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DETECTION OF LOW FREQUENCY IMPULSIVE NOISE FROM LARGE WIND TURBINE GENERATORS

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SUMMARY

A laboratory study was conducted to examine thresholds of detection of low frequency, impulsive wind turbine sounds in the presence of background noise. Seven wind turbine sounds, six of which were synthesized, were used in conjunction with three background noise conditions; quiet, 35 and 45 dB(A). The results indicate that thresholds of detection are predictable based on assumed characteristics of the auditory system. The synthesized wind turbine sounds were found to adequately represent a real recording.

INTRODUCTION

A wind turbine may produce both impulsive and broadband noise (refs. 1-4). The former is a characteristic of downwind machines for which the inflow encounters the supporting tower before encountering the rotor blades. Broadband noise is generated by all types of wind turbines.

Little information is available regarding human response to wind turbine noise (refs. 5,6). In particular the impulsive noise generated by wind turbines has spectral and temporal characteristics which are in a region where little subjective data or experience are available. The detection of low frequency impulsive noise from large wind turbine generators is examined in this laboratory study. Specific objectives include determination of the effect of background noise and the adequacy of utilizing synthesized wind turbine noise.

EXPERIMENTAL METHOD

Test Facility

The testing was conducted in a small anechoic listening room at the NASA Langley Aircraft Noise Reduction Laboratory. This facility has dimensions of 4 x 2.5 x 2.5m, and is equipped with a sound reproduction system having a frequency response of 10 Hz to 20 kHz. Further details may be found in reference 7.

Noise Stimuli

Each of the seven noise stimuli consisted of a train of impulses having a one-second period, thus representing a wind turbine having a blade passage frequency of 1 Hz. The long term r.m.s. spectrum of a such a sound thus consists of discrete components at 1Hz intervals. Five of the seven sounds were designed such that detection would be achieved over a narrow frequency range. For example, if the level of the spectrum in figure 1 is uniformly raised, the frequency components near 60 Hz will be the first to intersect the pure tone threshold (minimum audible field - MAF)(ref. 8) and hence this frequency range is considered dominant. Figure 2 presents the wind turbine noise spectra used in this study. Spectrum levels designated by the data points are shown at 1 Hz intervals. Sounds 1-5 were synthesized and are dominated, respectively, by components near 20, 40, 60, 80 and 100 Hz. Sound 7 was derived from a recording of the WTS-4 wind turbine made at a downwind distance of 150m. A tape loop containing four blade passages was constructed and low-pass filtered at 100 Hz. This was sound 7. The spectral shape of sound 7 was then used as a basis for the synthesis of Sound 6. Typical pressure time histories are shown in figure 3.

Thresholds of detection were determined for these seven sounds with and without the presence of background noise. The spectrum of the background noise used in this study was based on measurements made in a suburban/rural location (ref. 5) and is shown in figure 4. This noise was synthesized by spectrally shaping pink noise, and was presented at levels of 35 and 45 dB(A).

Experimental Design Procedure

Eight test subjects, all with normal hearing (ref. 8), were used in this study. The sequence of presentation of sounds and background noise conditions was determined by a modified Latin square design (Table I). This design was used to minimize any order effects due to learning or fatigue. Sound 7 was presented last under each background noise condition for logistical reasons since this sound was played from a tape recorder and the other six synthesized sounds were computer generated.

Upon arrival at the laboratory a single test subject was seated in the anechoic chamber and was instructed to press a hand held switch when the wind turbine sound was heard. The sound pressure level 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. The standard deviation (across subjects) of measured threshold levels was in the range 1-2.5 dB, with a clear tendency for the higher values to be associated with the "no background noise" condition.

RESULTS

Detection in Quiet

The wind turbine noise spectra, at the mean (across subjects) threshold level, are presented in figure 5. These are narrow band

(Δf=1Hz) spectra where at each frequency the sound pressure level is expressed relative to the pure tone threshold at that frequency (ref.8). One explanation for the peak level of each sound being well below audiometric zero (MAF) is that the bandwidth of these spectra (1 Hz) is much less than the bandwidth of the human auditory system.

Various estimates of this so-called critical bandwidth are available (refs. 9-15), four of which are examined in the present study:

1. Patterson (refs. 9-11) has extensively studied the shape of the auditory filter at frequencies above 500 Hz and suggests the following:
   $$10 \log (BW) = 8.6 \log (fo/1000) + 22.2$$
   where BW = rectangular bandwidth and fo = center frequency.
   This relationship has been extrapolated to low frequencies and is labeled "Patterson" in figure 6.

2. Patterson (ref. 11) has also proposed a two parameter rounded exponential filter shape, designated roex (p,r). For the present study a value of 25 was chosen for 'p' and a value of 0.0001 for 'r'. The equivalent rectangular bandwidth is given for comparison in figure 6.

3. Horonjeff and Fidell (ref. 14), in a review of studies of critical bandwidth, concluded that Greenwood's estimates (ref. 15) are too large by a factor of at least two. One half of Greenwood's values are presented in figure 6 and labeled "Fidell". The extrapolation to the lowest frequencies was based on the recommendation of Abrahamson (ref. 13).

4. The fourth estimate of critical bandwidth used in this study is one-third octave bands, also shown in figure 6.

Thus four estimates of critical bandwidth were used in this this study, three of which are rectangular, the fourth being a rounded exponential (roex(p,r)).

In order to calculate critical band levels it is necessary to sum the narrow band spectral components (figure 5) over the appropriate bandwidths. The results of such a calculation are presented in figure 7 for one-third octave critical bandwidths (number 4, above). The calculation procedure was based on a one-third octave band filter (bandwidth = 0.23 x center frequency) traversing the frequency range 12 to 98 Hz in 1 Hz intervals. Thus the data points of figure 7 represent one-third octave critical band levels at 1 Hz intervals for each of the sounds at threshold. Note that these spectra differ from those obtained from a standard one-third octave analysis because the choice of center frequencies results in adjacent filters that greatly overlap one another. Results for sound 6, which is synthesized, and sound 7 which is a real recording, are in good agreement, indicating that the synthesis is adequate.

Similar calculation procedures were followed for the other critical bandwidths (figure 6). The results of all four sets of critical bandwidth calculations are summarized in figure 8.

The range of peak sound pressure levels is similar for each estimated critical bandwidth. The roex(p,r) critical band gives generally lower values since this has the smallest bandwidth at all frequencies (figure 6). In almost all cases the calculated peak sound pressure levels are below audiometric zero (0 dB in figure 8). It must be remembered that the spectra that have been presented are averaged over multiple periods and represent the average energy per period. The sounds are highly impulsive and the majority of the acoustic energy is confined to a small fraction of the period (1 sec). If it is assumed that the time constant of the ear is 250 msecs (e.g., ref. 12) and that all the acoustic energy falls within this interval, then the sound pressure levels in figure 7 and 8 would be raised by 6 dB (10 log (Period/ 0.25)) in order to compensate for the impulsive nature of the sound stimuli. Clearly the sound levels presented in figure 8 will then fall closer to audiometric zero.

Detection with Ambient Noise

Thresholds of detection were determined for each sound in the presence of ambient noise presented at 35 and 45 dB(A). The one-third octave band levels, at 1 Hz intervals, are presented in figure 9 for the spectra at the mean threshold level in the presence of ambient noise at 35 dB(A). The spectrum of the ambient noise is also included in the figure.

