GE MOD-1 NOISE STUDY

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ABSTRACT

Noise studies of the MOD-1 Wind Turbine Generator are summarized, and a simple mathematical model is presented which is adequate to correlate the sound levels found near the machine.

A simple acoustic measure is suggested for use in evaluating far field sound levels. Use of this measure as input to a currently available sound complaint prediction program is discussed.

Results of a recent statistical survey relative to the far field variation of this acoustic measure because of atmospheric effects are described.

INTRODUCTION

For more than a year, the General Electric Company has been actively studying the problem of adverse community reaction to the noise of the MOD-1 Wind Turbine Generator at Boone, North Carolina. Sound measurements were made near the machine itself and at some of the residential locations from which complaints originated.

Early data were confusing from the standpoint of variability - especially in the far field. Much of this variability was recognized to be due to atmospherical focusing of the sound waves because of wind and temperature gradients, etc. However, the noise also varied widely with different modes of wind turbine operation, and an early need was felt for a simple mathematical model which could be employed to correlate the data.

The question of selecting a suitable simple acoustic measure with which to correlate complaints was also of concern. Wind turbine noise is characteristically different from that of any other machine. All of the noise of interest is confined to low frequencies. In fact, the highest peaks in a noise spectrum are typically below 10 Hz; and during the early stages, the problem was often considered to be purely infrasonic in nature. Because of the frequency range involved, commonly used acoustic measures such as dB(A), and perceived noise level (PNL), were recognized to be inapplicable. The general statistical variation of sound propagation through the atmosphere was also recognized as important.

A SIMPLE MATHEMATICAL MODEL

Dimensional Arguments

Wind turbine noise appears to be largely due to blades cutting the turbulent wakes introduced by the tower structure. This should produce a dipole source of noise. Morse and Ingard (ref. 1) have shown that for such sound sources the acoustic power can be approximately expressed in the form

$$W_A = K_1 f_x^2 f_o^2 \qquad (1)$$

where f_x represents the strength of the dipole and f_o is the acoustic frequency. (The quantity, K_1, contains other dimensional parameters to be taken as constant for these considerations.)

Now f_x must be the fluctuating force induced on the blade and can be roughly approximated by one-half the difference between the force acting on the blades outside the wake, and the force acting within the wake. Aerodynamic reasoning of this nature leads to the expression

$$f_x = K_2 \, cD \, v_t v_w \qquad (2)$$

where c is blade chord (75% span), D is blade diameter, v_t is tip speed, and v_w is wind velocity. (Again K_2 contains other dimensional parameters which are neglected for simplicity.)

Also

$$f_o \sim \frac{v_t}{D} \qquad (3)$$

for a given order of blade harmonic, and substitution of (2) and (3) into (1) yields

$$W_A = K_3 c^2 v_t^4 v_w^2 \qquad (4)$$

applicable to each harmonic and hence to the total rotational noise.

Hence, the square of the on-axis sound pressure at a given distance, R, may be expressed as

$$p^2 = Kc^2 v_t^4 v_w^2 R^{-2} \qquad (5)$$

Principles of Scaling

Note that (5) is consistent with the generally accepted concept of scaling as applied to similar fans, etc. - under the assumption of constant tip Mach number, or constant v_t. Thus, if we have two machines of similar design, we may write

$$\begin{aligned} p_1^2 &= K c_1^2 v_{t_1}^4 v_w^2 R_1^{-2} \\ p_2^2 &= K c_2^2 v_{t_2}^4 v_w^2 R_2^{-2} \end{aligned} \qquad (6)$$

and assuming

$$v_{t_2} = v_{t_1} \qquad (7)$$

and geometrical scaling - with a ratio s - so that

$$c_2 = s.c_1 \ ; \ R_2 = s.R_1 \qquad (8)$$

we find

$$p_2^2 = p_1^2 \qquad (9)$$

For example, if the second machine has twice the diameter and twice the blade chord of the first machine (and is rotating at half the rpm to preserve tip Mach number), one would expect to find the same overall sound pressure if measured at the same distance in terms of blade diameters. The spectral components would all be shifted downwards in frequency by a factor of 2, however, in accordance with (3).

