SANDIA REPORT

SAND87—1506 • UC—60
Unlimited Release
Printed April 1988

Modal Testing the EOLE

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Hassine Benjannet

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

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

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

SAND87−1506
Unlimited Release
Printed April 1988

Distribution
Category UC−60

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Abstract

This report presents the results of the modal test of the 110-m-tall EOLE wind turbine. Modal testing an immense and flexible wind turbine poses a number of problems. It requires innovative excitation techniques since the modal frequencies of this type of structure are quite low—some below 1.0 Hz. Also, substantial energy must be input to the structure to obtain reasonable levels of response. Step-relaxation and wind were used to excite the structure.

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Modal Testing the EOLE

Introduction

Figure 1 is a photograph of the EOLE turbine just after construction was finished in December 1986. One can still see the truss structure used as the construction crane. In the design of large, flexible structures that are subjected to dynamic loads, knowledge of the modal frequencies and mode shapes is essential in predicting structural response and fatigue life. For large, rotating wind turbines, these modal parameters are particularly important since the applied forces acting on the turbine have large periodic components at integral multiples of the fixed rotation speed. During the design process, analytical or finite-element models must be relied upon for estimates of the modal parameters. However, when the turbine hardware becomes available for testing, the actual modal parameters can be measured and compared to the analytical predictions.

The model is used for design, for redesign if required, for choosing the range of operating speeds, for setting limits on the operational wind speeds, and for computation of predicted fatigue life. Consequently, it is of the utmost importance to have a test-verified model.

Vertical-axis wind turbines are excited by the applied aerodynamic forces that have primary spectral content at integral multiples of the rotation speed. If these discrete frequencies are close to any modal frequency, a resonance can result in which very high strains reduce the fatigue life of the structure. Figure 2 shows analytical mode shapes of a typical vertical-axis turbine. Displayed in the figure are the top, side, and front views of the deformed shapes. They are not necessarily in increasing order of frequency that would occur in an actual design, nor are they the exact mode shape for a particular turbine.

For the EOLE modal test, providing adequate low-frequency excitation was troublesome since its modal frequencies were very low. Also, because the structure is very large, great amounts of energy must be input to the structure to obtain adequate response signal levels. Two different methods of excitation were evaluated: step-relaxation and wind excitation. In the step-relaxation technique, a large, static force is applied to the turbine and then suddenly released. Frequency response functions (FRFs) can be computed and the modal parameters extracted. With wind excitation, the turbine is instrumented in the normal manner, but ambient wind is used to excite the structure instead of an externally applied force. A number of response transducers are chosen as references, and cross-spectra are computed between the references and the other transducers. Using the cross-spectra, the modal frequencies and mode shapes are determined.

In the remaining sections of this report, the two techniques are described in more detail, followed by a Results section, which compares the two techniques and compares the test results with analysis.