At the lowest frequencies the ambient noise is well below audiometric zero (0dB in figure 9) and thus is clearly inaudible. Detection of wind turbine sounds at these frequencies must therefore be determined by a presumed "noise floor" of the human auditory system. At higher frequencies detection is presumably determined by a combination of the ambient noise and this "noise floor". It is possible to infer a numerical value of this "noise floor" from examination of the change in threshold levels of the sounds which occur when ambient noise is added.

The power spectrum model of masking assumes that, at threshold, the signal power is proportional to the masking noise power where both are measured at the output of the auditory filter. Thus, with no ambient noise present,

$$S_Q = K \cdot N_Q$$

where S_Q is the signal power and N_Q is the "noise floor" of the auditory system.

If ambient noise is added the resulting signal power, S_A, is:

$$S_A = K\ (N_Q + N_A)$$

where N_A is the ambient noise power.

Assuming that the output power level of the auditory filter is proportional to sound pressure level, the difference in signal power level between ambient and quiet conditions is:

$$\Delta\ SPL = 10 \log S_A - 10 \log S_Q = 10 \log \frac{N_Q + N_A}{N_Q}$$

and,

$$10 \log N_Q = 10 \log N_A - 10 \log [\ 10^{\Delta SPL/10} - 1]$$

The "noise floor" of the auditory system was thus calculated to be -8 dB (re MAF) for one-third octave bands, -7 dB for "Fidell", -10 dB for roex(p,r), and -8 dB for "Patterson". An example calculation may be found in the Appendix.

These calculated values of the "noise floor" were added, on an energy basis, to the measured ambient noise to yield a "corrected ambient" spectrum. The peak sound levels of the wind turbine noises, relative to this "corrected ambient", were calculated for each critical bandwidth and are presented in figure 10. There is clearly little difference in the results for the four critical bandwidths.

This process was repeated for detection in the presence of ambient noise at 45 dB(A), the results of which are shown in figure 11. Again, it is apparent that there is little difference in the results for the four critical bandwidths.

The results for the three ambient noise conditions are summarized in Table II. The standard deviations are generally higher for the "quiet" condition, presumbably due to the higher variation between test subjects' threshold measures for this condition. The differences in the results for the four estimates of critical bandwidth are generally small, thus, in practice, the complexity of using anything other than one-third octave bandwidths is probably not justified. From examination of Table II, it may be concluded that at threshold the sound pressure level of the wind turbine sounds are approximately equal to the "corrected ambient" sound pressure level when both spectra are expressed relative to the I.S.O pure tone threshold (ref. 8) and then summed within critical bands.

An alternative approach is to sum the spectral components within critical bands and then to weight them according to the pure tone threshold of the center frequency of each band. All the preceding laboratory data were analyzed in this manner and summary results are presented in Table III. A comparison of the standard deviations of Table III with those presented in Table II clearly shows that less variablility is found when spectral levels are weighted prior to summation within critical bands.

Yet another possible approach is to use one-third octave bands and their conventional center frequencies; all the preceding analyses have been based on one-third octaves whose center frequencies have been incremented in 1 Hz intervals. The peak one-third octave band sound pressure levels of the wind turbine sounds, relative to "corrected" ambient one-third octave band levels, are given in Table IV. These results are clearly very similar to those presented in Table III for non-standard center frequencies. This result is expected since, for the wind turbine sounds used in this experiment, the dominant frequency components generally coincide with standard one-third octave band center frequencies.

GENERALIZED METHOD FOR PREDICTION OF DETECTION OF WIND TURBINE NOISE

The above results enable the detection of wind turbine noise to be predicted. Following is a step-by-step procedure which may be applied to any large wind turbine producing low frequency impulsive noise. In essence the procedure consists of a comparison of the wind turbine noise and the ambient noise, both of which are frequency weighted and summed within critical bands.

Calculation of Corrected Ambient Spectrum

Step 1. - Compute a narrow band spectrum of the ambient noise. The upper frequency should be determined by the highest frequency wind turbine components of interest. This is typically about 100 Hz or less.

Step 2. - Weight the narrow band levels according to the I.S.O. pure tone threshold levels (ref. 8), i.e., calculate, at each frequency, the ambient noise level minus the pure tone threshold level.

Step 3. - Calculate weighted one-third octave band levels for center frequencies at 1 Hz intervals over the frequency range of interest. Bandwidth is 0.23 x center frequency of band.

Step 4. - Add, on an energy basis, -8 dB to each of the one-third octave levels. This is the "corrected ambient" spectrum.

Calculation of Wind Turbine Noise Spectrum

Step 1. - Compute a narrow band spectrum of the wind turbine noise. Line spacing (Δf) should be narrower than the blade passage frequency of the wind turbine.

Step 2. - Weight the narrow band levels according to the I.S.O. pure tone threshold.

Step 3. - Calculate weighted one-third octave band levels for center frequencies at 1 Hz intervals.

Step 4. - Adjust these calculated levels to be equivalent to a wind turbine having a 1 Hz blade passage frequency, i.e., add [10 log (period, secs.)] dB to calculated levels.

Step 5. - Compare these adjusted wind turbine levels with the "corrected ambient" spectrum. The wind turbine noise will be detectable if, at any frequency, the wind turbine noise levels are equal to or exceed the "corrected ambient" levels.

CONCLUSIONS

Thresholds of detection were determined for seven wind turbine sounds, six of which were synthesized, for three backgroud noise conditions. The main conclusions were as follows:

1. Thresholds of detection are predictable based on assumed characteristics of the auditory system.
2. For the range examined in this study the choice of critical bandwidth of the auditory system is not critical for predicting the detection of wind turbine sounds.
3. Synthesized wind turbine noise is an adequate representation of a real recording for determination of thresholds of detection.

APPENDIX

Example Calculation of Noise Floor of Auditory System.

$$10 \log N_Q = 10 \log N_A - 10 \log [10^{\Delta SPL/10} - 1]$$

Sound 3. Detection occurs in 1/3 O.B. centered at 60 Hz. Ambient noise in 1/3 O.B. centered at 60 Hz is -2.1 dB(re MAF) (= $10 \log N_1$). The change in signal level when ambient noise was added was found to be 6.4 dB (= Δ SPL). Thus, $10 \log N_Q = -7.4$ dB.

Similarly, $10 \log N_Q = -8.9$ dB for Sound 2
$= -8.0$ dB for Sound 5.

An average value of -8dB was assumed. The same calculation procedure was followed for the other critical bandwidths.

[Note: Sounds 1, 4, 6, and 7 were not used since it was not clear that detection, with and without ambient noise, occurred at the same frequency].

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Table I. - Experimental Design

Subject #	Sequence of Presentation of Sounds	Sequence of Background Noise
1	1 2 6 3 5 4 7	1 2 3
2	2 3 1 4 6 5 7	2 3 1
3	3 4 2 5 1 6 7	3 1 2
4	4 5 3 6 2 1 7	1 2 3
5	5 6 4 1 3 2 7	2 3 1
6	6 1 5 2 4 3 7	3 1 2
7	1 2 6 3 5 4 7	1 2 3
8	2 3 1 4 6 5 7	2 3 1

1 = None
2 = 35 dB (A)
3 = 45 dB (A)

Table II. - MEAN & STANDARD DEVIATION (in parentheses) OF PEAK WIND TURBINE SOUND PRESSURE LEVELS AT THRESHOLD (re. CORRECTED AMBIENT)

(Levels weighted prior to summation in critical bands)