A Generalized Curve

For a given machine, it should be possible to correlate on-axis sound pressure spectra obtained under different conditions of operation in a manner similar to that which has been employed for fan noise (ref. 2, 3). Thus, the sound spectral density may be considered as

$$s(f) = \frac{p^2(f)}{\Delta f} \qquad (10)$$

and this quantity may be determined experimentally as a function of frequency. It then follows that

$$p^2 = \int s(f)df = Kc^2 v_t^4 v_w^2 R^{-2} \qquad (11)$$

from (3). Since

$$v_t \sim N.D \qquad (12)$$

where N = RPM, (11) may also be expressed as

$$p^2 = \int s(f)df = Kc^2 N^4 D^4 v_w^2 R^{-2} \qquad (13)$$

Now, we may introduce a nondimensional variable, X, a form of Strouhal number, defined by

$$X = \frac{f}{N} \qquad (14)$$

and it may be shown that (13) can be put into the form:

$$\int \left(\frac{R^2 s(f)}{c^2 N^3 D^4 v_w^2} \right) dX = K \qquad (15)$$

This yields a normalization concept which may be employed to correlate wind turbine sound data. Such a procedure may be carried out in decibel notation.

Assuming sound levels are measured in one-third octave bands, they may be converted to sound spectrum levels (generally analogous to s(f) above) by subtracting 10 log (Δf) from each band level. Here Δf represents the effective bandwidth of the individual one-third octave bands. Then, the spectrum levels are normalized by subtracting the quantity

$$\begin{aligned} &20 \log_{10}(c) + 30 \log_{10}(N) + 40 \log_{10}(D) \\ &+ 20 \log_{10}(v_w) - 20 \log_{10}(R) \end{aligned} \qquad (16)$$

from each value. Finally, plotting these normalized values vs. $\log_{10}(f/N)$ would be expected to yield some degree of data collapse. Figure 1 shows an average regression line fit of this nature to a large group of different MOD-1 sound spectra (ref. 4). (In this calculation, conventional dimensions of inches, rpm, feet, mph, and feet were employed for c, N, D, v_w and R respectively, as consistency of units was not of concern.) The standard deviation of this data fit was about 1.6 dB, and it was possible to reduce this value to about 1.5 dB by including regression against parameters of secondary effect - such as pitch angle and load.

Actually, in the data analysis described above the sound levels were not measured on the wind turbine axis, but rather at a wide variety of angles and corrected to on-axis by means of the approximate directivity pattern shown in Figure 2 and based on previously published information (refs. 5-7). Figure 2 also agrees in general with recent calculations using the NASA LeRC Wind Turbine Sound Prediction Code.