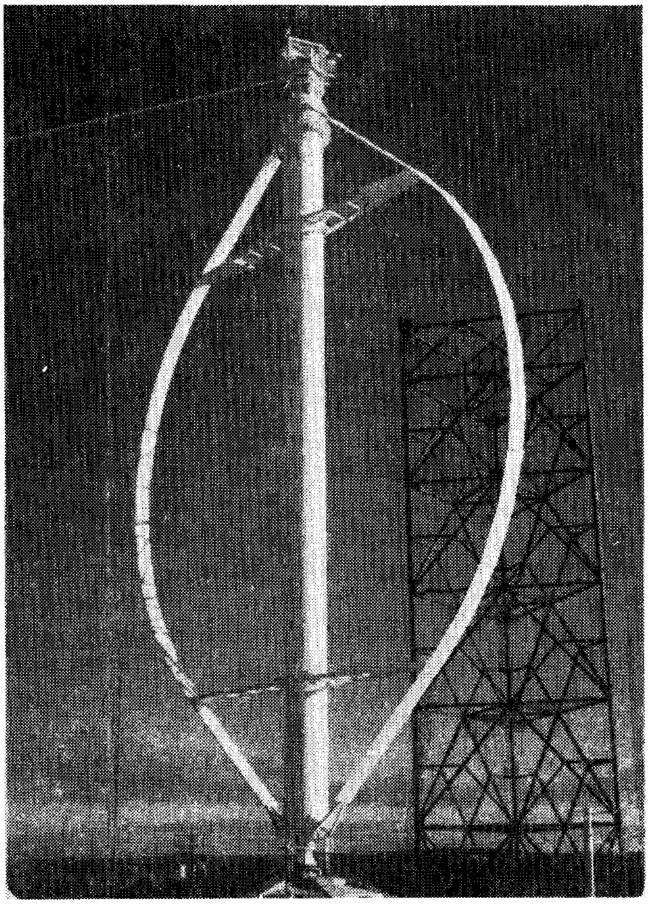
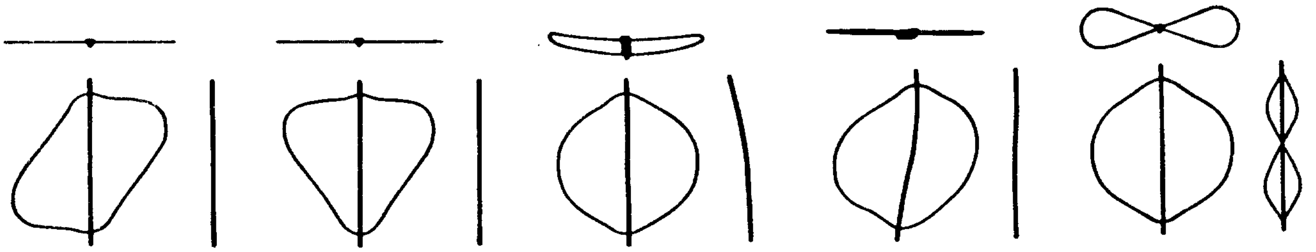
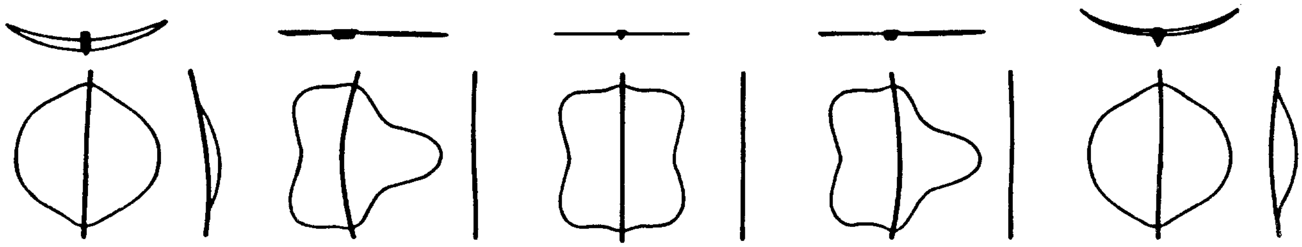


Figure 1. The EOLE Vertical-Axis Wind Turbine



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 Vertical-Axis Wind Turbine Modes (front, top, side views)

Excitation Using Step-Relaxation

The step-relaxation method of structural excitation involves applying a static load to the structure and then suddenly releasing this load. This process is analogous to plucking a violin string. Step-relaxation excitation has been discussed in several previous papers; see, for example, References 1 and 2. It is a technique that is seldom used because it can be mechanically difficult to implement; also, problems are involved in performing a fast Fourier transform (FFT) of the step function force signal. However, the low-frequency weighting of the step 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 modal frequencies.

In step-relaxation on the EOLE turbine, two force-application points were used, one on the tower and one on a blade. This resulted in two sets of FRFs referenced to these two driving points. The forces were applied to the turbine rotor with a high- strength steel cable and loaded with a diesel-powered winch, which was located on the ground ~100 m from the base of the turbine. For the tower driving point, a load of 135 kN (30 000 lb) was applied at mid-span on the tower in a direction slightly out of the plane of the rotor. For the blade driving point, a 45-kN (10 000 lb) load was applied at a point between the lower horizontal strut and mid-span on the blade (Figure 1). The required force magnitude, direction, and location of application were calculated as part of the pre-test planning and will be discussed later in this section.

