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WIND TURBINE ACOUSTICS RESEARCH – BIBLIOGRAPHY WITH SELECTED ANNOTATION

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CONTENTS

INTRODUCTION

This document has been prepared as part of the Department of Energy Wind Energy Program which is managed by the Solar Energy Research Institute. It is a selected bibiography, with some annotation, of wind turbine acoustics research papers. They are grouped together for convenience into the following sections: General Wind Turbine Acoustics Publications; Wind Turbine Noise Generation, Prediction and Measurements; Wind Turbine Noise Propagation; Effects of Wind Turbine Noise on People and Communities; Effects of Wind Turbine Noise on Buildings; and Wind Turbine Noise Measurement Technology. For those sections relating to propagation, measurement and the effects of noise; some generally relevant papers are also included.

The intent is to include those English language papers which collectively represent the state of the art in each of the subject areas. Certain key documents are listed first and abstracts are included when available. Other documents are then listed in chronological order without annotation. All documents are believed to be available, on request, from one of the sources listed below. The appropriate acquisition numbers are included when available to facilitate the filling of requests from the following sources:

Source	Type of Material	Acquisition Number
American Institute of Aeronautics and Astronautics Technical Information Service 555 West 57th St., 12th Floor New York, NY 10019	AIAA papers and published literature available from AIAA or in journals, conferences, etc., as indicated	A Numbers Example: A75-25583
National Technical Information Service (NTIS) 5285 Port Royal Road Springfield, VA 22161	Report literature having no distribution limitation	N Numbers Example: N67-37604
NASA Scientific and Technical Information Facility (STIF) P. O. Box 8757 B.W.I. Airport, MD 21240	Report literature having some kind of distribution limitation	X Numbers Example: X71-83753
	Tech Briefs	B Numbers Example: B63-10579
Defense Technical Information Center Cameron Station Alexandria, VA 22314	Report literature with or without distribution limitation	AD Numbers Example: AD 475 662

For those documents having no acquisition number listed, copies may be obtained from NTIS, provided a complete citation is furnished. Some relevant documents have not been listed because it is known that certain material was published in other forms. In the latter case, preference is given to the more recent publications. Many of the key documents, particularly those listed as general publications, have extensive reference lists and bibliographies which are complementary to those listed herein.

GENERAL WIND TURBINE ACOUSTICS PUBLICATIONS

1. Thresher, Robert W., Editor: **Wind Turbine Dynamics.** Proceedings for a Workshop held at Cleveland State University, Cleveland, OH, February 24-26, 1981, NASA CP 2185, 1981.

N82-23684

Included in this document are ten individual papers relating to a wide range of topics in the acoustics of wind turbines. Information is presented for full scale and model measurements of noise from the MOD-1 machine, comparisons of theory and measurements, prediction methodology, refractive focusing due to wind gradients and wind turbine acoustic standards for community acceptance.

2. Anonymous: Proceedings of the 1981 Wind Energy Technology Conference, University of Missouri, Columbia, MO, March 1981.

N83-73571

3. Stephens, David G.; Shepherd, Kevin P.; Hubbard, Harvey H.; and Grosveld, Ferdinand W.: **Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines.** NASA TM 83288, March 1982.

N82-24051

This document is intended for use in designing and siting future large wind turbine systems as well as for assessing the noise environment of existing wind turbine systems. Guidance for evaluating human exposure to wind turbine noise is provided and includes consideration of the source characteristics, the propagation to the receiver location, and the exposure of the receiver to the noise. The criteria for evaluation of human exposure are based on comparisons of the noise at the receiver location with the human perception thresholds for wind turbine noise and noise-induced building vibrations in the presence of background noise.

4. Seebold, J. C., Editor: Proceedings of InterNoise 82, The 1982 International Conference on Noise Control Engineering, May 17-19, 1982, San Francisco, Ca, Vols. I and II, 1982.

This document contains extended abstracts of seven papers presented in a special session on wind turbine acoustics. Included are noise emission characteristics of large wind turbines, noise prediction methods, wind tunnel noise measurements, parametric evaluations and acoustical criteria for siting and operations.

5. Anonymous: Proceedings of the IEA Workshop on Wind Turbine Noise Measurements, Stockholm, Sweden, November 12-13, 1984. The Aeronautical Research Institute of Sweden, FFAP-110, 1984.

