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AERODYNAMIC SOURCES OF ACOUSTIC RADIATION FROM A SINGLE MOD-2 WIND TURBINE

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ABSTRACT

Results are presented of an extensive acoustic measurement program conducted recently using one of the MOD-2 wind turbines in the DOE/NASA/BPA cluster at Goodnoe Hills, Washington. A summary of low-frequency acoustic emission characteristics is also presented. The MOD-2 acoustic emissions are compared with other large-scale turbines, including the DOE/NASA MOD-OA, the MOD-1 horizontal-axis, and the DOE/Sandia vertical-axis designs. The unsteady aerodynamic forcing, in response to certain freestream turbulence characteristics, is identified as the source of observed acoustic and rotor aeroelastic responses.

1. INTRODUCTION

In this paper, we report a few of the results of extensive acoustic monitoring of a single MOD-2 wind turbine installed in the Goodnoe Hills, Washington, cluster. One of the objectives of this effort has been to identify the dominant physical mechanisms responsible for both the normally audible and the low-frequency regions of the radiated acoustic pressure spectrum. Of particular concern are the MOD-2 low-frequency acoustic emission characteristics that occur over a wide range of operating conditions. These emissions are capable of causing annoyance to humans in nearby residences if certain minimum acoustic energy levels are exceeded and an optimum propagating path exists [1,2]. Considerable care has been exercised in siting the MOD-2s at Goodnoe Hills to minimize any possible human annoyance, not only from acoustic noise but from television interference as well. Both goals have been met sucessfully.

Figure 1 summarizes the interaction between the low-frequency acoustic radiation associated with the operation of large wind turbines and the structural, pneumatic, and acoustic resonances of the interiors of typical residential buildings. Also indicated are typical human body resonances which, we believe, are subjectively responsible for many of the complaints related to the impulsive noise associated with the MOD-1 turbine--discussed more fully in Ref. [1]. As seen in Figure 1, the critical resonance-controlled frequency region of typical housing construction ranges from about 5 to 100 Hz. This region, particularly at the lower end of the range, tends to contain a multitude of very lightly damped modes (often less than 5% of critical) that are susceptible to excitation from both external and internal dynamic pressure fields which, in turn, are responsible for exciting both internal Helmholtz-type and acoustic (room) resonances.

The dashed vertical line area in Figure 1 represents the spectral content of the wind turbine acoustic emissions related to unsteady blade airloads (lift forces) resulting from inflow turbulence structures encountered as the rotor sweeps around the disk. The slow rotational speed of most large wind turbine blades establishes the low-frequency characteristic of both steady and unsteady airload acoustic noise, as diagrammed in Figure 1. Because of this coincidence of turbulence-induced, unsteady load noise and lightly damped structural resonance bands, it is important to achieve rotor designs and operating envelopes that will minimize the radiation of potentially annoying levels of partially coherent, low-frequency acoustic energy.

The strongly fluctuating blade airloads associated with the turbulence we observed may not only be responsible for excessive levels of potentially annoying low-frequency noise emissions but could also be a potential source of enhanced structural fatigue through the oscillatory aeroelastic response of the lightly damped modes of the blade structure itself. Figure 2 shows a rough physical process chart for acoustic noise production from the moving blade of a wind turbine. The upper portion of the diagram traces the physical mechanisms that shape the turbulence characteristics of the wind as seen by the turbine blades. The lower section outlines

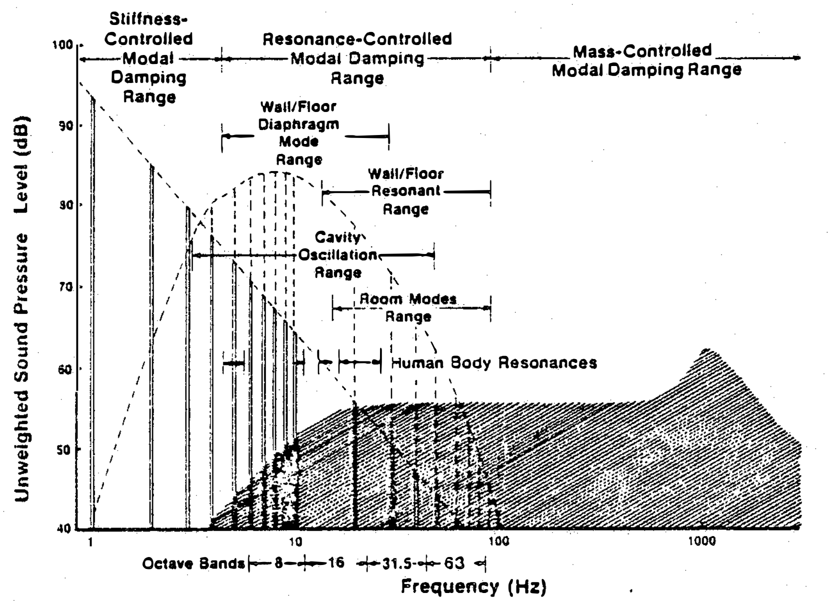

Fig.1. Schematic of Large Wind Turbine Average Sound Spectrum with Residential Housing Structural and Acoustic Modes Shown