A quick-release device was used between the winch and the cable to allow an immediate relaxation of the load. For the loads required by this structure, the quick-release device used an explosively driven cable cutter, which cut a small piece of replaceable steel cable. A load cell was placed in-line with the cable to measure the force signal. It is important that the load cell be close to the structure so that it senses the force actually being applied to the structure. A total of 45 accelerometers measured the response on both the tower and the two blades. The entire setup is displayed in Figure 3. Not shown in Figure 3, however, is a crucial element in the design of step-relaxation hardware. Depending on the forces used and the length of the pull-down cable, a tremendous amount of strain energy can be stored in the cable and then suddenly converted into kinetic energy in the cable. To prevent the cable rebound from striking and damaging the turbine, a nylon restraint strap was designed to absorb the strain energy stored in the steel pull-down cable. At maximum deformation, the nylon strap experienced ~10% strain.

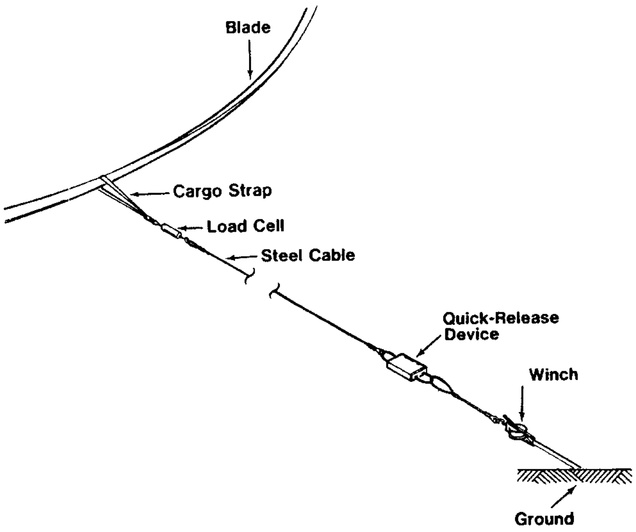


Figure 3. Step-Relaxation Hardware

Another of the difficulties in testing a very large structure is that the test plan must be well established before the test since changes may be impossible once testing has started. For example, all the equipment required to apply the 135-kN load to the tower had to be designed and acquired in advance; thus, one could not increase that load if it proved insufficient during data acquisition.

Pre-test analysis was performed to determine the required forces and the application points that would excite all the modes of interest and result in adequate response levels. Using the finite-element model that had been developed for the design of the turbine, all the modes were computed and their responses to various load inputs were examined. Using the model in this way, we determined that all the modes could be excited with two driving points. Further, the required force magnitudes were computed to provide adequate signals from the response accelerometers. Static and transient analyses were performed to ascertain whether the particular excitation would excite the modes to the desired levels. Figure 4 shows a result of one of these preliminary analyses; it is a display of the static deformation caused by application of a load on the blade.

In doing a step-relaxation test, special consideration must be directed to the signal processing used for the force signal because the step function cannot be digitally Fourier transformed without extensive leakage errors. To alleviate this difficulty, the force signal was ac-coupled at the input to the FFT analyzer. The ac-coupling network is a high-pass filter with its 3-dB down point at 0.8 Hz. Such coupling converts the step function into a pulse with a rapidly decaying trailing edge, making the force-time history Fourier transformable without leakage errors. 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, therefore eliminating the leakage error. Reference 2 provides a more thorough discussion of this subject.

