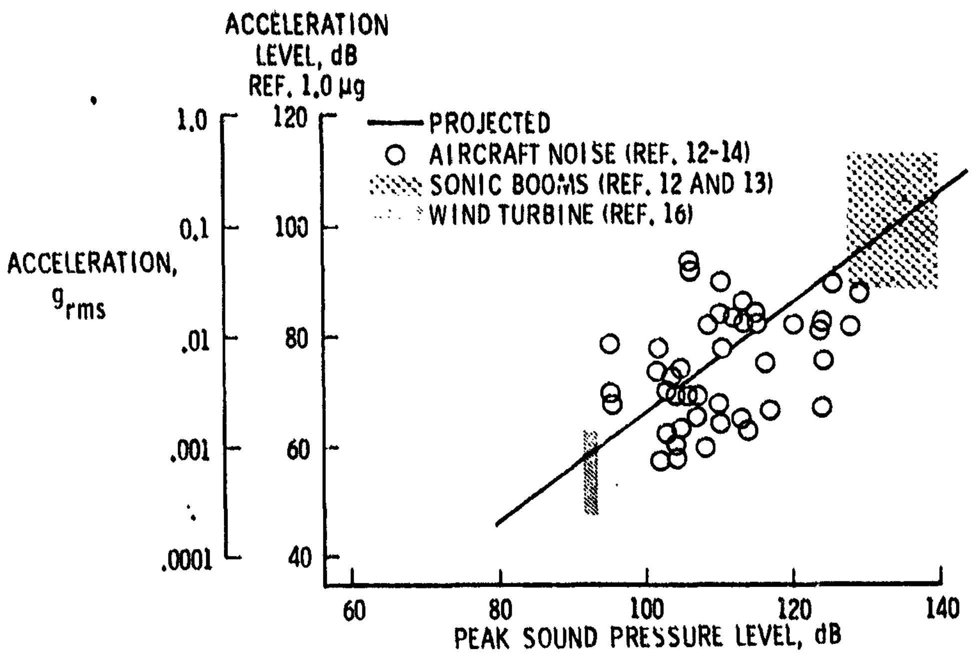

Figure C-5.- Measured house floor vertical acceleration responses due to noise excitation.

Similar results are presented in figure C-5 for house floor vertical acceleration responses. Note that a limited amount of wind turbine data are also included from (ref. 16). All of the other data shown are for the same test structures as in figure C-5, and apply directly to the ground floor only. Floor accelerations seem to follow generally a linear response relationship as did the wall response data. The scatter is, however, considerably greater than for the wall data and the responses are about 10 dB lower in level for a given noise level input. For comparable inputs, the associated horizontal acceleration values are noted in refs. 12-14 to be about equal to or are slightly greater than the vertical values given in the figure.

Measured acceleration responses for several conventional double hung windows are shown in figure C-6. Good correlation is seen for a range of widely different aircraft, helicopter and wind turbine-noise inputs, and the trend of the data indicates linear responses (refs. 14-16 and unpublished work of R. DeLoach, K. P. Shepherd, and E. F. Daniels). For a given input level the window responses are noted to be about 10 dB higher in level than the associated wall responses.

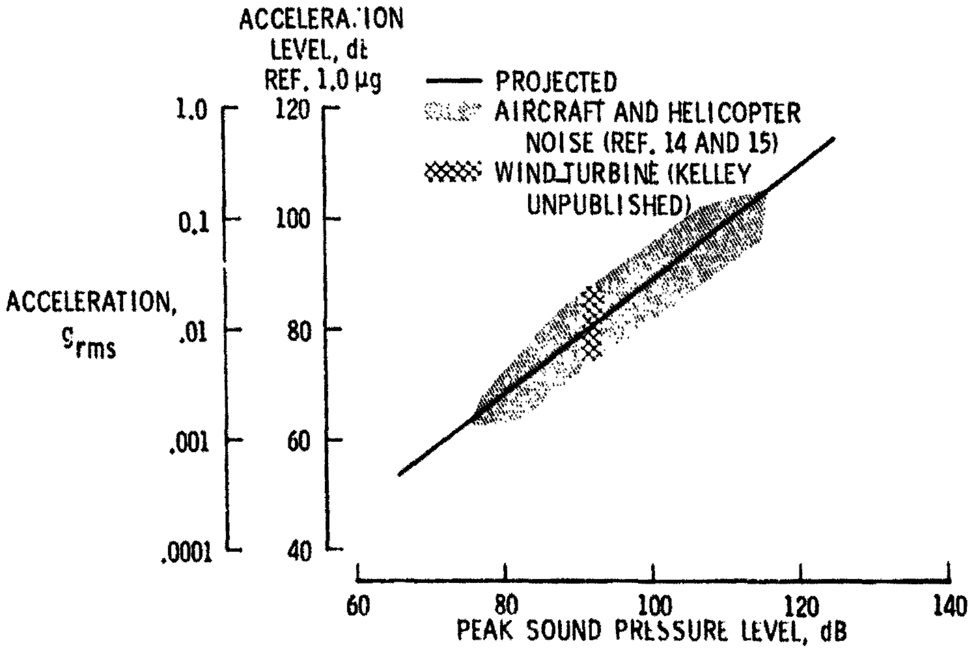

Figure C-6.- Measured house window acceleration responses due to noise excitation.

Damage Experience

Very little if any damage to elements of the structure is expected except at extreme values of the input noise level. Experience for blasting, explosions and for sonic booms suggest that damage to houses may occur at peak acceleration values between about 0.3 g and 3.0 g in the frequency range of 10 Hz to 100 Hz respectively (ref. 17). It can be seen that the measured levels of wall, floor and window accelerations which are cited for aircraft, helicopter, and wind turbine noise are generally lower than 0.3 g and hence no damage is expected. Sonic boom excitation which is associated with the extreme values of input pressure has been blamed for some insipient damage to light structural elements such as windows, plaster and tile surfaces, etc., (refs. 7 and 10).

VIBRATIONS OF ACCESSORIES

Wall or floor vibrations of the types described above can give rise to the vibration of wall or floor mounted objects such as pictures, mirrors, plaques, lamps, etc. Such objects are usually in contact with the larger surface at one or more discrete points or along a boundary line, and are put into motion because of the vibratory motions of the surface. Such excitation of objects results in high frequency impact sounds, high frequency vibrations or some associated optical phenomena which serve to identify the event and by so doing cause annoyance of nearby observers. This is an example of nonlinear vibration responses, for which the subaudible frequency excitation of a wall for instance can cause audible frequency range responses in a wall mounted object such as a picture (refs. 2, 3 and 9). The rattling of such accessories can be a factor in annoyance.