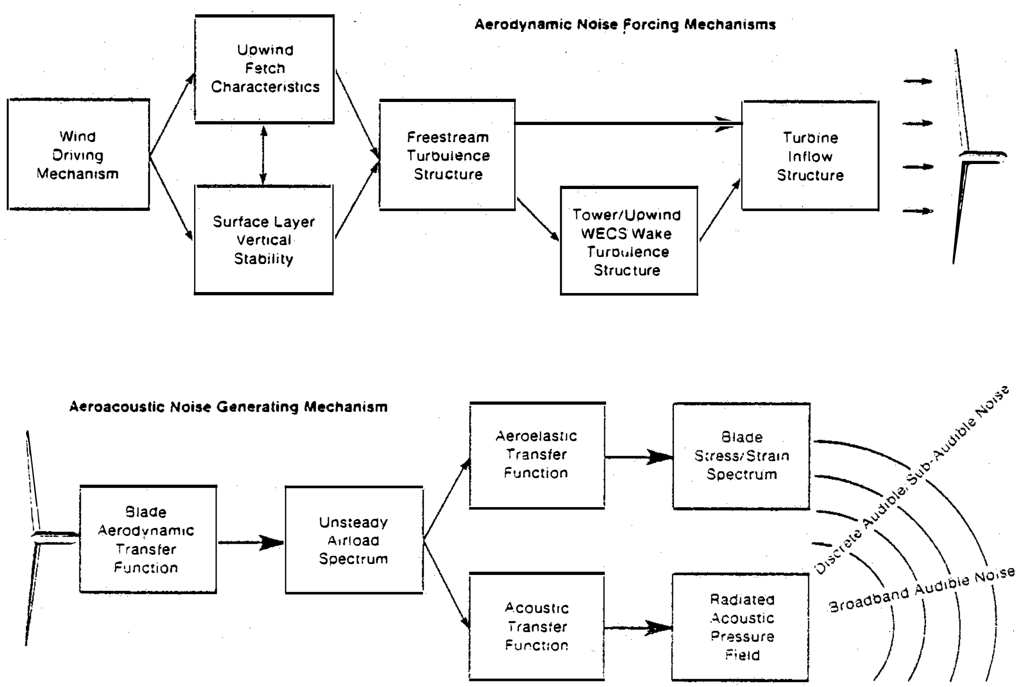

Fig. 2. Physical Mechanisms Responsible for Noise Generation by Wind Energy Conversion Systems (WECS)

some of the key processes that influence the temporal and spectral characteristics of the radiated acoustic pressure field. The interrelationship between the aeroacoustic and aeroelastic responses of the turbine blades is seen by observing their common roots in the unsteady airload spectrum itself. In actuality, there is a connection between the aeroelastic and aeroacoustic transfer functions because (1) complex feedback mechanisms exist between the structural response and the aerodynamic transfer function, and (2) peaks in the acoustic radiation spectrum tend to occur at excited structural modes. Currently, little is known about deterministic aerodynamic, aeroelastic, and aeroacoustic transfer functions for large wind turbines (or indeed for any wind turbine). Thus, to understand the acoustic response of a wind turbine, even in a probabilistic sense (in terms of the component physical processes indicated by Figure 2), it is important to develop some measure of the characteristics or "quality" of the turbine inflow structure and its accompanying aeroelastic and aeroacoustic response. The experiment described here was an initial attempt to obtain at least a qualitative measure of some of these dynamic characteristics of a MOD-2 turbine.