Ambient Noise Condition	CRITICAL BAND LEVEL, dB			
	1/3 O.B.	FIDELL	PATTERSON	roex (p,r)
QUIET	0.24	-0.64	0.33	0.86
	(1.71)	(1.79)	(1.74)	(1.66)
35 dB(A)	-1.09	-1.60	-1.16	-1.02
	(1.46)	(1.29)	(1.38)	(1.78)
45 dB(A)	-0.44	-0.93	-0.60	-0.42
	(1.21)	(1.13)	(1.14)	(1.39)
MEAN	-0.43	-1.06	-0.60	-0.19
	(1.50)	(1.42)	(1.14)	(1.73)

Table III. - MEAN & STANDARD DEVIATION (in parentheses) OF PEAK WIND TURBINE SOUND PRESSURE LEVELS AT THRESHOLD (re. CORRECTED AMBIENT)

(Levels summed in critical bands prior to weighting)

Ambient Noise Condition	CRITICAL BAND LEVEL, dB			
	1/3 O.B.	FIDELL	PATTERSON	roex(p,r)
QUIET	0.60 (2.20)	0.58 (4.09)	0.81 (2.10)	0.39 (1.73)
35 dB(A)	-1.08 (1.61)	-1.43 (1.54)	-0.98 (1.67)	-0.85 (1.95)
45 dB(A)	-0.37 (1.31)	-1.25 (1.49)	-0.40 (1.32)	-1.11 (1.57)
MEAN	-0.29 (1.80)	-1.00 (1.70)	-0.19 (1.81)	-0.53 (1.80)

Table IV. - MEAN AND STANDARD DEVIATION (in parentheses) OF PEAK ONE-THIRD OCTAVE BAND LEVELS OF WIND TURBINE SOUNDS RELATIVE TO "CORRECTED AMBIENT"

(Standard one-third octave center frequecies)

Ambient Noise Condition	One-Third Octave Band Level
Quiet	1.06 (2.02)
35 dB(A)	-1.20 (1.58)
45 dB(A)	-0.47 (1.21)
Mean	-0.20 (1.83)

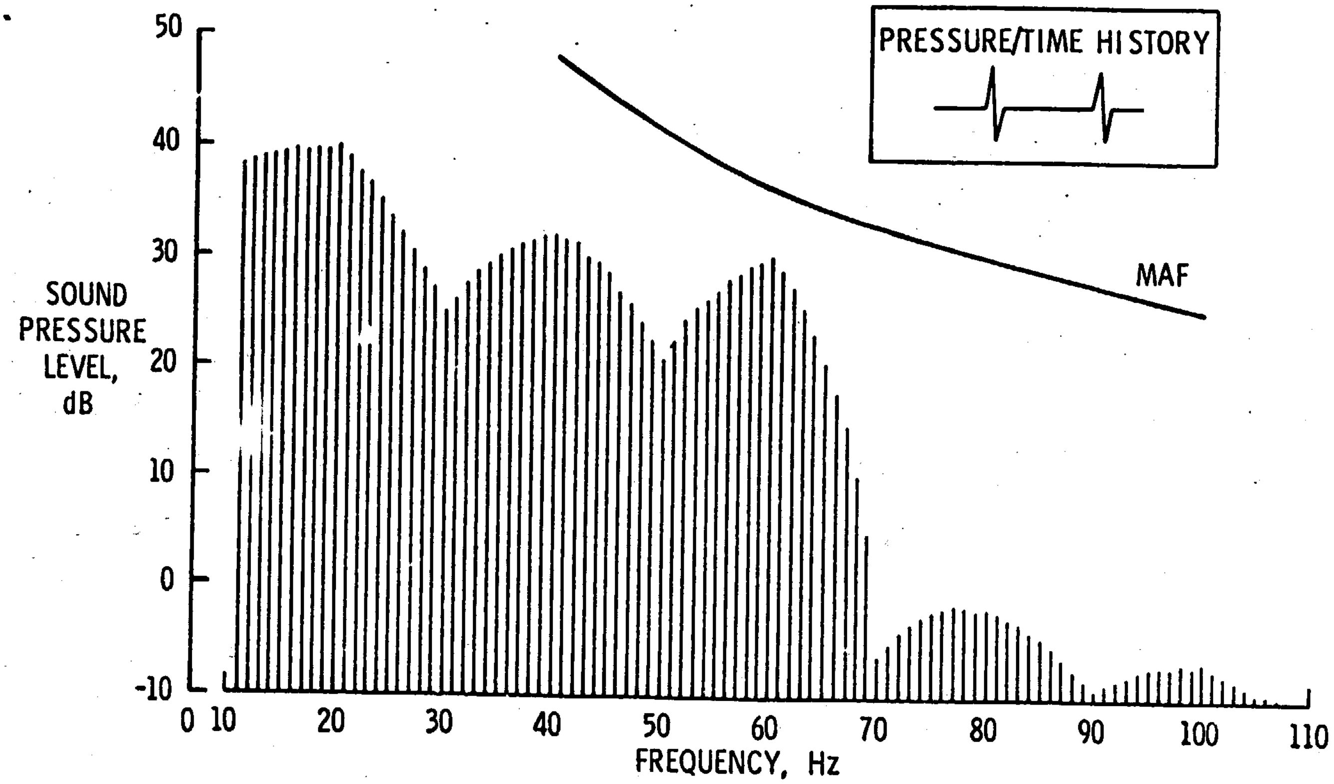
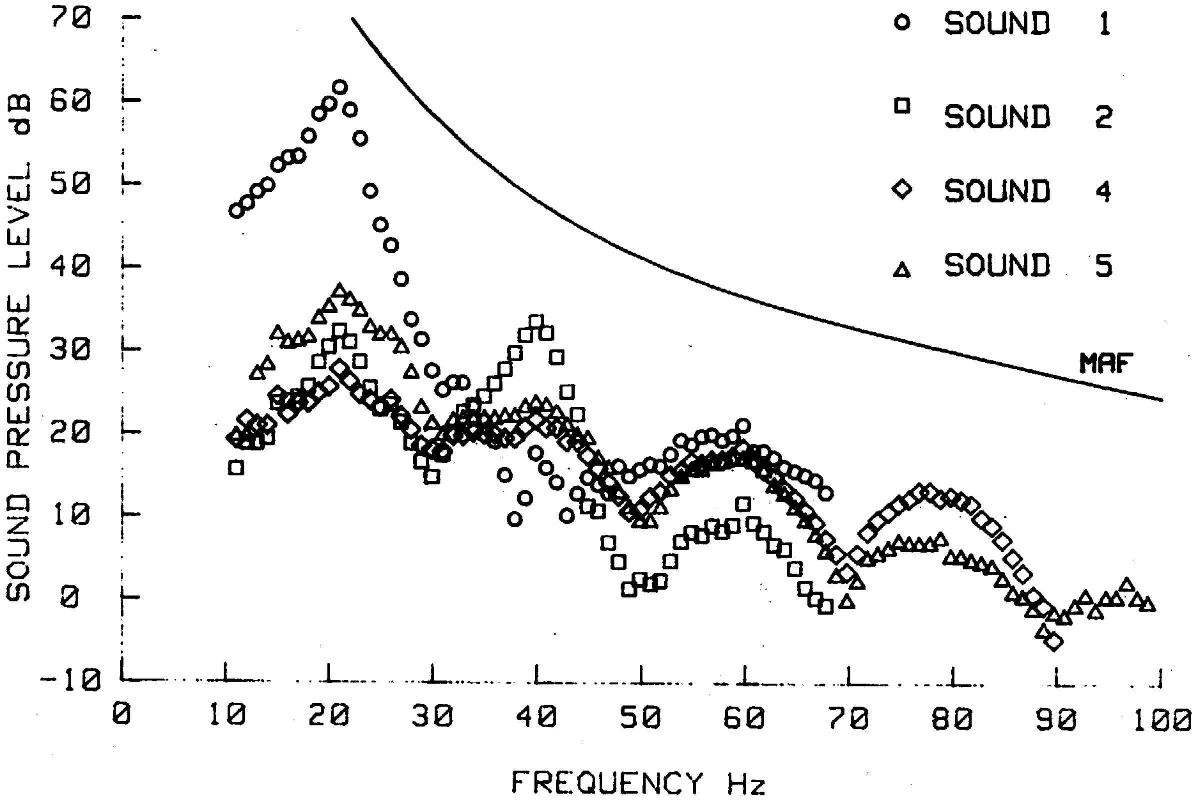


Figure 1. - Schematic Wind Turbine Noise Spectrum.



