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# ANECHOIC WIND TUNNEL STUDY OF TURBULENCE EFFECTS ON WIND TURBINE BROADBAND NOISE*

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ABSTRACT

This paper describes recent results obtained at MIT on the experimental and theoretical modelling of aerodynamic broadband noise generated by a downwind rotor horizontal axis wind turbine. The aerodynamic broadband noise generated by the wind turbine rotor is attributed to the interaction of ingested turbulence with the rotor blades. The turbulence was generated in the MIT anechoic wind tunnel facility with the aid of biplanar grids of various sizes. The spectra and the intensity of the aerodynamic broadband noise have been studied as a function of parameters which characterize the turbulence and of wind turbine performance parameters. Specifically, the longitudinal integral scale of turbulence, the size scale of turbulence, the number of turbine blades, and free stream velocity were varied. Simultaneous measurements of acoustic and turbulence signals were made. The sound pressure level was found to vary directly with the integral scale of the ingested turbulence but not with its intensity level. A theoretical model based on unsteady aerodynamics is proposed.

NOMENCLATURE

| | |
|---|---|
| $B$ | Number of rotor blades |
| $b$ | Rotor blade span |
| $c$ | Rotor blade chord |
| $c_o$ | Ambient speed of sound |
| $D_r(\phi,f)$ | Power spectral density of the dipole radiation |
| $f$ | Frequency |
| $k_x$ | x component of turbulent wavenumber vector |
| $m$ | Rotational harmonic |
| $M_o$ | Rotational Mach number at radial position $R_o$ |
| $\rho_o$ | Ambient density |
| $R_o$ | Radial location of the effective velocity |
| $r$ | Radial position |
| $\langle S_{pp}(x,t)\rangle$ | Radiation spectra |
| $U_o$ | Velocity |
| $x$ | Vector coordinate |
| $\Lambda$ | Integral scale of turbulence |
| $\Lambda_f$ | Longitudinal integral scale of turbulence |
| $\phi$ | Azimuthal angle |
| $\Omega$ | Rotational speed |

## I. INTRODUCTION

The potential advantages derived from wind power as a source of world energy needs are not independent of their environmental impact. The essential factor in such an environment impact is the negative aspects associated with the aerodynamic noise generated by wind turbines[1,2,3,4]. The aerodynamic noise generated by wind loading on the blades of wind turbine may be classified as: (1) Gutin noise resulting from Doppler modulation of the steady blade loads, (2) blade tower wake interaction noise generated by continued blade passage through the downwind wake of the wind turbine support tower, and (3) broadband noise due to blade interaction with incident turbulence. Previous research at MIT has addressed Gutin noise and blade tower wake interaction noise from a theoretical and experimental perspective[3,4]. This paper presents results of our investigation of the effects of turbulence on wind turbine broadband noise.

## II. EXPERIMENTAL APPARATUS

The MIT anechoic wind tunnel facility was used to investigate the effects of controlled free-stream turbulence on the broadband noise generated by a scaled model wind turbine. Turbulence of varying intensity and scale was generated in the wind tunnel test section by inserting biplanar grids of different sizes in the tunnel contraction section. The experimental apparatus used in obtaining and analyzing both turbulence and acoustic data is described.

### II.A. THE M.I.T. ANECHOIC TUNNEL

The wind tunnel has a 1.52x2.29-m inlet open-jet test section which is enclosed in a 3.65x3.65x7.3-m anechoic chamber. The sides of the chamber were covered with Cremer blocks and the floor of the chamber was covered with 15-cm-thick polyurethene foam. The anechoic properties of the tunnel were measured and the acoustic cutoff frequency above which free-field conditions prevail was found to be 160 Hz. The effects of the shear layer of the open jet on refraction and scattering of acoustic waves were studied by using aeolian tones as sound source and were found to be insignificant under the present test conditions. The details of the aerodynamic and acoustic calibrations of the wind tunnel facility are described in Harris and Lee.[5]

### II.B. WIND TURBINE MODEL

Experiments were conducted on a 1/53 scale model of the NASA-DOE MOD-1 wind turbine. NACA 0012 model rotor blades were used. The blades have a 5.08 cm chord, -8° linear twist, and a radius of 59.6 cm.

