SANDIA REPORT

SAND87–2461 • UC–60
Unlimited Release
Printed April 1988

Modal Testing in the Design Evaluation of Wind Turbines

James P. Lauffer, Thomas G. Carne, Thomas D. Ashwill

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A02
Microfiche copy: A01

SAND87-2461
Unlimited Release
Printed April 1988

Distribution
Category UC-60

Modal Testing in the Design Evaluation of Wind Turbines

James P. Lauffer and Thomas G. Carne
Modal and Structural Mechanics Division
Thomas D. Ashwill
Wind Energy Research Division
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

In the design of large, flexible wind turbines subjected to dynamic loads, knowledge of the modal frequencies and mode shapes is essential in predicting structural response and fatigue life. During design, analytical models must be depended upon for estimating modal parameters. When turbine hardware becomes available for testing, actual modal parameters can be measured and used to update the analytical predictions or modify the model. The modified model can then be used to reevaluate the adequacy of the structural design. Because of problems in providing low-frequency excitation (0.1 to 5.0 Hz), modal testing of large turbines can be difficult. This report reviews several techniques of low-frequency excitation used successfully to measure modal parameters for wind turbines, including impact, wind, step-relaxation, and human input. As one application of these techniques, a prototype turbine was tested and two modal frequencies were found to be close to integral multiples of the operating speed, which caused a resonant condition. The design was modified to shift these frequencies, and the turbine was retested to confirm expected changes in modal frequencies.

Acknowledgments

We especially acknowledge the efforts of C. M. Grassham, M. D. Tucker, and A. J. Gomez for assistance in acquiring data and for assembling and maintaining the excitation, instrumentation, and data-gathering systems.

Contents

Figures

Table

Modal Testing in the Design Evaluation of Wind Turbines

Introduction

Figure 1 shows the Sandia 17-m wind turbine, which was one of the subjects used during this investigation. During operation, the blades and tower rotate at a constant speed. The aerodynamic forces acting on the blades are transmitted through the tower as torques to the electric generator. Because the orientation of the blades in the wind repeats itself at the constant rotation speed, the aerodynamic forces are periodic and have large spectral components at integral multiples of the rotation speed. Broadband forces caused by wind variability also act on the wind turbine, and these are added to the discrete frequency components. Because of the discrete frequency nature of the forces, an understanding of the modal characteristics of the turbine is needed to prevent the operating speed, or one of its harmonics, from coinciding with a resonance of the turbine. Understanding the modal parameters is complicated by the differences between the modal characteristics of a parked turbine and a rotating turbine.[1] Consequently, the rotational effects must be included in the computation of the modal parameters. This has been done by using a preprocessor that operates in conjunction with NASTRAN.[2,3]

The analytical model is a critical design tool since it is used to predict fatigue life, evaluate operational constraints (wind speed and rotation speed), and determine modal frequencies of the rotating turbine. As a rule of thumb, modal frequencies must be 10% away from harmonics of the operating speed, although certain modes are orthogonal to forcing functions of particular harmonics and therefore are not excited. As a result, modal frequencies must be accurately known (~3%). Typical wind-turbine mode shapes are displayed in Figure 2. Because of the accuracy required, it is critical that a finite-element model, which is used as a design tool to analyze a wind turbine, be verified by a modal survey.

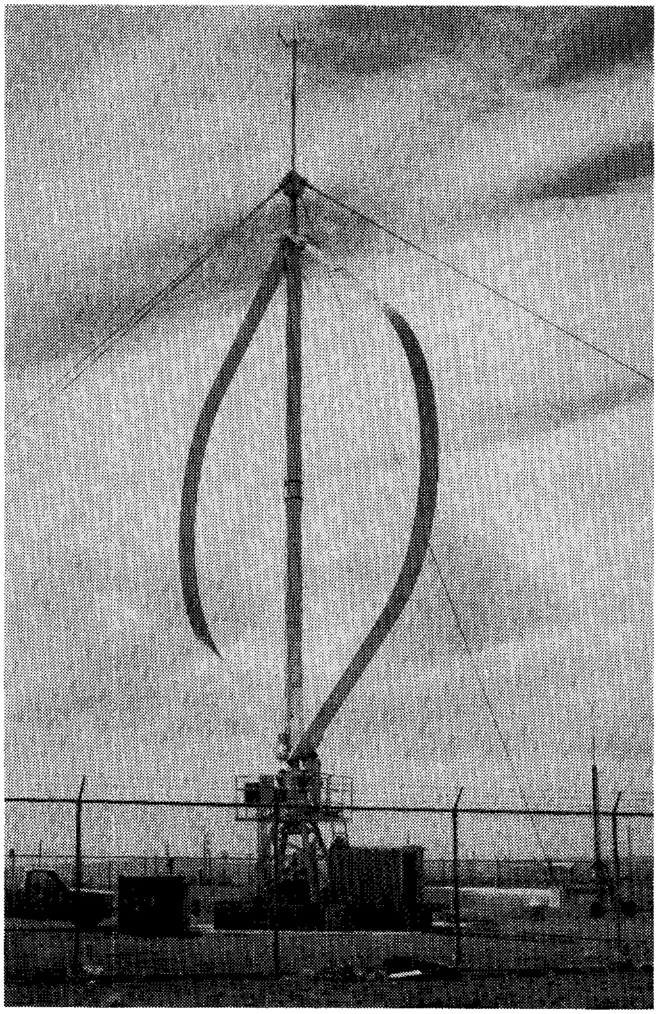
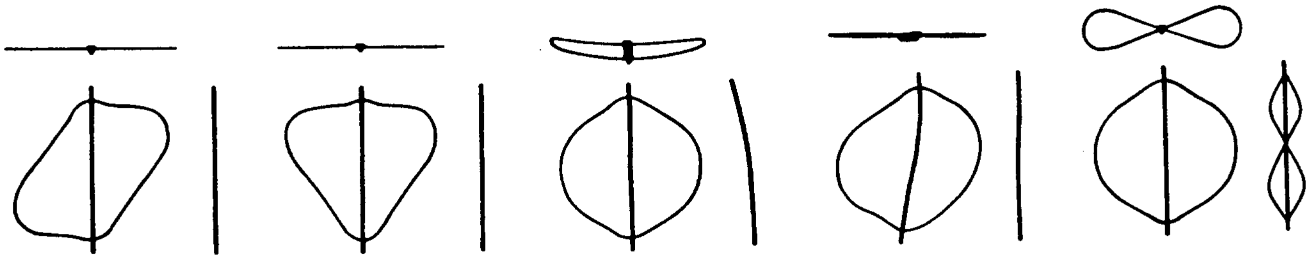
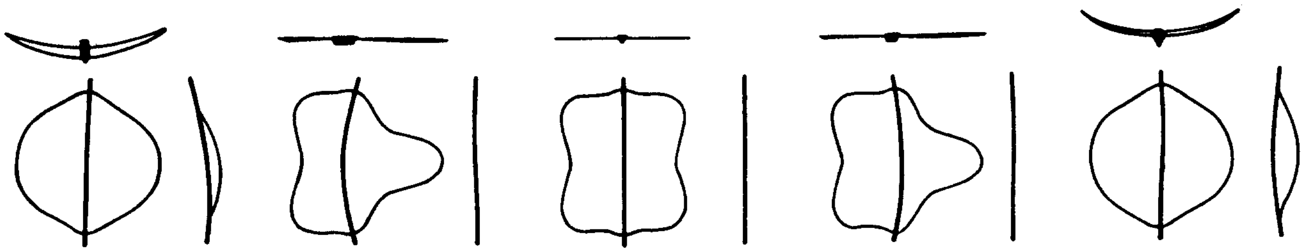


Figure 1. Sandia's 17-m Research Turbine

If the finite-element model is not accurate, it must be corrected to reflect the measured modal properties. A subsequent analysis of the wind turbine, including rotational effects, may indicate modal frequencies coinciding with one or more harmonics of the operating speed, indicating the need for a design modification.