The data of figure C-7 are included to indicate the range of acceleration responses expected from vibrating accessories. Two different criteria lines are included from ref. 9. Both are shown as being horizontal because no significant

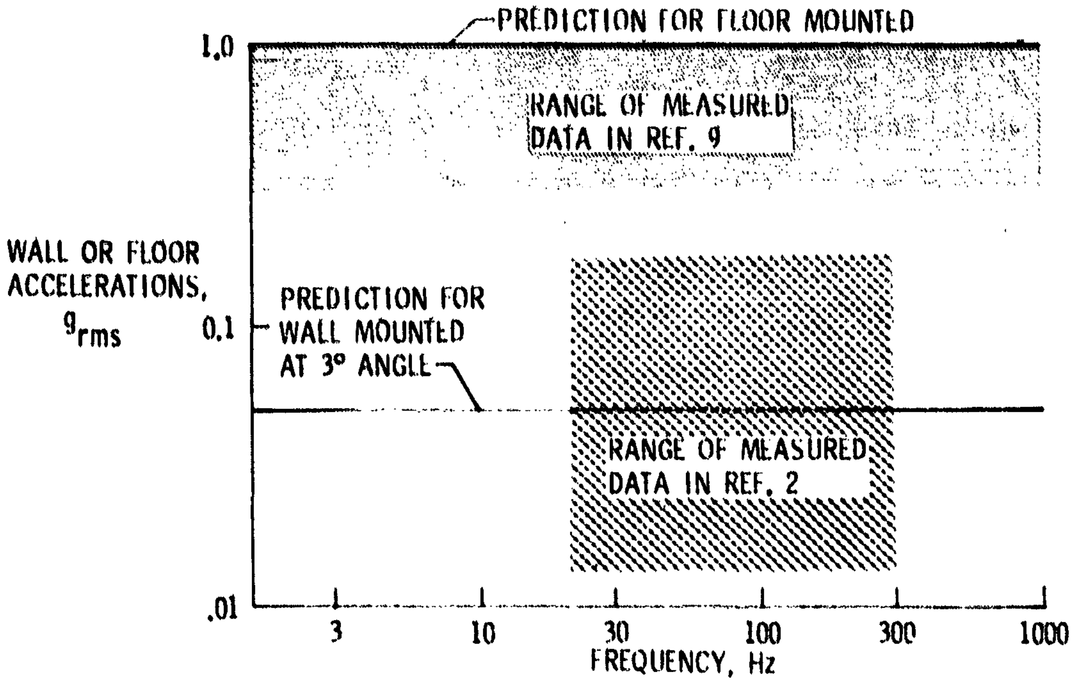

Figure C-7.- Criteria for the rattling of wall and floor mounted objects due to vibratory excitation (ref. 9).

effects of frequency were identified in any of the experimental data. The top line is drawn at 1.0 g and is the prediction for rattling in the case of normal contact as for an object resting on a horizontal vibrating surface such as the floor. The hatched area represents the range of comparable experimental data and suggests that in practical cases some rattling might occur at acceleration levels less than 1.0 g.

For cases where objects are suspended in pendulum fashion from the wall the lower criteria line might apply. It should apply theoretically to situations where the hang angle (angle between wall and hanging flat object) is about 3°. The cross hatching represents the range of data available for a number of objects such as plaques, pictures and mirrors, from house situations and for a steel ball in laboratory tests. The scatter of measured results suggests that small variations in the wall geometry or that of the suspended object can be significant. By implication, objects that hang by smaller hang angles are susceptible to rattle at lower acceleration levels.

VIBRATION PERCEPTION CRITERIA

One of the common ways by which a person may sense the noise induced excitation of a house is through structural vibrations. This mode of observation is particularly significant at frequencies below the threshold of normal hearing or in the low frequency range where the ear is less sensitive.

There are no standards available for the threshold of perception of vibration by occupants of buildings. The ISO Technical Committee 108 has, however, published guidelines (refs. 18 and 19) for interim use. Together they cover the frequency range .063 Hz to 80 Hz. The appropriate curves from each of the above documents are reproduced in figure C-8 and are represented by the composite heavy line curve. This curve represents the combined responses of a person in either the up and down, fore and aft, or sideways directions whichever is the most sensitive. This is believed appropriate for the house vibration case because persons may be in various positions when experiencing vibrations. For

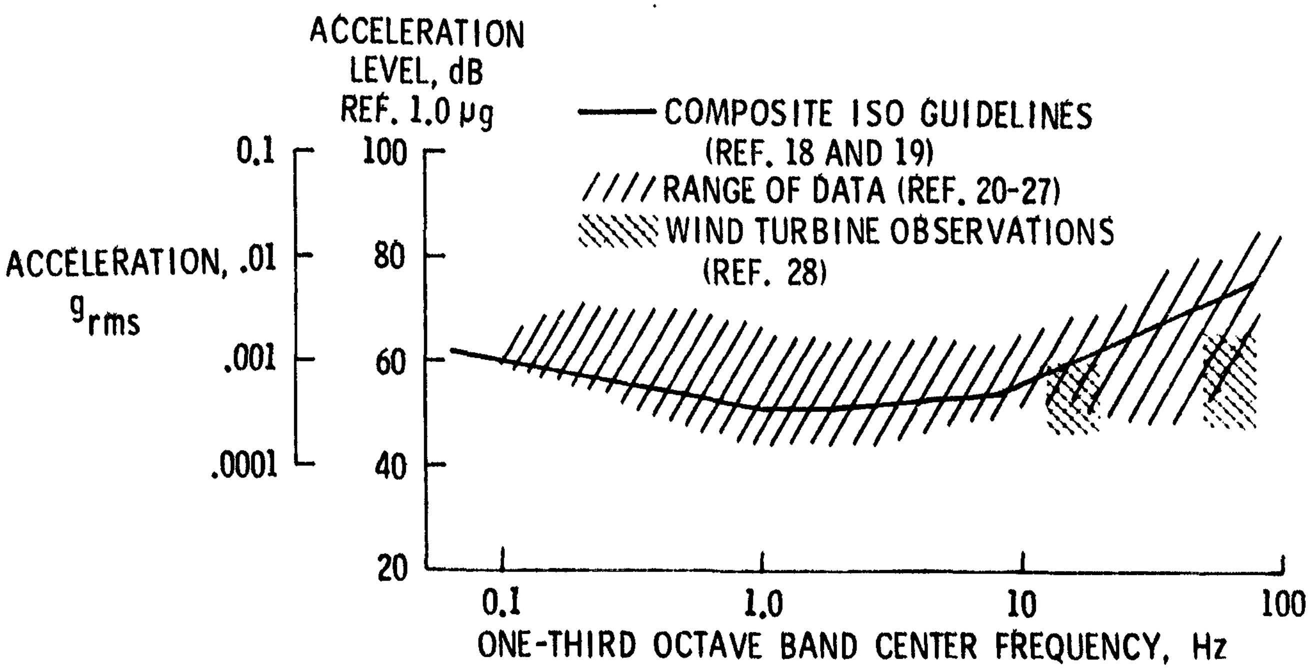

Figure C-8.- Most sensitive threshold of perception of vibratory motion by humans.

the conditions of the above curve the buildings are assumed to be properly sealed and acoustically insulated so that significant sounds are not transmitted to the occupants and thus only vibrations are sensed.

The hatched region of figure C-8 encompasses the perception threshold data obtained in a number of independent studies (refs. 20-25). Different investigators, using different measurement techniques have obtained values which extend over a range of about a factor of 10 in vibration amplitude. The composite ISO guidelines curve of figure C-8 is judged to be the best representation of the available whole body vibration perception data.

Note the two cross hatched regions on figure C-8 from the data of ref. 26. These are estimated one-third octave band levels of vibrations which were judged perceptible in two different house structures excited by wind turbine noise. Based on the values of the ISO guidelines curve they would be judged marginally perceptible and thus seem to constitute a good confirmation of the other perception threshold data of figure C-8.