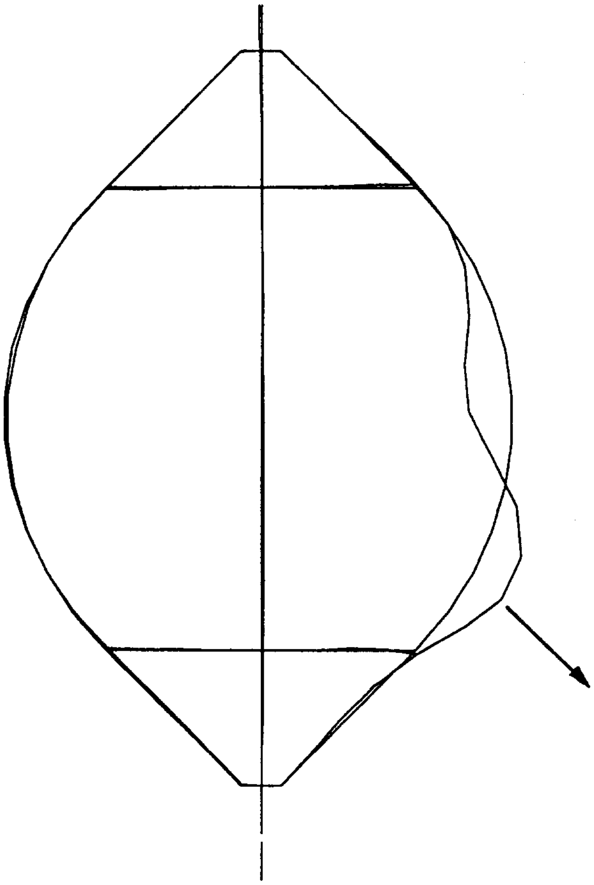


Figure 4. Deformation Due to Static Load Applied to a Blade

The response signals were also ac-coupled to cancel out the phase shift effects of high-pass filtering the force signal. After ac-coupling, the resulting input and response signals are similar to those obtained by impact testing and can be processed in a similar manner. For example, the resulting force signals can be used to trigger data acquisition. Further, one can apply windows to the data to reduce the effects of noise, including a force window or exponential window.[2] Exponential windowing is particularly important for removing structural response caused by wind excitation after the response caused by the intended applied excitation has diminished. Figure 5 shows a typical FRF using the step-relaxation plotted from 0.4 to 4.0 Hz. The function is not noise-free as is manifest at the notches in the FRF. This noise is due to wind-excited response as the wind was rarely <10 m/s (20 mph) during the test.

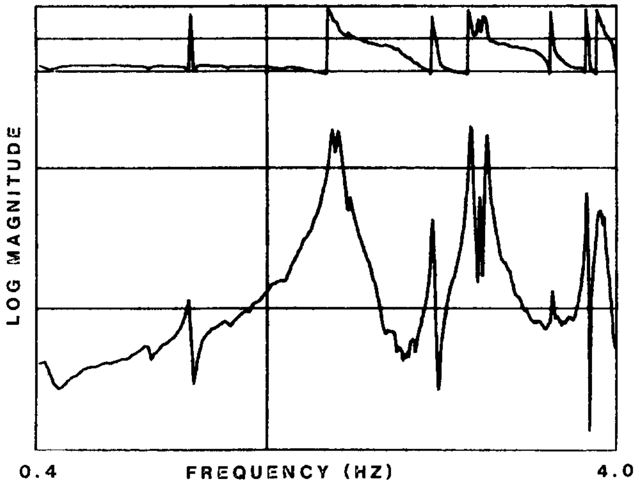


Figure 5. Frequency Response Function Acquired From Step-Relaxation

Using the 45 FRFs for a particular driving point, we extracted the mode shapes and frequencies from these data by using standard techniques. Figures 6 and 7 show two of the mode shapes from these step-relaxation data. These figures have the undeformed shape in a dashed line and the mode shape superimposed in a solid line. Referencing Figure 2, the mode shapes are the first blade flatwise anti-symmetric (front view) and the second rotor out-of-plane (side view). More discussion of the test results, along with a comparison with the analytical predictions, appears in the Results section.

