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The NASA-LeRC Wind Turbine Sound Prediction Code

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ABSTRACT

Since regular operation of the DOE/NASA Mod-1 wind turbine began in October 1979 about 10 nearby households have complained of noise from the machine. Development of the NASA-LeRC wind turbine sound prediction code began in May 1980 as part of an effort to understand and reduce the noise generated by Mod-1. Tone sound levels predicted with this code are in generally good agreement with measured data taken in the vicinity Mod-1 wind turbine (less than 2 rotor diameters). Comparison in the far field indicates that propagation effects due to terrain and atmospheric conditions may be amplifying the actual sound levels by about 6 db. Parametric analysis using the code has shown that the predominant contributors to Mod-1 rotor noise are (1) the velocity deficit in the wake of the support tower, (2) the high rotor speed, and (3) off-optimum operation.

INTRODUCTION

Since regular operation of the Mod-1 wind turbine began in October 1979 about ten households have complained of noise from the machine. The character of the noise is described as an audible "thump" at a repetition rate equal to the blade passing frequency. In some instances, low frequency acoustic energy has resulted in complaints of vibrations within the homes.

Since January 1980, efforts have been directed at identifying the causes of the noise and methods of reducing it. One effort has been the development of computer prediction codes and obtaining experimental data to verify these codes. The objective of this effort is to understand the noise generated by Mod-1 and to prevent it from being a problem on advanced machines. Development of a wind turbine sound prediction code began at the NASA-LeRC in May 1980. This report presents (1) measured data that characterize the noise problem at Mod-1, (2) the analytical method used in the NASA LeRC code, (3) validation of the code using experimental data from Mod-1, and (4) applications of the code to the Mod-1 situation.

SUMMARY

Measured data taken at the Mod-1 site show that the impulsive character of the noise is composed of harmonics of the blade passing frequency. While some of these harmonics exist below the audible frequency range (about 20 to 20,000 Hz), many are above the nominal audible threshold of 20 Hz.

A computer program (WTSOUND) has been developed for calculating the intensity and frequency characteristics of sounds generated by wind turbines in a non-uniform wind flow field. The results calculated with this code are generally in good agreement with Mod-1 measured sound spectra. However, propagation effects due to terrain and atmospheric conditions have complicated the amplitude correlation with Mod-1 data in the far field. These effects have been estimated by the code to cause an amplification of 6 dB or more at a home that has registered complaints.

The WTSOUND code has been used to determine the source of the noise generation from Mod-1 as well as identifying operating conditions associated with the highest noise levels. Modeling of the wind flow field characteristics shows that the predominant source of noise from Mod-1 is the wind velocity deficit in the wake of the tower. Because the rotor plane is downwind of the tower, this deficit produces changes in the aerodynamic forces on the blades resulting in sound pressure variations in the acoustic field. The level of the sound pressure variations is most strongly a function of rotor speed and wind speed. Reducing the rotor speed from 35 to 23 rpm is predicted to reduce sound levels by about 11 dB. The increase in sound levels with windspeed is expected to be about 12 dB between cutin and rated windspeeds. Variation in sound level with power is not clear-cut since high sound levels can occur during both high and low power conditions.

MOD-1 MEASURED DATA

In January 1980, the Solar Energy Research Institute (SERI) and the General Electric Company under DOE funding began visiting the Mod-1 site to investigate the noise problem. During those visits, tape recordings of the sound pressures were made both near the Mod-1 and at residences that had complained of noise.

A good example of the recorded time history of the pressure variation near the Mod-1 recorded by SERI is shown in Figure 1. The impulsive nature is clearly apparent as each blade passes behind the tower structure. The passage of the blade through the wake of each leg of the tower is seen as the two upper peaks approximately 0.075 seconds apart.