First blade flatwise antisymmetric **First blade flatwise symmetric** **First tower out-of-plane** **First tower in-plane** **Rotor twist**



Second tower out-of-plane **Second tower in-plane** **Second blade flatwise symmetric** **Second blade flatwise antisymmetric** **Third tower out-of-plane**

Figure 2. Typical Wind-Turbine Mode Shapes

Experimental Modal Analysis

Performing a modal test of a parked wind turbine can be difficult for several reasons. First and most important is the size. Typical turbine rotors range in size from 17 to 100 m tall; therefore, mounting and moving accelerometers requires the use of a crane, which can be time consuming. Second, the modal frequencies are very low, requiring long sampling periods. On the Sandia 17-m research turbine, 11 modes are in the range of 0 to 8 Hz. Because of this low-frequency range, each time record requires over a minute. Even so, because of light damping, exponential windowing had to be applied to the data to avoid substantial leakage errors when performing the fast Fourier transforms (FFTs). Third, windy or inclement weather can lengthen the test duration. Consequently, a complete survey typically requires two people working two weeks. This time requirement can prolong product development time or affect testing schedules.

This excessive time required to perform a complete modal survey made it necessary to devise a technique that would yield sufficient data to confirm the accuracy of a model in a minimum amount of time. This led to the "mini-modal" concept. In a "mini-modal," a small number of response measurements are used in conjunction with a reasonably accurate analytical model to determine the modal frequencies and identify the mode shapes that correspond to the measured frequencies. The advantage of this technique is that it requires substantially less time than performing a complete modal survey.

Because speed was of the essence, it was necessary to use an excitation technique that would minimize the test time. Four excitation techniques were considered: step-relaxation, human, wind, and hammer impact. A pendulum-style impact technique was considered but not pursued because it required an additional crane to support the impact mass.

Step-Relaxation

The step-relaxation method of structural excitation involves applying a static load to a structure and then suddenly releasing this load. This process is analogous to plucking a violin string. Step-relaxation excitation has been critically reviewed in previous papers[4,5] and used for testing a rotating wind turbine.[6] It is a technique that has seldom been used because it can be mechanically difficult to implement and because problems are involved in performing an FFT on the Heaviside function (also referred to as the step function). However, the low-frequency content of the Heaviside function, which rolls off as 1/frequency, and the large amount of strain energy that can be input to the structure make it ideal for testing large structures with very low natural frequencies (such as wind turbines). Also, implementing this technique for large, flexible structures is mechanically straightforward.

In using step-relaxation, the loads were applied by using a winch and a reasonably light steel cable, depending upon the ultimate load. The winch was kept at ground level. A quick-release device was installed between the winch and the cable to allow an immediate relaxation of the applied load. A load cell was placed close to the structure in-line with the cable. It is important that the load cell be close to the structure so that it senses the force actually being applied to the structure. All joints in the load path were taped to avoid rattling. The entire setup is displayed in Figure 3.

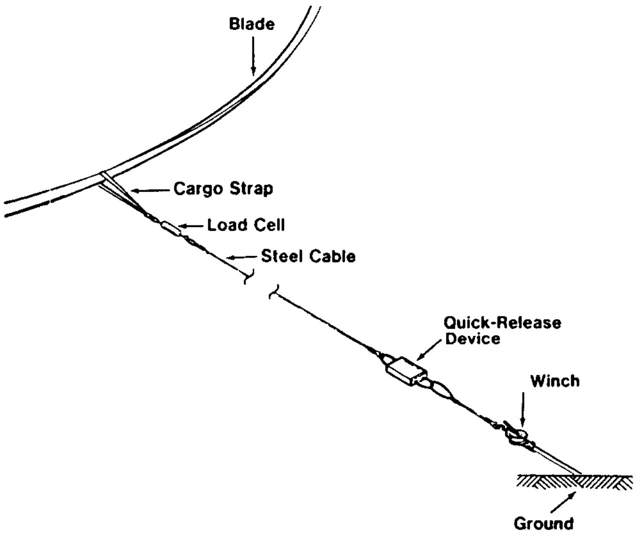


Figure 3. Step-Relaxation Hardware

Steel cable, rather than nylon rope, was used to transmit the force because it allows a crisp release of the force. If the force is relatively low (<1000 lb), it is easily applied with a hand winch. For higher force levels, a powered winch is more convenient to use. The load-cell amplifier contained a digital readout of the force to allow precise setting of the input level. The key to the setup was the quick-release device which, upon the cue of the tester, released the load.

In testing the turbines, two methods have been evaluated for attaching the excitation source to the structure: using a fixture or using a cargo strap that conforms to the shape of the structure. Although both methods yield comparable results, using a cargo strap is preferred because mass loading is negligible and no special fixturing is required.

Because these large turbines have low modal frequencies, their acceleration responses were low. Also, the transducer cables were quite long, making noise a special consideration. To address this problem, response of the structure was sensed by very high sensitivity accelerometers (1000 pC/g) with low noise cables.

The accelerometers were bonded in place with synthetic putty for easy attachment and removal. Response measurements were made normal and parallel to the blade. All signals were low-pass filtered by using external analog filters to remove out-of-band response and allow for optimal use of the analog-to-digital converters (ADCs).

Special consideration must be directed to the signal processing used for the force signal because the Heaviside (step) function cannot be Fourier transformed without tremendous leakage. To alleviate this difficulty, the force signal was ac-coupled at the input of the FFT analyzer. The ac-coupling is a high-pass filter with a 3-dB down point at 0.8 Hz. Such coupling converts the Heaviside function into a pulse with a rapidly decaying trailing edge, making the force-time history Fourier transformable without leakage. This ac-coupling also creates a pulse that allows repeatable triggering. To illustrate the leakage, which can result without the ac-coupling filters, Figure 4 shows an unfiltered force-time history; Figure 5 is the ac-coupled version of this force-time history. The magnitudes of the Fourier transforms of these time histories are displayed in Figures 6 and 7, respectively.