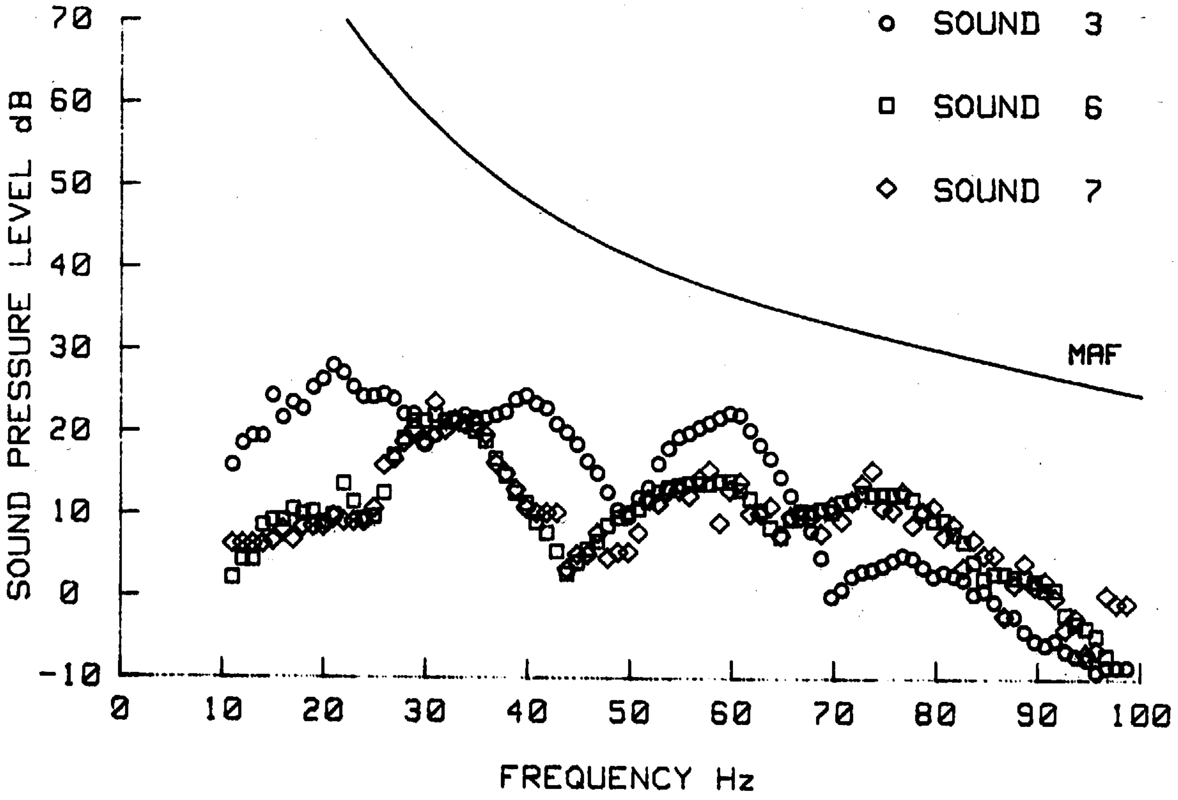


Figure 2. - Narrow band ($\Delta f = 1$ Hz) Spectra of Wind Turbine Sounds.

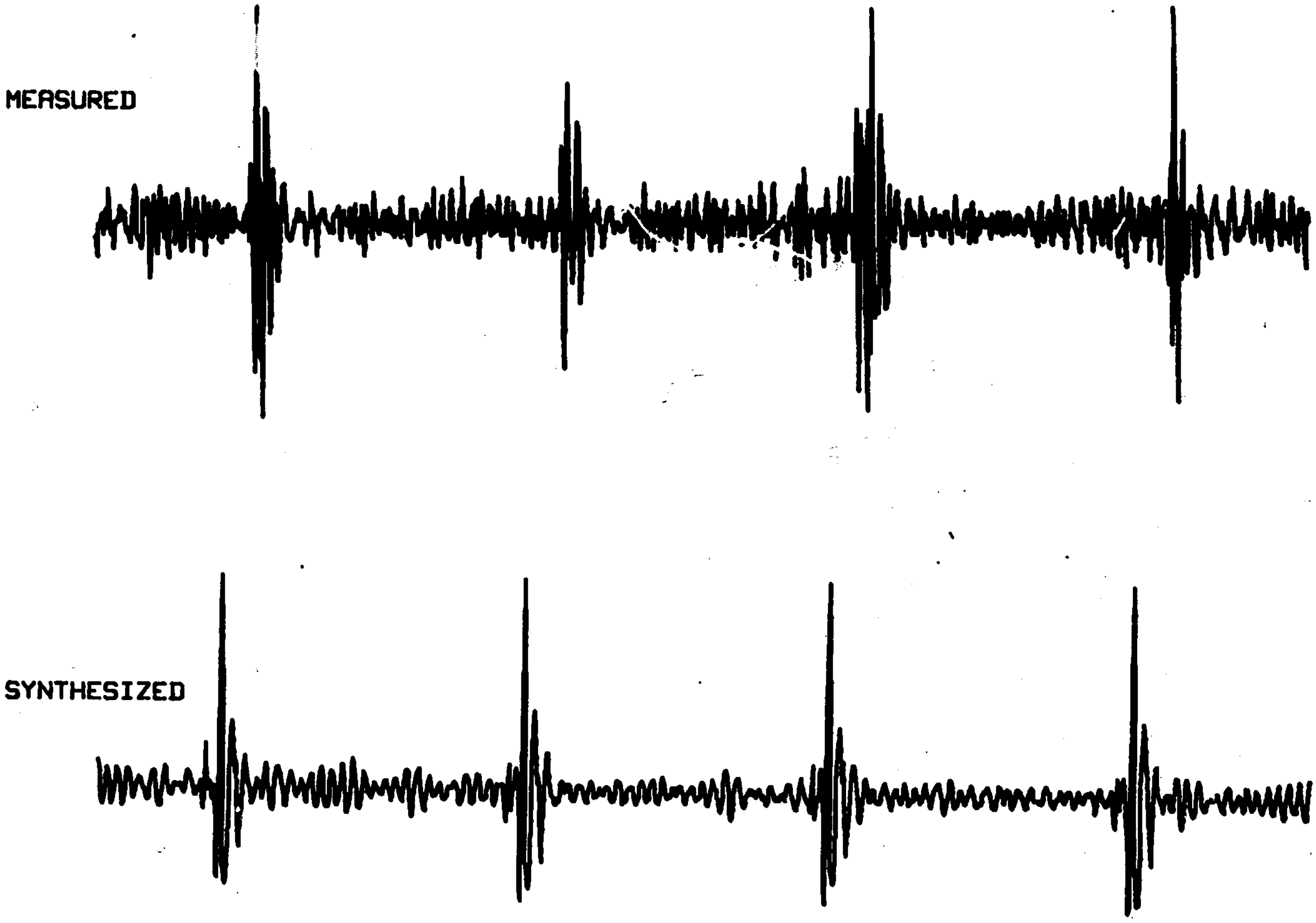


Figure 3. - Typical Wind Turbine Noise Pressure - Time Histories.