House building vibrations of walls and windows may also be observed by means of tactile perception. The available tactile perception data in the frequency range of interest is shown in figure C-9. The most extensive study is reported in ref. 27 and is represented by the solid curve. Results of a series of more abbreviated studies from ref. 28 are represented by the hatched area. It can be seen that there is a trend toward lower sensitivity as the frequency increases. The sensitivity to tactile perception is about equal to that for whole body perception (fig. C-8) in the range of frequencies near 100 Hz. Note that window and wall vibrations may be observed by tactile perception at peak noise level excitations of about 90 dB (fig. C-6) and 100 dB (fig. C-4) respectively.

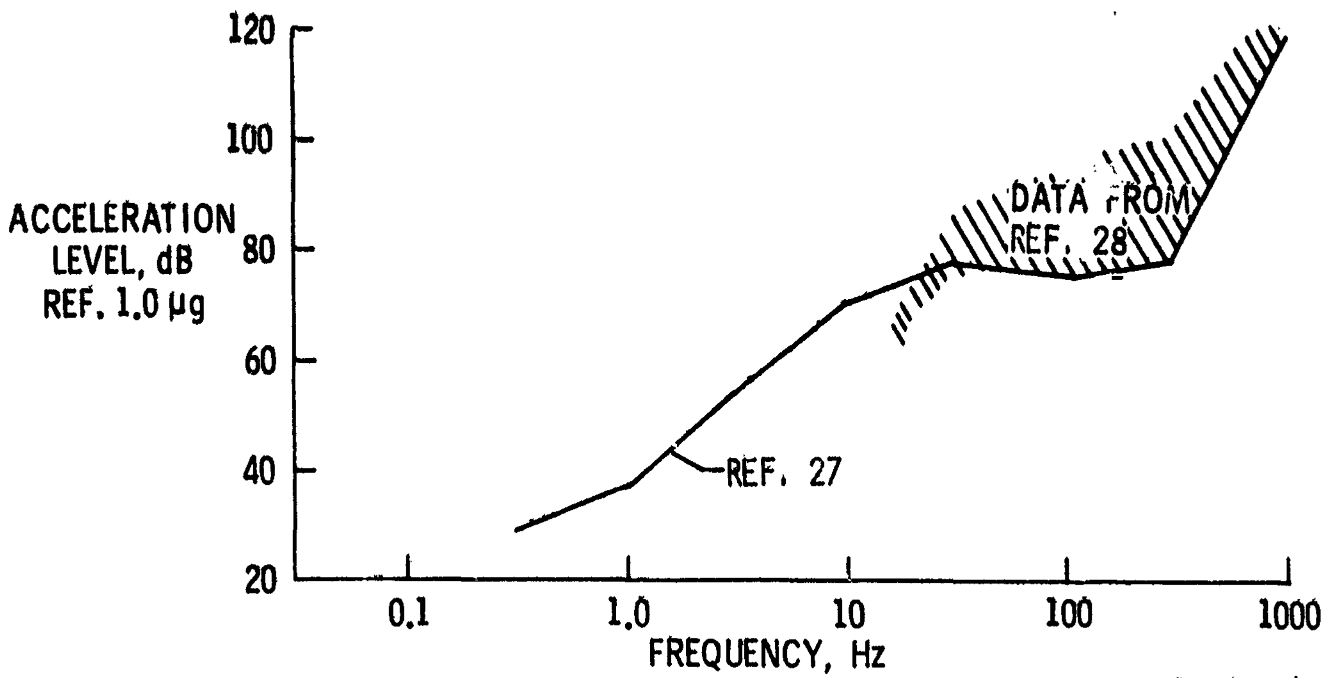

Figure C-9.- Thresholds of tactile perception.

HOUSE NOISE ATTENUATIONS

Another phenomenon observed by the occupants of a house is the noise transmitted to the inside spaces from the outside. The inside noise exposures are different from those on the outside because of the influence of the house structure as the noise is transmitted through it. Under normal circumstances the noise levels are reduced. Data showing example house noise reductions as a function of frequency are given in figure C-10. The hatched area encompasses results obtained in refs. 1-6. The noise reduction values of the ordinate are the differences between inside and outside readings. The most obvious result is that the noise reductions are larger at the higher frequencies. This implies that the measured spectra inside the house will have relatively less high frequency content than those on the outside.

There are very few data available at the low frequencies (below 50 Hz). In this range the wavelengths are comparable to the dimensions of the rooms and there is no longer a diffuse sound field on the inside (ref. 29). Other complicating factors are the role of stiffness at these lower frequencies and

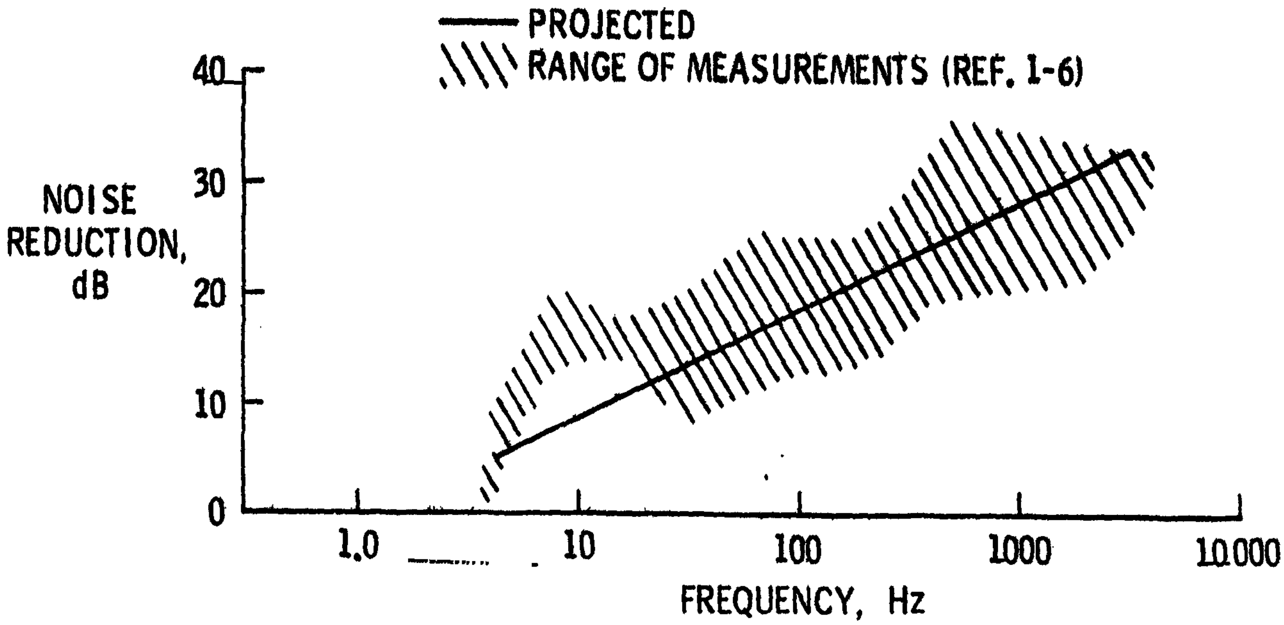

Figure C-10.- House noise reduction as a function of frequency for the windows closed condition.

the existence of pressure leaks. The inside distribution of pressure can be non-uniform because of standing wave patterns, organ pipe modes and cavity resonances due to room, closet and hall way configurations. The anticipated large variation of sound pressure levels from one location to another at very low excitation frequencies has not been documented for houses. Thus, it is difficult to characterize the low frequency noise environment inside a house structure based on a knowledge of the outside noise environment.