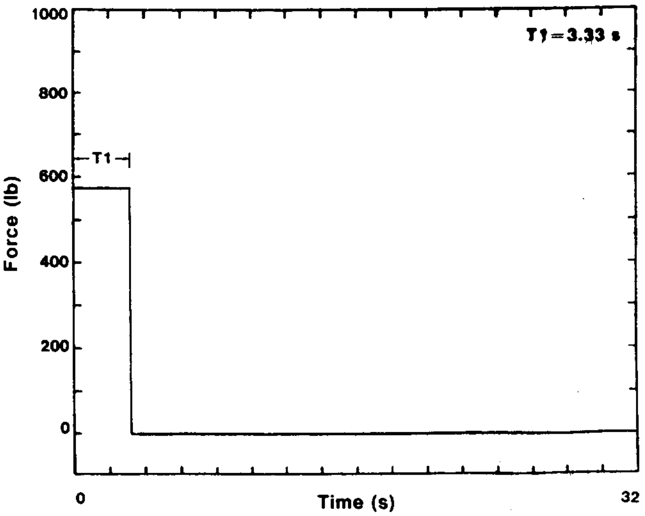


Figure 4. Unfiltered Force-Time History

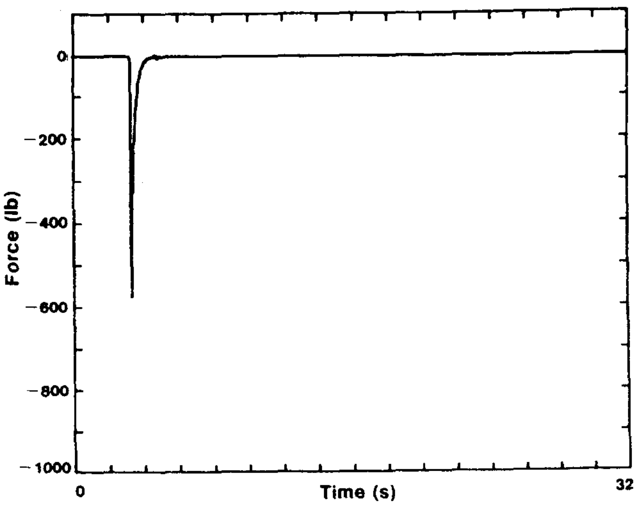


Figure 5. ac-Coupled Force-Time History

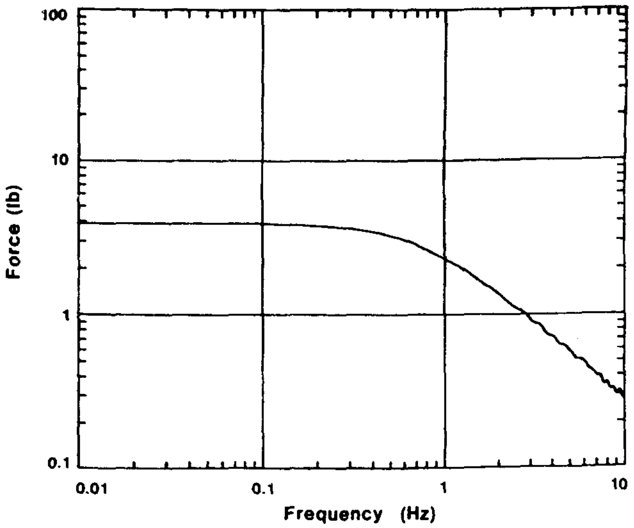


Figure 7. FFT Magnitude of ac-Coupled Force

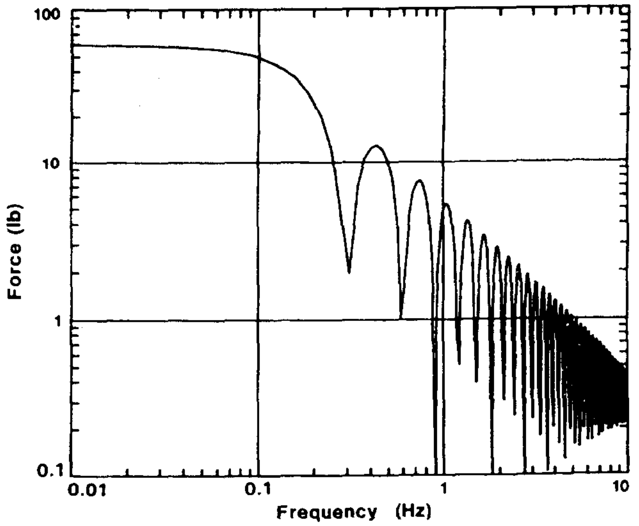


Figure 6. FFT Magnitude of Unfiltered Force

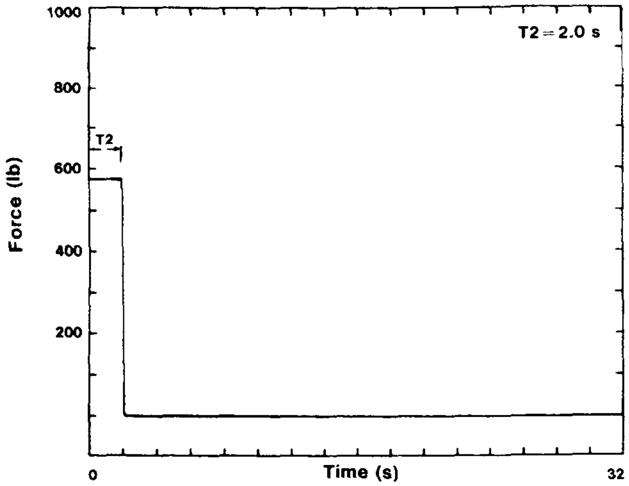


Figure 8. Unfiltered Force With Time Shift

The effect of ac-coupling the force is to generate a waveform that is totally observable within the sample window, whereas the unfiltered signal is not. As a result, no leakage error is associated with transforming the filtered signal. The finite sample time causes the unfiltered force to appear as a rectangular pulse whose width is shown as T1 in Figure 4. Varying the delay period (Figure 8) has the effect of changing the pulse width, thereby altering the form of the Fourier transform magnitude (Figure 9). The holes in the Fourier transform magnitude appear at multiples of the inverse of the pulse duration (1/T).

The response signals were also ac-coupled to cancel the effects of high-pass filtering of the force signal when computing the frequency-response functions. This ac-coupling of the channels did not induce a detectable phase shift between channels.

An alternative to ac-coupling the channels would be to differentiate both the input and response signal in the time domain.[7] This would result in the excitation appearing as sharp pulse. The resulting response would be the time derivative of acceleration (jerk). This technique was not pursued because it requires additional data processing and tends to increase noise levels, whereas the first method can be directly implemented by using standard data-acquisition techniques. After ac-coupling, the resulting input and response signals are not unlike those obtained by impact testing and can be processed in a similar manner. For example, one can apply a force or exponential window. Exponential windowing is particularly important for removing structural response caused by wind excitation, after the response caused by the intended excitation has diminished. If the response of the structure to wind excitation is not significant, comb filtering could also be used to eliminate leakage.[8] A typical frequency-response function measurement using step-relaxation is shown in Figure 10.

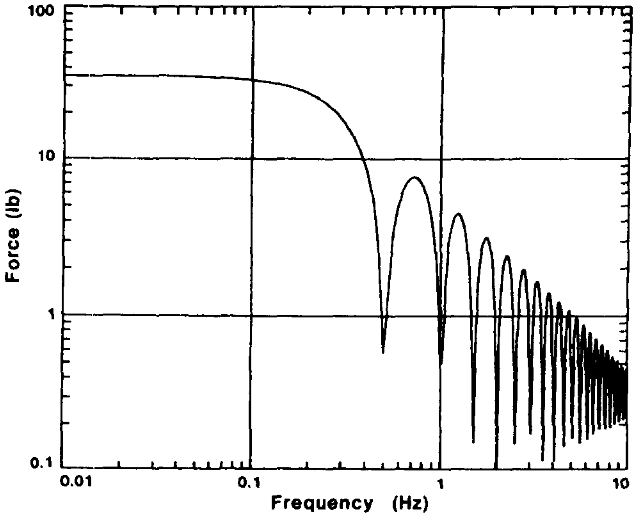


Figure 9. FFT Magnitude of Time-Shifted Force

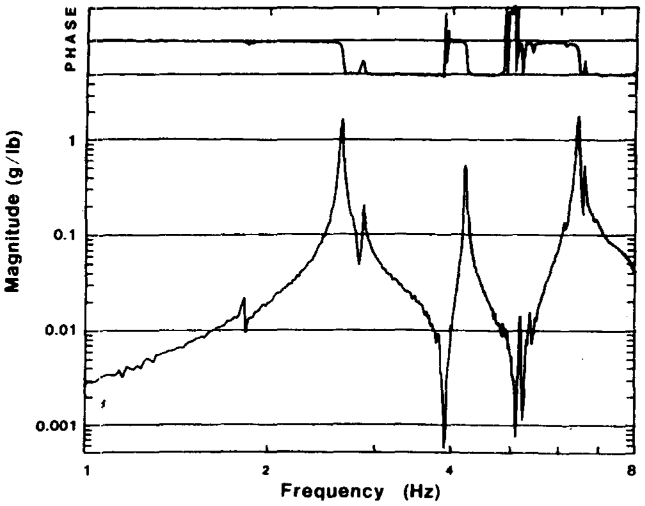


Figure 10. Typical Frequency-Response Function Measured Using Step-Relaxation

Frequency-response functions are the desired quantities being measured during a step-relaxation test. These functions are curve-fitted to extract the modal frequencies, damping, and mode shapes. Performing a "mini-modal" test is identical to a complete modal survey except that fewer frequency-response functions are measured. Consequently, modal frequency, damping, mode vector entries, and modal mass can be determined by standard curve-fitting algorithms. The obvious drawback to this technique with respect to a complete modal survey is that a detailed mode-shape description is not available. Therefore, some confusion might arise when modes are closely spaced.

Human Excitation

Human excitation is exactly what its name implies—a person shakes the turbine directly or with a rope. This technique has been applied to moderate-size turbines; application to large turbines may not be easily implemented. Either of two types of tests can be performed: forced response or free vibration decay. Forced-response testing is equivalent to performing a sine dwell test. The person supplying the force shakes the turbine and synchronizes in on the natural vibration. The turbine is then driven at this frequency at a constant response level while an acceleration power spectrum of the driving-point response is measured. The resultant peak in the power spectrum occurs at the resonance frequency. A typical example of a power spectrum measured in this manner is shown in Figure 11.