N86-29619

Seven individual papers relating to measurement of background noise around wind turbines; masking of wind turbine noise by wind noise; acoustic power levels of wind turbines; wind turbine noise; and tower wake effects on wind turbine noise.

6. Anonymous: **Implementing Agreement for Cooperation in the Development of Large Scale Wind Energy Conversion Systems.** Proceedings of 11th Experts Meeting on General Environment Aspects of Large Scale Wind Utilization, Munich, May 7-9, 1984, organized by Kernsforschungsanlage, Juelich, West Germany and Tech. University of Denmark. Report No. JUEL-SPEZ-278, November 1984.

N85-35473

Fourteen individual papers relating to the effects of megawatt-sized wind energy converters on noise pollution, television reception, birds, agriculture and scenery are included. Also covered are site selection, performance assessment and safety factors.

7. Kelly, N. D.; McKenna, H. E.; Hemphill, R. R.; Etter, C. L.; Garrelts, R. L.; and Linn, N. C.: **Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact and Control.** SERI/TR-635-1166, February 1985.

N85-29700

Extensive research by staff of the Solar Energy Research Institute and its subcontractors conducted to establish the origin and possible amelioration of acoustic disturbances associated with the operation of the DOE/NASA MOD-1 wind turbine installed in 1979 near Boone, North Carolina is summarized. Results have shown that the source of this acoustic annoyance was the transient, unsteady aerodynamic lift imparted to the turbine blades as they passed through the lee wakes of the large, cylindrical tower supports. Nearby residents were annoyed by the low-frequency, acoustic impulses propagated into the structures in which the complainants lived. The situation was aggravated further by a complex sound propagation process controlled by terrain and atmospheric focusing. Several techniques for reducing the abrupt, unsteady blade load transients were researched and are discussed.

8. Kelly, N. D.; McKenna, H. E.; Jacobs, E. W.; Hemphill, R. R.; and Birkenheur, N. R.: **The MOD-2 Wind Turbine: Volume I, Aeroacoustical Noise Sources, Emissions and Potential Impact.** SERI/TR-217-3036, April 1987.

A description is given of an extensive series of acoustic measurements at the MOD-2 Wind turbine site at Goldendale, WA. Sound pressure level and spectral data are presented for frequencies from sub audible range, for single and multiple machines. The resultant noise is shown to be related to atmospheric parameters such as wind speed and stability.

9. Viterna, L. A.: **Method for Predicting Impulsive Noise Generated by Wind Turbine Rotors.** NASA TM 82794, 1982.

N82-21714

Since regular operation of the DOE/NASA MOD-1 wind turbine began in October 1979 about 10 nearby households 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 enhancing 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.

10. Hubbard, H. H.; and Shepherd, K. P.: **Noise Measurements for Single and Multiple Operation of 50KW Wind Turbine Generators.** NASA CR 166052, December 1982.

N83-17236

The noise characteristics of the U.S. Windpower Inc., 50 kw wind turbine generator have been measured at various distances from 30 m to 1100 m and for a range of output power. The generated noise is affected by the aerodynamic wakes of the tower legs at frequencies below about 120 Hz and the blade trailing edge thickness at frequencies of about 2 kHz. Rope strakes and airfoil fairings on the legs did not result in substantial noise reductions. Sharpening the blade trailing edges near the tip was effective in reducing broad band noise near 2 kHz.

For multiple machines the sound fields are superposed. A three-fold increase in number of machines (from 1 to 3) results in a predicted increase in the sound pressure level of about 5 dB. The detection threshold for 14 machines operating in a 13 - 20 mph wind is observed to be at approximately 1160 m in the downwind direction.

11. Hubbard, H. H.; Grosveld, F. W.; and Shepherd, K. P.: **Noise Characteristics of Large Wind Turbine Generators.** Noise Control Engineering Journal, vol. 21, no. 1, pp. 21-29, 1983.

A83-43638

The noise characteristics of three representative large wind turbine generators are summarized. The main noise sources are identified along with state of the art noise prediction methods. Loading noise components are a characteristic of downwind machines and are usually confined to frequencies below 100 Hz. Broadband components extend throughout the audible frequency range and are observed for both upwind and downwind machines.