LOW FREQUENCY NOISE PERCEPTION CRITERIA

There are fragmentary reports (ref. 5) that indicate some unusual reactions to noise at very low frequencies, particularly when such noises are observed inside a structure or a vehicle. The data of figure C-11 are representative of some of the documented cases. A number of these are cited where low frequency noise from industrial operations has propagated relatively long distances into residential areas and has resulted in complaints. The hatched area of figure C-11 encompasses the ranges of frequency and noise level which are believed to

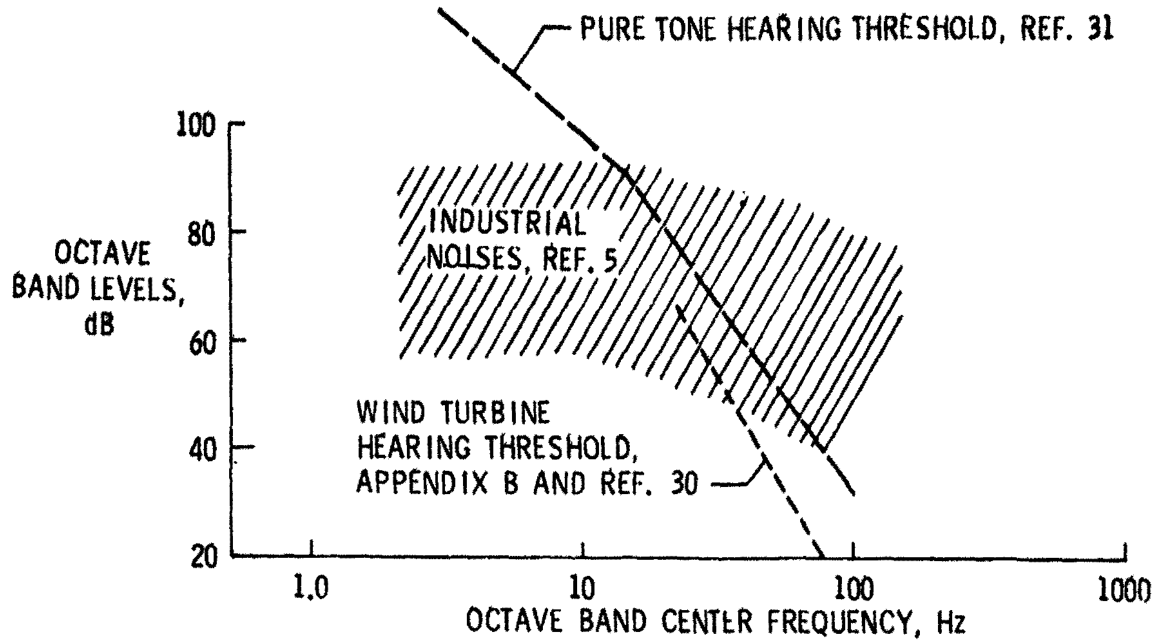

Figure C-11.- Range of low frequency inside noise levels which caused adverse reactions by occupants.

have caused the complaints. In all cases the levels of the higher frequency noise portions of the spectra were judged to be well within known tolerable limits. The low frequency components (below 125 Hz) are thus believed to be most significant.

It can be seen that many of the frequency-noise level combinations are below those of the hearing thresholds of references 30 and 31. Thus there is an indication that there are significant extra-auditory effects such as noise induced house vibration or that there are localized areas in the houses where the inside noise levels are considerably higher than the limited data indicate.

CONCLUDING REMARKS

Buildings respond readily to noise excitations and their responses can play an important role in community reactions to noise. Walls, floors, ceilings and large windows respond mainly in the "oil canning" modes at frequencies below 100 Hz and their motions are controlled largely by the beam elements. At higher frequencies the sheathing panels play a greater role and are the dominant elements at frequencies above about 300 Hz. Measured accelerations for a number of different types of noise inputs correlate generally on the basis of peak noise level and increase linearly as the input level increases. Wall and floor mounted objects such as lamps, pictures, mirrors, etc., may rattle by excitation of the main structure.

Criteria are included for perception of vibration, perception of low frequency noise, the rattling of wall and floor mounted objects, and noise induced damage of secondary structures and furnishings.

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APPENDIX D

CONSIDERATIONS FOR ATMOSPHERIC PROPAGATION OF WIND TURBINE NOISE

INTRODUCTION

The attenuation of sound as it propagates from a source to an observer is influenced by various phenomena, including geometric spreading, air and ground absorption, refraction, diffraction and scattering. The relative importance of these mechanisms will vary from one particular situation to another.

A brief description of each phenomenon will be given and prediction techniques applicable to large wind turbine operations will be described.

SOUND PROPAGATION PHENOMENA

Geometric Spreading

The propagation of sound from a point source in a homogeneous, loss-less atmosphere, far from any boundaries will cause the sound pressure level to decrease with increasing distance due to the expansion of the acoustic wave fronts. There is a constant decrease when the propagation distance is changed by a fixed ratio. This may be expressed by:

$$SPL_1 - SPL_2 = 20 \log_{10} \left(\frac{r_2}{r_1}\right)$$

where SPL_1 is the sound pressure level at a distance r_1 from the source. SPL_2 is the sound pressure level at a reference distance r_2 from the source.

This phenomenon is often referred to as spherical spreading and may be quantified as 6 dB per halving or doubling of distance. It is independent of frequency, and is of major importance in all situations of sound propagation.

Air Absorption

Atmospheric absorption losses have two basic forms:

(1) Classical losses associated with the change of acoustical energy into heat by fundamental gas transport properties

(2) For polyatomic gases, relaxation losses associated with the change of kinetic energy of the molecules into internal energy within the molecules themselves (ref. 1).

The absorption due to both these effects is frequency dependent and is a function of the propagation path distance, the humidity content and the temperature. The effects of distance and humidity are well established (ref. 1).

Atmospheric absorption losses are generally expressed in terms of a change in sound pressure level per unit of distance. At low frequencies these losses are extremely small, increasing to a few decibels per 1000 ft at 2 kHz. Except at very high frequencies, atmospheric absorption need only be considered when the propagation distances are long. However, this effect may be important for wind turbine applications, particularly for downwind propagation (see later section - Refraction). The data of reference 1 for standard atmospheric conditions (20°C, 70 percent relative humidity) have been adapted for use in the guide. Changes in humidity are unimportant unless below 20 percent, in which case reference 1 should be consulted.

Figure D-1 illustrates the combined effects of spherical spreading and atmospheric absorption. Shown in this figure are sound pressure level reductions to be applied to a reference sound pressure level (measured or predicted at 200 m) as a function of frequency and distance from the wind turbine.