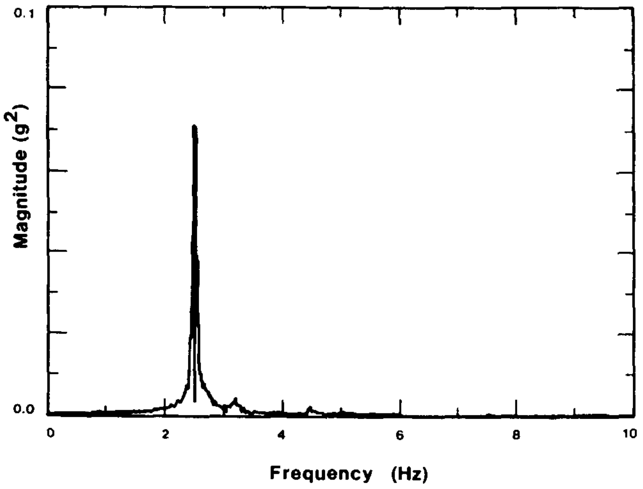


Figure 11. Driving-Point ASD Measured During Human Excitation

Free-decay measurements are similar to forced response except that after the turbine is excited to the desired steady-state level, the input excitation is halted, and the vibrational decay of the structure is measured. Curve-fitting algorithms can then be used to extract modal frequency and damping from this free decay of the structure. A typical free-decay curve is shown in Figure 12.

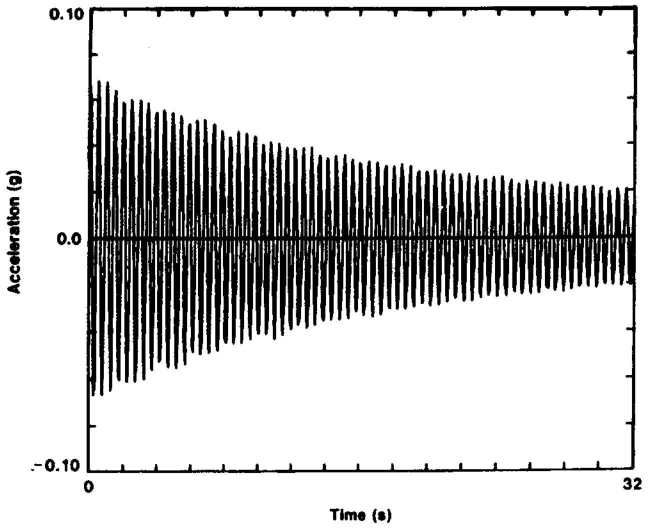


Figure 12. Free Vibration Response Measurement

Either of these two techniques is repeated at different directions and locations and at various frequencies until all of the modal frequencies of interest are determined.

Because the mode-shape characteristics of the turbine are known before the test from the finite-element model, the tester actually tries to excite one particular mode when he shakes the wind turbine. This is accomplished by exciting a point in a direction where a particular mode has a large participation and other modes participate very little. The fact that the tester has excited a particular mode is verified by visually observing the deformation pattern. In fact, the mode can be studied in some detail while the structure is being excited. Because it is relatively easy to excite any point on the structure, this is an excellent method for decoupling closely spaced modes.

The low-frequency modes are extremely easy to excite because the vibration amplitude is large and the motion of the turbine is slow enough for the exciter to track. In fact, the amplitude of vibration for these modes can be as much as a foot. Exciting the higher-frequency modes, above 4 Hz, is more difficult because consistently maintaining the higher frequencies is physically demanding and the exciter eventually falls out of sync. Also, because of the higher frequencies, the displacement of a given mode is smaller, making the deformation pattern harder to observe. In this instance, more reliance is placed on the model to determine the mode shape. Exciting the structure at frequencies above 5 Hz was virtually impossible.

An original concern was that the human exciter might mass-load the structure. Yet, this did not occur, presumably because the individual exciting the structure did not simply go along for the ride; he sensed the vibration and applied a force that was ~90° out of phase with the displacement and sufficient to maintain motion. As a result, mass loading was negligible, evidenced by the fact that natural frequencies determined by this method and by step-relaxation were essentially the same. The only instruments used were an accelerometer, transducer cable, amplifier, and an FFT analyzer, all of which could be placed in the back of a pickup truck, from which the test could be directed.

Benefits of human excitation include fast results, accurate natural-frequency information, and qualitative mode-shape information. The negative aspects are that modal frequencies above 4 Hz were difficult to obtain and quantitative mode-shape information was not available.

Wind Excitation

Wind can be used as an excitation source because of its availability and its ability to excite the structure—the vibration of wind turbines can be visually observed during moderate winds. For a fully instrumented prototype, all necessary response data can be collected on the parked turbine during high winds. Response auto-spectral densities (ASD) and cross-spectral densities (CSD) can be used to determine modal frequencies and mode shapes. Figure 13 shows an acceleration ASD measured during high winds for the 100-m EOLE turbine, displayed using a log scale. The peaks clearly indicate the presence of modes at the frequencies of the peaks.

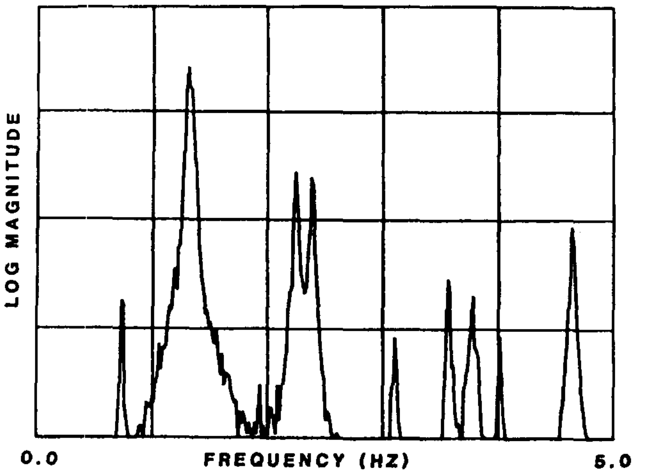


Figure 13. Acceleration ASD Measured During High Winds

The procedure for performing wind-excitation testing is similar to that used in performing step-excitation testing. One significant difference is that the forces acting on the structure are not measured. Several reference degrees-of-freedom (DOFs) are selected based upon their degree of participation in each of the mode shapes. The complete set of references should strongly participate in all of the modes of the structure within the frequency band of interest. From the response measurements, ASDs of the reference DOFs are evaluated, and CSDs are computed between the response DOFs and the reference DOFs.

The modal frequencies are determined from the peaks in the ASDs of the reference DOFs and the peaks of a mode-indicator function. The indicator function is created by summing the magnitude squared of response ASDs. Particular modes can be enhanced by selecting response DOFs based upon a knowledge of the mode shape. Shown in Figure 14 is a typical mode-indicator function calculated to enhance the flatwise blade modes. The mode shapes are then computed from the ratios of the CSDs and a reference ASD. The values from these ratios at the resonant frequency are taken as the corresponding components of the mode-shape vector.

Hammer Excitation

Hammer excitation has been attempted with a PCB 12-lb impact hammer on a moderate-size turbine. Although reasonable success was obtained with this technique in that frequency-response functions could be measured, the drawbacks were considerable: (1) Because of the low-frequency range of interest, excitation could not be properly shaped by adjusting hammer tip stiffness and hammer mass. Also, foam pads used to decrease the hammer tip stiffness yielded inconsistent results. (2) Impacting at oblique angles to the blades would require special fixturing. (3) Inconsistent impacts overloaded the ADC, requiring additional averages that took more time. (4) For larger turbines, it may not be possible to input enough energy to excite the structure sufficiently. It was felt that these problems could be overcome or tolerated; but because the other techniques worked well and required little time, this excitation method has not been pursued.

Modal Testing in the Design Process: An Example Implementation

A typical application of the use of modal testing as part of the design process was the VAWTpower 185. The excitation techniques used were human excitation and step-relaxation.

For the step-relaxation portion of the test, one driving point was used. It was on a blade at an angle of ~45° with respect to the plane defined by the blades and the tower. From this location, all modes of interest could be excited. Frequency-response functions were measured at three points on the turbine, using three triaxial accelerometers: at the driving point, on the second blade at a point opposite the driving point, and at the midpoint on the tower. The accelerometer mounting locations are shown in Figure 15. Of the nine frequency-response functions measured, only five were required to identify the modal parameters for the VAWTpower 185; the other four were obtained with no additional effort because triaxial accelerometers were used.