12. Marcus, E. N.; and Harris, W. L.: **An Experimental Study of Wind Turbine Noise from Blade-Tower Wake Interaction.** AIAA Reprint No. 83-0691, 1983.
A83-25913

A program of experiments has been conducted to study the impulsive noise of a horizontal axis wind-turbine. These tests were performed on a 1/53 scale model of the DOE-NASA MOD-1 wind turbine. Experiments were performed in the M.I.T. 5' x 7-1/2' Anechoic Wind tunnel Facility. The impulsive noise of a horizontal axis wind turbine is observed to result from repeated blade passage through the mean velocity deficit induced in the lee of the wind turbine support tower. The two factors which most influence this noise are rotation speed and tower drag coefficient. The intensity of noise from blade tower wake interaction is predicted to increase with the fourth power of the RPM and the second power of the tower drag coefficient. These predictions are confirmed in experiments. Further experiments are also presented in order to observe directionality of the acoustic field as well as the acoustic influence of tower shape and blade number.

13. Grosveld, F. W.: **Prediction of Broadband Noise from Horizontal Axis Wind Turbines.** Journal of Propulsion and Power, vol. 1, no. 4, July-August 1985.
A85-39583.

A method is presented for predicting the broadband noise spectra of horizontal axis wind turbine generators. It includes contributions from such noise sources as the inflow turbulence to the rotor, the interactions between the turbulent boundary layers on the blade surfaces with their trailing edges, and the wake due to a blunt trailing edge. The method is partly empirical and is based on acoustic measurements of large wind turbines and airfoil models. The predicted frequency spectra are compared with measured data from several machines, including the MOD-OA, MOD-2, WTS-4, and U.S. Windpower Inc. machine. The significance of the effects of machine size, power output, trailing-edge bluntness, and distance to the receiver is illustrated. Good agreement is obtained between the predicted and measured far-field noise spectra.

14. Kelly, N. D.; McKenna, H. E.; Hemphill, R. R.; Etter, C. L.; Garrelts, R. L.; and Linn, N. C.: **Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact and Control.** SERI/TR-635-1166, February 1985.
N85-29700

Extensive research by staff of the Solar Energy Research Institute and its subcontractors conducted to establish the origin and possible amelioration of acoustic disturbances associated with the operation of the DOE/NASA MOD-1 wind turbine installed in 1979 near Boone, North Carolina is summarized. Results have shown that the source of this acoustic annoyance was the transient, unsteady aerodynamic lift imparted to the turbine blades as they passed through the lee wakes of the large, cylindrical tower supports. Nearby residents were annoyed by the low-frequency, acoustic impulses propagated into the structures in which the complainants lived. The situation was aggravated further by a complex sound propagation process controlled by terrain and atmospheric focusing. Several techniques for reducing the abrupt, unsteady blade load transients were researched and are discussed.

15. Shepherd, K. P.; and Hubbard, H. H.: **Prediction of Far Field Noise from Wind Energy Farms.** NASA CR 177956, April 1986.

N86-25215

Included in this paper are a review of the basic physical factors involved in making predictions of wind turbine noise; and an approach which allows for differences in the machines, the wind energy farm configurations and propagation conditions. Example calculations are presented to illustrate the sensitivity of the radiated noise to such variables as machine size, spacing and numbers; and such atmosphere variables as absorption (relative humidity and temperature) and wind direction. Calculated far field distances to particular sound level contours are greater for lower values of atmospheric absorption, for a large total number of machines, for additional rows of machines and for more powerful machines. At short and intermediate distances, higher sound pressure levels are calculated for closer machine spacings, for more powerful machines, for longer row lengths and for closer row spacings.

16. Kelly, N. D.; McKenna, H. E.; Jacobs, E. W.; Hemphill, R. R.; and Birkenheur, N. R.: **The MOD-2 Wind Turbine: Volume I, Aeroacoustical Noise Sources, Emissions and Potential Impact.** SERI/TR-217-3036, April 1987.

A description is given of an extensive series of acoustic measurements at the MOD-2 wind turbine site at Goldendale, WA. Sound pressure level and spectral data are presented for frequencies from sub audible to the normal audible range, for single and multiple machines. The resultant noise is shown to be related to atmospheric parameters such as wind speed and stability.