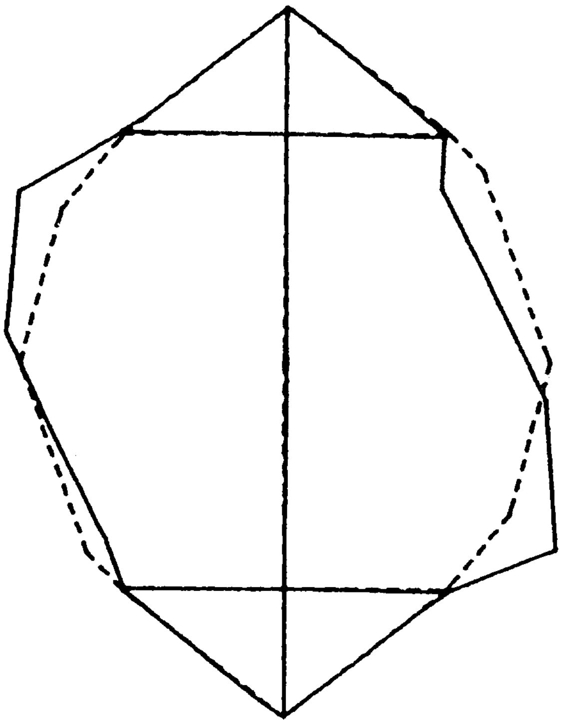


Figure 6. First Blade Anti-Symmetric Flatwise From Step-Relaxation

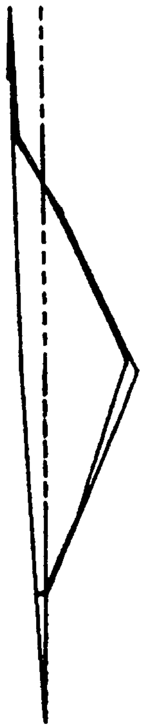


Figure 7. Second Rotor Out-of-Plane From Step-Relaxation

Wind-Excitation Testing

During previous wind-turbine tests, high winds have induced large vibratory responses that interfere with the measurement of the responses from the step-relaxation excitation, resulting in poor estimates of the FRFs. Waiting for the winds to cease, however, is not a reasonable alternative since test scheduling on a prototype is extremely tight. Consequently, an alternative method of testing was devised to complement step-relaxation excitation testing. It was decided to measure the wind-induced vibration of the EOLE to determine its modal parameters.

References 3, 4, and 5 have indicated that for broadband excitation, response data alone could be used to determine modal parameters. No measurement of the force would be required. Reference 3 indicates that it is possible to extract modal parameters from transmittance functions, which are defined as the complex ratio between Fourier transforms of response points. This was the approach followed in this test. The method used to calculate the transmittance functions was to take the ratio of the cross-spectrum to the auto-spectrum.

The procedure for performing the wind-excitation testing is similar to that used in performing artificial-excitation testing. One significant difference is that the forces acting on the structure are not measured. 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.

Because 16 data-acquisition channels were available for acquiring data, and 42 response locations were selected, three separate measurement sets were needed to acquire responses at all of the locations of interest. For each set of response measurements, auto-spectra of the reference DOFs were evaluated, and cross-spectra were measured between the response DOFs and the reference DOFs. The reference auto-spectra provided appropriate scaling of the mode shape to account for different levels of wind excitation for different sets of response measurements.

For this test, time histories of the vibrational response of the turbine were digitized and recorded on disk. For each measurement set, the vibrational response of the three reference DOFs were also recorded. The time histories were then processed to generate power spectra as described above. This process was performed for each of the three measurement sets. Shown in Figures 8 and 9 are typical auto- and cross-spectra.

Modal frequencies were determined from the peaks in the auto-spectra of the reference DOFs and the peaks of the indicator function. The indicator function was created by summing the magnitude squared of the power spectra. Particular modes were enhanced by selecting response DOFs based upon a knowledge of the mode shape. Shown in Figure 10 is a typical mode indicator function calculated to enhance the flatwise blade modes.