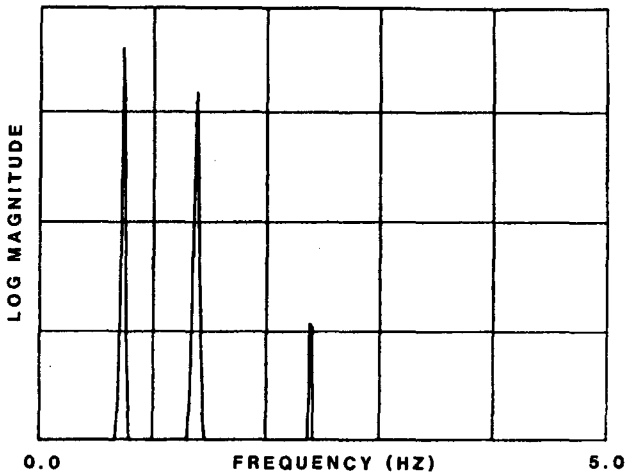


Figure 14. Mode Indicator Function

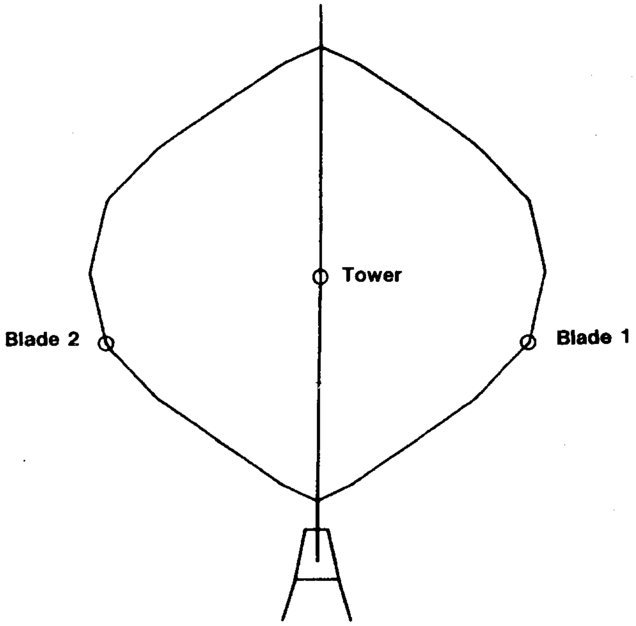


Figure 15. Accelerometer Locations for Step-Relaxation Test

The frequency-response functions measured on blade 1 revealed the first and second flatwise modes, first tower in-plane, and first and second tower out-of-plane. The edgewise frequency-response functions measured for blade 2 yielded phase information to separate and identify the third tower out-of-plane and the rotor twist mode. The in-plane frequency-response functions measured for the tower indicated the second tower in-plane mode. All of these modes are illustrated in Figure 2. Proper modal identification was cross-checked by reviewing each of the frequency-response functions to determine whether they were consistent with the assumed mode shapes. The number of frequency-response functions could have been reduced to three (those on blade 1) if only the first six modes were required. From start to finish, this "mini-modal" test took just one day, including setup time, data interpretation, and mode-shape identification.

After the modal data were identified using step-relaxation, the turbine was tested using human excitation. The human exciter gained access to the turbine by standing in a manbucket and being lifted into position by a crane. The bucket was positioned at various points of the turbine where the modes of interest had large participation factors. At these locations, accelerometers were mounted and the structure was excited by hand. Using an FFT analyzer, the accelerometer output was processed into auto-spectral densities. The crane positioned the bucket at three locations, from which all modes of interest were excited.

Both excitation techniques took about the same time (less than one day) and yielded virtually identical results. The modal frequencies determined using human and step-relaxation excitation and finite-element analysis are listed in Table 1.

Table 1. Modal Frequencies of VAWTpower 185 (Hz)

Description	Finite Element (Initial)	Step Relaxation	Human	Finite Element (Final)
Propeller	0.44	0.45	0.43	0.44
First blade flatwise symmetric & anti-symmetric	1.72	1.36	1.35	1.37
First tower out-of-plane	2.34	1.75	1.75	1.72
First tower in-plane	2.84	2.53	2.54	2.58
Second blade flatwise symmetric	3.77	3.17	3.15	3.14
Second tower out-of-plane	4.01	3.20	3.20	3.21
Second blade flatwise anti-symmetric	3.80	3.23	3.15	3.23

A comparison of the finite-element analysis and testing results revealed that the initial finite-element model needed to be corrected. The model was reviewed in detail and several changes and corrections were made. The resultant model predicted modal frequencies within 3% of the measured modal frequencies for the parked turbine (see Table 1). As a further check on the accuracy of the model, the modes of the turbine, including the effects of rotation, were computed and compared to the modal frequencies determined from turbine operating data. The agreement was very good.

The updated model then predicted that two modal frequencies occurred near harmonics of the operating speed, causing high stresses in the prototype turbine. The two modes causing the problem were the first flatwise symmetric and the first tower in-plane (see Figure 2). These two modes had their modal frequencies at nearly two and three times the turbine rotation speed (0.84 Hz). The occurrences of resonant conditions are clearly revealed in the fan plot display of Figure 16. This plot shows the modal frequencies versus turbine operating speed with the harmonic lines superimposed on the plot. Wherever modal frequencies approach a harmonic line, resonance can occur.

Because the resonant conditions caused high stress and reduced the fatigue life of the turbine, a design modification of the turbine was required. The finite-element model was used to investigate possible structural improvements to the turbine. The first design iteration involved stiffening the blade-to-tower joints with an added strut between the tower and each blade. A mini-modal, using human excitation, was quickly performed to determine experimentally the shifts in the modal frequencies. An additional mini-modal survey was conducted to determine the effects of decreasing cable tension, which reduces cable stiffness. The final modifications to the turbine included three design changes: (1) stiffening the blade-to-tower joints by adding struts, (2) increasing the guy cable stiffness by doubling the cable cross-section, and (3) reducing by one-half the length of the tower between the base and the blades. These alterations to the turbine have eliminated any near-resonance problem.