17. Shepherd, K. P.; Hubbard, H. H.; and Willshire, W. L.: **Results of Simultaneous Acoustic Measurements Around a Large Horizontal Axis Wind Turbine Generator.** Proposed NASA TM.

The large data set is useful in characterizing the acoustic output of the WTS-4 machine for comparison with available prediction methods. It is also useful for defining the directivity patterns for the various noise components including both the low frequency rotational harmonics and the higher frequency broadband noise.

18. Hubbard, H. H.; and Shepherd, K. P.: **Wind Turbine Noise.** Chapter 6 of ASME/DOE Wind Turbine Technology Book, 1988.

Included in this chapter are discussions of the physical characteristics of wind turbine noise, prediction methodology for noise from single and multiple machines, atmospheric propagation, evaluation of receiver responses both indoors and outdoors, and a summary of measurement technology including wind screens.

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31. Martinez, R.; Widnall, S. E.; and Harris, W. L.: **Predictions of Low Frequency and Impulsive Sound Radiation from Horizontal Axis Wind Turbines.** NASA CP 2185, February 1981. Also Journal of Solar Energy Engineering, May 1982, pp. 401-409.

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A general review is presented of most areas of sound-propagation that are of interest for the control of community noise. These areas are geometrical spreading, atmospheric absorption, ground effect, (near horizontal propagation in a homogenous atmosphere close to flat ground), refraction, the effect of atmospheric turbulence, and the effect of topography (elevation, hillsides, foliage, etc.). The current state of knowledge in each area is presented and suggestions made concerning research activities, applications of existing research, and practical problems which arise in the prediction of noise levels.

94. Thompson, D. W.: **Analytical Studies and Field Measurements of Infra-Sound Propagation at Howard's Knob, NC.** Dept. of Meteorology, Penn State University, Final Report, September 18, 1980.

Meteorology studies have been conducted for the locale of the MOD-1 machine in an attempt to explain the apparent focusing of its noise in some nearby communities. Data from radiosound and sodar soundings were used as a basis for modeling the acoustic propagation at the site. Results of computed ray tracing runs clearly showed that caustics (zones of enhancement) could occur in the region of complainants homes.

95. Shepherd, K. P.; and Hubbard, H. H.: **Sound Propagation Studies for a Large Horizontal Axis Wind Turbine.** NASA CR 172564, March 1985.

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Included in this paper are the results of systemmatic noise measurements in three directions with respect to the wind vector, over a range of distances to 1050 m, over a range of frequencies from 8 Hz to 2000 Hz, and for a stable wind turbine noise source (WTS-4) in windy conditions (V = 9.4 - 13.0 m/s). At frequencies above 63 Hz in the downwind and crosswind directions the sound pressure levels decay with distance according to predictions based on atmospheric absorption and spherical spreading, assuming no excess attenuation due to ground effects. In the upwind direction there is excess attenaution due to an acoustic shadow zone. The assumption of a distributed noise source leads to better noise estimates in the upwind direction. For very low frequencies (8-16 Hz) no excess attenuation was observed in the upwind direction at distances up to 1050 m and a sound pressure level decay rate of approximately 3 dB per doubling of distance was observed in the downwind direction.

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The propagation of low-frequency noise outdoors was studied using as the source a large (80-m diameter) 4-megawatt horizontal axis wind turbine. Acoustic measurements were made with low-frequency microphone systems placed on the ground at downwind sites ranging from 300 m to 20,000 m and at upwind sites ranging from 200 m to 4,000 m away from the wind turbine. The wind turbine fundamental was 1 Hz and the wind speed was generally 12 - 15 m/s at the hub height (80 m). The harmonic levels, when plotted versus propagation distance, exhibit a 6dB per doubling of distance devergence in the upwind direction and a 3 dB per doubling of distance divergence in the downwind direction. Predictions of both ray tracing and normal mode theoretical models supported the down wind cylindrical spreading. A consequence of this is that low-frequency noise signals propgate further in the presence of wind in the downwind direction. The measured frequency dependence and effect of boundary layer shape on the downwind horizontal exponential attenuation coefficients were consistent with normal mode theory. However, the predicted attenuation coefficients were less than those measured. In the upwind direction, no low frequency acoustic shadow zone was observed; the low-frequency acoustic signals propagated upwind exhibited spherical spreading.