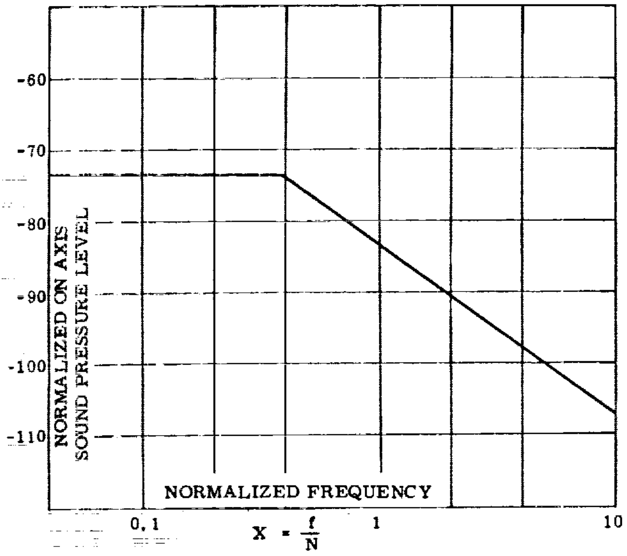

Figure 1: Generalized Wind Turbine Noise Curve

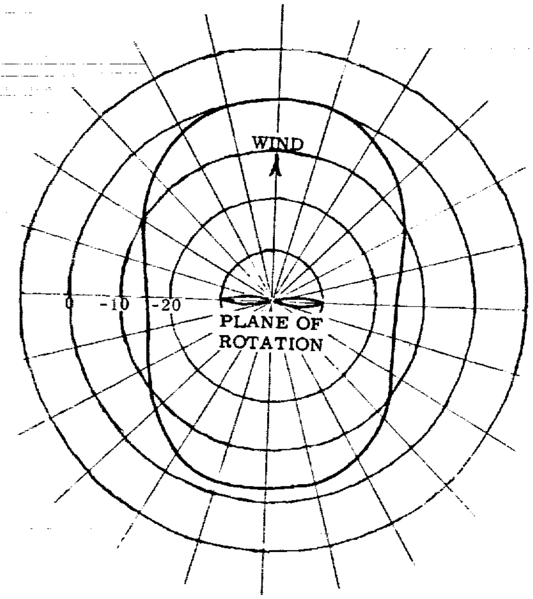

Figure 2: Estimated Directivity Index Pattern of Wind Turbine Noise

It should be noted that the plot of Figure 1 cannot be expected to apply to all possible wind turbine designs. However, it should apply to similar designs - where all dimensions are varied by the same factor and tip Mach number held to reasonable limits. Inherently, direct application of Figure 1 also assumes similarity in tower design, in minimum clearances between blades and tower, and downwind machine operation with but two blades. It is believed, however, that changing such basic design parameters would not invalidate the general concept, but rather simply result in a generalized curve different from that of Figure 1.

The data of Figure 1 included many cases of both 35 RPM operation and 23 RPM operation, both with and without a resistive load bank. The data collapse was sufficient to allow the simple curve to fit both 35 and 23 RPM sets about equally well. These tests also predicted about a 10 dB reduction in noise (except at very low frequencies) when the original 1800 RPM generator was replaced with a 1200 RPM unit. Recent tests with the new generator have confirmed this prediction.

COMMUNITY REACTION TO THE NOISE

A Suitable Noise Measure

During studies carried out about a year ago, both sound and vibration levels were examined at one of the residences about 1 kilometer from the MOD-1 site (ref. 8). Although it was found that both sound and vibration spectra did show predominant peaks at frequencies of the order of 5-10 Hz, neither were at levels sufficiently high to be considered objectionable based on current literature of this subject (refs. 9-12).

However, at somewhat higher frequencies, notably of the order of 20-70 Hz, sound levels were occasionally found which were high enough to be of more concern. In particular, it was noticed that - for 35 RPM at least - the condition often referred to as "thump" seemed to be characterized by a spectral peak in the 20-30 Hz range (ref. 8). Quantitatively, it was also noted that when thump was said to exist, the outdoor sound level in the 25 Hz one-third octave band was typically of the order of 65 dB or more.

Figure 3 shows typical wind turbine noise outside of this residence (based partially on the generalized curve concept) versus a typical ambient spectrum and an approximate threshold of audibility (refs. 11, 12). In many instances, there has been a rather narrow frequency range where the sound levels were above both the ambient levels and the threshold of audibility. Yet complaints have arisen, and general experience confirms, that some reaction to noise will usually occur if an intrusive sound is audible and appreciably above the normal ambient. (Studies relative to the actual amount of this excess above ambient were conducted at General Electric some years ago (ref. 13).)