To better understand the character of the pressure impulse, spectrum analyses were performed on the measured data. One sample spectrum of the sound near the Mod-1 is shown in Figure 2. This was recorded when the machine was generating a heavy "thumping" sound at a residence. From this analysis, it is obvious that the impulsive character is composed of harmonics of the blade passage frequency (1.16 Hz). While the highest amplitude harmonics

are in the sub-audible frequency range (less than about 20 Hz), tones are apparent in the audible frequency range above 20 Hz.

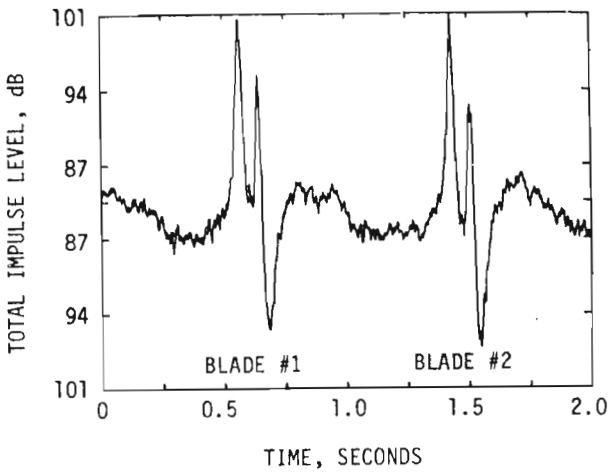

Figure 1 - Time history of the sound pressure variation near the Mod-1

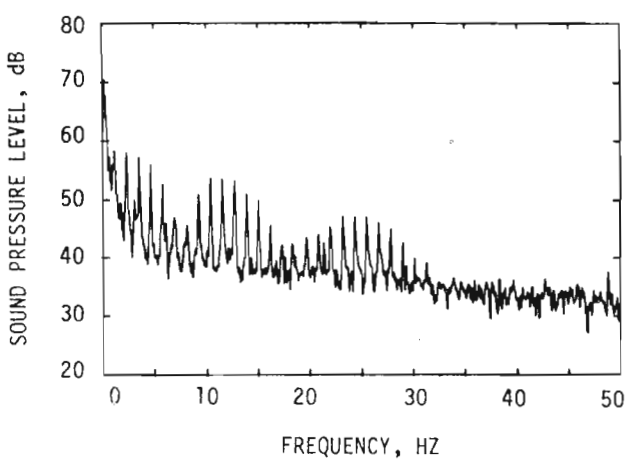

Figure 2 - Spectrum Analysis of sound variation near the Mod-1

ANALYTICAL METHOD OF THE WTSOUND CODE

The approach used in developing the wind turbine sound prediction code, WTSOUND, was to apply an available theory used for calculating noise from conventional aircraft propellers. The development of such theories goes back to 1937, when Gutin first successfully calculated the noise from a propeller in a uniform flow field (ref. 1). Since then, Gutin's theory has been extended to include the effects of non-uniform flow fields (ref. 2) and applied to helicopters and turbomachinery as well as propellers. The WTSOUND code was written using this theory to provide a means of calculating sound intensity and frequency characteristics specifically for wind turbines in non-uniform flow fields.

The predominant sound produced by a wind turbine is associated directly with the aerodynamic pressures on the blades. These pressures can be related for convenience to the thrust and torque forces on the rotor. The thrust and torque forces have components that are both steady and unsteady in time. The steady forces produce sound called rotational noise, which consists of pressure variations in the acoustic field at the blade passing frequency with harmonics of rapidly decreasing magnitude. The unsteady forces may be either periodic (i.e. tower shadow and windshear) or random (i.e. gusts). Noise due to periodic unsteady forces may be dominant over rotational noise and generated higher harmonics of amplitude comparable to that of the fundamental.

The method used to determine the sound pressure levels in the acoustic field is described by the flow chart in Figure 3. This procedure can be summarized as follows: (1) calculation of the steady aerodynamic blade forces, (2) variation in these forces due to unsteady aerodynamics, (3) Fourier analysis of the force variation, and (4) calculation of sound pressure levels in the acoustic field. These steps are explained in more detail in the following sections.