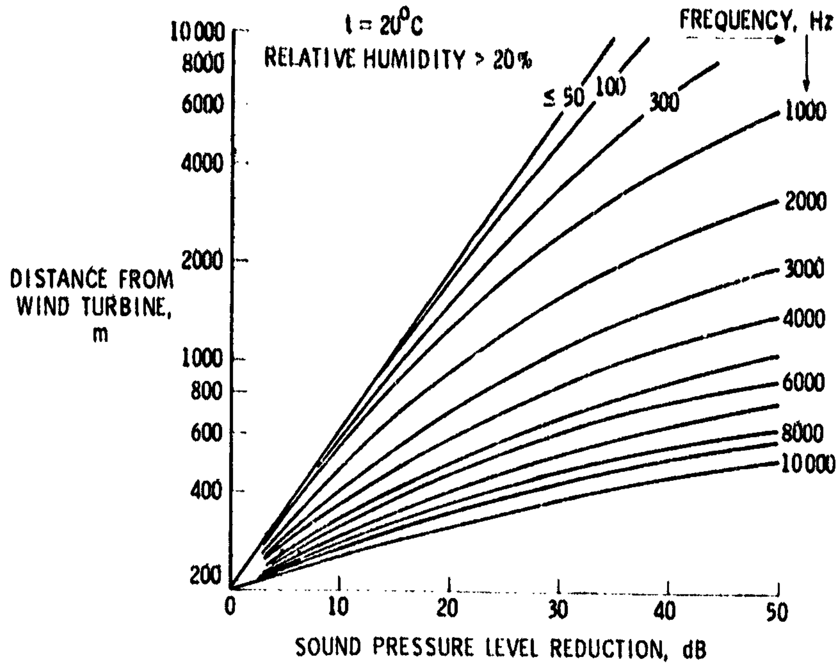
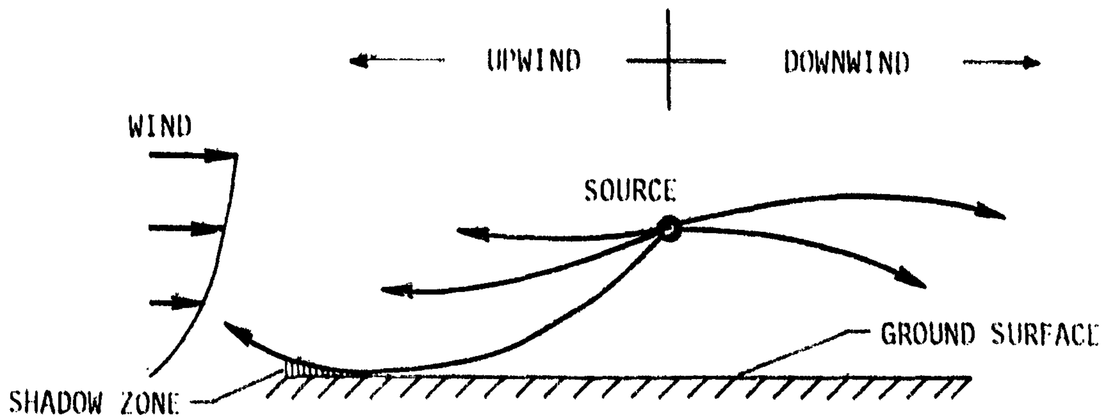


Figure D-1.- Noise level reductions due to spherical spreading and atmospheric absorption for various frequencies as a function of distance from wind turbine.

Refraction

Vertical temperature and wind gradients are generally present close to a ground surface due to heat exchange between the ground and the air and due to friction between the moving air and the ground. Wind velocity adds to or subtracts from the speed of sound depending on whether the propagation is downwind or upwind. A vertical wind gradient thus results in an effective speed of sound gradient. In the case of upwind propagation, the sound waves are bent upwards resulting in the formation of a shadow zone, inside which rapid sound attenuation takes place. In the downwind direction sound waves are bent downwards and may result in focusing, which causes an increase in sound level over that which would normally be expected.



In a normal adiabatic atmosphere, temperature decreases with height above the ground. Since the speed of sound is proportional to the square root of temperature, the decreasing sound speed gradient causes sound waves to be bent upwards as in upwind propagation, with the resulting formation of a shadow zone. Under certain conditions temperature inversions occur, resulting in sound waves being bent downwards.

Upwind Propagation

For flat terrain, the distance along the ground from the noise source to the edge of the shadow zone is given by (ref. 5):

$$D = \sqrt{\frac{2\ h\ c_0}{A + B \cos \theta}}\ \text{, meters}$$

h = source height, m
c_0 = speed of sound, m/s
A = speed of sound gradient due to temperature, sec^{-1}
B = wind velocity gradient, sec^{-1}
θ = angle between wind vector and propagation direction

For wind turbine applications it may be assumed that the effects of temperature gradients are small compared to those of wind gradients. Furthermore if the sound is propagating upwind and the value of wind velocity gradient is chosen at a point h/2 it may be shown that, for grass covered terrain,

$$D \approx h\sqrt{\frac{c_o \log_e(h/0.05)}{V}} \quad V = \text{wind velocity at the source, m/s}$$

It is apparent that the distance to the shadow zone increases with increasing source height and decreasing wind velocity. The guide, therefore, uses a conservative approach based upon the lowest operating wind speed.

Low-frequency impulsive noise is caused by blade/tower-wake interactions. It is recommended that for this type of noise the source height be the bottom of the rotor disk (h_1 in fig. D-2), the distance at which the blade is closest to the ground surface. For higher frequency (trailing edge) noise the source height should be the top of the rotor disk (h_2). Figure D-2 illustrates the effects of source height and wind velocity on the distance to the shadow zone.

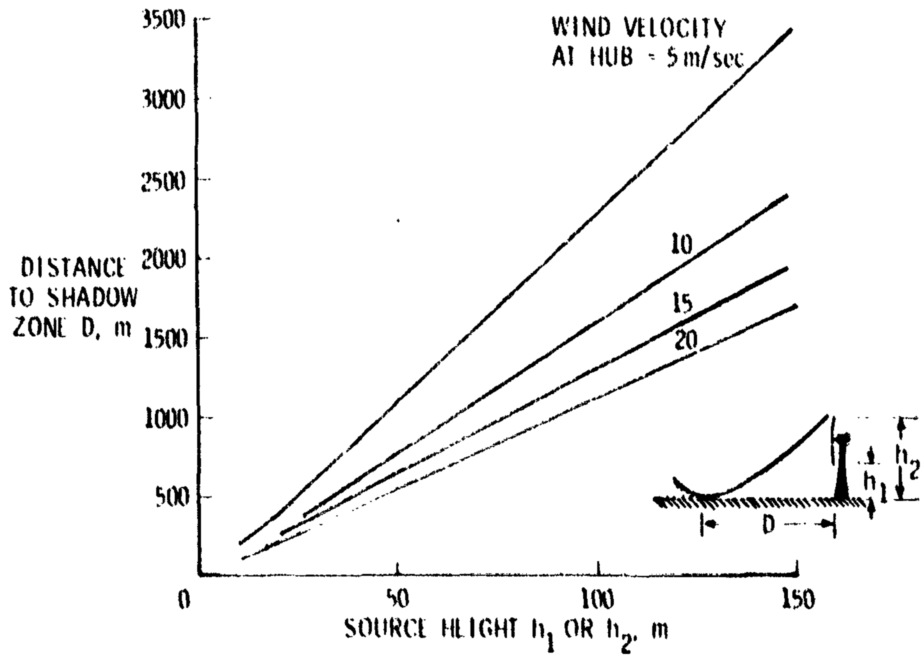


Figure D-2.- Distance to the edge of shadow zone as a function of source height and wind velocity.