### II.C. TURBULENCE GENERATION

The grids employed in this study were designed based on the data of Baines and Peterson.[6] The grids were biplanar consisting of bars of 1.91 cm with a mesh size of 15 cm and bars of 8.9 cm with a mesh size of 50.8 cm. The grid solidity were 0.23 and 0.32 respectively. The grid Reynolds number based on the lowest tunnel velocity were $9 \times 10^4$ and $3 \times 10^5$, respectively.

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The longitudinal and vertical integral scales $\Lambda_f$ and $\Lambda_g$ of the grid generated turbulence were determined near the axis of rotor. For convenience, we estimated $\Lambda_f$ from the Eularian integral time scale $\tau_e$. The values of $\tau_e$ were determined from the extrapolated zero intercept of the power spectra of longitudinal and vertical velocities. The length scales, then are given by

$$\Lambda_f = U_o\tau_{ef}; \quad \Lambda_g = U_o\tau_{eg} \tag{1}$$

The measured longitudinal and vertical integral scales of grid generated turbulence were observed to be independent of free-stream velocity. In absence of grids, the Eularian time scales were very large and fluctuating. This resulted in large length scales that vary considerably with free-stream velocity, but do not follow any definite pattern.

The biplanar grids used to generate the controlled turbulence were located 2.08 m from the plane of the rotor. This corresponds to approximately 15 mesh lengths for the small grid and 4.6 mesh lengths for the larger grid. The controlled turbulence is assumed isotropic at the rotor plane. Characteristic turbulence data are given in Table 1.

### II.D. INSTRUMENTATION

Data flow for all the experiments was from microphones and hot wire sensors to a magnetic tape and later from the magnetic tape to a spectrum analyzer.

The acoustic measurements were made on axis and in the plane of the rotor as shown in Fig. 1. Acoustic signals were measured using two 1/2 inch B&K microphones type 4133. Wind screens were used on both microphones. The on axis microphone was amplified with a B&K 2107 frequency analyzer, while the off axis microphone was amplified by a B&K 2604 microphone analyzer. The microphones were calibrated using a B&K piston phone type 4220.

The fluctuating velocity signals were measured with a DISA 55H24 S-type hot wire sensor. The probe was calibrated over the anticipated test velocities and the responses of both wires were found to be roughly linear. The probe was placed at 91.6% span 12 cm upstream of the blade of the rotor. DISA 55D05 constant temperature anemometers were used in conjunction with a DISA 55D15 linearizer. Both signals were monitored constantly with two (true) rms voltmeters type HP 3400 A. The gain control on one of the linearizers was used to achieve uniform sensitivity of both wires.

The X-wire signals were fed into a home-built sum and difference unit to yield the longitudinal and vertical components of the velocity. The signal from the summing unit was passed through a Krohn Hite model 3340 filter to eliminate the offset voltage inherent in the linearizer output signal. Acoustic, turbulence, rpm and flow speed measurements were made simultaneously. A schematic of instrumentation used in the acquisition of turbulence, acoustic, and rpm data is shown in Fig. 2.

The measured acoustic, turbulence, and rpm signals were recorded on magnetic tape with an Ampex FR1300 14 channel recorder. The recorded signals were subsequently analyzed with a Nicolet 660B dual channel FFT analyzer and plotted on a Tektronix 4662 digital plotter. All of the data was analyzed by taking the averages of 50 time windows of the taped signal.

### III. EXPERIMENTAL RESULTS

To investigate the effects of ingested turbulence on the emitted broadband noise, the turbine blade pitch, flow speed, and number of blades were fixed at 15°, 10.1 m/sec and 2 respectively while the controlled turbulence was varied. Typical results are shown in Figs. 3 and 4. Comparing Figs. 3 and 4 we observe that an increase in length scales along with a decrease in turbulence intensity, has a significant effect on the broadband noise spectrum. The smaller scale and higher intensity turbulence dominates the spectrum at the lower frequencies while the larger scale and lower intensity turbulence dominates at the higher frequencies. The longer length eddies tend to produce a more pronounced blade-to-blade correlation effect and leads to more positive and negative interference between acoustic waves generated by the wind turbine blades.

Figures 5 and 6 show the influence of free stream velocity on the radiated broadband noise. The observed increase in sound pressure level with increasing forward speed is attributed to the corresponding increase in the rms value of the turbulence in the tunnel with increased forward speed. Note the difference in rpm between Figs. 5 and 6. This difference is a result of both cases corresponding to a fixed blade pitch of 15°.

The relatively negligible effect of number of wind turbine rotor blades on the generated broadband noise is shown in Figs. 7 and 8. The main difference being an increase width of peak centered at approximately 3,000 Hz with increasing number of blades.