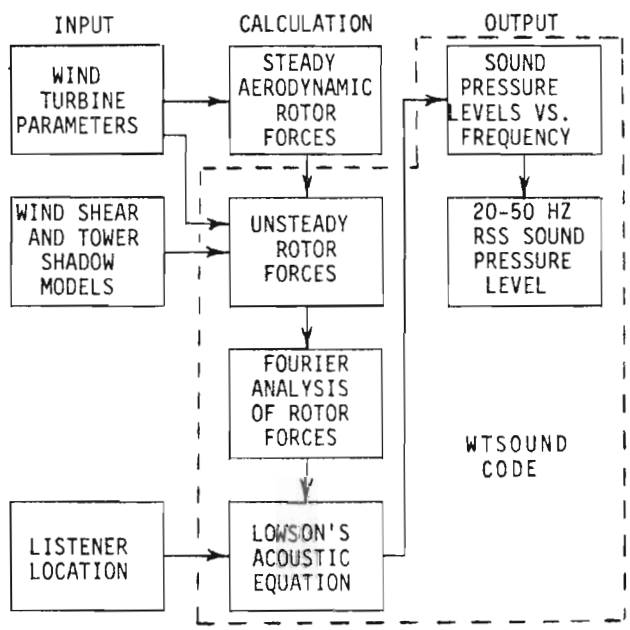

Figure 3 - Flow chart of sound pressure level calculation

Steady Aerodynamic Blade Forces

The total thrust force and torque on a rotor in uniform flow is determined from blade element-momentum theory. The reader is referred to reference 3 for development of this theory. There are several computer programs available that use blade element-momentum theory,

including the PROP code (ref. 3). The PROP code requires modeling of the wind turbine characteristics and operating conditions (i.e. planform, twist, rpm, windspeed, etc) to calculate the steady torque and thrust force on the rotor. The total torque and thrust on the rotor can then be resolved into equivalent forces acting on each blade at a single point. The point used in this analysis is the 75 percent radius of the blade. That radial location is also used when modeling the unsteady aerodynamic variation.

Unsteady Aerodynamic Blade Forces

Once the steady forces have been determined, the unsteady forces are obtained through perturbation with non-dimensional force coefficients. Figure 4 shows the the wind velocity and force vector diagram of an airfoil element of chord length c. This airfoil is operating at a pitch angle θ with respect to the plane of rotation. The velocity of the wind at the rotor plane, V_W, combines with the velocity due to rotation, V_Ω, to give the relative velocity vector, V_R. The relative velocity vector acts at an angle of attack α with respect to the airfoil chord line. The relative velocity and angle of attack are given by

$$V_R = \left(V_w^2 + V_\Omega^2\right)^{1/2} \tag{1}$$

and

$$\alpha = \tan^{-1}\left(\frac{V_w}{V_\Omega}\right) - \theta \tag{2}$$

The airfoil lift and drag coefficients are shown as the heavy line vectors in Figure 4.

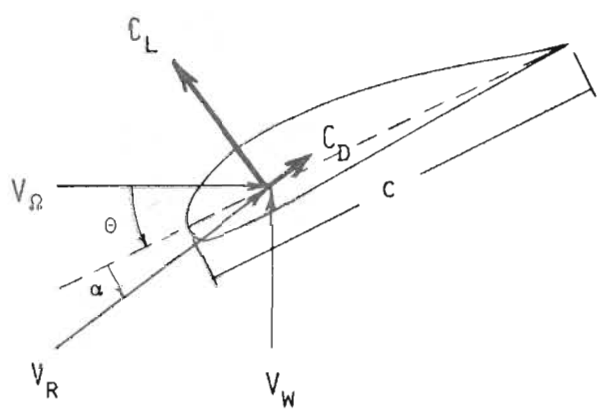

Figure 4 - Wind velocity and force vector diagram

These coefficients can be transformed into a thrust force coefficient, C_T, acting perpendicular to the rotor plane and a torque force coefficient, C_Q, acting parallel to the rotor plane where