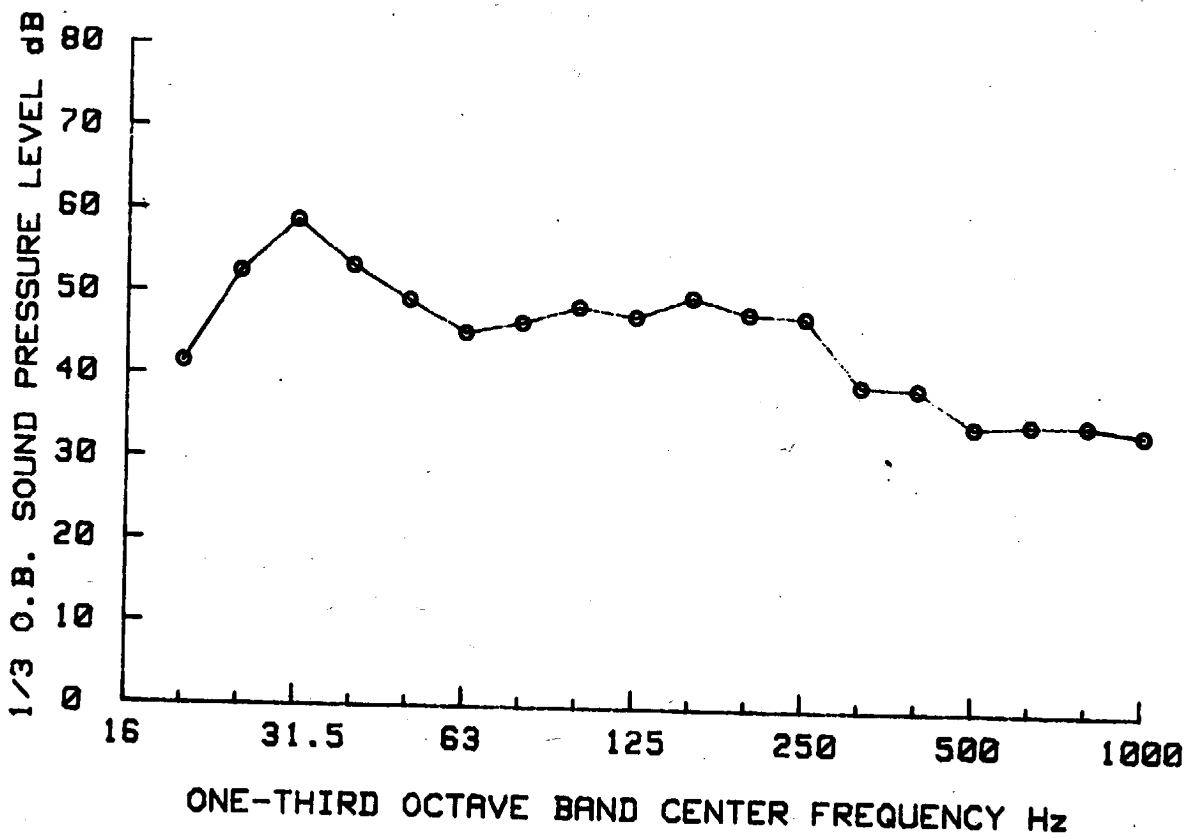


Figure 4. - One-third Octave band spectrum of Artificial Ambient Noise at 45 dB(A).

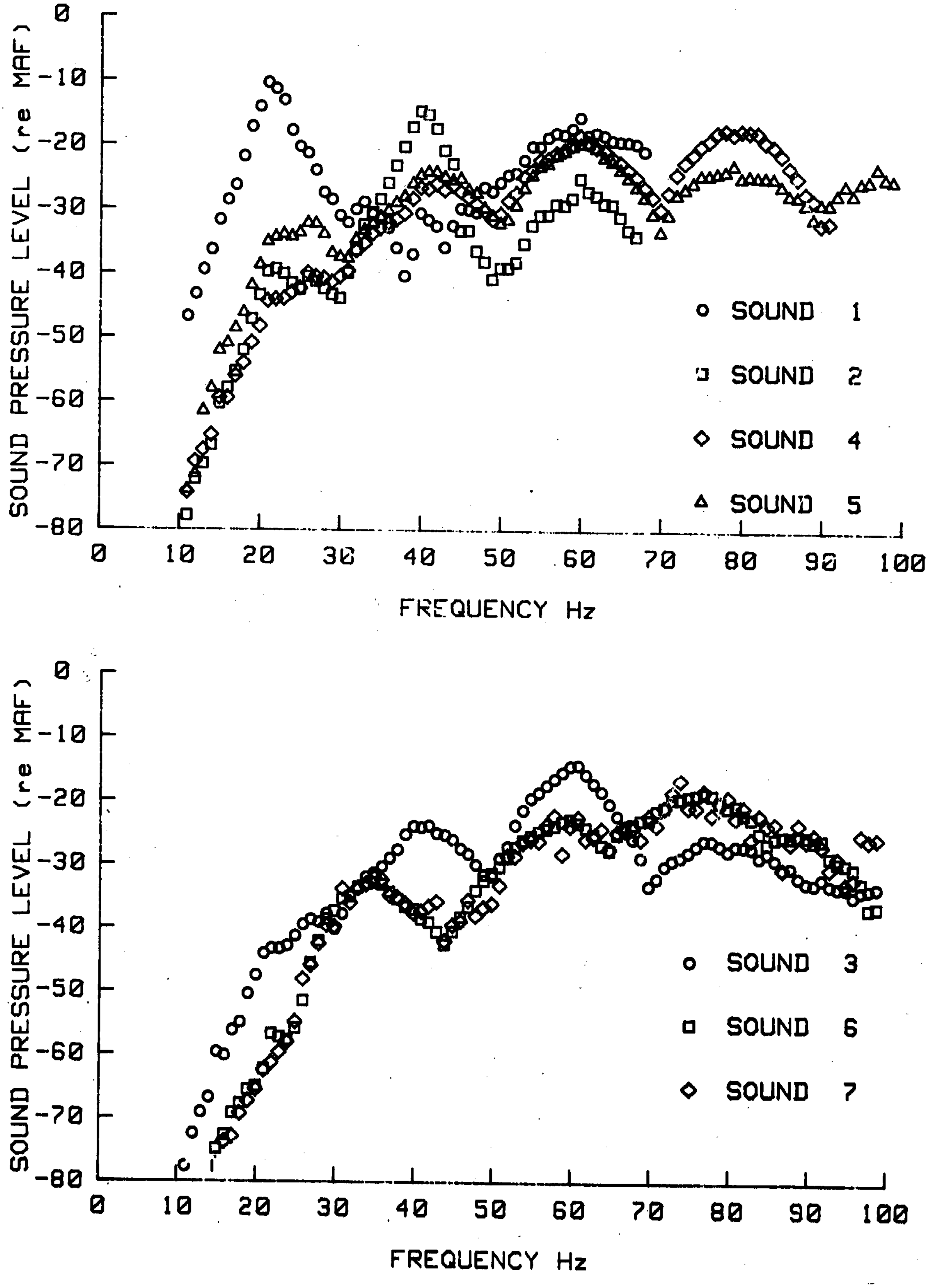


Figure 5. - Spectra ($\Delta f = 1$ Hz) of Wind Turbine Sounds at Mean Threshold with no ambient noise.