The off axis microphone verified the above results. The off axis microphone sound pressure level was always less than that of the on axis microphone confirming the dipole nature of the broadband noise. A typical comparison between on axis and off axis microphone readings is shown in Figs. 7 and 9.

### IV. BROADBAND NOISE THEORY

When there is no significant blade-to-blade correlation Aravamudan and Harris[7] have shown that the spectrum of low-frequency broadband noise may be expressed as

$$\langle S_{pp}(x,f)\rangle = \frac{f^2\sin^2\phi}{2U_o c^3 r^2 \rho_o (1+bf/U_o)} \times \sum_{n=-\infty}^{\infty} D_r(f-n\Omega) J_n^2\left(\frac{fR_o\sin\phi}{c_o}\right) \tag{2}$$

where

$$D_r(f) = \frac{\pi^2\rho^2U_o^2b^2c^2(0.4548)}{\beta^2} w^2\Lambda_f^4 \int_0^\infty dk_y \frac{[(f/U_o)^2+k_y^2](J_o^2\{M_o^2\pi c/\beta^2)[(f/U_o)^2+k_y^2]^{1/2}\}+J_1^2\{(M_o^2\pi c/\beta^2)[(f/U_o)^2+k_y^2]^{1/2}\})}{\{1+(2\pi^2c/\beta^2)[(f/U_o)^2+k_y^2]^{1/2}\}\{1 + 1.793\Lambda_f^2[(f/U_o)^2+k_y^2]\}^{7/3}} \quad (3)$$

The two-dimensional model of rotor blade-turbulence interaction developed above is equivalent to exploiting the effective radius approach at 80% span, to assuming chordwise and spanwise compactness, and to a neglect of retarded time considerations associated with the sweep of the skewed gusts in the spanwise direction. Our objective in developing this model is to correlate the measured data. Additional experiments and calculations are in progress with a goal of correlating theory and experiment.

## V. CONCLUSIONS

Measurements in the M.I.T. anechoic wind tunnel of broadband noise generated by a 1/53 scale model of the NASA-DOE MOD-1 wind turbine have been made. The experiments and related analytical development described in this paper are concerned with the effects of turbulence on broadband noise generated by a model wind turbine. Our measurements suggest the following:

1. The smaller scale and higher intensity turbulence dominates the broadband noise spectrum at the lower frequencies while the larger scale and lower intensity turbulence dominates at the higher frequencies.

2. The sound pressure level of the broadband noise spectrum increases with increasing forward speed due to the corresponding increase in the rms value of the turbulence in the tunnel.

3. Increasing the number of blades from two to three has a negligible effect on the sound pressure level of the broadband noise spectrum.

4. Off-axis microphone measurements confirm the dipole nature of the broadband noise generated by the model wind turbine.

5. A broadband noise model has been developed and is to be compared with experimental results.

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Table 1:

Characteristics of Turbulence $U_o$ = 10.1 m/sec

| | Grid #0 (free stream) | Grid #1 1.92x15.38cm | Grid #2 8.97x51.28cm |
|---|---|---|---|
| Longitudinal Scale (cm) | 34.4 | 9.6 | 14.6 |
| Vertical Scale (cm) | 20.4 | 5.8 | 9.3 |
| Ratio of $\Lambda_v/\Lambda_1$ | 0.59 | 0.61 | 0.64 |
| Intensity | 1.7% | 6.25% | 11% |
| Solidity | 0 | 0.23 | 0.32 |
| Grid Reynolds Number | -- | $9x10^4$ | $3x10^5$ |