$$C_T = C_L \cos(\alpha + \theta) + C_D \sin(\alpha + \theta) \tag{3a}$$

and

$$C_Q = C_L \sin(\alpha + \theta) - C_D \cos(\alpha + \theta) \tag{3b}$$

The thrust and torque coefficients can now be used to determine the unsteady forces associated with periodic variations in the wind velocity, V_W. Such a periodic variation will occur as the blade rotates through wind shear or behind the wind turbine support tower. The quasi-steady state values of blade thrust force, T^ψ, and torque force, Q^ψ, at any rotor azimuth position, ψ, are given by

$$T^\psi = \frac{C_T^\psi}{C_T^s} T^s \tag{4a}$$

and

$$Q^\psi = \frac{C_Q^\psi}{C_Q^s} Q^s \tag{4b}$$

in which the superscript s denotes the steady forces and coefficients respectively.

Fourier Analysis of the Force Variation

The next step is to a perform a Fourier analysis of the blade force variation. The complex Fourier coefficients for the thrust and torque forces respectively are given by

$$a_p^T = \frac{\Omega}{2\pi} \int_0^{2\pi/\Omega} e^{ip\Omega\tau} T^\psi(\tau)\,d\tau \tag{5a}$$

and

$$a_p^Q = \frac{\Omega}{2\pi} \int_0^{2\pi/\Omega} e^{ip\Omega\tau} Q^\psi(\tau)\,d\tau \tag{5b}$$

in which Ω is the rotor speed.

These coefficients are determined in the program using the IBM subroutine FORIT. FORIT gives real Fourier coefficients A_p and B_p for the cosine and sine terms respectively. The transformation to complex coefficients is

$$a_p = A_p + iB_p \tag{6a}$$

or

$$a_{-p} = A_p - iB_p \tag{6b}$$

for

$$p \geq 0$$

A correction to the quasi-steady state analysis can now be made by including the effects of unsteady aerodynamics. The approach used here to determine the response of the airfoil was developed by Sears (ref. 4). The correction is

given by a simple expression called a Sears function, which is used as a factor to the Fourier coefficients. The expression used to approximate the Sears function is

$$S(\sigma) \simeq \frac{\exp\left\{-i\sigma\left[1 - \frac{\pi^2}{2(1 + 2\pi\sigma)}\right]\right\}}{(1 + 2\pi\sigma)^{1/2}} \qquad (7a)$$

for $\sigma \geq 0$

where $$\sigma = \frac{p\Omega c}{2V_R} \qquad (7b)$$

The coefficients a_p and a_{-p} in Equations (6) are multiplied by the Sears factor before use in calculating sound pressure levels.

Sound Pressure Levels in the Acoustic Field

The mathematical relationship for calculating the sound pressure levels from the Fourier coefficients of the blade force variation was obtained by Lowson (ref. 5). The RMS pressure variation of the nth harmonic of the blade passage frequency is given by the following equations:

$$P_n = \frac{k_n\sqrt{2}}{4\pi s} \sum_{p=1}^{\infty}\Bigg[e^{-ip(\phi-\pi/2)} J_{nB-p}(k_n r_m \sin\gamma) \times \left(a_p^T \cos\gamma - \frac{nB-p}{k_n r_m} a_p^Q\right) + e^{ip(\phi-\pi/2)} J_{nB+p}(k_n r_m \sin\gamma) \times \left(a_{-p}^T \cos\gamma - \frac{nB+p}{k_n r_m} a_{-p}^Q\right)\Bigg] + J_{nB}(k_n r_m \sin\gamma)\left(T^s \cos\gamma - \frac{nB}{k_n r_m} Q^s\right) \qquad (8a)$$

and $$k_n = \frac{nB\Omega}{C_o} \qquad (8b)$$

in which

- B is the number of blades
- S is the distance from the rotor
- γ, ϕ are azimuth and altitude angles to the listener
- r_m is the blade radius where the thrust and torque forces are assumed to act
- J is the standard Bessel function
- Co is the speed of sound

VALIDATION OF THE WTSOUND CODE

To verify the accuracy of the WTSOUND code, measured data from the Mod-1 wind turbine were used. The data presented here were taken from General Electric Company reports (unpublished by R. J. Wells.

