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Method for Predicting Impulsive Noise Generated by Wind-Turbine Rotors

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U.S. DEPARTMENT OF ENERGY
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INTRODUCTION

The impulsive sound produced by a wind turbine is associated 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 with 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 (e.g. tower shadow and wind shear) or random (e.g. gusts). Impulsive noise due to periodic unsteady forces may be dominant over rotational noise and generate higher harmonics of amplitude comparable to that of the fundamental.

A computer program (WTSOUND) has been developed to predict the impulsive noise generated by wind turbine rotors [1]. The analytical method used and some results are presented here. Also some experimental comparisons are given.

ANALYTICAL METHOD

The method used to determine the sound pressure levels in the acoustic field 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.

The total thrust force and torque on a rotor in uniform flow is determined from blade element-momentum theory. The development of this theory and a computer code PROP is contained in reference 2. The PROP code requires modeling of the wind turbine characteristics and operating conditions (e.g. planform, twist, rpm, wind-speed, 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 at the 75 percent blade span.

Once the steady forces have been determined, the unsteady forces are obtained through perturbation with non-dimensional force coefficients. The airfoil lift and drag coefficients are resolved into thrust force and torque force coefficients acting perpendicular and parallel to the rotor plane, respectively. The thrust and torque coefficients are then used to determine the unsteady forces associated with periodic variations in the wind velocity. Such a periodic variation will occur as the blade rotates through wind shear or near the wind turbine support tower.

Next a Fourier analysis is performed on the blade force variation. The Fourier coefficients are determined in the WTSOUND program using the IBM subroutine FORIT. Correction to the quasi-steady state analysis is made by including the effects of unsteady aerodynamics on the response of the airfoil [3]. The correction is given by a simple expression called a Sears function, which is used as a factor to the Fourier coefficients.

The sound pressure levels are calculated using a compact source noise theory with an effective radius equal to 75 percent of the blade span. The mathematical equations for calculating the sound pressure levels from the Fourier coefficients of the blade force variation are contained in reference 4. Since the acoustic equations give free-space sound pressures with no effect of reflection from nearby solid bodies, a 6 dB increase is included to account for ground reflection in accordance with standard practice.

COMPARISON WITH MEASURED SOUND LEVELS

To verify the accuracy of the WTSOUND code, measured data from the DOE/NASA Mod-1 wind turbine were used. On June 10, 1980 at 12:36 a.m. sound levels were being measured with a microphone located about 70 m from the Mod-1 wind turbine. The wind turbine was operating at 34.6 rpm in a 13 m/s wind and generating about 750 kw.

An analytical model of the Mod-1 wind turbine was developed for the above operating condition. 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 span. The velocity profiles were taken from scale model wind tunnel tests of the Mod-1 tower [5].

The squares shown in Figure 1 are measured data, 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 of the harmonics compare favorably. The small differences that do exist are believed to be associated with time varying changes in the actual wake velocity profiles. To more conveniently characterize the overall sound level of this spectrum, the level of the full octave centered at 31.5 Hz was calculated. The theoretical 31.5 Hz full octave level is 2 dB lower than measured. This agreement is felt to be very good. Measured sound levels far from the Mod-1, however, can be much higher than calculated. Simultaneous measurements of sound at 2 and 15 rotor diameters show levels in the far field about 12 dB higher than expected from spherical propagation (Figure 2). It is believed that this is the result of propagation effects due to terrain and atmospheric conditions.

EFFECT OF WIND TURBINE DESIGN PARAMETERS

The impulsive noises can be controlled by proper choice of wind turbine design parameters. The WTSOUND code was used to study the effects of tower configuration, rotor location with respect to the support tower, and operating tip speed.

Future generations of wind turbines are expected to have single tube-type towers for reduced cost compared to the truss-type tower used on the Mod-1. Furthermore, many machines may operate with the rotor upwind of the support tower to reduce the unsteady aerodynamic loading on the blades. Figure 3 shows the envelopes of the predicted harmonic sound levels for a 75 m diameter wind turbine with its rotor operating (1) downwind of a truss-type tower, (2) downwind of a tube-type tower, and (3) upwind of a tube-type tower. The wind velocity profiles near the tube towers were obtained from wind tunnel tests [6] and potential flow theory for the downwind and upwind cases, respectively. The highest 31.5 Hz octave level is from the tube-type tower with the downwind rotor (65 dB). However, much of the energy is in the subaudible frequencies and thus it may be perceived by the human ear as comparable to noise generated by the truss-type tower configuration (60 dB 31.5 Hz octave level). The tube-type tower with the upwind rotor has a substantially reduced sound level (22 dB 31.5 Hz octave level) due to the small velocity deficit in the flow near the tower.

