# WIND TURBINE ACOUSTIC STANDARDS

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## ABSTRACT

A program is being conducted to develop noise standards for wind turbines which minimize annoyance and which can be used in design specifications. The approach consists of presenting wind turbine noise stimuli to test subjects in a laboratory listening chamber. The responses of the subjects are recorded for a range of stimuli which encompass the designs, operating conditions, and ambient noise levels of current and future installations. Results to date have established the threshold of detectability for a range of impulsive stimuli of the type associated with blade/tower-wake interactions. The status of the ongoing psychoacoustic tests, the subjective data, and the approach to the development of acoustic criteria/standards are described.

## 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. Subjective data on wind turbine operations, however, are virtually nonexistent with the exception of a few cases of reported annoyance with the MOD-1, a 2000 kw downwind machine located at Boone, North Carolina. Furthermore the noise associated with wind turbines, and in particular the low frequency blade/tower-interaction noise, have temporal and spectral characteristics which are in a range where very little subjective data and/or experience are available (ref. 1). Thus, a laboratory study has been initiated to better understand wind turbine type noise to provide guidance in the design and siting of future machines.

The factors which are believed to be important to the development and application of wind turbine noise criteria are shown schematically in figure 1. As indicated, the turbine may produce noise through several source mechanisms which may result in both impulsive characteristics due to blade/tower-wake interactions ("thumping") and nonimpulsive ("swishing") noise due to unsteady flow over the blades. These source characteristics are modified before reaching the receiver due to atmospheric propagation and terrain effects. Finally, the effects of wind turbine noise on the receiver may be modified by many factors such as the background or ambient noise level, the time of day, the activity and location of the receiver (indoors/outdoors), and the presence of any perceptible house vibrations induced by the noise. To assess the impact of the noise, criteria must be developed which consider the receiver's perception of, and response to, the acoustical factors (noise level and frequency, for example) and nonacoustical factors (e.g. time of day) associated with the operation of the wind turbine. These criteria must include the various source and path effects both separately and in combination in order to be useful for the design and siting of future machines.

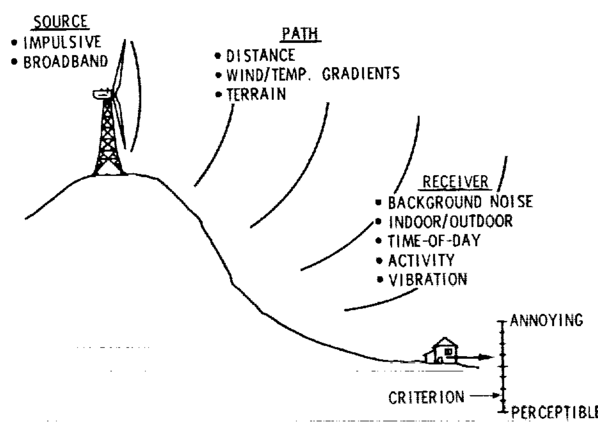



Figure 1 - Wind turbine noise factors.

This paper is a status report of an ongoing program to develop noise criteria to be applied at the receiver location. Emphasis to date has been on the determination of the perception threshold of wind turbine spectra covering the range of anticipated designs and operating conditions. It should be noted that building vibration, despite the fact that it has received considerable attention in the case of the MOD-1 operation will not be considered in this report for two reasons. First, the levels recorded to date suggest that the building response is below the human (whole-body) threshold of detectability and, secondly, it is believed that any noise standards resulting from these studies will yield noise levels low enough to preclude perceptible building vibration (refs. 2 and 3).

## PROCEDURE

Tests were conducted to determine the threshold of detectability 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 the blade passing 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 detectability 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 detectability was found to be independent of phase and lower in level than that found for the random phase condition. For this reason, the sounds used in this study had a coherent phase relationship between harmonic components.

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. 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, figure 2. This facility has dimensions of 4m x 2.5m x 2.5m (cutoff frequency of 150 Hz) and is equipped with two loudspeakers having a frequency response of 5 Hz to 20 kHz.