2. FIELD MEASUREMENT PROGRAM

In late April and early May 1982, SERI performed an extensive set of measurements associated with the operation of a single MOD-2 wind turbine (Unit No. 2) located in the Goodnoe Hills cluster. We made an initial attempt to at least semiquantify the major physical processes shown in Figure 2, in terms of estimates of characteristics of the turbine inflow structure and measures of the corresponding aeroacoustic and aeroelastic spectral response. In particular, a tethered balloon equipped for measuring atmospheric pressure (height), air temperature, and wind speed and direction was flown immediately upwind of the turbine when conditions would permit. Before and at the end of each data-taking run (nominally 30 minutes long), the balloon system was operated in a vertical profiling mode to determine (1) the vertical, hydrodynamic stability and (2) the existing vertical velocity profile. Based on the profile taken before a specific data run began, a height was chosen in terms of a windspeed maximum (positive profile inflexion point), and the balloon was nominally flown at this altitude (referenced to the tower base elevation) for the duration of the data recording period. The windspeed signal was radiotelemetered and recorded along with acoustic and turbine operational parameters on a multichannel FM magnetic recording. Continuous recordings were also made on FM magnetic tape of the windspeed and direction from a 60-m level (approximately turbine hub height) of the nearby Bonneville Power Administration (BPA) meteorological tower, which uses standard rugged, low-resolution sensors, and from a SERI high-resolution, hot-film velocity sensor mounted at a 24-m elevation. The mean vertical stability was determined from the temperature and wind velocity differences between 10- and 107-m levels of the Pacific Northwest Laboratories (PNL) tower located southeast of the test turbine.

Turbine acoustic emissions were recorded from an array of special low-frequency microphones placed both on the rotor's axis and in its plane 137 m from the hub. On three of the data runs (the only ones in which the signals were available), the chordwise and flapwise moments at approximately the 85% span location on Blade #1 were also recorded. The testing was based on three major criteria: (1) two hub-height windspeed (turbine loading) ranges (7 to 11.5 and 12 to 21 msec^{-1}); (2) three wind directions (upwind fetch differences), and (3) three vertical stability regimes, as defined by the gradient Richardson Number (Ri) measured from the two PNL tower elevations above and defined by

$$Ri = g/\overline{\Theta}\ [(\overline{\Delta\Theta_z}/\Delta z)/(\overline{\Delta U_z}/\Delta z)^2] \ , \qquad (1)$$

where g is the gravity acceleration, $\overline{\Theta}$ the mean potential temperature of the layer Δz given by $\Theta = T_z(1000/p_z)^{0.286}$, and T_z, p_z, and U_z--the absolute air temperature, local static pressure, and windspeed at height z, respectively. The three stability regimes included $Ri < 0$ (unstable case), $0 < Ri < 0.25$ (the so-called "stable-turbulent" case), and $Ri > 0.25$ ("stable-laminar"). Only a single wind direction was achieved (a westerly fetch), but cases involving most of the other test parameters were obtained.

3. ACOUSTIC RESULTS AND COMPARISONS

One of the major objectives of this study was to evaluate the observed levels and temporal characteristics of radiated acoustic pressure levels in the critical 5- to 100-Hz frequency band. Previously [1,3,4], we have employed the 8-, 16-, 31.5-, and 63-Hz standard octave bands, that contiguously almost cover the frequency range of interest (5.6 to 89.1 Hz rather than 5 to 100 Hz). The level of coherency or impulsiveness in the turbine acoustic emissions can be evaluated in terms of joint probability levels between pairs of these octave band pressure levels, in terms of direct evaluation, and in terms of a condition of the existence of certain minimum levels in the 8-Hz band. A MOD-1 emissions case during which the most severe human annoyance and structural excitation was observed is used as a reference. Further, from measurements taken near the MOD-1 and from comparisons with other data [5], it is apparent that if critical levels of these band emission levels (measured at ground level approximately 1.5 rotor diameters on-axis from the turbine hub) are exceeded, there is a risk of exciting nearby residential structures enough to cause human annoyance. These band pressure levels (BPLs) are 50, 40, and 40 dB, respectively (with respect to 20 μPa linear weighting), in the 16-, 31.5-, and 63-Hz octave bands, respectively, simultaneously occurring with an 8-Hz BPL of 60 dB or more.

The above criteria allow us to make a rough comparison about the low-frequency radiative characteristics (and, therefore, estimate the annoyance potential under the most adverse propagation conditions) between turbine designs under similar environmental conditions or for the same turbine under a range of conditions, as here. Joint probability estimates were arrived at by taking ensemble averages of 100 random samples 2 seconds long from 10-minute segments of each of the 30-minute data runs. These acoustic spectral estimates were derived from the real-time, cross-spectral processing of two signals recorded from two identical microphones placed approximately 8 m apart, perpendicular to the rotor axis. This technique was employed to minimize contamination by uncorrelated, wind-induced pressure fluctuations at the lowest frequencies of interest (~5 Hz). The technique has provided wind-induced noise reductions exceeding 17 dB at the lowest frequencies, in comparison with a conventional technique using a single microphone and windscreen exposed in winds averaging 16 $msec^{-1}$ measured at hub height.