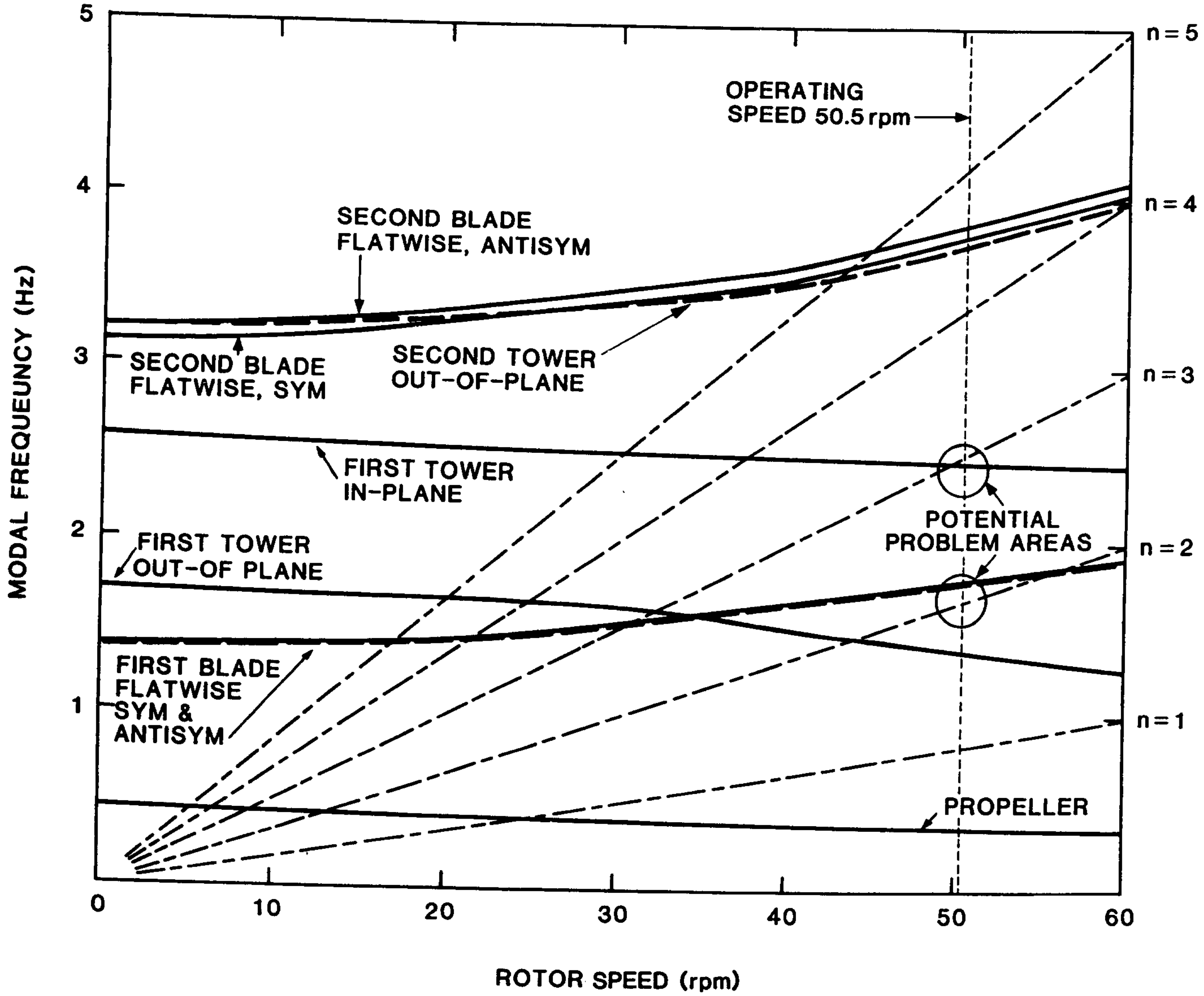


Figure 16. VAWTpower 185 Fan Plot

Conclusions

Of the different approaches to exciting a wind turbine for a modal test, human excitation, step-relaxation, and wind are the most useful. For mini-modal testing, human excitation is preferred because it is the fastest method and requires no special instrumentation or fixturing and little user interpretation. Use of this technique is limited because small turbines have natural frequencies too high to be excited manually and larger turbines may be too massive to excite.

For a standard modal test or a mini-modal, both wind and step-relaxation testing methods work extremely well, although they require more time than human excitation. Step-relaxation methods require pretest analysis for sizing of excitation hardware and significant ground support. Both methods require a crane and personnel to mount the accelerometers. Step-relaxation testing requires a higher dependence on the site workers. However, damping information is not as readily available from the power spectra obtained from wind excitation as it is from FRFs obtained using step-relaxation testing. Finally, and most importantly, we were able to extract modal data from FRFs measured, using step-relaxation, during high winds. However, it would not be possible to obtain meaningful wind-response measurements during completely calm days.

References

[1] T. G. Carne et al, "Finite Element Analysis and Modal Testing of a Rotating Wind Turbine," AIAA Paper 82-0097, 23rd Structures, Structural Dynamics, and Materials Conference, Part 2, New Orleans, May 1982, pp 335-47.

[2] J. S. Pate and S. M. Seltzer, "Complex Eigenvalue Solution to a Spinning Skylab Problem," NASA TMX-2378, Vol II (Springfield, VA: National Technical Information Service, Sept 1971).

[3] D. W. Lobitz, *Dynamic Analysis of Darrieus Vertical Axis Wind Turbine Rotors*, SAND80-2820 (Albuquerque, NM: Sandia National Laboratories, May 1981).

[4] D. L. Brown, G. D. Carbon, and K. Ramsey, "Survey of Excitation Technique Applicable to the Testing of Automotive Structures," SAE Paper 770029, International Automotive Engineering Congress and Exposition, Detroit, MI, Feb 1977.

[5] D. L. Brown, "Grinding Dynamics," PhD Thesis, University of Cincinnati, 1976.

[6] T. G. Carne and A. R. Nord, "Modal Testing of a Rotating Wind Turbine," *Proc Sixth Biennial Wind Energy Conf and Workshop,* Minneapolis, MN, June 1983, pp 825-34.

[7] G. F. Mutch et al, "The Dynamic Analysis of a Space Lattice Structure via the Use of Step Relaxation Testing," *Proc Second International Modal Analysis Conf*, Orlando, FL, Feb 1984, pp 368-77.

[8] C. Van Karson and R. J. Allemang, "Single and Multiple Input Modal Analysis, A Comparison of Averaging Techniques," *Proc Second International Modal Analysis Conf*, Orlando, FL, Feb 1984, pp 172-78.

DISTRIBUTION:

Advanced Alternative Energy Solutions
Attn: U. Ortabasi
PO Box 5246
Pleasanton, CA 94566

Aerospace Corporation
Spacecraft Dynamics Section
Attn: A. Kabe, DS-1727E
2350 E. El Segundo Blvd.
El Segundo, CA 90245

Aerospace Corporation
Vehicle Engineering Division
Attn: S. Rubin
2350 E. El Segundo Blvd.
El Segundo, CA 90245

Aluminum Company of America (5)
Alcoa Technical Center
Attn: D. K. Ai
J. T. Huang
J. R. Jombock
M. Klingensmith
J. L. Prohaska
Alcoa Center, PA 15069

Alternative Sources of Energy
Attn: L. Stoiaken
Milaca, MN 56353

Amarillo College
Attn: E. Gilmore
Amarillo, TX 79100

American Wind Energy Association
1017 King Street
Alexandria, VA 22314

Battelle-Pacific Northwest Laboratory
Attn: L. Wendell
PO Box 999
Richland, WA 99352

Bechtel Group, Inc.
Attn: B. Lessley
PO Box 3965
San Francisco, CA 94119

Bonneville Power Administration
Attn: N. Butler
PO Box 3621
Portland, OR 97208

Burns & Roe, Inc.
Attn: G. A. Fontana
800 Kinderkamack Road
Oradell, NJ 07649

California Institute of Technology
Applied Mechanics Department
Attn: K. Knowles
Pasadena, CA 91109

Colorado State University
Dept of Civil Engineering
Attn: R. N. Meroney
Fort Collins, CO 80521

Commonwealth Electric Co.
Attn: D. W. Dunham
Box 368
Vineyard Haven, MA 02568

CSA Engineering, Inc. (2)
Attn: D. A. Kienholz
C. D. Johnson
Suite 101
560 San Antonio Road
Palo Alto, CA 94306

M. M. Curvin
11169 Loop Road
Soddy Daisy, TN 37379

State of Wyoming
Department of Economic Planning and Development
Attn: G. N. Monsson
Barrett Building
Cheyenne, WY 82002

DOE/ALO
Attn: G. P. Tennyson
PO Box 5400
Albuquerque, NM 87115

DISTRIBUTION (Continued):

DOE/ALO
Energy Technology Liaison Office
NGD
Attn: Capt. J. L. Hanson, USAF
PO Box 5400
Albuquerque, NM 87115

DOE Headquarters (5)
Wind/Oceans Technologies Division
Attn: L. J. Rogers
P. R. Goldman
1000 Independence Avenue
Washington, DC 20585

Electric Power Research Institute (2)
Attn: E. Demeo
F. Goodman
3412 Hillview Avenue
Palo Alto, CA 94304

Engineering Mechanics Assoc., Inc.
Attn: T. K. Hasselman
3820 Del Amo Blvd.
Torrance, CA 90503

Dr. N. E. Farb
10705 Providence Drive
Villa Park, CA 92667

Fayette Manufacturing Corporation
Attn: W. Thompson
PO Box 1149
Tracy, CA 95378-1149

FloWind Corporation (2)
Attn: L. Schienbein
B. Im
1183 Quarry Lane
Pleasanton, CA 94566

General Dynamics Company
Convair Division
Attn: A. L. Hale
MZ22-6020
PO Box 85357
San Diego, CA 92138

General Motors Research Labs (3)
Engineering Mechanics Dept.
Attn: J. A. Wolf, Jr.
J. Howell
D. Nefske
Warren, MI 48090-9055

Southern University
Department of Mechanical Engineering
Attn: I. J. Graham
PO Box 9445
Baton Rouge, LA 70813-9445

Helion, Inc.
Attn: J. Park, President
Box 445
Brownsville, CA 95919

Iowa State University
Agricultural Engineering, Room 213
Attn: L. H. Soderholm
Ames, IA 50010