Correlation with the Mod-1 Measured Data

On June 10, 1980 at 12:36 a.m. sound levels were being measured with a microphone located about 240 ft from the Mod-1. The wind turbine was operating at 34.6 rpm in a 30 mph wind and generating about 750 kw into a load bank. The measured sound spectrum is shown in Figure 5 and has been designated case GE 180. These measured sound levels consist of both tones and broad-band noise. The tone levels, shown as the narrow peaks, are generated by the wind turbine. The broad-band level, shown as the flat areas of the spectrum, is composed of ambient wind noise as well as blade vortex noise.

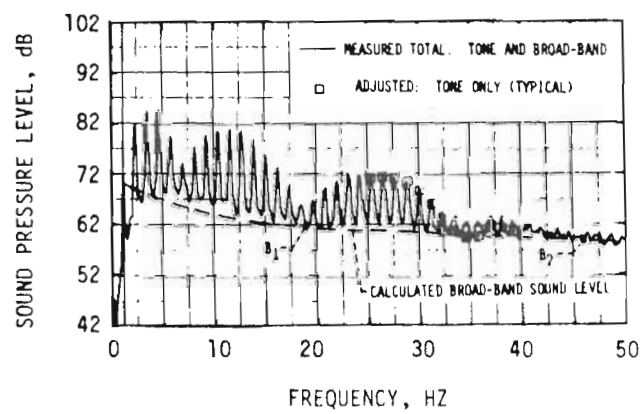

Figure 5 - Mod-1 measured sound levels for case GE 180

Since the WTSOUND code calculates tone sound pressure levels, the effect of the broad-band noise on the spectrum must be removed for comparison with the code. To do this, two points on the spectrum were chosen that were believed to be at the broad-band noise level (B_1 and B_2 in Figure 5). The broad-band levels throughout the spectrum were calculated using the following empirical model:

$$L_f^b = \left(\frac{L_2^b - L_1^b}{\log\frac{f_2}{f_1}}\right)\log\left(\frac{f}{f_2}\right) + L_2^b \qquad (9)$$

where

- L_f^b is the broadband sound level in dB at frequency f
- L_1^b, L_2^b are the broadband sound levels in dB at points B_1 and B_2
- f_1, f_2 are the frequencies corresponding to points B_1 and B_2

The tone-only levels were then determined by

$$L_f^t = 10 \log\left(10^{L_f^m/10} - 10^{L_f^b/10}\right) \qquad (10)$$

where

L_f^t is the tone sound level in dB at frequency f

L_f^m is the measured total sound level in dB at frequency f

Some typical adjusted tone-only sound pressure levels are shown as the squares in Figure 5. Note that this correction is small and can only be seen in areas where the tone and broad-band levels are comparable.

An analytical model of the Mod-1 wind turbine was developed for case GE 180. Steady thrust and torque forces, required input for the WTSOUND code, were calculated using the PROP performance code. The wind velocity deficit in the wake of the tower was approximated as an average of the velocity profiles at the 69, 75, and 81 percent blade radius. The velocity profiles were taken from scale model wind tunnel tests of the Mod-1 tower (ref. 6). Figure 6 shows the measured wake velocities as well as the analytical wake model assumed. Note that the measured and assumed profiles were taken at different distances downwind of the tower. No correction to the wake for distance appears to be required, and none was made.