Wind turbines are often designed for optimum performance at a given tip speed and wind speed condition. Figure 4 shows the effect of operating tip speed on the 31.5 Hz full octave level under a condition of constant wind speed for several rotor diameters. The optimum tip speed for this particular wind turbine is 120 m/s. From this analysis it is apparent that noise considerations may require that the rotor be operated at lower tip speeds than optimum to reduce annoyance. This is especially true of the smaller diameter rotors for which much of the acoustic energy is in the higher frequencies due to their higher rotational speed.

CONCLUSIONS

The impulsive noise generated by a wind turbine is the result of unsteady air loads on the rotor blades. A method has been described which can be used by the engineer to assess the sound generation of a proposed wind turbine design. Using this method the sound levels can be controlled by proper design of the wind turbine configuration and operating conditions.

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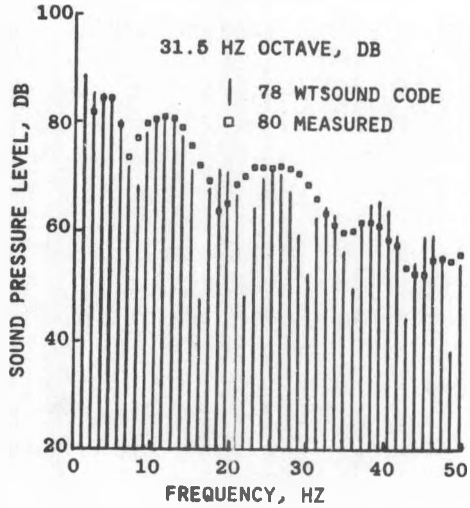

Figure 1 - Comparison of Theoretical and Measured Sound Spectra of the Mod-1 Wind Turbine.

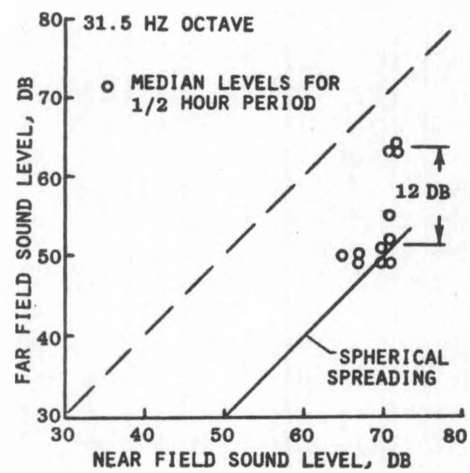

Figure 2 - Measured Propagation Effects 15 Rotor Diameters from the Mod-1.

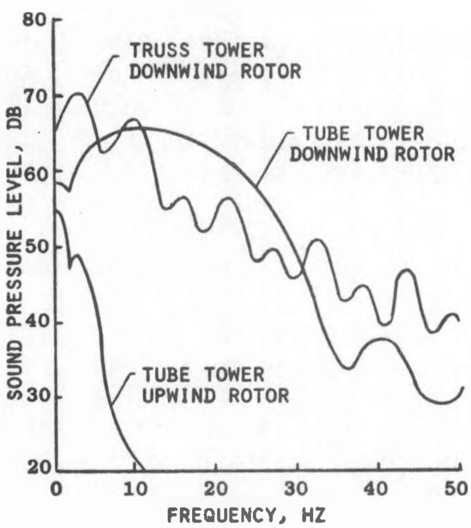

Figure 3 - Effect of Tower Configuration and Rotor Location on Sound Levels of a 75 m Diameter Wind Turbine.

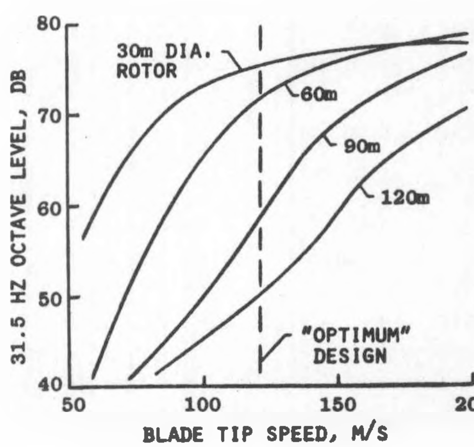

Figure 4 - Effect of Blade Tip Speed on Sound Levels for Various Rotor Diameters.