West Wind Industries
Attn: K. Jackson
PO Box 1705
Davis, CA 95617

McAllester Financial
Attn: M. Jackson
1816 Summit
W. Lafayette, IN 47906

Jet Propulsion Laboratories
Applied Mechanics Division
Attn: J. C. Chen
4800 Oak Grove Dr. 157-316
Pasadena, CA 91109

Kaiser Aluminum and Chemical
Sales, Inc.
Attn: A. A. Hagman
14200 Cottage Grove Avenue
Dolton, IL 60419

Kaiser Aluminum and Chemical
Sales, Inc.
Attn: D. D. Doerr
PO Box 877
Pleasanton, CA 94566

DISTRIBUTION (Continued):

Kansas State University
Electrical Engineering Department
Attn: G. L. Johnson
Manhattan, KS 66506

Kinetics Group, Inc.
Attn: J. Sladky, Jr.
PO Box 1071
Mercer Island, WA 98040

KW Control Systems, Inc.
Attn: R. H. Klein
RD#4, Box 914C
South Plank Road
Middletown, NY 10940

L. K. Liljergren
1260 S.E. Walnut #5
Tustin, CA 92680

Barc-West
Attn: L. Liljidahl
Building 005, Room 304
Beltsville, MD 20705

Los Alamos National Laboratory
Attn: N. F. Hunter, WX-11, MSC931
PO Box 1663
Los Alamos, NM 87545

R. Lynette & Assoc., Inc.
Attn: R. Lynette
15042 NE 40th Street
Suite 206
Redmond, WA 98052

Martin Marietta Corporation
Attn: R. F. Hruda
Mail Stop G-6496
PO Box 179
Denver, CO 80201

Massachusetts Inst of Tech (2)
Attn: N. D. Ham
W. L. Harris, Aero/Astro Dept.
77 Massachusetts Avenue
Cambridge, MA 02139

US Wind Power
Attn: G. M. McNerney
160 Wheeler Road
Burlington, MA 01803

Michigan State University
Division of Engineering Research
Attn: O. Krauss
East Lansing, MI 48825

NASA Langley Research Center (2)
Structural Dynamics Division
Attn: L. Pinson
B. R. Hanks
Mail Stop 230
Hampton, VA 23655

National Rural Electric
Cooperative Assn
Attn: W. Prichett III
1800 Massachusetts Avenue, NW
Washington, DC 20036

Natural Power, Inc.
Attn: L. Nichols
New Boston, NH 03070

New Mexico Engineering
Research Institute
Attn: G. G. Leigh
Campus PO Box 25
Albuquerque, NM 87131

Ohio State University
Aeronautical and Astronautical Dept.
Attn: G. Gregorek
2070 Neil Avenue
Columbus, OH 43210

Oklahoma State University
Mechanical Engineering Dept.
Attn: D. K. McLaughlin
Stillwater, OK 76074

Old Dominion University
Dept of Mech Engineering &
Mechanics
Attn: S. R. Ibrahim
Norfolk, VA 23508

Oregon State University
Mechanical Engineering Dept.
Attn: R. E. Wilson
Corvallis, OR 97331

DISTRIBUTION (Continued):

Pacific Gas & Electric Co.
Attn: T. Hillesland
3400 Crow Canyon Road
San Ramon, CA 94583

J. M. Turner Technologies, Inc.
Attn: E. N. Hinrichsen
PO Box 1058
Schenectady, NY 12301-1058

Public Service Co. of New Hampshire
Attn: D. L. C. Frederick
1000 Elm Street
Manchester, NH 03105

Public Service Company of New Mexico
Attn: M. Lechner
PO Box 2267
Albuquerque, NM 87103

Purdue University
School of Civil Engineering
Attn: J. T. P. Yao
West Lafayette, IN 47907

RANN, Inc.
Attn: A. J. Eggers, Jr.
260 Sheridan Ave., Suite 414
Palo Alto, CA 94306

Iowa State University
Aerospace Engineering Department
Attn: R. G. Rajagopalan
404 Town Engineering Bldg.
Ames, IA 50011

State of California Resources Agency
Department of Water Resources
Energy Division
Attn: R. G. Ferreira
PO Box 388
Sacramento, CA 95802

Reynolds Metals Company
Mill Products Division
Attn: G. E. Lennox
6601 West Broad Street
Richmond, VA 23261

National Atomic Museum
Attn: G. Schreiner, Librarian
Albuquerque, NM 87185

Wind Energy News Service
Attn: F. S. Seiler, Editor
PO Box 4008
St. Johnsbury, VT 05819

Solar Energy Research Institute
Attn: R. W. Thresher
1617 Cole Boulevard
Golden, CO 80401

Southern California Edison
Research & Development Dept
Room 497
Attn: R. L. Scheffler
PO Box 800
Rosemead, CA 91770

Stanford University
Dept. of Aeronautics and
Astronautics Mechanical Engineering
Attn: H. Ashley
Stanford, CA 94305

Structural Dynamics Research Corp. (2)
Attn: M. Baker
D. Hunt
11055 Roselle
San Diego, CA 92121

Structural Dynamics Research Corp. (2)
Attn: G. Townley
M. Abrishaman
2000 Eastman Drive
Milford, OH 45150

Synergistics Technology, Inc.
Attn: R. C. Stroud
20065 Stevens Creek Blvd., Ste. 106
Cupertino, CA 95014

State University of NY at Buffalo
Dept of Mechanical & Aerospace Engr
Attn: D. J. Inman
1006 Furnas Hall
Buffalo, NY 14260

Texas Tech University (2)
Mechanical Engineering Dept.
Attn: J. W. Oler
PO Box 4289
Lubbock, TX 79409

DISTRIBUTION (Continued):

Moriah Research
Attn: K. J. Touryan
6200 Plateau Dr.
Englewood, CO 80111

TRW Corporation
Dynamics Dept RB/B240
Attn: S. Simonian
One Space Park
Redondo Beach, CA 90278

Tulane University
Dept. of Mechanical Engineering
Attn: R. G. Watts
New Orleans, LA 70018

United Engineers and Constructors,
Inc.
Attn: A. J. Karalis
PO Box 8223
Philadelphia, PA 19101

Universal Data Systems
Attn: C. W. Dodd
5000 Bradford Drive
Huntsville, AL 35805

University of California
Institute of Geophysics
and Planetary Physics
Attn: P. J. Baum
Riverside, CA 92521

University of Cincinnati (2)
Mechanical Engineering Dept
Attn: D. L. Brown
R. L. Allemang
Cincinnati, OH 45221

University of Colorado
Dept. of Aerospace Engineering
Sciences
Attn: J. D. Fock, Jr.
Boulder, CO 80309

University of Dayton
Research Institute
Attn: M. Soni, JPC-326
Dayton, OH 45469

University of Massachusetts
Mechanical and Aerospace
Engineering Dept.
Attn: D. E. Cromack
Amherst, MA 01003

University of New Mexico
Mechanical Engineering Dept
Attn: F. D. Ju
Albuquerque, NM 87131

University of Oklahoma
Aero Engineering Department
Attn: K. Bergey
Norman, OK 73069

The University of Tennessee
Dept. of Electrical Engineering
Attn: T. W. Reddoch
Knoxville, TN 37916

The University of Texas at Austin
Dept of Aerospace Engineering
and Engineering Mechanics
Attn: R. D. Craig
Austin, TX 78712

USDA, Agricultural Research Service
Southwest Great Plains Research
Center
Attn: R. N. Clark
Bushland, TX 79012

Virginia Polytechnic Institute and
State University
Dept of Mechanical Engineering
Attn: L. D. Mitchell
Randolph Hall
Blacksburg, VA 24061

W. A. Vachon & Associates
Attn: W. A. Vachon
PO Box 149
Manchester, MA 01944

Washington and Lee University
Attn: R. E. Akins
PO Box 735
Lexington, VA 24450

DISTRIBUTION (Continued):

Washington State University
Dept. of Electrical Engineering
Attn: F. K. Bechtel
Pullman, WA 99163

Westinghouse Electric Corporation
Attn: S. Sattinger
Senior Research Engineer
1310 Beulah Road
Pittsburgh, PA 15235

West Texas State University
Government Depository Library
Number 613
Canyon, TX 79015