The prediction of sound levels at distances within the shadow zone is based upon the method presented in reference 5. Figure D-3 illustrates the expected attenuation as a function of frequency at various distances into the shadow zone from the downwind edge. This excess attenuation is a strong function of frequency, the largest attenuation being associated with the higher frequencies. For instance, at a distance of 400 m into the shadow zone the excess attenuation is 5 dB at 50 Hz and 25 dB at 500 Hz.

The prediction of sound pressure levels at distances greater than 400 m is based upon spherical spreading and atmospheric absorption (fig. D-1).

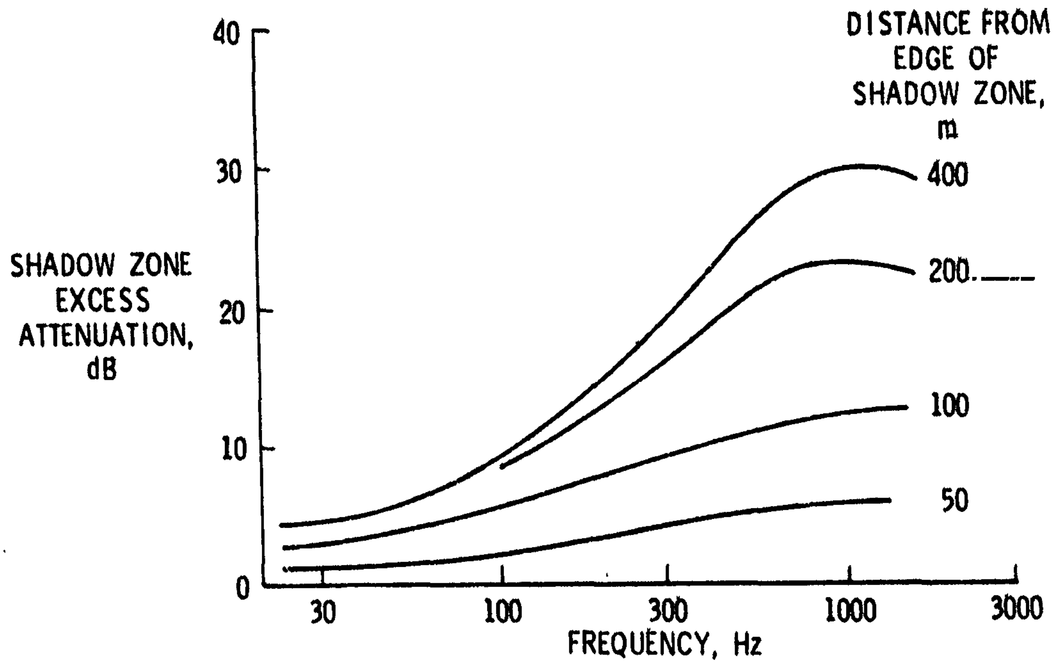


Figure D-3.- Excess sound attenuation inside the shadow zone as a function of frequency and distance.

Downwind Propagation

Empirical data have shown that focusing of sound rays downwind of a source can result in enhanced far field noise levels of 25-30 dB (ref. 6). Geometric ray theory has been shown to be useful for prediction purposes but requires, as input, high resolution meteorological data, which is generally not available.

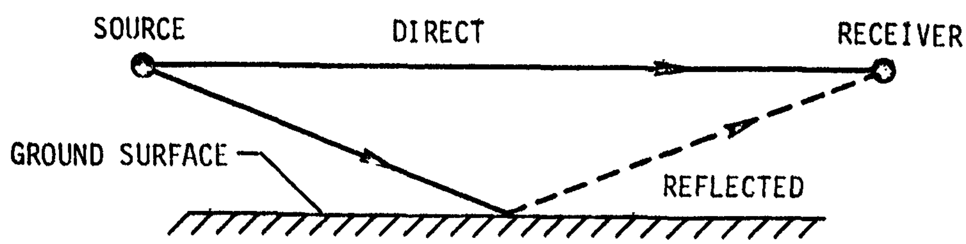
Hence, precise estimates of the location and magnitude of enhanced sound levels is extremely difficult. The recommended procedure does not include the effects of focusing.

Crosswind Propagation

A wind gradient will only minimally affect crosswind sound propagation. Consequently the recommended procedure treats crosswind propagation the same as downwind propagation.

Ground Absorption

Reflection of sound by a surface may affect observed sound pressure levels by two processes. An acoustic wave reflected from the surface may interfere with the direct wave.



In a still, homogeneous atmosphere the interference pattern may be predicted from knowledge of the difference in path length between the direct and reflected ray and from knowledge of any phase change introduced by reflection at the ground surface. For frequencies at which the direct and reflected waves are in phase at the receiver, a pressure doubling will occur, yielding a 6 dB increase in sound pressure level. If the direct and reflected waves are 180° out of phase, cancellation will occur.

Sound levels are also affected by loss of energy upon reflection. This process is referred to as surface absorption and is particularly important when both source and receiver are close to the ground. Procedures based upon theoretical and empirical results are available which predict sound pressure levels at receiver positions above uniform surfaces of known acoustical impedance in the absence of strong wind and/or temperature gradients (refs. 2-4). Predictions of ground attenuation were made using the procedure of reference 3 for a flat grass-covered surface and various source heights and receiver distances. The receiver height was chosen to be close to the ground so that destructive interference only occurred at frequencies higher than those of interest. Summary data are given in figure D-4. For large receiver distances and any reasonable receiver height (less than 3m) reflection at the ground surface will result in increased sound pressure levels at the lowest frequencies (less than 20 Hz). If the recommended propagation procedure is applied to measured data this effect will automatically be included. If based upon theoretical predictions a correction should be applied. This has not been included in the recommended procedure due to the relative unimportance of frequencies below 20 Hz.

The interference pattern at higher frequencies is very sensitive to the source-receiver geometry and the choice of an appropriate receiver height is far from obvious. A further complication concerns the effect of wind gradients on the interference pattern. There are some indications (ref. 7) that sound propagation above 500 Hz in the downwind direction shows no effect of ground absorption. At lower frequencies some absorption is observed but since the recommended procedure does not account for focusing in the downwind direction, the effects of the ground have been omitted for reasons of conservatism and simplicity. The propagation distances in the upwind direction are relatively short, and again due to uncertainties regarding the receiver height and effects of refraction, ground absorption has been omitted.

Diffraction and Scattering

In a shielded region, for example behind a house or a hill, sound levels may be limited by diffraction and scattering. These phenomena are so site-specific that they have not been considered in the guide.

