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The MOD-2 Wind Turbine:

Aeroacoustical Noise Sources, Emissions, and Potential Impact

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PREFACE

This report summarizes extensive research by the staff of the Solar Energy Research Institute into characteristics of acoustic noise emissions of the DOE/NASA MOD-2 wind turbine. The results of this study have shown that the MOD-2 noise levels are well below annoyance thresholds within residential structures a kilometer or more from the turbine rotor. It was also found that the inflow turbulent structure has a major influence on the level and characteristics of the low-frequency (2-160 Hz) range acoustic emissions which, in turn, have implications for the associated structural response of the rotor assembly. The high-frequency range (A-weighted) levels were found to vary primarily with the mean hub-height wind speed. In addition, the rotor inflow turbulence characteristics at the Goodnoe Hills Site were found to be controlled almost entirely by the diurnal variation in the vertical stability of the first 100 m of the atmospheric boundary layer.

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SUMMARY

Objective

This document summarizes the results of an extensive investigation by the Solar Energy Research Institute (SERI) into the factors relating to acoustic emissions associated with the operation of a MOD-2 wind turbine. The MOD-2 was the sixth in a series of turbine designs developed for the U.S. Department of Energy (DOE) by the Lewis Research Center of the National Aeronautics and Space Administration (NASA) as part of the Federal Wind Energy Program. The MOD-2 turbine has a rotor diameter of 91 m (300 ft) and is capable of generating 2.5 MW of electrical power at its rated wind speed of about 13 m/s (28 mph), measured at a rotor hub elevation of 61 m (200 ft). A cluster of three MOD-2 turbines installed on the Goodnoe Hills near Goldendale, Wash., was used for the experiments described in this report.

An investigation of the characteristics of the MOD-2's acoustic emissions was undertaken as a result of the experience SERI gained with its predecessor, the 2-MW MOD-1 turbine. One of the primary motivations for designing the MOD-2 turbine with its rotor upwind of the support tower was to avoid the impulsive, low-frequency noise associated with the downwind MOD-1. It was expected that placing the MOD-2 rotor upwind would largely eliminate the community annoyance problem that was characteristic of the impulsive MOD-1 emissions. It was not known, however, whether similar or perhaps greater levels of nonimpulsive, low-frequency noise that radiated from the large MOD-2 rotor as a result of inflow turbulence interactions would annoy the residents nearby. We designed our MOD-2 test program to answer these questions, including the following specific objectives:

- A general characterization of both low- (under 200 Hz) and high-frequency-range acoustic emissions
- The development of a methodology for making acoustic measurements in a windy environment
- The development of a methodology relating low-frequency acoustic emissions to the turbulent inflow structure
- The development of a methodology for predicting the interior annoyance potential of nearby residential structures from a wind turbine's low-frequency acoustic loadings
- The application of the annoyance potential criteria using MOD-2 emission levels measured under a range of operating conditions and a comparison of the results with similar ones for the MOD-1 turbine.

Discussion

We undertook a series of five experiments from February 1981 to August 1986 to characterize the MOD-2's acoustic emissions. The primary experiments, however, were performed during May 1982 and August 1983, using Turbine No. 2 at the Goodnoe Hills site. The 1982 experiments collected statistical measurements of high-frequency-range emissions as well as low-frequency data. The 1983 experiment was designed to be more narrow in scope but included additional parameters not available in 1982, such as rotor surface pressures and

high-frequency turbulence measurements made from a fixed tower location and a tethered balloon flown in the turbine inflow. Major modifications were made to Turbine No. 2 between the 1982 and 1983 experiments as a result of operational instabilities. These included installing vortex generators along the rotor's leading edge over 70% of the blade span and establishing a different blade pitch sequence in the control system software. These changes required us to stratify the low-frequency data collected during these two experiments by year.

In order to make low-frequency noise measurements in a windy environment, we developed a technique that employs a pair of ground-mounted microphones spaced 15 m apart. Cross-correlation signal processing procedures were then used to obtain the in-phase acoustic portion of the signal while largely rejecting the random, turbulence-induced contribution. Inflow measurements were made from fixed meteorological towers located outside the turbine induction zone and from a tethered balloon flown approximately 1.5 rotor diameters (1.5D) upwind of the rotor plane. Both standard-response and high-frequency anemometers were used on both platforms. Twelve surface-mounted pressure transducers were attached to the upper and lower surfaces of Blade No. 1 on Turbine No. 2 at two span locations during the 1983 experiment.