Figures 3, 4, and 5 summarize the 8- to 16-, 16- to 31.5-, and 31.5- to 63-Hz octave BPL joint probability distributions in 5 dB bin increments and 10% contour intervals for three runs covering three windspeed regimes: 20.8, 27.1, and 32.5 mph (10, 12.5, and 15 $msec^{-1}$) average speeds, with the corresponding severe MOD-1 situation included for reference. It is clear from these plots that peak radiated levels increase with increasing blade loading (windspeed), but the persistence (as identified by the number of probability contours present) generally decreases, indicating less contiguous-band or coherent radiation (the 31.5- and 63-Hz bands are exceptions). In all three plots, the levels exceed the recommended emission maximums for hub-height windspeeds exceeding about 10 $msec^{-1}$ Figures 6 and 7 compare the MOD-2 with representative distributions from the MOD-0A and MOD-1 horizontal-axis and the 17-m DOE/Sandia vertical-axis turbines in terms of low-frequency-band joint emission levels in the 16- and 31.5-Hz bands, with a condition of 70 dB or more in the 8-Hz band. A tentative conclusion to be drawn

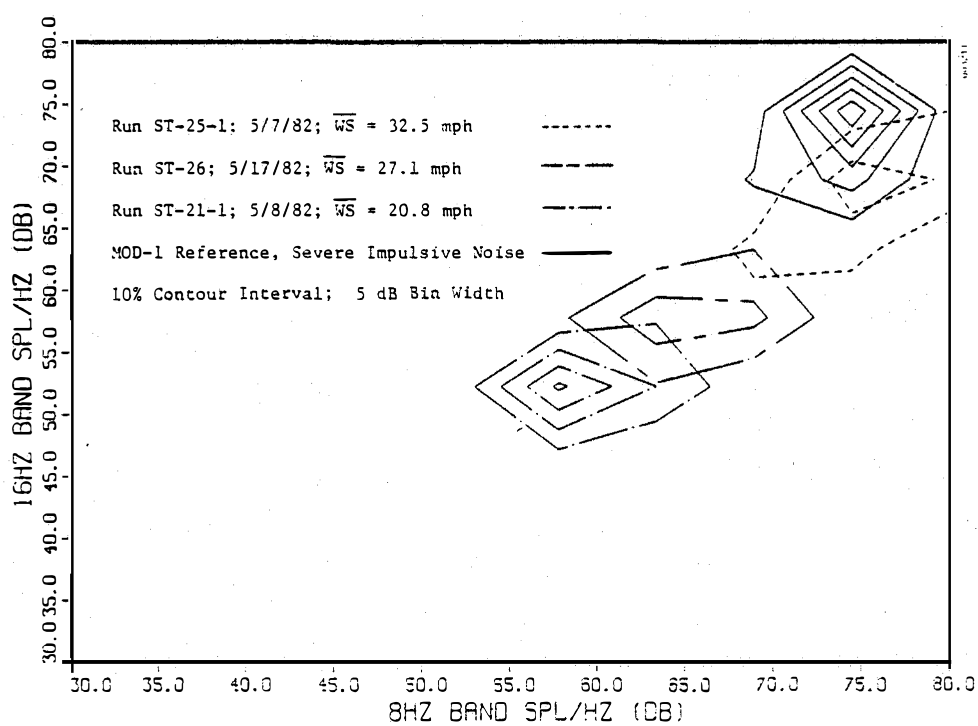

Fig. 3. Joint Probabilities of the 8/16-Hz Octave Band Levels for Three MOD-2 Data Runs with the MOD-1 Severe Levels for Comparison