Figure 2 - Anechoic test facility.

Each subject was seated in front of the loudspeakers and instructed to press a hand-held switch when they heard the sound (fig. 3). This switch activated a light which indicated to the test conductor that a given sound was heard. 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 detectability.

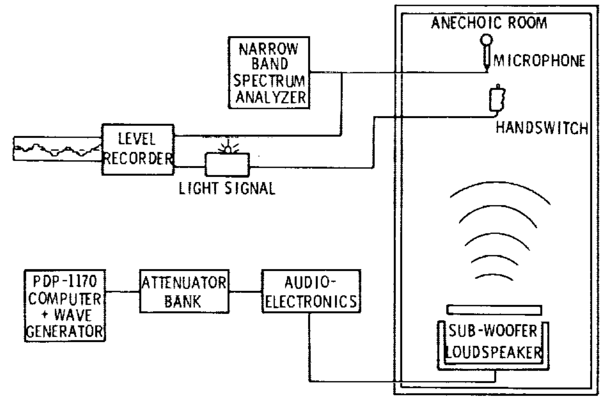


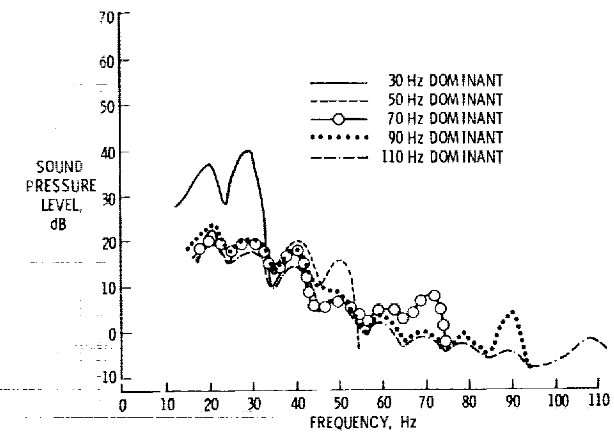

Figure 3 - Stimuli presentation and subjective response system.

RESULTS AND DISCUSSION

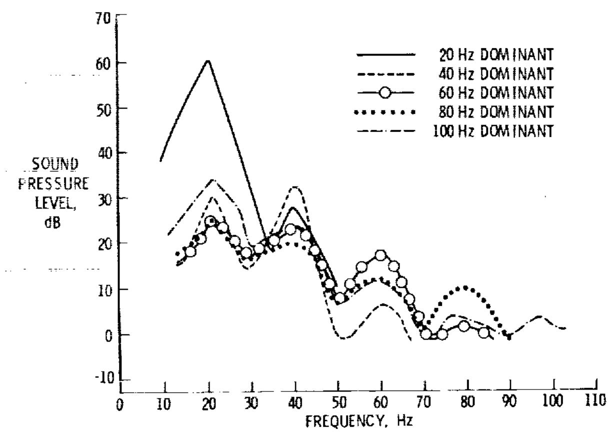
The primary objective of the study to date has been the determination of the threshold of detectability for impulsive turbine noise having a variety of spectra in the frequency range from 20 to 110 Hz. Frequencies below 20 Hz, were considered to be unimportant due to the extreme insensitivity of the 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. 4 and 5). No broadband ("swishing") noise has been included nor have ambient noise effects been studied.