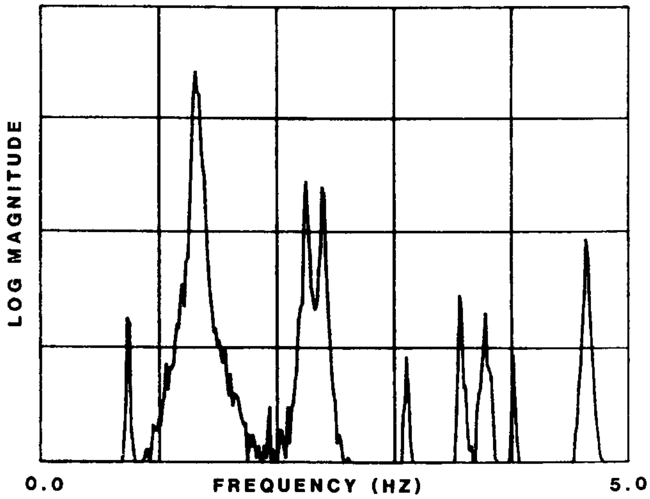


Figure 8. Acceleration Auto-Spectrum From Wind Excitation

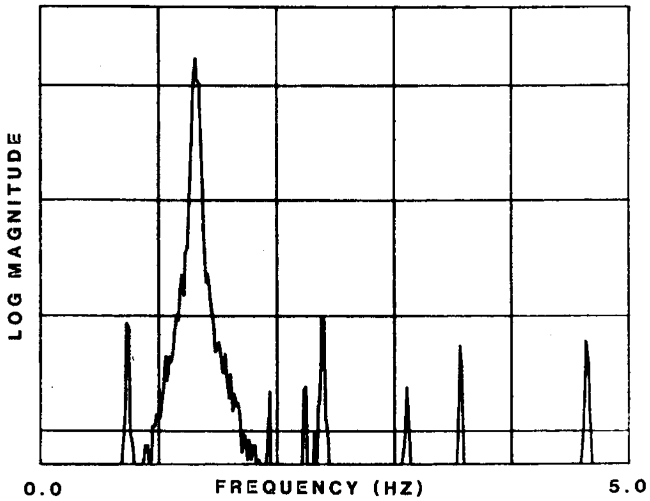


Figure 9. Acceleration Cross-Spectrum From Wind Excitation

In the vicinity of a resonance, where the response is dominated by a single mode, the transmittance function is flat and its value can be taken as the mode shape component for that mode at that DOF. If the transmittance function is directly calculated by using block floating-point arithmetic, dynamic range problems can exist because of zero and near-zero values in the denominator. To avoid this problem, the spectra were zeroed at all frequencies except those corresponding to a narrow band about the resonances. The zero values in the reference spectra (the denominators) were replaced by a small number to prevent division by zero. Transmittance functions were then calculated by taking the ratio of the cross-spectra to the reference auto-spectra for each data set. A typical transmittance is shown in Figure 11. The function is zero at all frequencies except near resonances, where it is fairly flat.

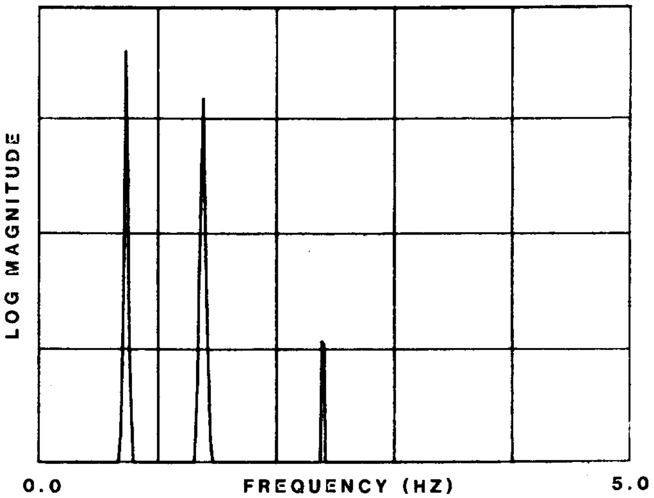


Figure 10. Summation Mode Indicator Function

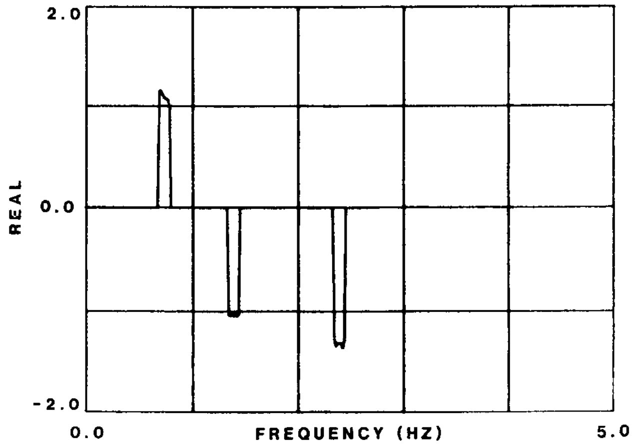


Figure 11. Processed Transmittance Function

Mode shapes can be calculated from the transmittance database by taking the value of the transmittance, at resonance, as the component of the mode vector. Two typical mode shapes are shown in Figures 12 and 13. These are the same two mode shapes shown in the step-relaxation section. Because damping was not a principal consideration in this test, no attempt was made to estimate it using the wind-excited response data.