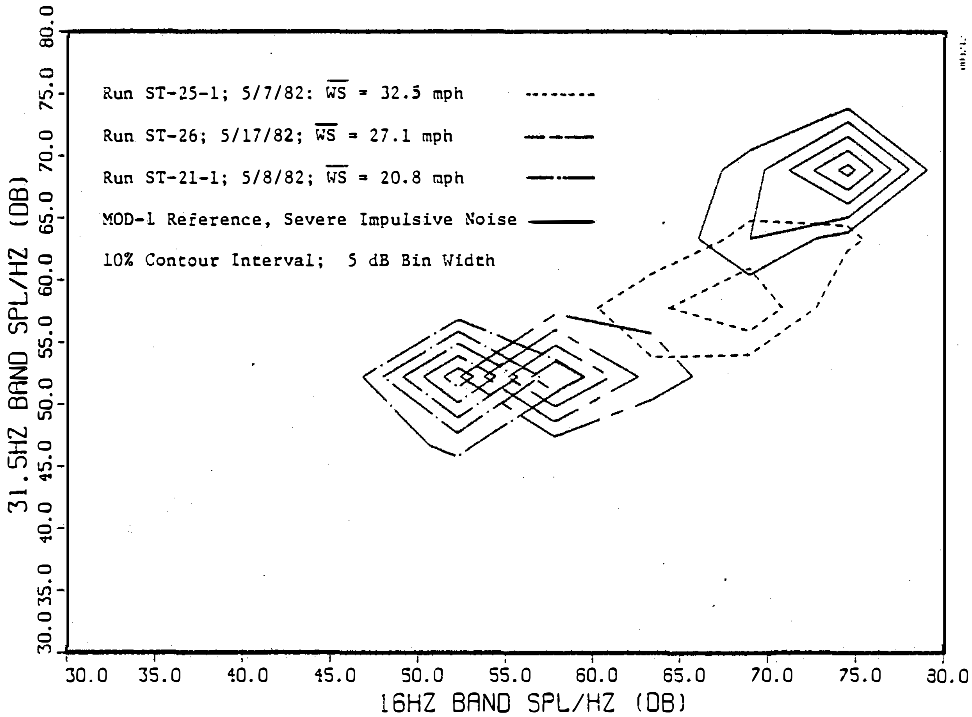

Fig. 4. Joint Probabilities of the 16/31.5-Hz Octave Band Levels for Three MOD-2 Data Runs with the MOD-1 Severe Levels for Comparison

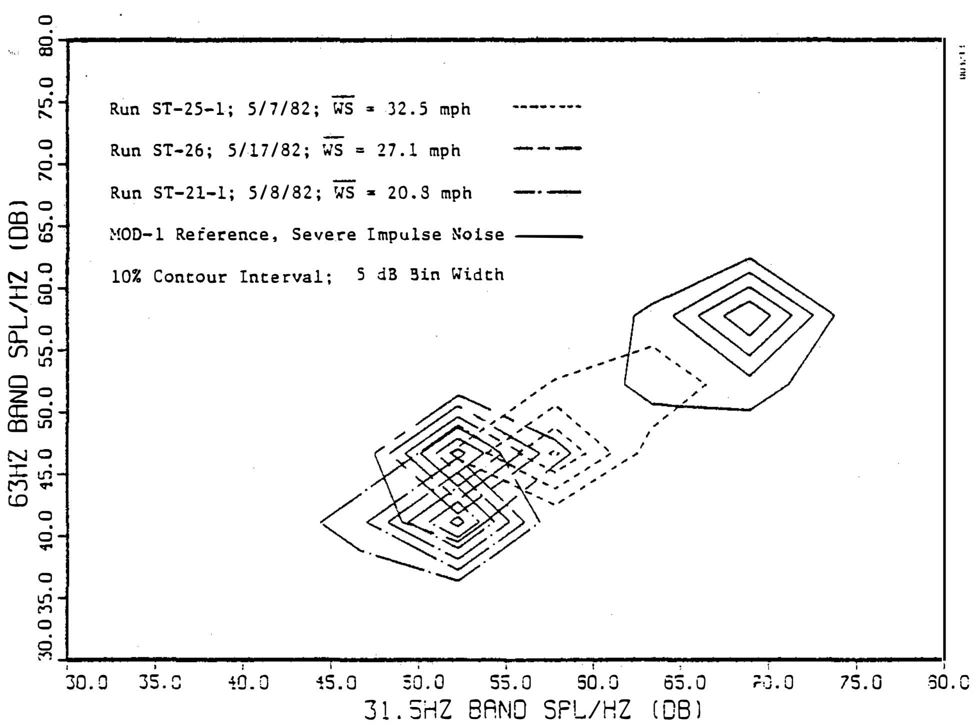

Fig. 5. Joint Probabilities of the 31.5/63-Hz Octave Band Levels for Three MOD-2 Data Runs with the MOD-1 Severe Levels for Comparison

from these limited samples is the upwind MOD-2 is capable of radiating high levels of acoustic energy in the sensitive residential structural resonance region (particularly under conditions of high blade loading), but the temporal characteristics of these emissions are generally much less coherent or impulsive compared with downwind horizontal- or vertical-axis wind turbine designs. Therefore, any potential for acoustic excitation of nearby structures will tend to peak during periods when the turbine is operating in a slightly below rated regime (a windspeed range of about 10 to 14 $msec^{-1}$ for this particular MOD-2).

5. CRITICAL TURBULENCE BAND EFFECTS

In our investigation of the physical mechanisms responsible for the MOD-1 acoustic noise situation [1], we determined through wind tunnel experimentation that there exists a relatively narrow range of freestream perturbative wavelengths which can initiate a variety of unsteady lift responses when encountered by a moving wind turbine blade. These responses include such transient unsteady phenomena as leading-edge separation; turbulence-induced buffet; and the real possibility of stall flutter, under the right circumstances. Further, we found that the crossflow component of these perturbations (i.e., perturbations which are correlated in the blade spanwise direction, such as the vortex wakes shed from the legs of pipe truss tower structure) also may play a significant role in the severity of the lift fluctuations, or equivalently, the level of coherence or impulsiveness in the emitted acoustic pressure field.