West Texas State University
Department of Physics
Attn: V. Nelson
PO Box 248
Canyon, TX 79016

West Virginia University
Dept. of Aero Engineering
Attn: R. Walters
1062 Kountz Avenue
Morgantown, WV 26505

Central Lincoln People's Utility
District
Attn: D. Westlind
2129 North Coast Highway
Newport, OR 97365-1795

Wichita State University (2)
Aero Engineering Department
Attn: M. Snyder
W. Wentz
Wichita, KS 67208

Wind Power Digest
Attn: M. Evans
PO Box 700
Bascom, OH 44809

Wisconsin State Division of Energy
Attn: Wind Program Manager
101 South Webster Street, 8th Floor
Madison, WI 53702

Wright Patterson AFB
Attn: V. B. Venkayya
AFWAL/FIBR
Dayton, OH 45433

State Univ. of Ghent
Attn: D. Vandenberghe
St. Pietersniewstraat 41
9000 Ghent
BELGIUM

Pontificia Universidade Catolica-
PUC/Rj
Mechanical Engineering Department
Attn: A. de Faro Orlando
R. Marques de S. Vicente 225
Rio de Janeiro
BRAZIL

The College of Trades and Technology
Attn: R. E. Kelland
PO Box 1693
Prince Philip Drive
St. John's, Newfoundland, A1C 5P7
CANADA

Indal Technologies, Inc. (2)
Attn: D. Malcolm
C. Wood
3570 Hawkestone Road
Mississauga, Ontario
CANADA L5C 2V8

Institut de Recherche d'Hydro-Quebec
Attn: B. Masse
1800, Montee Ste-Julie
Varennes, Quebec, JOL 2P.O.
CANADA

Trinity Western
Attn: A. S. Barker
7600 Glover Road
Langley, BC
CANADA V3A 4R9

Canadian Standards Association
Attn: T. Watson
178 Rexdale Blvd.
Rexdale, Ontario, M9W 1R3
CANADA

DISTRIBUTION (Continued):

National Research Council
of Canada
Energy, Mines and Resources
Attn: M. Carpentier
Montreal Road
Ottawa, Ontario
CANADA K1A OR6

Universite Laval-Quebec
Faculty of Sciences and Engineering
Mechanical Engineering Department
Attn: H. Gerardin
Quebec G1K 7P4
CANADA

Ecole Polytecnique
Department of Mechanical Engineering
Attn: I. Paraschivoiu
CP 6079
Succursale A
Montreal H3C 3A7
CANADA

Hydro Quebec
Attn: J. Plante
Place Dupuis Ile etage
855 est rue Ste-Catherine
Montreal, Quebec
CANADA H2L 4P5

Atlantic Wind Test Site
Attn: R. G. Richards
PO Box 189
Tignish P.E.I., COB 2BO
CANADA

Shawinigan Engineering Co., Ltd. (10)
Attn: H. Benjannet
1100 Dorchester Blvd. West, 8th Floor
Montreal, Quebec
CANADA H3B 4P3

ADECON
Attn: P. South
32 Rivalda Road
Weston, Ontario, M9M 2M3
CANADA

NRC-National Aeronautical Estab (3)
Low Speed Aerodynamics Laboratory
Attn: R. J. Templin
Montreal Road
Ottawa, Ontario, K1A OR6
CANADA

University of Sherbrooke (2)
Faculty of Applied Science
Attn: A. Laneville
P. Vittecoq
Sherbrooke, Quebec, J1K 2R1
CANADA

Instituto Technologico Costa Rica
Attn: K. Smith
Apartado 159 Cartago
COSTA RICA

Riso National Laboratory (2)
Attn: T. F. Pedersen
H. Petersen
Postbox 49
DK-4000 Roskilde
DENMARK

Roskilde University Center
Energy Group, Bldg. 17.2
IMFUFA
Attn: B. Sorenson
PO Box 260
DK-400 Roskilde
DENMARK

Institut fur Leichbau
Technische Hochschule Aachen
Attn: I. H. Ruscheweyh
Wullnerstrasse 7
Aachen
FEDERAL REPUBLIC OF GERMANY

France (2)
Attn: D. Bonnecase
J. C. Cromer
19 bis Chemin de Mouilles
69130 Ecully
FRANCE

DISTRIBUTION (Continued):

Establissement d'Etudes et de
Recherches Meteorologiques
Attn: B. de Saint Louvent
77 Rue de Serves
92106 Boulogne-Billancourt Cedex
FRANCE

National Technical University
Dept of Mechanical Engineering
Attn: G. Bergeles
42, Patission Street
Athens
GREECE

Technion-Israel Institute of
Technology
Aeronautical Engineering Dept.
Attn: A. Seginer
Professor of Aerodynamics
Haifa
ISRAEL

Toray Industries, Inc.
Pioneering R&D Laboratories
Composite Materials Laboratory
Attn: H. S. Matsuda
Sonoyama, Otsu, Shiga
JAPAN 520

University of Auckland
School of Engineering
Attn: V. A. L. Chasteau
Private Bag
Auckland
NEW ZEALAND

FFA, The Aeronautical Research
Institute
Attn: O. Ljungstrom
Box 11021
S-16111 Bromma
SWEDEN

National Aerospace Laboratory
Attn: O. de Vries
Anthony Fokkerweg 2
Amsterdam 1017
THE NETHERLANDS

Nederlands Energy Research
Foundation (E.C.N.)
Physics Department
Attn: J. B. Dragt
Westerduinweg 3
Petten (nh)
THE NETHERLANDS

Garrad Hasson
Attn: A. D. Garrad
10 Northampton Square
London EC1M 5PA
UNITED KINGDOM

Imperial College of Science & Technology
Dept. of Mechanical Engineering
Attn: D. J. Ewins
Exhibition Road
London SW7 2BX
UNITED KINGDOM

Napier College of Commerce and
Technology
Tutor Librarian, Technology Faculty
Colinton Road
Edinburgh, EH10 5DT
UNITED KINGDOM

Open University
Alternative Energy Group
Walton Hall
Attn: D. Taylor
Milton Keynes, MK7 6AA
UNITED KINGDOM

Queen Mary College
Dept of Aeronautical Engineering
Attn: D. Sharpe
Mile End Road
London, E1 4NS
UNITED KINGDOM

The University of Reading
Department of Engineering
Attn: G. Stacey
Whiteknights, Reading, RG6 2AY
UNITED KINGDOM

DISTRIBUTION (Continued):

University College of Swansea
Dept of Mechanical Engineering
Attn: R. T. Griffiths
Singleton Park
Swansea, SA2 8PP
UNITED KINGDOM

1520	C. W. Peterson
1522	R. C. Reuter, Jr.
1522	D. W. Lobitz
1522	D. R. Martinez
1523	J. H. Biffle
1524	A. K. Miller
1524	C. R. Dohrmann
1524	P. S. Veers
1550	R. C. Maydew
1552	J. H. Strickland
1556	G. F. Homicz
2525	R. B. Diegle
3160	J. E. Mitchell (15)
3162	P. S. Wilson
6000	D. L. Hartley
6200	V. L. Dugan
6220	D. G. Schueler
6225	H. M. Dodd (50)
6225	T. D. Ashwill (10)
6225	D. E. Berg
6225	T. C. Bryant
6225	L. R. Gallo
6225	P. C. Klimas
6225	S. D. Nicolaysen
6225	D. S. Oscar
6225	M. E. Ralph
6225	D. C. Reda
6225	M. A. Rumsey
6225	L. L. Schluter
6225	W. A. Stephenson
6225	H. J. Sutherland
7290	T. S. Church
7500	D. M. Olson
7531	D. R. Schafer
7540	T. B. Lane
7541	R. Rodeman
7542	T. G. Priddy
7543	D. E. Miller
7544	D. O. Smallwood
7544	V. I. Bateman
7544	T. G. Carne (20)
7544	A. J. Gomez (10)
7544	J. P. Lauffer (20)
7544	A. R. Nord
7544	M. D. Tucker
8240	C. W. Robinson
8243	M. L. Callabresi
9100	R. G. Clem
9122	T. M. Leonard
8524	P. W. Dean
3141	S. A. Landenberger (5)
3151	W. L. Garner (3)
3154-1	C. H. Dalin (8) For DOE/OSTI