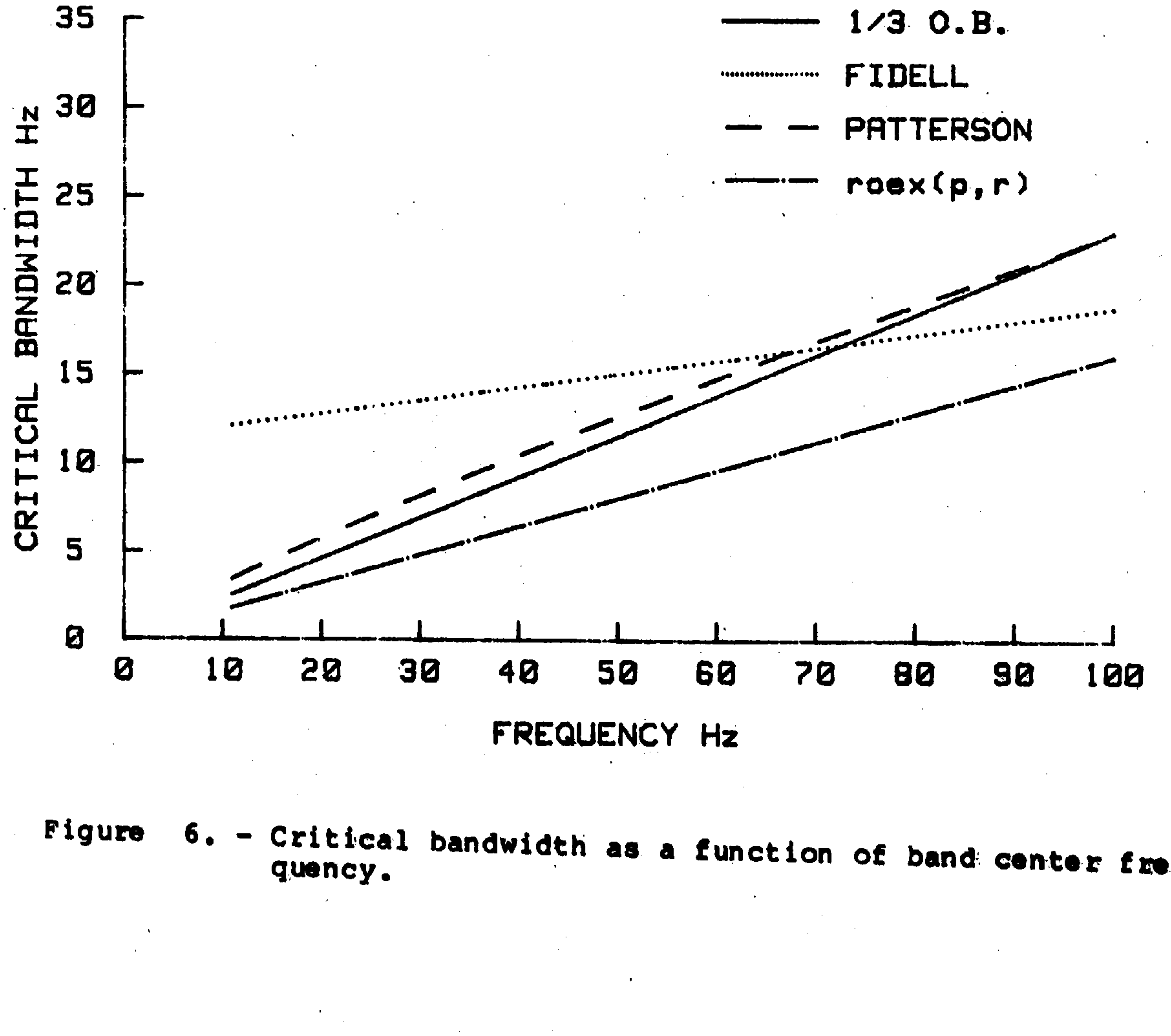


Figure 6. - Critical bandwidth as a function of band center frequency.

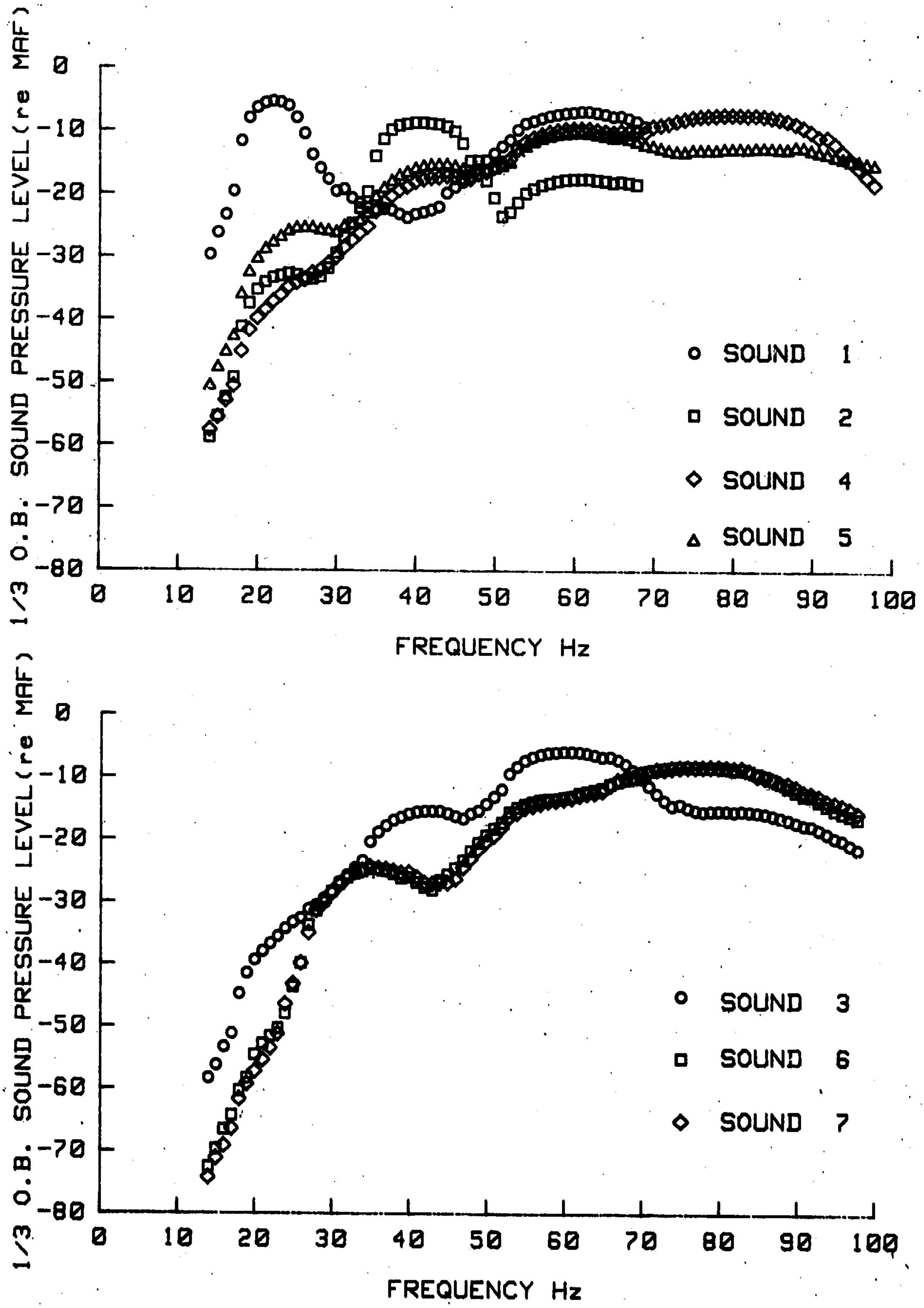


Figure 7. - One-third octave critical band spectra of Wind Turbine Sounds at threshold with no ambient noise.