SERI wind tunnel experimentation has revealed within this critical perturbative length scale range that the degree of leading-edge separation and associated unsteady aerodynamic and aeroelastic response increases dramatically as the quasi-steady incidence angle is increased. This is spectrally expressed in terms of the reduced frequency parameter k:

$$k = \omega_p/2U_\infty = \pi c/\lambda_p , \qquad (2)$$

where ω_p and λ_p are the perturbation radian frequency and the wavelength, respectively; c is the airfoil chord dimension; and U_∞ is the blade velocity relative to the surrounding medium. Our measurements indicated a maximum unsteady aerodynamic and aeroelastic response (severe buffeting and possibly times when stall flutter was present and dominant) for a range of nominally spanwise coherent perturbations generated by an upstream cylinder, the diameter of which was an integral whole value or fraction of the airfoil blade chord length. The k-values, which invoked noticeable levels of buffet response, ranged from about 0.5 to approximately 2 with an apparent peak at k = 1. At k = π, we noted intense acoustic radiation corresponding to the perturbative exciting frequency, but little or no evidence of the severe buffeting response generally observed at lower k values. Stated in terms of a perturbative length scale and normalized by the section chord dimension, this critical aeroelastic and acoustic range (both are present) would include a range of about $\pi/2$ to π chord lengths, with a peak near k = 1.

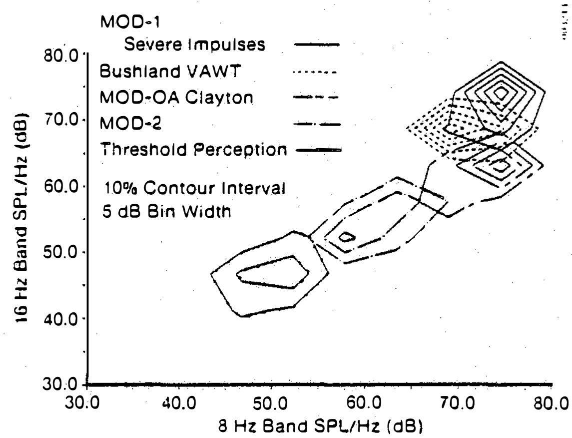

Fig. 6. Comparison of 8/16-Hz Octave Band Joint Probability Levels for MOD-1, Vertical Axis (VAWT), MOD-OA, and MOD-2 Turbines

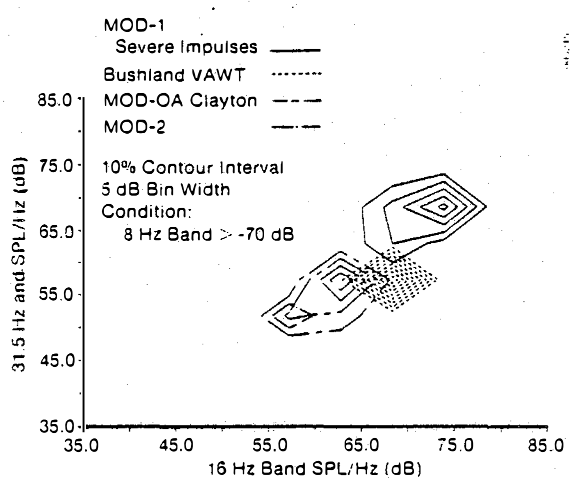

Fig 7. Similar to Fig. 6 but of 16/31.5-Hz Octave Band Joint Probability Levels with Condition of 70 dB or more in the 8-Hz Band

6. AN EMPIRICAL MOD-2 AEROACOUSTIC TRANSFER FUNCTION

Thirty-two 10-minute data segments were collected under a wide range of operating conditions and were processed by the statistical spectral sampling procedure outlined above. The resulting ensemble averages of each of the 17 1/3-octave BPLs covering the structurally sensitive frequency range of 5 to 100 Hz were combined with the run averages of the hub-height windspeed, the logarithm of the mean-square turbulence level in the 0.5- to 3.15-Hz band (the upper limit was actually determined by the propellor-type anemometer, which is less than the 3.15-Hz upper band limit), and the vertical stability of the rotor layer as expressed by the Richardson Number parameter defined by (1). These parameters constituted a 3 × 17 × 32 matrix from which a multiple linear regression model was calculated. This model explains, on the average, 90% of the observed acoustic pressure variance in the 5- to 25-Hz 1/3-octaves and about 75% of the variance in the higher bands up to 100 Hz.