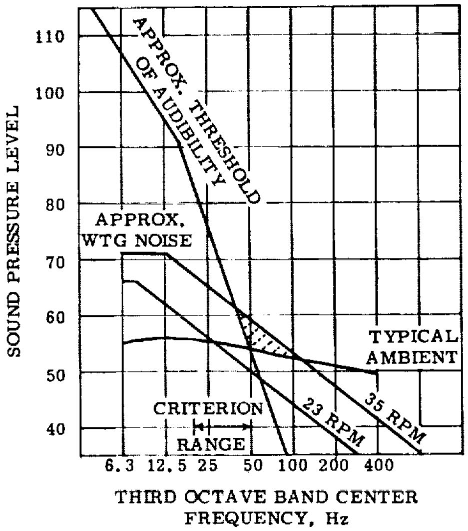

Figure 3: Wind Turbine Noise vs. Ambient and Threshold of Hearing

In Figure 3, the frequency range from 20 to 50 Hz has been labeled the "criterion range". This range was chosen for several reasons:

- It includes at least the lower frequency portion of the range where sound levels are likely to exceed both ambient and threshold levels.
- Experience shows that the presence of sound an octave or so above this range correlates well with the presence of sound in this range, though instantaneous variations may be greater at the higher frequencies.
- Levels at 60 Hz should be excluded from such a criterion because of possible electrical noise interference.
- Historically (in gas turbine noise studies, for example) the range from 20 to 40 Hz has been a "problem range", both with regard to audible sound and acoustically induced house vibration.

With regard to the latter point above, it might be added that a 31.5 Hz octave band level approaching 70 dB would usually give rise to noise complaints, while a level above 75 dB in this band almost always did.

It is well known that the human ear may be considered as analogous to a sound analyzer with an effective bandwidth which increases as frequency is reduced. In the frequency range under consideration, the typical ear has a bandwidth several octaves wide - and any spectral components below 20 Hz are not likely to be even audible. For these reasons, the character, or shape of the noise spectrum at these low frequencies cannot be critical.

Consideration of all of the above has led to the conclusion that the total sound level within the range from 20 to 50 Hz is a suitable measure of wind turbine sound for our purposes. A simplified measure, more suitable for most commercial sound measuring equipment, and yet still adequate for the purpose, is provided by the 31.5 Hz octave band level. This was recently employed in tests described later.

Noise Complaint Prediction

About ten years ago, a computer program was devised at the General Electric Company for the purpose of estimating the numerical probability of complaints due to excessive noise. As an example, this program has been widely used for gas turbine power plant installations as a means of defining the necessary acoustic treatment for exhaust stacks. With but minor modifications, the program may be extended to the wind turbine generator.

The basic input to the program is the measure of wind turbine noise just described, viz the total sound pressure level in the frequency range from 20 to 50 Hz - or alternatively, in the 31.5 Hz octave band.

In general, the computer program employs a cumulative normal distribution function as representative of expected complaints from a specific community of homes. The ordinate of the curve is percent probability of a serious complaint. The abcissa of the curve is related to the difference between noise level and normal ambient level. Different curves of the same family are used for different numbers of homes in the community, and the concept may be modified to include structures other than homes.

The time period during which operation takes place also has an effect on reaction to the noise. The computer program includes this factor by the introduction of a time period category as specified below.

Period	Category
Weekdays:	
7 a.m. - 6 p.m.	C
6 p.m. - 10 p.m.	B
10 p.m. - 7 a.m.	A
Saturdays and Sundays:	
7 a.m. - 10 p.m.	B
10 p.m. - 7 a.m.	A

One merely estimates the number of operation hours per week in each category and enters such data as A, B, C in the program. (For A and B categories, one hour is considered as the minimum time for any period of operation.) The computer program basically makes an effective correction, T, to the actual sound levels as defined below:

$$T = 10 \log_{10} \frac{1}{21} \{A + \frac{B}{10^{.25}} + \frac{C}{10^{.50}}\}$$

T is an additive quantity, in decibels, normalized to three hours per day of category A for T = 0. Other time periods are considered in similar fashion with 2.5 dB more tolerance assumed for category B, and 5 dB more for category C. These latter values are derived from many noise complaint case histories in several departments of General Electric and elsewhere.