The data categories--acoustic, atmospheric, and blade surface pressures--each necessitated somewhat different processing procedures. Because of the random or stochastic nature of the inflow turbulence responsible for exciting the acoustic response of the turbine, we developed a statistical sampling approach for presenting and quantifying the radiated acoustic spectra. Consistent with this approach, we characterized the turbulent inflow using the methods of statistical fluid mechanics and calculated a range of "bulk" flow parameters. We employed standard time-series analysis procedures in determining the MOD-2 aeroacoustic and surface pressure response functions.

Our detailed measurements of the inflow to Turbine No. 2 revealed a regime that is often stably stratified and contains multiple, thin layers of small-scale, anisotropic turbulence. There is strong evidence of the development of an internal boundary layer within the rotor disk's vertical envelope, whose formation and depth vary diurnally. Further, the vertical layer encompassing the rotor disk is influenced by the presence and breakdown of internal wave motions, accompanied by intense, small-scale turbulence. For example, under stable conditions, typical longitudinal or axial turbulence component length scales are in the neighborhood of 200 m, but those of the vertical or upwash (in-plane) component are often more than an order of magnitude smaller.

Measurements of emissions in the high-frequency range (400-8000 Hz) have shown that close to the rotor disk the radiation pattern resembles that of a classic quadrupole source. This pattern is then distorted by the prevailing wind at larger distances, i.e., extended downstream and contracted upstream of the rotor disk. Statistical measures of the A-weighted emissions over periods of several hours have shown the observed levels to be essentially normally distributed. The decay of these emission levels with distance (at Goodnoe Hills) can be described by the following polynomial:

$$L_{eq}(A) = -3.89464\ x^4 + 46.6729\ x^3 - 191.884\ x^2 + 287.15\ x - 28.4\ ,$$

where x is the $\log_{10}$ of the downwind distance, in feet. The departure from an r^2 dependence is apparently the result of local propagation effects. The average audible range of a single MOD-2 at the Goodnoe Hills site has been estimated to be 1220 m (4000 ft) downwind of the turbine. Statistical measurements of the acoustic environment downwind of the site with up to three turbines operating show that the turbine noise level experienced by an observer is dominated by the closest turbine. The effects of multiple turbine operation, however, are most noticeable when the turbines are located at nearly the same upstream distance from the observer.

The A-weighted, equivalent sound pressure level or $L_{eq}(A)$ at a distance of 1.5D (137 m or 450 ft) from the rotor disk was found to vary primarily with the hub-height wind speed, though some slight dependency was noted on the vertical stability (Richardson number) and wind direction. The $L_{eq}(A)$ variation, at this reference distance, can be expressed to within ±0.5 dB by $1/2\ U_H + 57$ over a hub wind speed (U_H) range of 6-15 m/s (13 to 34 mph).

An examination of the variation of 1/3-octave band spectra with inflow characteristics revealed that there was essentially a uniform increase in the observed average band pressure levels [$L_{eq}(f_{1/3})$] across the spectrum with wind speed and stability. A "peaking behavior" (distinct peaks in the exceedence level, 1/3-octave band spectra) was noted, principally in the L_{10}, L_5, and L_1 levels of the 2500-Hz band. This was most noticeable in measurements made in the plane of the rotor, and it appears to be load-related. We believe this peaking characteristic may be related to some form of oscillatory fluctuations in the rotor's aerodynamic boundary layer.

Comparisons made between on-axis measurements taken during the 1982 and 1983 experiments revealed a sharp spectral cut-off in the 1983 emissions above 1600 Hz. While some of the "peaking" behavior we noted above was present in 1983, a downshift appears to have occurred in the 1/3-octave band in which it was dominant, i.e., 2500 Hz in 1982 to 1000 Hz in 1983. We have attributed the lower spectral cut-off and lower "peaking" frequency in the 1983 emissions directly to the vortex generators, with their inherent ability to limit boundary-layer separation. It is also possible that these changes may be somehow related to the modifications in the pitch angle schedule, i.e., perhaps because they reduced the maximum attack angles encountered.

No significant, steady-tone noise components were found in analyses of representative narrowband (25-Hz resolution) spectra. This indicates that mechanical noise sources associated with the drivetrain are well controlled and that there are no discrete aeroacoustic sources of consequence.