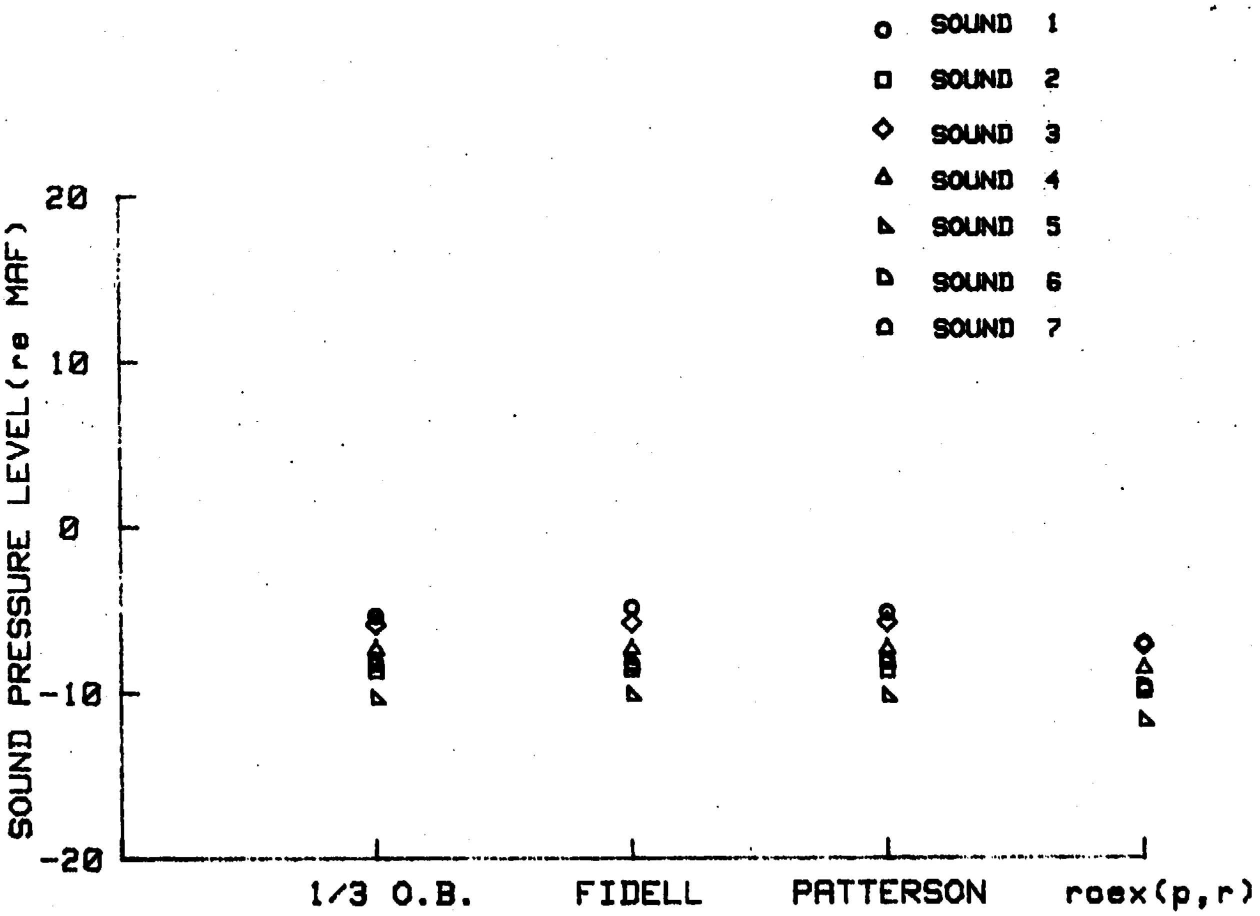


Figure 8. - Peak sound pressure levels of sounds at threshold for each critical bandwidth with no ambient noise.

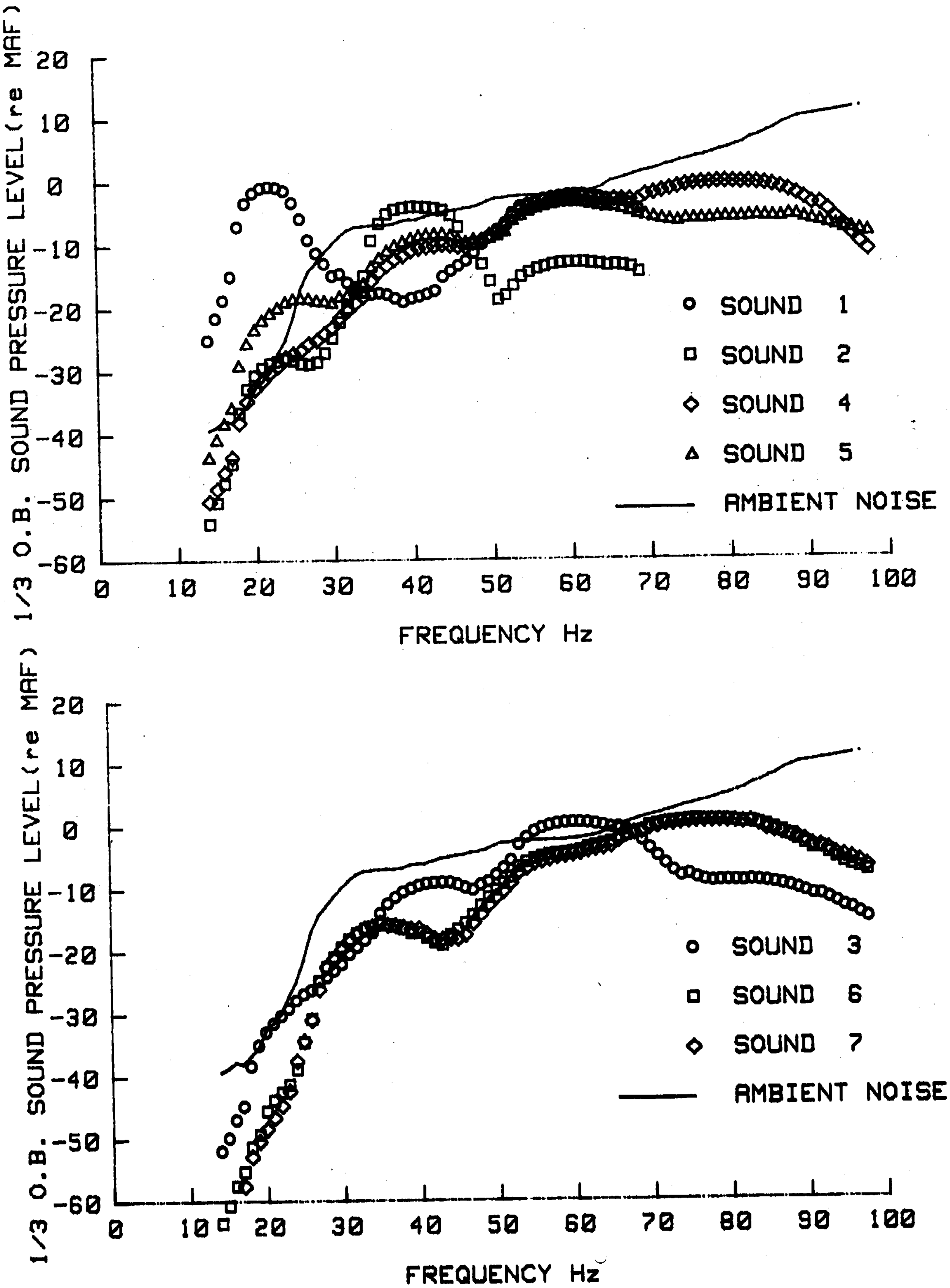


Figure 9. - One-third octave critical band spectra of ambient noise (35 dB (A)) and wind turbine sounds at threshold in presence of 35 dB(A) ambient noise.