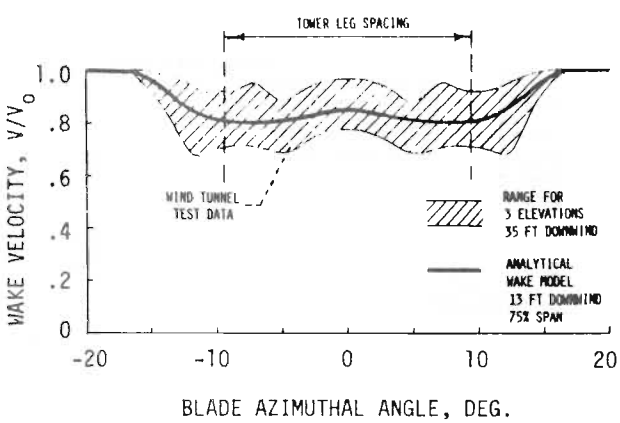

Figure 6 - Mod-1 tower shadow

Lowson's equation gives free-space sound pressures with no effect of reflection from nearby solid bodies. A 6 dB increase has been included in the WTSOUND code analysis to account for reflection when using microphones near the ground. This correction is common practice when calculating airplane propeller noise at ground level (ref. 7).

Figure 7 shows the comparison of measured and predicted sound levels. The squares are the same as those shown in Figure 5. The vertical lines are the tone levels predicted by the WTSOUND code. In general the code predicts the amplitudes of the highest harmonics very well. Also the roll-off rates (amplitude decreasing with frequency) of the harmonics compare favorably. The differences that do exist are believed to be associated with the tower shadow model mentioned earlier.

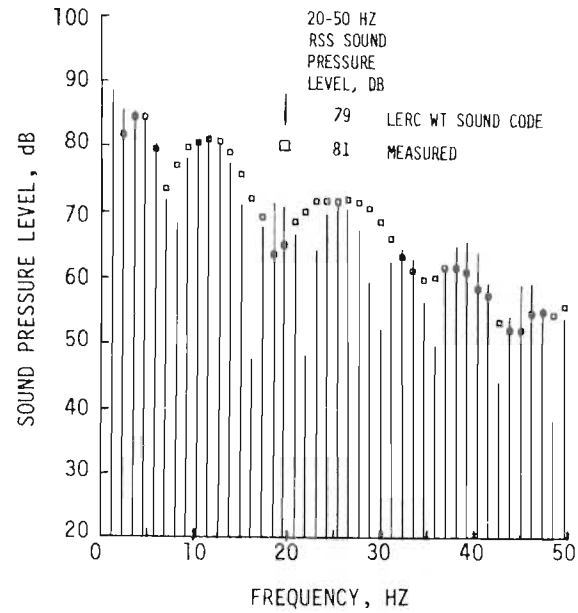

Figure 7 - Comparison of theoretical and measured sound spectra for case GE 180

To more conveniently characterize the overall sound level of this spectrum, the root sum square (RSS) of the harmonics between 20 and 50 Hz was calculated. The lower end of this range was chosen as the nominal threshold of hearing. The upper bound was chosen because the tone levels above this frequency fall below the broad-band noise. As shown in Figure 7 the 20-50 Hz RSS sound pressure level given by the WTSOUND code is 2 dB lower than the measured data. This agreement is felt to be very good.

Table 1 summarizes the results from GE 180 as well as two other examples, cases GE 140 and GE 1B. These two cases were chosen to test the ability of the code to predict changes in rotor speed and distance from the machine.

GE 140 documents the sound levels near the Mod-1 on June 9, 1980 at 9:22 p.m. The wind turbine was operating at a reduced speed of 22.7 rpm while again generating 750 kw. The wind speed of 26 mph was lower than the 30 mph wind of GE 180. The measured RSS sound level for GE 140 is 17 dB less than GE 180. Note that this reduction is exactly the same as predicted by the code.

GE 1B documents the sound levels at some distance from the Mod-1 (3100 ft. downwind) on March 31 at 12:26 pm. This location is near a residence that has complained of noise from the

machine. At this time the Mod-1 was operating at 34.7 rpm in a 30 mph wind and producing about 1850 kw into the utility grid. The measured 20-50 Hz RSS sound level is 21 dB lower than GE 180. The predicted level, however, was 27 dB lower. Thus the actual level is about 6 dB higher than predicted by normal spherical dispersion. This 6 dB increase is believed to be associated with focusing of the sound due to terrain and atmospheric conditions. Though the amount of amplification may vary, this case demonstrates the use of the code to quantify the effects on sound propagation.