We measured the MOD-2 low-frequency (LF)-range acoustic transfer function directly by means of balloon-borne instruments flown in the turbine inflow. We found that the radiated acoustic spectrum changes characteristics at inflow turbulent scales less than the measured longitudinal or axial integral scale, i.e., for turbulent eddies less than this scale length. Statistical correlations between five characteristic scales of the inflow and the mean and the first three moments of the 1/3-octave band spectrum level distributions (expressed as the variance, skewness, and relative kurtosis coefficients) were derived from the 1983 data set. Using these five inflow scales as predictors in a linear, multivariate model of the band spectral levels, we found that a high degree of convergence of the model could be obtained; i.e., a high percentage of the observed variation of the mean and the first three moments could be explained. The most efficient predictors included the following:

(1) A reference mean wind speed (U_z) measured at a height z within the rotor disk layer (vertical layer occupied by the rotor disk)

(2) The gradient Richardson number (Ri) stability parameter measured over the rotor disk layer

(3) The Monin-Obukov length scale, L (see Section 2.4.2), or

(4) The vertical or in-plane turbulence component scale length along the vertical z-direction, I_w^z, measured at the height noted in (3).

The statistical distributions of the emitted 1/3-octave band spectra were most highly correlated with the U_z, Ri, and I_w^z predictors or scales. The inclusion of (1) and (4) agrees with the generalized theory of Homicz and George for subsonic rotor noise generated in homogeneous, isotropic turbulence. The need to include the Richardson number reflects the inhomogeneous, vertically stratified characteristics of the rotor inflow at the Goodnoe Hills site. We found that an increase in the stability above critical values (Ri > +0.25) led to a decrease in the vertical or in-plane turbulence scales. This in turn had the effect of increasing the LF acoustic output below a frequency of 10 Hz, with a corresponding decrease above that.

We attempted to relate the spectral characteristics of the tower-measured axial and in-plane (upwash) turbulence components to the shape of the LF acoustic mean 1/3-octave band spectra. We suggest using

$$f' = (2_\pi \Omega \, R_o / I_w^z) f$$

as a fixed to rotating space frequency (f') transformation, where Ω is the rotor rotation rate and R_o is the effective radius (75% span length). Using this conversion, we found that

(1) There is a small positive slope change in the mean acoustic pressure spectra, in the vicinity of the rotor effective chord length. This also seems to coincide with the isotropic turbulence region (indicated by the two turbulence component spectra becoming parallel).

(2) The acoustic pressure spectral roll-off approximates a -5/3 slope for reference wind speeds less than about 10 m/s.

Because of the substantive changes made to Turbine No. 2 between the 1982 and 1983 experiments, we made an effort to compare the acoustic emission characteristics and their relation to the inflow for both years. We were limited to comparing the LF-range results, since we did not have sufficient high-frequency (HF)-range acoustic data from the 1983 experiment. We determined that the 1983 configuration of the turbine was far more acoustically sensitive to inflow stability. We also determined that the 1982 configuration was influenced by flow stability at all frequencies. We found that the 1983 emissions exhibited less coherent (impulsive) tendencies above 9-10 m/s than those of the 1982 configuration. It is clear that, because of whatever instabilities were present, the upwind 1982 MOD-2 turbine at times performed acoustically in a manner similar to its predecessor, the downwind MOD-1. Thus, a definite improvement was achieved in reducing the degree of coherency in the LF-range emissions by adding the vortex generators and making the pitch schedule modifications.

In order to better understand the physical processes responsible for aeroacoustic noise generation, we performed a space-time correlation analysis using three parameters measured on the blade itself and the far-field acoustic pressure as measured in the 8-Hz octave band. Our results showed, at least at the 87% span station, that the processes related to the observed flap and chordwise moments, the blade normal surface pressures, and the radiated acoustic pressure field are correlated over time periods of 65-75 ms, which translate to a movement of the rotor through about 5 m in space.

Our experience with the MOD-1 turbine reinforced the desirability of assessing the MOD-2's potential to cause interior annoyance problems in nearby residential structures by means of low-frequency acoustical loads. Through a limited, interior low-frequency noise evaluation experiment, using volunteer subjects, we identified what we believe to be an efficient descriptor or metric for measuring the degree of annoyance from such stimuli. From data available to us, we modified the derivation of this descriptor to include internal dynamic pressure effects resulting from the application of external, low-frequency acoustical loads. Using this modified descriptor, we then developed a procedure for establishing a "figure-of-merit" for a given turbine, which attempted to take into account worst-case conditions of surface reflection and atmospheric focusing. By using 1/3-octave band acoustic spectra measured at a reference distance from a turbine's rotor plane, we were then able to establish a predicted worst-case figure for the MOD-2. We were then able to compare that result with the documented community annoyance associated with emissions from the MOD-1 operating at both 35 and 23 RPM.

Conclusion

We determined from our analysis of both the high- and low-frequency-range acoustic data that annoyance to the community from the 1983 configuration of the MOD-2 turbine can be considered very unlikely at distances greater than 1 km (0.6 mile) from the rotor plane.

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