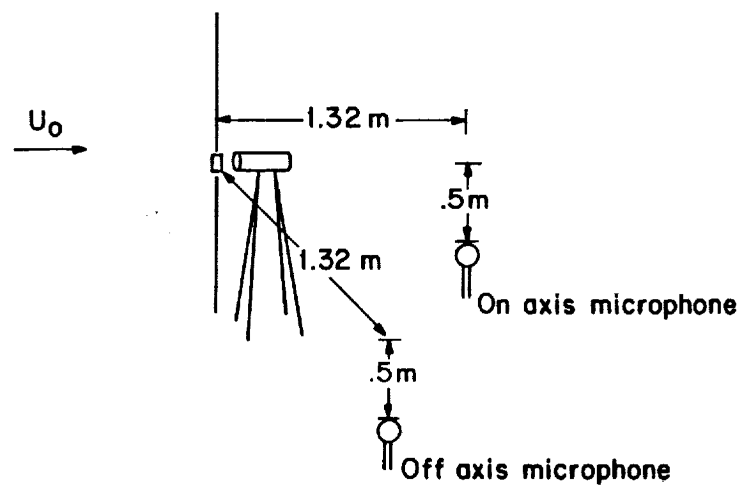


FIGURE 1 - POSITION OF MICROPHONES

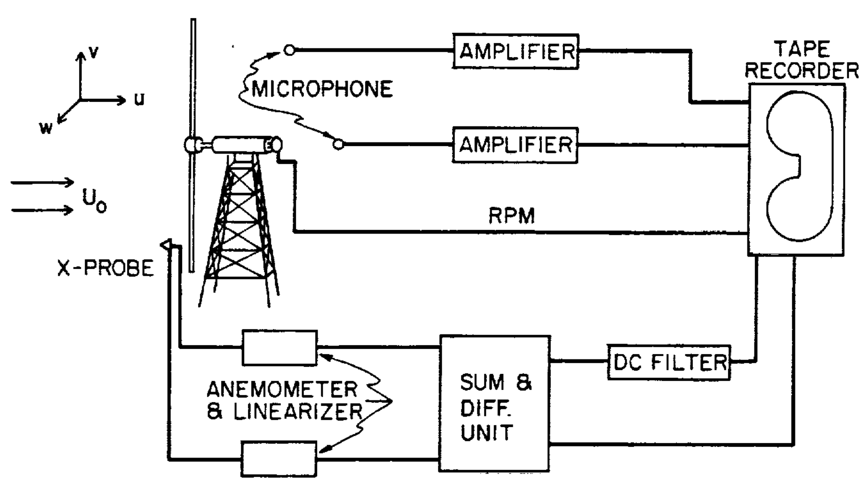


FIGURE 2 - SCHEMATIC OF INSTRUMENTATION

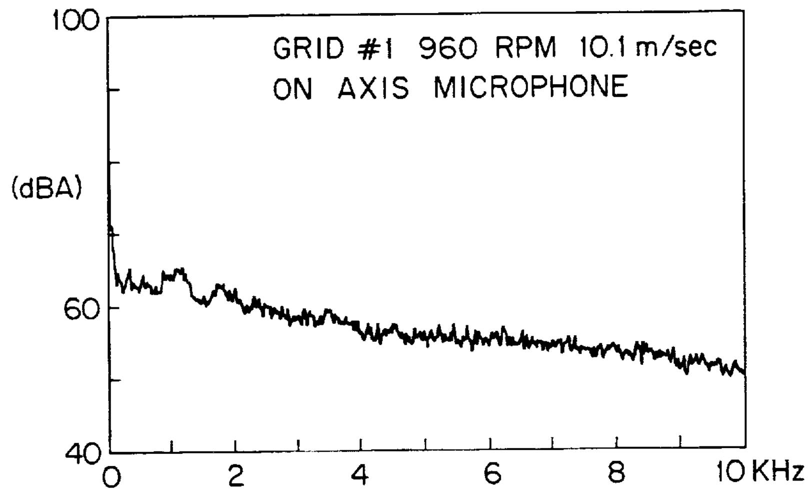


FIGURE 3 - SOUND PRESSURE LEVEL WITH GRID #1

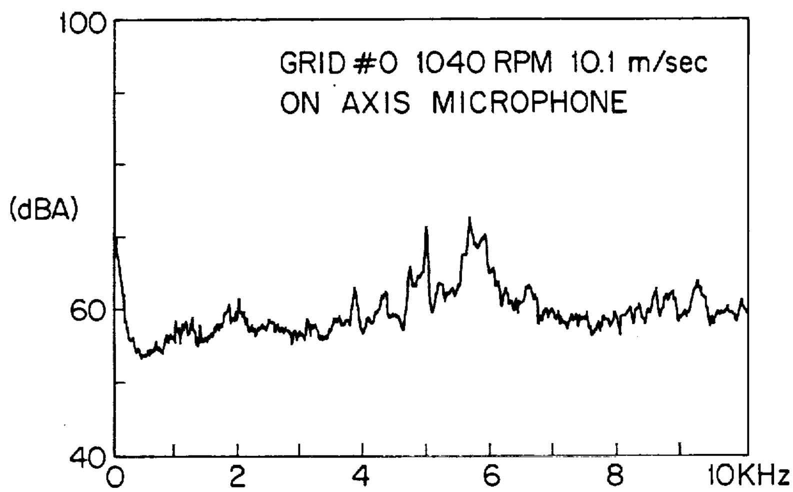


FIGURE 4 - SOUND PRESSURE LEVEL WITH NO GRID

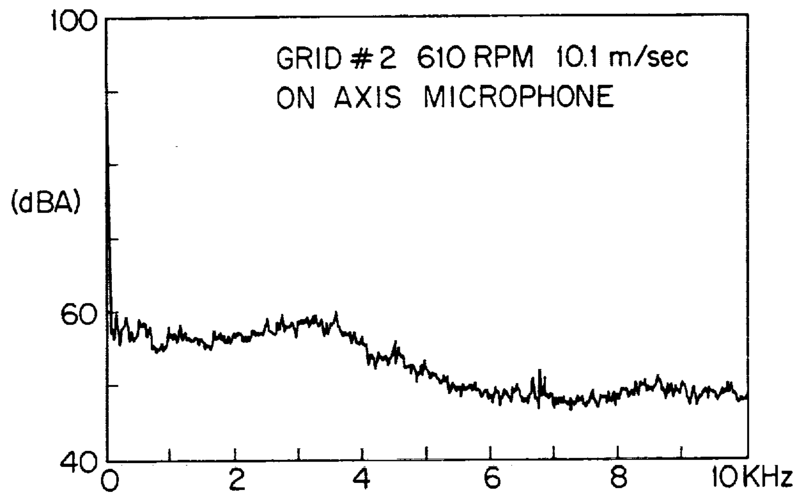


FIGURE 5 - EFFECT OF FREE STREAM VELOCITY ON SOUND PRESSURE LEVEL, $U_o$ = 10.1 m/s

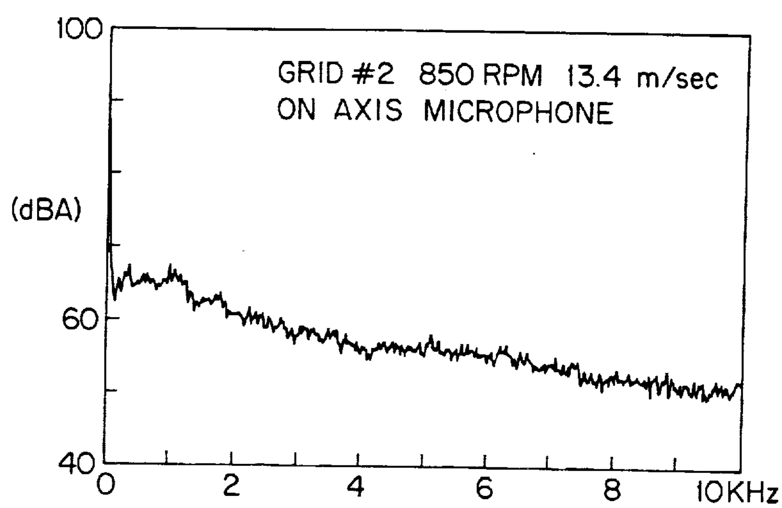


FIGURE - 6 EFFECT OF FREE STREAM VELOCITY ON SOUND PRESSURE LEVEL, $U_o$ = 13.4 m/s

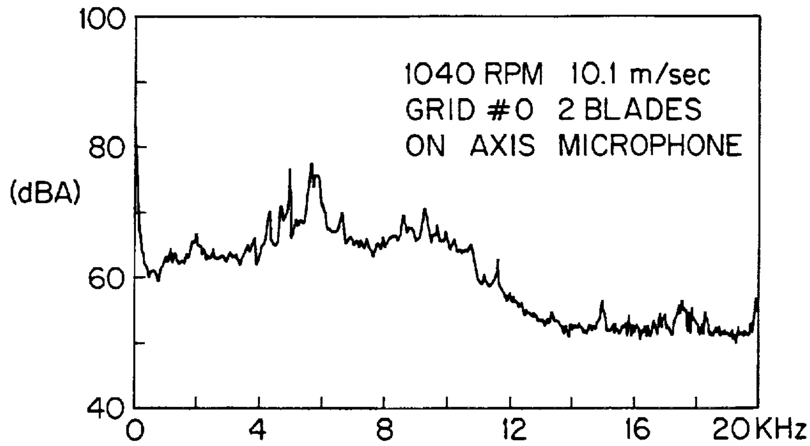


FIGURE 7 - EFFECT OF NUMBER OF BLADES ON SOUND PRESSURE LEVEL, B = 2

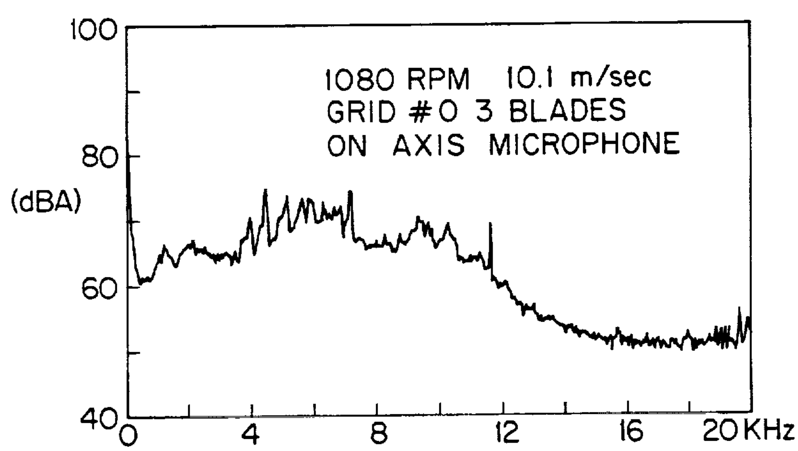


FIGURE 8 - EFFECT OF NUMBER OF BLADES ON SOUND PRESSURE LEVEL, B = 3

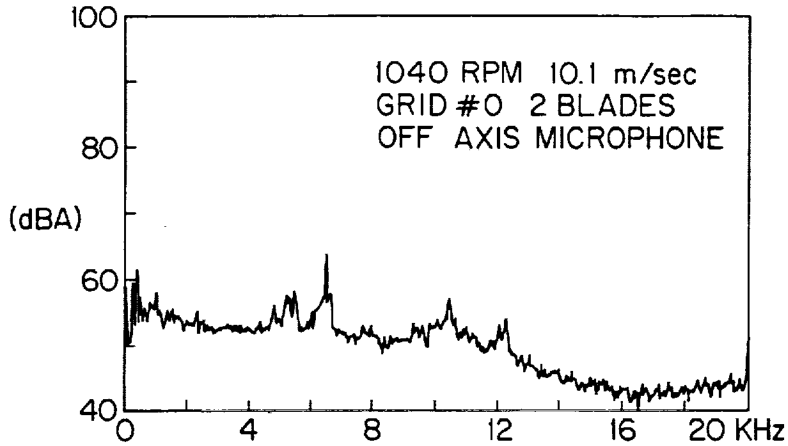


FIGURE 9 - SOUND PRESSURE LEVEL, NO GRID, B = 2, OFF AXIS MICROPHONES