In addition, the general class of homes, and other details of the environment affect the prediction. In essence, the computer program also makes a correction of 5 dB multiplied by the code numbers listed below:

District	Code
Very expensive homes	-1
Middle class homes	0
Low cost housing	1
Substandard housing	2
Schools and hospitals	-1
Motels, hotels, stores	1
Light and medium industry	1
Heavy industrial area	2

In summary, for each area of concern the following items must be specified:

- Wind turbine generator sound pressure levels in area by one-third octave bands from 20 Hz through 50 Hz, or alternatively in the 31.5 Hz octave band.
- Normal ambient noise (wind turbine generator not running) in above frequency range.
- Number of building units (homes) in area. For apartments or other building complexes, each individual apartment, store, etc., to be considered as a building unit.
- District code number.
- Operation hours per week by category.

Calculations were made with this program for several cases relevant to the MOD-1 operation. Twenty homes were assumed - as typical of the Boone situation, the district code number being taken as 0. For one set of computations, typical operation was assumed to be for 40 hours per week with two-thirds of this between 10 p.m. and 7 a.m., the remaining one-third being weekdays during the day; for the second set the assumed hours of operation were increased to 60 - with the same percentages relative to time period. For all cases, a typical ambient of 59 dB in the 31.5 Hz octave was assumed. Three values for wind turbine noise in this band were used: 69 dB as typical of 35 RPM operation during times "thump" was reported, 60 dB as typical of 23 RPM operation with comparable atmospheric sound propagation, and 65 dB as an intermediate value. The computed probabilities of complaint were as tabulated below:

Assumed Level in 31.5 Octave Band - Due to WTG Noise Alone (Ambient = 59 dB)	Assumed Time Category Values	
	A = 26.7 B = 0 C = 13.3	A = 40 B = 0 C = 20
69	60.1	78.9
60	4.7	11.8
65	22.6	40.9

The predicted 60.1% seems to correlate well with case histories at Boone. The 4.7% figure suggests that complaints would have been minimal if operation had been confined to 23 RPM. Of course, now that people have been sensitized to this noise, it is not unlikely that some may continue to complain for 23 RPM operation.

A Statistical Noise Study

During January 1981, a brief statistical study was carried out at the MOD-1 site. Although magnetic tape sound recordings were made, primary evaluation has been confined to acoustic levels in the 31.5 Hz octave band. For this purpose, a General Radio Model 1945 Community Noise Analyzer was employed. This instrument automatically computed exceedance levels - such as L1, L10, L50, L90 and L99 - for sound in this frequency range. (L10, for example, is defined as the sound level which was exceeded 10% of the time for the duration of a specific short test period.)

Short test periods of one-half hour duration were used, and statistical determinations were made in the near field, about 270 feet from the machine, and at selected locations near areas of complaint. For the entire study period of about two weeks' duration, the wind turbine was confined to normal on-line 23 RPM operation whenever weather permitted; and primary data analysis has been confined to periods when the wind turbine was on-line for a full thirty minute short period. Individual statistical curves were then combined (in a proper statistical fashion) in specific groups of interest.

The top curve of Figure 4 shows the result of such a procedure for fifteen cases of on-line operation with the wind predominantly from the west - blowing almost directly toward one of the residences of concern. (The microphone position was essentially upwind from the machine - this being selected due to the fact that the terrain dropped sharply downwind.) The L50 value for this curve is 71 dB; and the flatness of the curve should be noted - L10 was less than 74 dB and L90 was nearly 69 dB. The lower curve of Figure 4 is simply the lowest of several individual one-half hour determinations when the wind turbine was not operating.