97. Hawkins, J. A.: **Application of Ray Theory to Propagation of Low Frequency Noise from Wind Turbines.** Applied Research Laboratories, The University of Texas at Austin, TR-87-40, July 15, 1987, Also NASA CR-178367, July 1987.

Ray theory is used to explain the data from two experiments conducted by W. L. Willshire in which the low frequency sound levels downwind of the WTS-4 wind turbine located in Medicine Bow, Wyoming, were measured. In this thesis, general ray theory for a moving medium is reviewed and the ray equations are obtained. Restrictions are introduced that simplify the equations and allow the use of a ray theory program MEDUSA. The results are then compared to Willshire's data. In particular, the MEDUSA computed propagation loss curve is compared to Willshire's measurements. Good qualitative agreement is obtained with Willshire's 1984 downwind data. The results indicate that the downwind sound field is that of a near-ground sound channel. Although more scatter is seen in the 1985 data, agreement between theory and the data is also good. In particular, the position and magnitude of the jump in the sound levels associated with the beginning of the sound channel is correctly predicted. The comparison of theory and the 1985 upwind data is less successful. Ray theory calculations indicate the formulation of a shadow zone that, in fact, does not occur. While the sharp shadow zone predicted by using ray theory does not occur, the general expectation (based on ray theory) that the sound levels should be much reduced upwind is confirmed by the data.

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EFFECTS OF WIND TURBINE NOISE ON PEOPLE AND COMMUNITIES

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124. Stephens, D. G.; Shepherd, K. P.; Hubbard, H. H.; and Grosveld, F. W.: **Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines.** NASA TM 83288, March 1982.

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This document is intended for use in designing and siting future large wind turbine systems as well as for assessing the noise environment of existing wind turbine systems. Guidance for evaluating human exposure to wind turbine noise is provided and includes consideration of the source characteristics, the propagation to the receiver location, and the exposure of the receiver to the noise. The criteria for evaluation of human exposure are based on comparisons of the noise at the receiver location with the human perception thresholds for wind turbine noise and noise-induced building vibrations in the presence of background noise. Five appendices are included to present background information used in preparing the guide. These appendices cover wind turbine noise source characteristics, human perception thresholds, response of buildings to noise, atmospheric propagation and example calculations.

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The effects of megawatt wind energy converters on noise pollution, television reception, birds, agriculture, and scenery are included. Site selection, performance assessment, and safety factors are considered.

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Window and wall acceleration measurements and interior noise measurements were made for two different building structures during excitation by noise from the WTS-4 horizontal axis wind turbine generator operating in a normal power generation mode. Wind turbine noise input pulses resulted in acceleration pulses for the wall and window elements of the two test buildings. Responses of a house trailer were substantially greater than those for a building of sturdier construction. Peak acceleration values correlate well with similar data for houses excited by flyover noise from commercial and military airplanes and helicopters, and sonic booms from supersonic aircraft. Interior noise spectra have peaks at frequencies corresponding to structural vibration modes and room standing waves; and the levels for particular frequencies and locations can be higher than the outside levels.

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In order to empirically characterize a number of microphone windscreens of the type currently in use and to provide some indication of the mechanisms of wind induced noise, measurements of wind induced noise and windscreen insertion loss were made under laboratory conditions. Ten microphone windscreens were included in the study. Eight of these were reticulated polyester spheres of varying porosity. The remaining two windscreens were of the metal cage type generally used in long term outdoor noise monitoring. The measurements were made at two flow orientations and at seven wind speeds.

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This document describes the procedures to be used for the measurement and description of the noise emission of wind energy conversion systems (WECS). Included are definitions of symbols and commonly used terms, description of required instrumentation along with the number and location of acoustic measuring points and a list of required non-acoustic measurements.

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16. Abstract

Citations of documents are included, which represent the State of the Art of Technology in each of the following acoustics subject areas: Prediction of Wind Turbine Noise; Acoustic Measurements for Wind Turbines; Effects of Wind Turbine Noise on Building Structures, People and Communities; Atmospheric Propagation; and Measurement Technology Including Wind Screens. Documents are listed in chronological order in each section of the paper, with key documents and associated annotation listed first. The sources are given along with acquisition numbers, when available, to expedite the acquisiton of copies of the documents.

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