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**13. ABSTRACT** ***(Maximum 200 words)***

A major program of research and development projects on wind turbines for generating electricity was conducted at the NASA Lewis Research Center from 1973 to 1988. Most of these projects were sponsored by the U.S. Department of Energy (DOE), as a major element of its Federal Wind Energy Program. One other large-scale wind turbine project was sponsored by the Bureau of Reclamation of the U.S. Department of Interior (DOI). From 1988 to 1995, NASA wind energy activities have been directed toward the transfer of technology to commercial and academic organizations. As part of these technology transfer activities, a total of 22 previously unpublished manuscripts have been assembled and are presented here in order to share the results of valuable research on wind turbines with the wind energy community. A wide variety of wind turbine technology topics are discussed, including the following: Wind and wake models–3 papers; Airfoil properties–5 papers; Structural analysis and testing–5 papers; Control systems–3 papers; Variable-speed generators–3 papers; Acoustic noise–3 papers. Both experimental and theoretical investigations are described, with results which are relevant to the design, analysis, and testing of modern wind turbines. Wind energy activities sponsored under or related to the NASA/DOE wind turbine development program are documented in approximately 620 publications by over 520 authors and coauthors. A complete listing of citations to these publications, many with abstracts, can be obtained from the following reference: Spera, D.A., 1995, *Bibliography of NASA-Related Publications on Wind Turbine Technology, 1973–1995*, NASA CR-195462, DOE/NASA/5776-3, Cleveland, Ohio: NASA Lewis Research Center.

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