Table I - Summary of Mod-1 sound data cases

NEAR FIELD (1.3 D)

CASE	RPM	WIND SPEED, MPH	20-50 HZ RMS SOUND PRESSURE LEVEL, DB		
			CODE	MEASURED	DIFFERENCE
GE 180	34.6	30	79	81	-2
GE 140	22.7	26	62	64	-2

FAR FIELD (15.5 D)

GE 1B	34.7	30	52	60	-8

APPLICATION OF THE WTSOUND CODE

After gaining confidence in the ability of WTSOUND to predict the sound characteristics of wind turbines, the code was used to investigate the Mod-1 problem. In particular, studies were made of (1) the contribution to the sound level by characteristics of the flow field, and (2) the operating conditions that affect the Mod-1 sound problem.

Effect of Flow Field Characteristics

The WTSOUND code was used to determine the relative contribution to the sound level by the characteristics of the flow through the rotor. Figure 8 shows the effect of the uniform flow, wind shear, and tower shadow. As stated earlier, the uniform flow field contribute significantly only to the fundamental blade passing frequency. Similarly, wind shear, which is essentially a 1/rev. variation, contributes only to the first few harmonics. However, with the addition of tower shadow, many harmonics are introduced that have high amplitudes up into the audible frequency range. Thus, the predominant contribution to the noise problem of Mod-1 is the wind velocity deficit in the wake of the tower.

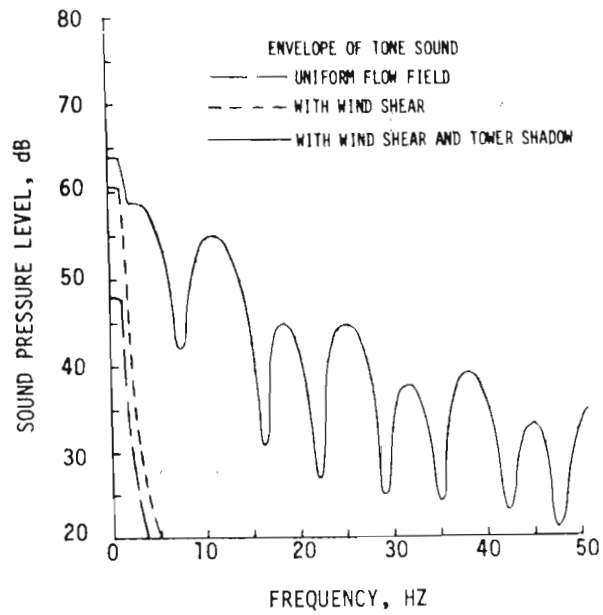

Figure 8 - Effect of wind shear and tower shadow on wind turbine sound level (Mod-1 case GE 1B)

Effect of Operating Conditions

In an effort to better understand the conditions under which the highest sound levels are produced, the WTSOUND code was used to study the effects of various operating parameters. In particular, the effects of power, rotor speed, wind speed, and direction were investigated.

Figure 9 shows the predicted sound levels versus power output for both 35 and 23 rpm operation. The solid line shows normal operation as the wind speed varies from cutin through rated to cutout wind speed (6, 15, and 20 m/sec respectively). This analysis shows about a 12 dB increase in sound level from cutin to rated wind speeds for both 35 and 23 rpm operation. This agrees reasonably well with empirical modeling of the measured data that indicates a variation of about 14 dB over those wind speeds.

During normal operation at 23 rpm, the sound levels predicted in Figure 9 are about 11 dB lower than those for 35 rpm. This also agrees well with measured data taken in June 1980. During those tests, the Mod-1 was operated at various speeds into a load bank. Analysis of these data showed a reduction of about 10 dB at a rotor speed of 23 rpm.