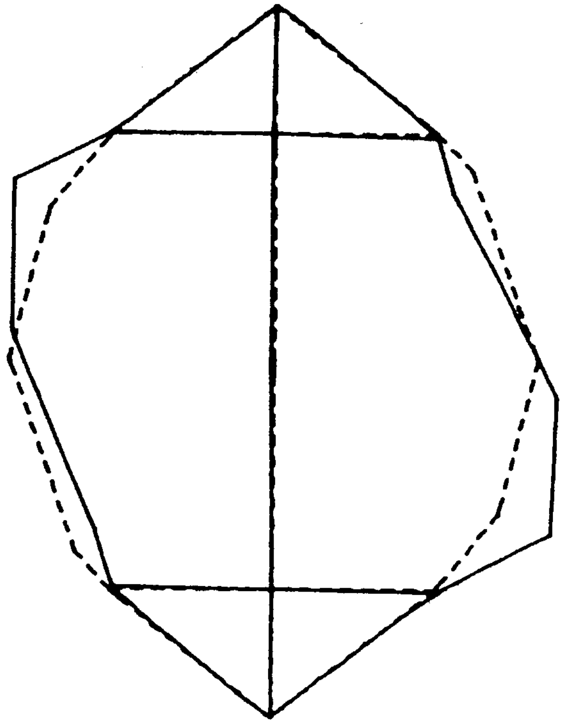


Figure 12. First Blade Anti-Symmetric Flatwise From Wind Excitation

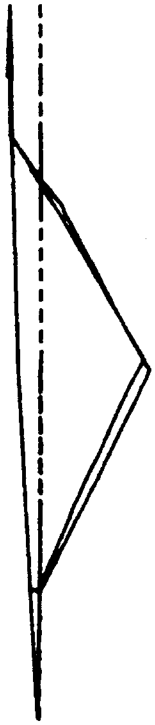
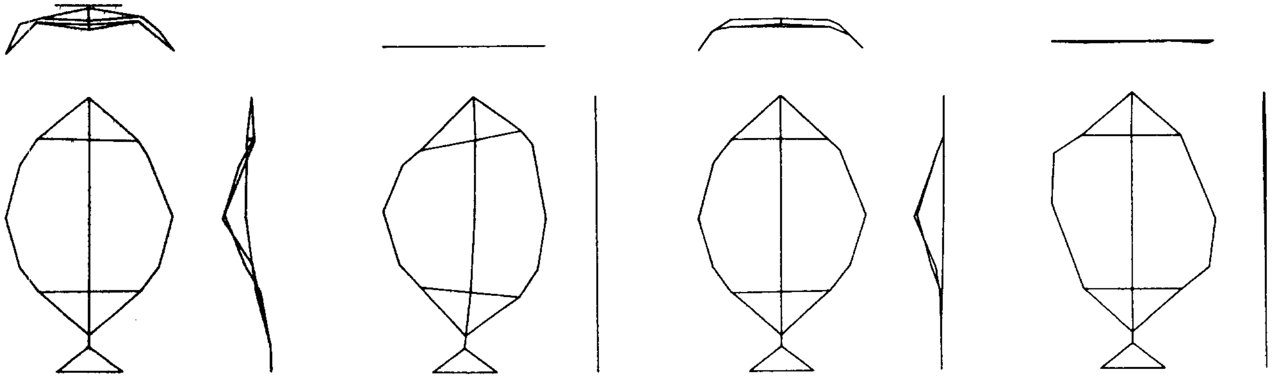


Figure 13. Second Rotor Out-of-Plane From Wind Excitation

Results

The principal results of interest from the modal test are the modal frequencies and test-derived mode shapes. Figures 6, 7, 12, and 13 show mode shapes of two different modes acquired using the two test techniques. The shapes are virtually the same. These plots have the deformed shape superimposed over the undeformed. Figure 14 shows the shapes for the first 12 elastic modes, deleting the first propeller mode. The modes are displayed with the front, side, or top views, with just the deformed shape displayed. These shapes are not nearly as smooth as the typical shapes shown in Figure 2, which were analytically generated. In the mode shapes of this latter figure, one can clearly observe the limited physical resolution of the experimentally measured shapes.