The model results indicate that the predictor quantities of windspeed, critical band turbulence level, and vertical stability are at least sufficient to estimate the mean acoustic emission levels to within a nominal standard error of ±2 dB. Further, these predictors are measures of factors affecting the unsteady aerodynamic performance of the turbine rotor. Specifically, the hub-height windspeed translates as a measure of the quasi-steady blade airload; the mean-square turbulence level, the excitation for unsteady buffet and stall phenomena; and the Richardson Number reflects the vertical layering of the atmosphere through which the blades pass.

One advantage of this model is that, at least qualitatively, it examines the sensitivity of each of the predictors on the spectral level of noise emissions. For example, Figures 8, 9, and 10 plot the predicted mean 1/3-octave BPLs for a constant hub-height windspeed of 11 $msec^{-1}$ (25 mph), varying the critical band turbulence level over three orders of magnitude (0.001 to 0.1 m^2sec^{-2}), and three vertical stability regimes, including near neutral (Ri = -0.05), stable-turbulent (Ri = +0.25), and stable-laminar (Ri = +0.75). The sensitivity to the hub-height windspeed (quasi-steady blade loads) is shown in Figure 11 for a mean-square turbulence level of 0.10 m^2sec^{-2} and a stable-turbulent vertical layer (Ri = +0.25). These figures show in the 5-Hz 1/3-octave band, for example, that the mean radiated acoustic pressure level increases (i) approximately 10 dB (a threefold linear increase) for a doubling in the windspeed from 7 to 14 $msec^{-1}$; (ii) about 5 dB (1.8 linearly) for each decade of increase in turbulence level; and (iii) 9 dB (2.8 linearly) as the vertical layer occupied by the rotor destabilizes from a Richardson Number of +0.75 to -0.05.

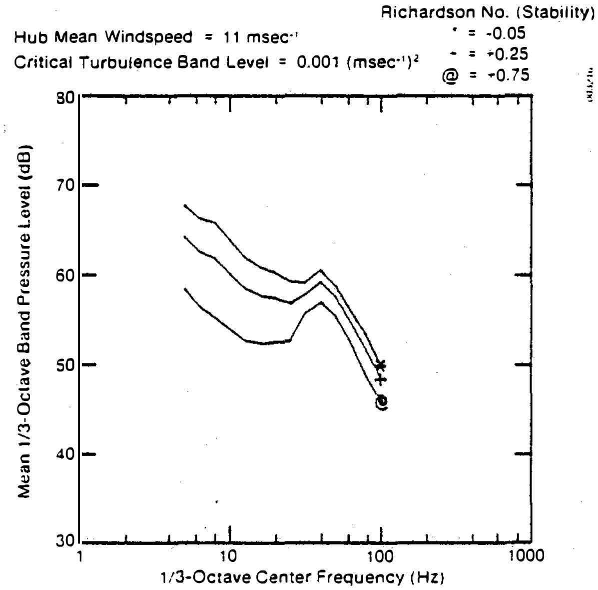

Fig. 8. MOD-2 Empirical Aeroacoustic Model Results Showing Emission Level Sensitivity with Richardson Number for 0.001 m^2sec^{-2} Turbulence Level and a Windspeed of 11 $msec^{-1}$

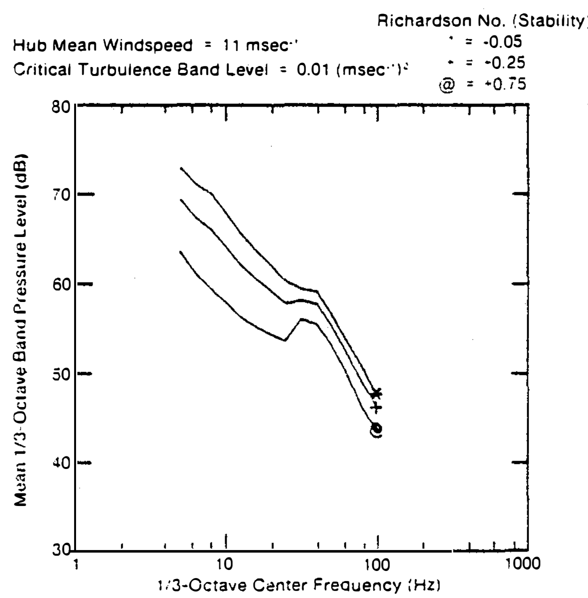

Fig. 9. MOD-2 Empirical Aeroacoustic Model Results Showing Emission Level Sensitivity with Richardson Number of 0.010 m^2sec^{-2} Turbulence Level and a Windspeed of 11 $msec^{-1}$