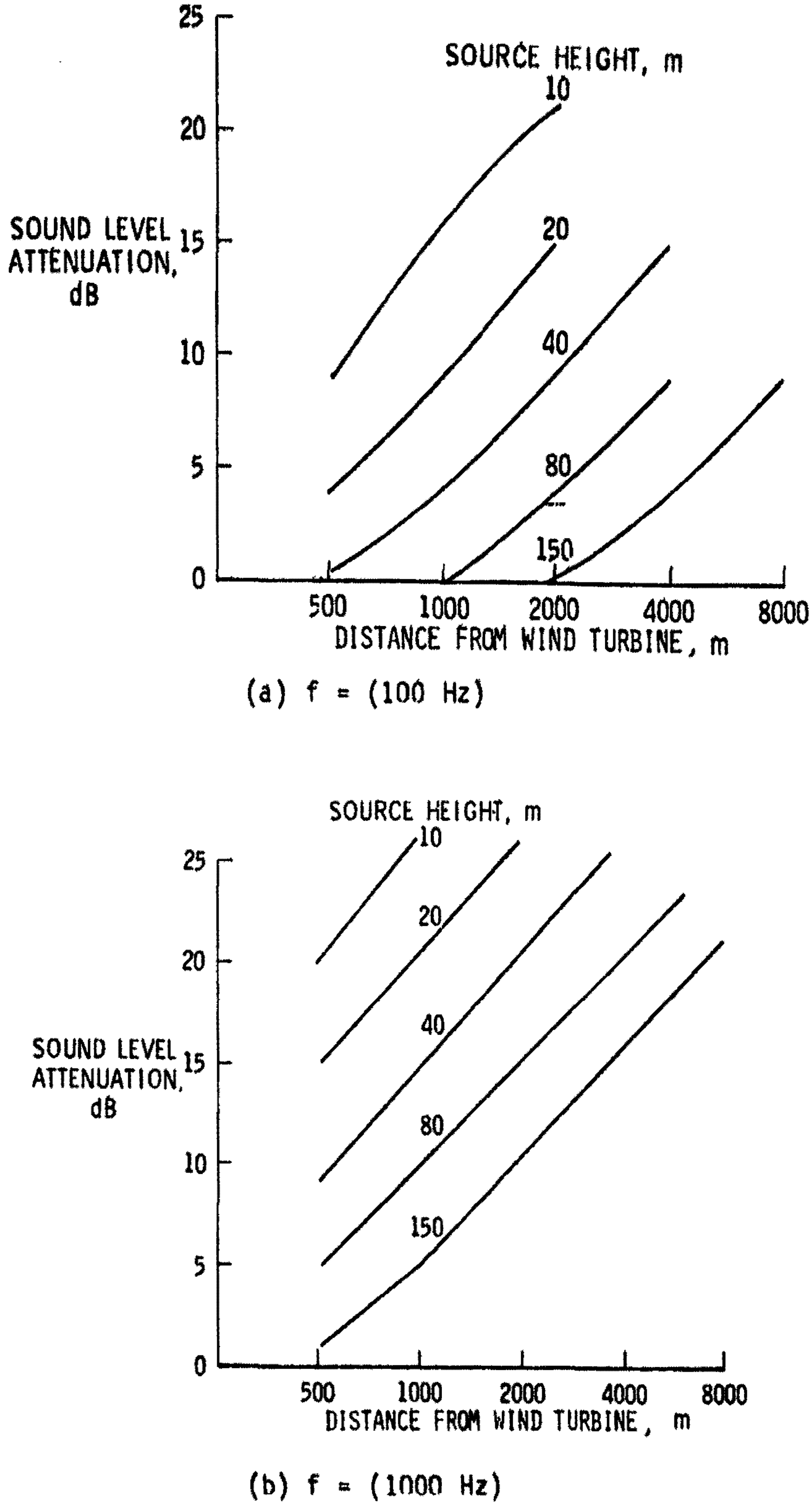


Figure D-4.- Ground attenuation as a function of source height and distance from wind turbine.

CONCLUDING REMARKS

The recommended procedure, in essence, consists of two parts: upwind propagation and downwind propagation. The decay of sound pressure level with distance in the downwind direction is simply the summation of losses due to atmospheric absorption, which is frequency dependent, and the reduction due to spherical spreading, which is independent of frequency. The procedure for calculating sound pressure levels upwind of the source is more complex and requires the computation of the distance to the shadow zone, which is determined by the source height above the ground surface and the wind velocity gradient. At locations between the source and the shadow zone, sound pressure levels are determined from spherical spreading and atmospheric absorption. Inside the shadow zone, there occurs a rapid reduction in sound pressure level, which is frequency dependent.

As should be clear from the preceding discussions, various assumptions and simplifications have been made in the development of the recommended procedures. It is believed that in the upwind direction the adopted approach is conservative so that measured sound pressure levels will be less than those predicted. However, in the downwind direction this may not be the case. As mentioned previously, refractive focusing can produce greatly enhanced sound pressure levels, but such effects are unstable in terms of both time and location of occurrence. An attempt has been made to compensate for such effects by neglecting ground attenuation in the calculation procedure. This deficiency is a reflection of the serious lack of data available for downwind sound propagation.

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APPENDIX E

EXAMPLE CALCULATIONS

INTRODUCTION

In this appendix a step-by-step procedure is outlined to enable the user to derive the theoretical sound pressure levels as a function of distance from the wind turbine from measured or predicted data obtained at one (preferably downwind) location. Numerical information is used in an effort to simulate a real-life situation. Detection thresholds are determined to assess human exposure to wind turbine noise. The example is graphically illustrated in figure E-1.

An example two-bladed wind turbine, having a diameter of 80 m,operates at 30 rpm in a 6 m/s wind, which was measured at the hub of the 60 m high supporting tower. The background noise was measured to be 35 dBA and was shaped similarly to the one-third octave ~~band~~ spectrum in figure B-6. The wind turbine sound was analyzed on a narrow band and a one-third octave band basis at a distance of 160 m from the machine. Although the whole spectrum should be evaluated, three frequencies representing the limiting cases of detection are chosen for use in this example:

(a) a 40 Hz impulsive sound with a narrow band sound pressure level of 72 dB; (b) a 10 Hz impulsive sound with a one-third octave band sound pressure level of 80 dB and (c) a 1000 Hz broadband sound with a one-third octave band sound pressure level of 59 dB.

EVALUATION PROCEDURE

The impulsive sound (narrow band and one-third octave) and broadband sound (one-third octave) will be evaluated individually for the upwind and downwind cases. They will be weighted against the detection thresholds for impulsive sound, building vibrations, and broadband sound.