Ten spectra, having a fundamental frequency of either 1.0 Hz or 0.5 Hz, were designed to be dominated, subjectively, by harmonics at different frequencies. 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. Detectability 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 narrowband spectra at the mean threshold level are presented in figure 4. Tangential curves were fitted to these spectra and are presented in figure 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 in the ISO pure tone or minimum audible field (MAF) threshold (ref. 6) which has the same general shape. The difference in level between the turbine curves and the MAF curve may be attributed to the critical bandwidth of the human ear (ref. 7) which is far greater than the bandwidth used in the spectral analysis.




a) 0.5 Hz fundamental




b) 1.0 Hz fundamental

Figure 4 - Narrowband spectra at the mean threshold level

The data (fig. 5) suggest that the frequency of the fundamental is a significant variable. It is recommended that the 1 Hz fundamental curve be used and then an adjustment made on a logarithmic (energy) basis for the actual fundamental blade passage frequency. Thus, the curve for 0.5 Hz fundamental would be 3 dB lower and the curve for 2 Hz would be 3 dB higher than the 1 Hz fundamental curve. Furthermore, the frequency analysis bandwidth should be less than the fundamental frequency. The use of 1/3 octave or octave band analysis is not recommended due to the steep slope of the threshold curves.

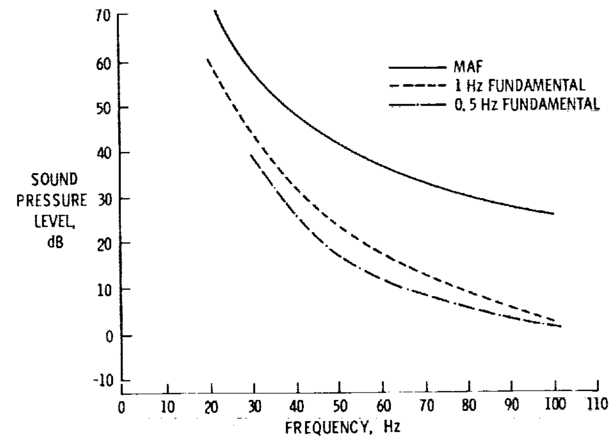



Figure 5 - Thresholds of detectability

Certain limitations of the preceding results need to be considered. Mean threshold data have been presented and consequently many people will be able to detect sounds at lower levels. Also these tests were conducted in an anechoic environment with extremely low background noise (masking by higher levels of background noise will be considered in the near future). The spectra used to generate the threshold curves were specifically designed such that detectability 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 point in time, but will be studied in future testing.

## CONCLUDING REMARKS

The thrust of the program is to develop the psychophysical functions relating human response to each of the wind turbine noise components such as "thumping" and swishing." Furthermore, the variation or dependence of these functions on other acoustical factors such as ambient noise will be examined. This will enable assessment of the acceptability of a predicted or measured noise condition at a receiver location. For example, if "thumping" is the dominant noise source in a low ambient noise situation, the ideal solution would be to design for noise levels below the threshold of detectability for impulsive noise (fig. 5). However, if the measured or predicted spectrum exceeds the detection threshold, annoyance may result. The degree of annoyance cannot be predicted at the present time due to absence of subjective data under actual operating conditions but an indication of the growth of annoyance may be found in classical loudness studies which show that the growth of loudness is frequency dependent as shown in Table 1.

| Frequency | dB/doubling of loudness |
|---|---|
| 20 | 4.5 |
| 50 | 6.1 |
| 100 | 7.2 |
| 500 | 8.6 |
| 1000 | 10.0 |

Table 1 - Growth of loudness

Exceeding the threshold of detectability at 20 Hz has more serious consequences than at higher frequencies. In general, the major use of the psychophysical relationships will be to guide the designer/operator in pinpointing the exact frequency components and hence source mechanisms which may cause problems with wind turbine operations.

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## QUESTIONS AND ANSWERS

D.G. Stephens

From: Anonymous

Q: Have you varied the background ambient noise level in your test room to simulate that at a residence?

A: *No, but we intend to.*

From: W. Beans

Q: From test subjects did you obtain the standard deviation due to subject age?

A: *No. All subjects used in the test had good hearing and consequently were relatively the same young age.*

From: D.W. Thomson

Q: Have you considered setting the individual subjects on a shaker table driven from your synthesizer system so as to provide "body" input? Another possibility would be to include a loaded china closet in the chamber which might pick up the vibrating stemware source.

A: *No answer was provided.*