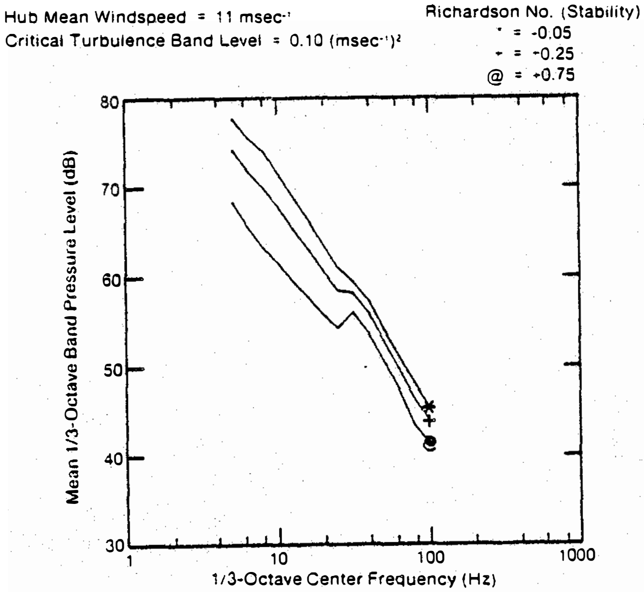

Fig. 10. MOD-2 Empirical Aeroacoustic Model Results Showing E ission Level Sensitivity with a Richardson Number for 0.10 m^2sec^{-2} Turbulence Level and a Windspeed of 11 $msec^{-1}$

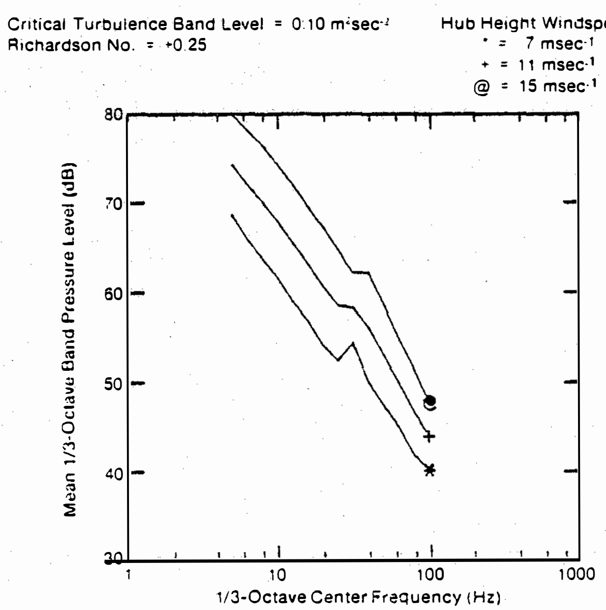

Fig. 11. MOD-2 Empirical Aeroacoustic Model Results Showing Emission Level Sensitivity with Hub-Height Windspeed for Turbulence Level of 0.10 m^2sec^{-2} and Richardson Number of +0.25

7. CONCLUDING REMARKS

In this paper we have shown that the intensity of low-frequency acoustic emissions from the isolated rotor of a single MOD-2 wind turbine can be estimated by a knowledge of the hub-height windspeed, the mean-square turbulence level in a critical perturbative space scale related to the unsteady aerodynamic excitation of the rotor, and a parameter reflecting the vertical hydrodynamic stability of the atmospheric layer occupied by the rotor disk. Because of the interrelationship of the level of low-frequency acoustic emissions and blade aeroelastic mode excitation, we believe that reducing the levels of the former will also reduce potentially life-robbing structure fatigue cycles in the latter. The results have also shown the degree to which a wind turbine is subjected to the conditions present in the earth's atmosphere that must be taken into account in the design process.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. Kelley, N. D.; et al. (in press). Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact, and Control. SERI/TR-215-1166. Golden, Colo.: Solar Energy Research Institute.

2. Thomson, D. W. 1982. Analytical Studies and Field Measurements of Infrasound Propagation at Howard's Knob, North Carolina. SERI/TR-635-1292. University Park, PA: The Pennsylvania State University, Department of Meteorology.

3. Kelley, N. D.; Hemphill, R. R.; McKenna, H. E. "A Methodology for Assessment of Wind Turbine Noise Generation." J. Solar Energy Engineering, Vol. 104 (No. 2): pp. 112-120.

4. Kelley, N. D.; Hemphill, R. R.; McKenna, H. E. "A Comparison of Acoustic Emission Characteristics of Three Large Wind Turbine Designs." Proc. 1982 International Conf. on Noise Control Engineering. 17-19 May 1982. Poughkeepsie, NY: Noise Control Foundation; pp. 351-354.

5. Stephens, D. G.; Shepherd, K. P.; Hubbard, H. H.; Grosveld, F. W. 1982. Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines. NASA/TM-83288. Hampton, VA: NASA Langley Research Center; 70 pp.