Impulsive Sound (Narrow band)

Upwind

Step 1: Calculate the sound pressure level SPL_2 at the reference distance (200 m), from the sound pressure level (SPL_1) measured at a distance r (in meters) from the wind turbine using the relationship:

$$SPL_2 = SPL_1 + 20 \log_{10} \frac{r}{200}$$

$$SPL_2 = 72 + 20 \log \frac{160}{200} = 70 \text{ dB}$$

Step 2: Determine the distance to the edge of the shadow zone (D) using figure 6.

$$\left.\begin{array}{l} h_1 = 20 \text{ m} \\ \text{wind velocity} = 6 \text{ m/s} \end{array}\right\} \quad D = 300 \text{ m}$$

Step 3: Determine the sound pressure level reduction (L_D) over the distance D using figure 5.

$$\left.\begin{array}{l} D = 300 \text{ m} \\ f = 40 \text{ Hz} \end{array}\right\} \quad L_D = 4 \text{ dB}$$

$$\rightarrow SPL_3 = 70 - 4 = 66 \text{ dB} \quad \text{at} \quad 300 \text{ m}$$

Step 4: Determine the excess sound attenuation (L_E) in the shadow zone by use of figure 7.

$$f = 40 \text{ Hz} \quad L_E = 6 \text{ dB}$$

Step 5: Determine the sound pressure level reduction at a distance D + 400m from the wind turbine with the help of figure 5.

$$\left.\begin{array}{l} D + 400 = 700 \text{ m} \\ f = 40 \text{ Hz} \end{array}\right\} \quad L_{D+400} = 11 \text{ dB}$$

Step 6: Determine the sound pressure level at the end of the shadow zone (SPL_4) by adding the numbers obtained under Steps 4 and 5 and subtracting the result from the number in Step 1.

$$SPL_4 = SPL_2 - (L_E + L_{D+400})$$

$$SPL_4 = 53 \text{ dB at } 700 \text{ m}$$

Step 7: Calculate the sound pressure level at any distance from the wind turbine past the shadow zone by determining the sound pressure level reduction found in figure 5 and correcting for the excess attenuation in the shadow zone.

$$SPL_X = SPL_2 - (L_E + L_X)$$

Downwind

Step 8: Calculate the sound pressure level at any distance from the wind turbine by determining the sound pressure level reduction from figure 5.

$$SPL_X = SPL_2 - L_X$$

Perception Threshold (Impulsive Sound)

Step 9: Determine the detection threshold for impulsive sound using figure 9 (narrow band)

$$\left.\begin{array}{l}\left.\begin{array}{l}30 \text{ rpm} \\ 2 \text{ blades}\end{array}\right\} 1 \text{ Hz fundamental} \\ \\ f = 40 \text{ Hz} \\ \text{background} = 35 \text{ dBA}\end{array}\right\} T_i = 45 \text{ dB}$$

Impulsive Sound (One-Third Octave Band)

Steps 1 through 8 are repeated for the one-third octave band frequency spectrum of the impulsive noise. Since the one-third octave band sound pressure level at a center frequency of 10 Hz is 8 dB higher than the narrow band level at 40 Hz, all numbers calculated in the procedure above have to be increased by 8 dB (figure E-1).

Perception Threshold (Building Vibration)

Step 9: Determine the perception threshold for building vibration using figure 11 (one-third octave tand)

$$\left.\begin{array}{l}\text{40 Hz}\\ \text{walls}\end{array}\right\} T_{wa} = 70 \text{ dB}$$

$$\left.\begin{array}{l}\text{40 Hz}\\ \text{floor}\end{array}\right\} T_{fl} = 80 \text{ dB}$$

Broadband Sound

The same procedure as for impulsive sound is applicable to the broadband sound. This will result in the following:

Upwind

Step 1: $SPL_2 = 59 + 20 \log \frac{160}{200} = 57$ dB

Step 2: $\left.\begin{array}{l}h_2 = 100 \text{ m}\\ \text{wind velocity} = 6 \text{ m/s}\end{array}\right\} D = 2200 \text{ m}$ (fig. 6)

Step 3: $\left.\begin{array}{l}D = 2200 \text{ m}\\ f = 1000 \text{ Hz}\end{array}\right\} L_D = 28 \text{ dB}$ (fig. 5)

$SPL = 57 - 28 = 29$ dB at 2200 m

Step 4: $f = 1000$ Hz $L_E = 30$ dB (fig. 7)

This will bring the sound pressure level in the shadow zone down to zero, and obviously, below the detection threshold. This is illustrated in figure E-1.

Downwind

Step 8: The sound pressure level at any distance from the wind turbine can be calculated by determining the sound pressure level reduction from figure 5.

$$SPL_X = SPL_2 - L_X$$

Perception Threshold (Broadband Sound)

Step 9: Determine the detection threshold for the broadband sound by comparing the one-third octave band sound pressure level of the wind turbine to the level of the background noise at the same center frequency.

$$\left.\begin{array}{l}\text{figure B-6}\\ f = 1000\ \text{Hz}\end{array}\right\}\quad T_b = 24\ \text{dB}$$

CONCLUDING REMARKS

For the example problem cited herein, no adverse human response due to building vibration is to be expected at locations in excess of 340 m upwind and in excess of 430 m downwind from the wind turbine generator (fig. E-1). Wind turbine sound will be limited by a broadband sound detection distance of 2250 m upwind and an impulsive sound detection distance of 3300 m in a downwind direction. Outside this region wind turbine sound is not detectable, while within these limiting distances community response may be estimated from Table I.

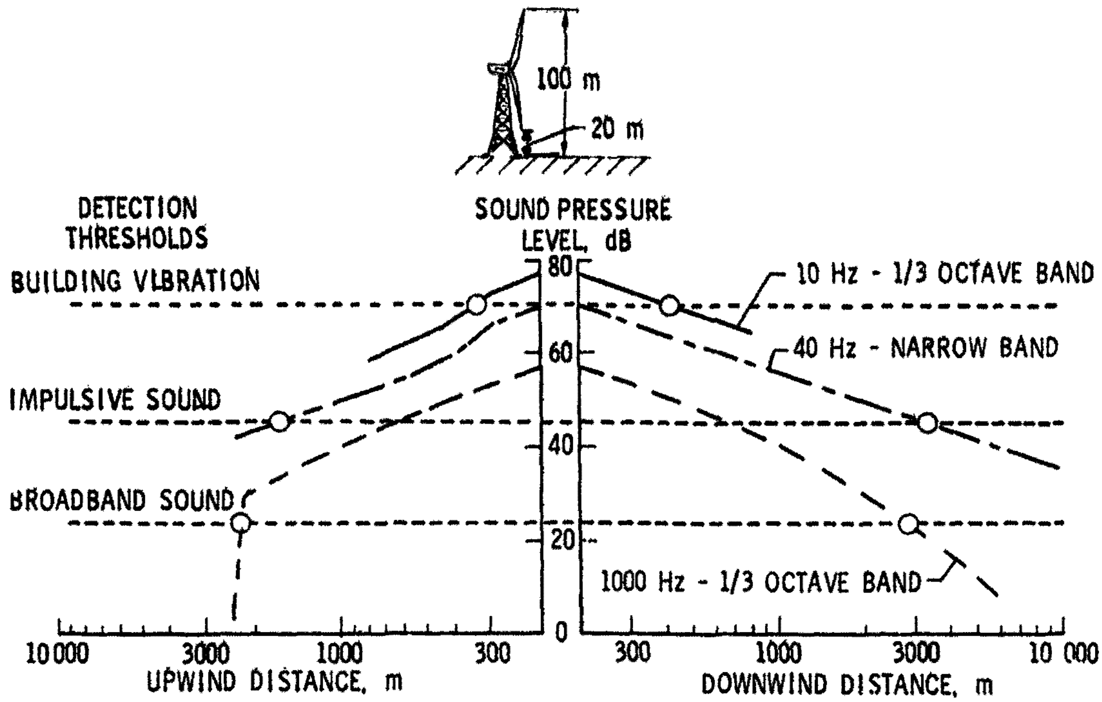

Figure E-1.- Sound pressure levels as a function of distance for example problem of Appendix E. (Results are used to assess human exposure to wind turbine noise.)