The shaded area in Figure 9 represents operation below the available power in the wind for wind speeds less than rated. Operation in this region is characterized as off-optimum. Under this situation the pitch of the blade is increased toward feather, to limit power below the rating of the machine. The shaded area shows that high sound levels may be produced even at low power levels. This conclusion seems to be supported by the fact that GE 180 (750 kw, 30 mph) is further from normal operation than GE 140 (750 kw, 26 mph) and is higher in sound

level than the 11 dB difference associated with rpm only.

The sound levels at off-optimum operation above rated have not been determined. Improvements in the unsteady aerodynamic force calculation in the WTSOUND code are being incorporated to analyze this area of operation.

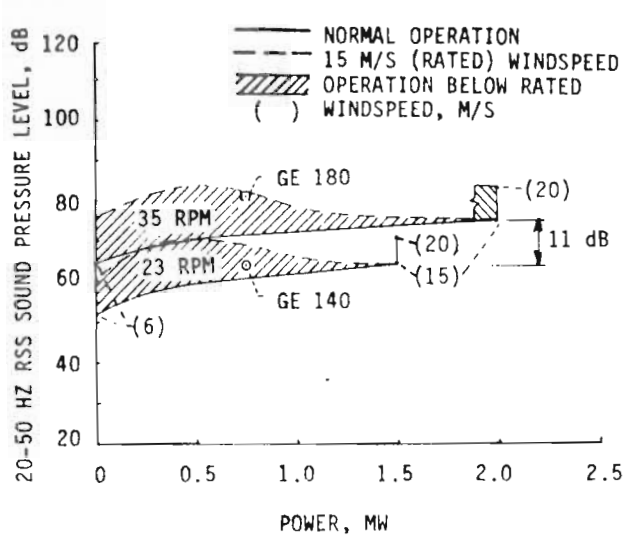

Figure 9 - Effect of power, rpm, and windspeed on Mod-1 wind turbine sound levels

The WTSOUND code can also be used to calculate the directivity pattern of the sound. Figure 10 shows the directivity pattern in a plane 1100 ft. below the Mod-1 hub height. The direction of highest sound pressure is directly downwind; however, it is nearly as high upwind. Minimum sound generation occurs in the rotor plane where levels are about 18 dB lower than downwind. This compares reasonably well with measured data in the near field showing about 15 dB variation.

CONCLUSIONS

The WTSOUND computer code shows generally good agreement with sound spectra measured in the vicinity of a wind turbine. In the far field, however, correlation of the absolute amplitude of the sound level is complicated by propagation effects. For the case in this study, terrain and meterological conditions caused an increase of about 6 dB.

Analysis using the SOUND code shows that the predominant contributor to the noise problem of Mod-1 is the wind velocity deficit in the wake of the tower. Changes in the aerodynamic forces, as the blades pass through the deficit, produce sound pressure variations in the acoustic field.

The level of the sound pressure variations are most directly affected by rotor speed and windspeed. Reducing the rotor speed from 35 to 23 rpm is predicted to reduce sound levels by about 11 dB. The increase in sound levels with windspeed is predicted to be 12 dB between cutin and rated.

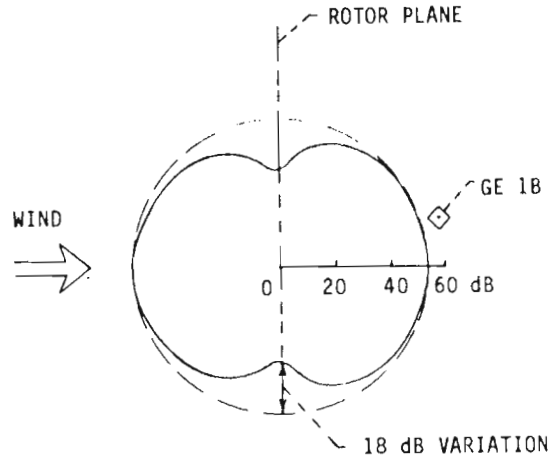

Figure 10 - Predicted sound directivity pattern in a plane 1100 ft. below the Mod-1

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16. Abstract

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