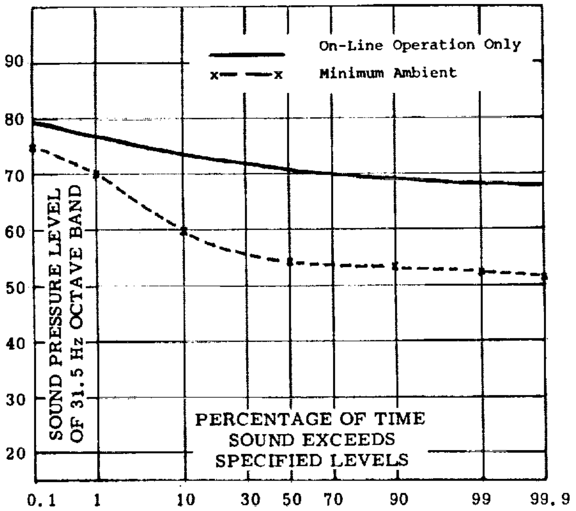

Figure 4: Sound Level Distribution at Position 1, 270 Feet from Center of Tower

During part of the time represented by the data of Figure 4, a strong noise complaint was received from the downwind residence. Excessive levels were noted there during an overall period of 2-3 hours. Three successive one-half hour statistical evaluations were obtained there during this period, and the combined evaluation is presented as the upper curve of Figure 5. Note that L50 for this curve is nearly 64 dB and L10 more than 72 dB. There is little doubt that the levels here actually exceeded the levels at 270 feet occasionally. With normal spherical divergence, one would have expected more than a 21 dB reduction in sound relative to the near field - thus bringing the expected L50 down to about 50 dB.

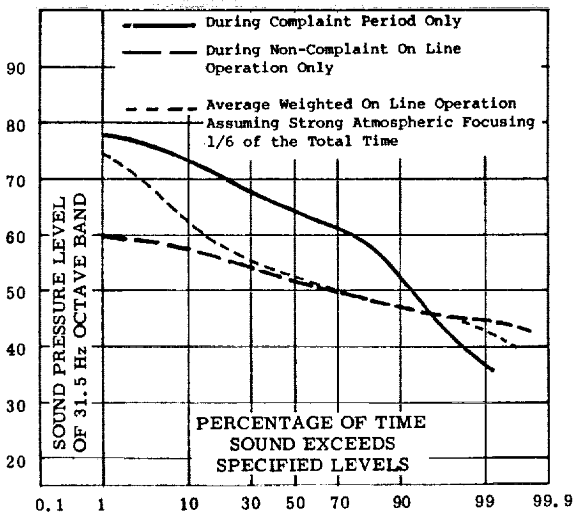

Figure 5: Sound Level Distributions at Residence of Concern

The lower curve of Figure 5 is a similar evaluation at this residence for other periods of on-line operation when complaints were not received. Note that for this curve, L50 is 51 dB - in close agreement with expectations. However, as shown by the upper curve of Figure 5, there were occasions during the complaint period when the sound levels were more than 25 dB in excess of what should have been expected on the basis of simple spherical divergence.

The middle curve of Figure 5 is a combination of the other two curves shown here made under the rough assumption that atmospheric conditions leading to such acoustic focusing might occur perhaps one-sixth of the total time. In this event, 31.5 Hz octave band levels of 65-70 dB might be expected to occur about 3-7% of the time.

It would be possible to combine a statistical level evaluation with the complaint prediction program previously discussed, but no attempt has yet been made in this direction.

CONCLUSIONS

The results of these studies indicate that for a given type of wind turbine design, the mathematical model concept presented should provide a useful tool for estimating wind turbine noise.

An acoustical measure consisting of the total sound level within the frequency range from 20 to 50 Hz seems to be suitable for correlating wind turbine noise with possible complaints. The use of the 31.5 octave band level is believed to be satisfactory as a rough approximation to this measure.

A previously developed computer program seems to provide reasonable agreement with complaints relative to MOD-1 noise, when used with the above measure as input.

The brief statistical study indicates that there are occasions when atmospherical focusing is sufficient to increase MOD-1 sound levels to more than 25 dB higher than would be expected with simple spherical divergence.

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