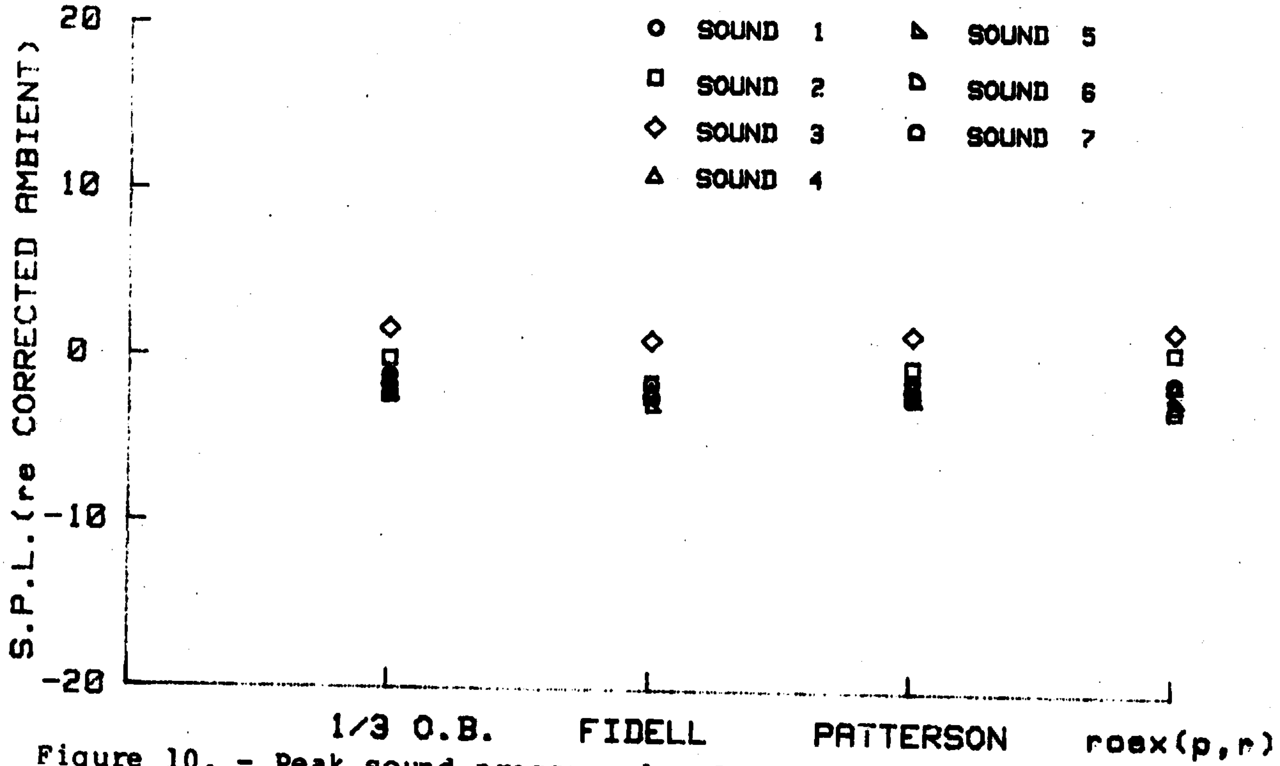


Figure 10. - Peak sound pressure levels (re. corrected ambient) of sounds at threshold in presence of 35 dB(A) ambient noise.

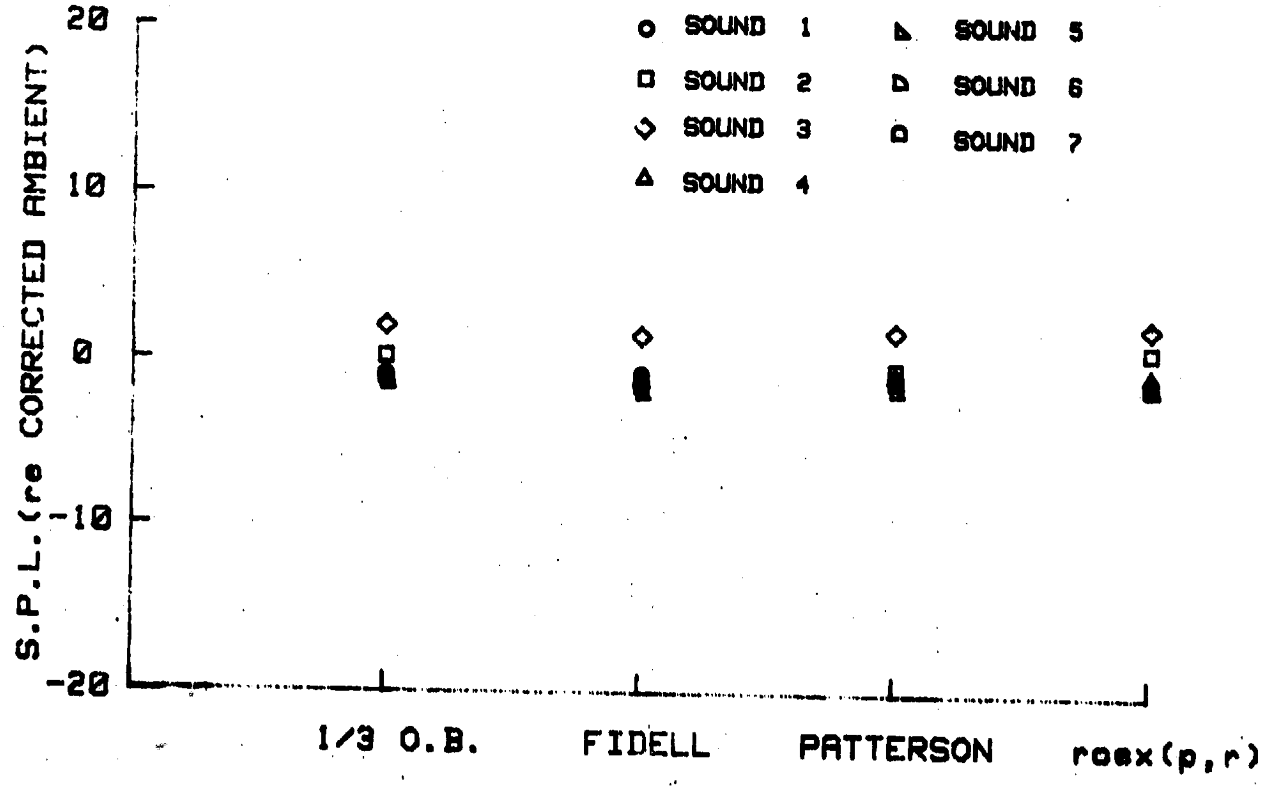


Figure 11. - Peak sound pressure levels (re. corrected ambient) of sounds at threshold in presence of 45 dB(A) ambient noise.