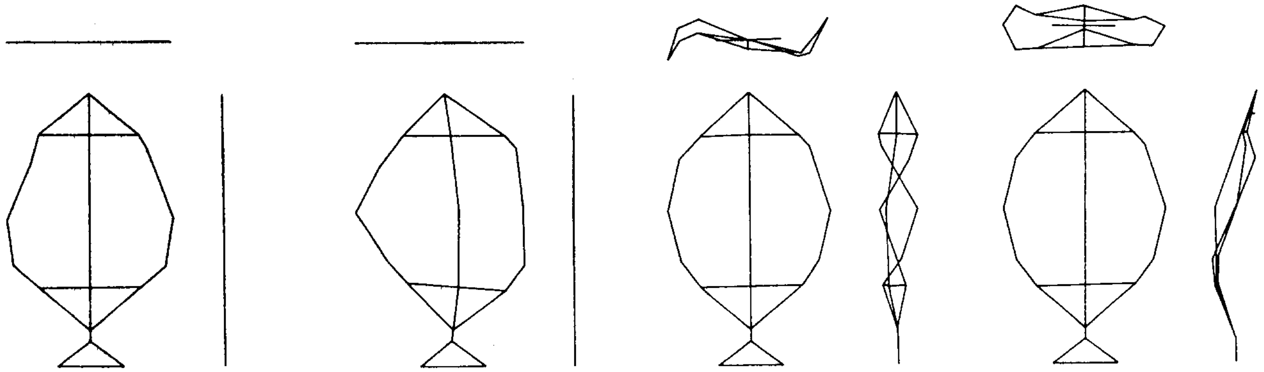


FIRST TOWER OUT-OF-PLANE

FIRST TOWER IN-PLANE

SECOND TOWER OUT-OF-PLANE

BLADE FLATWISE ANTI-SYMMETRIC

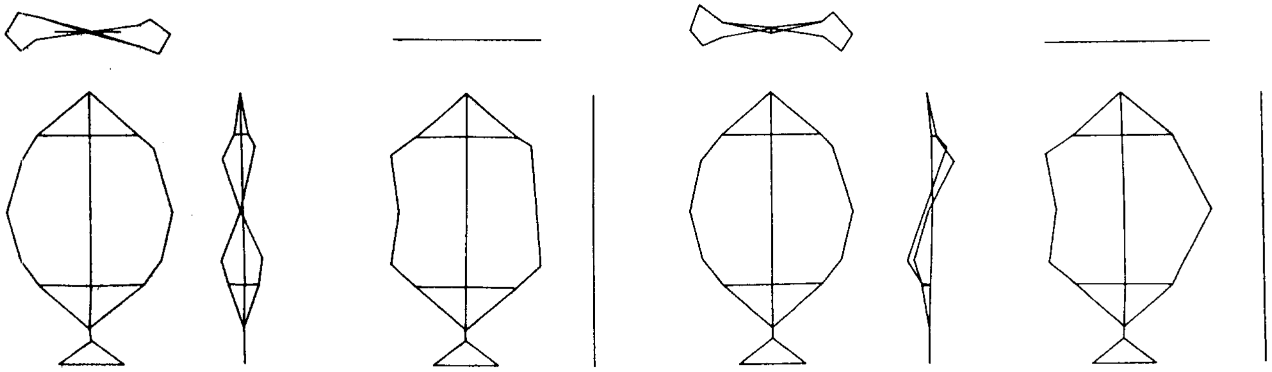


BLADE FLATWISE SYMMETRIC

SECOND TOWER IN-PLANE

BLADES BENDING OUT-OF-PLANE

THIRD TOWER OUT-OF-PLANE



ROTOR TWIST

SECOND FLATWISE SYMMETRIC

SECOND BLADES OUT-OF-PLANE

SECOND FLATWISE ANTI-SYMMETRIC

Figure 14. Experimentally Measured Mode Shapes for the EOLE Turbine

Table 1 compares the modal frequencies from the two test techniques for the first 15 modes. Agreement between the two sets of frequencies is excellent, with all the differences less than the resolution of the transmittance function (0.016 Hz), except for mode 6, where the difference is only 1.5%. The two excitation techniques have produced virtually identical results, with the exception of mode 9, which could not be observed in the wind-excited data.

Table 1. Modal Frequencies From Step-Relaxation and Wind-Excitation Tests

Mode Shape Description	Step-Relaxation (Hz)	Wind Excitation (Hz)
Propeller	0.421	0.420
First Tower Out-of-Plane	0.628	0.625
First Tower In-Plane	0.738	0.734
Second Tower Out-of-Plane	0.930	0.937
Blade Flatwise Anti-Symmetric	1.304	1.296
Blade Flatwise Symmetric	1.321	1.342
Second Tower In-Plane	1.383	1.391
Blades Bending Out-of-Plane	1.546	1.547
Third Tower Out-of-Plane	1.790	—
Rotor Twist (Dumbbell)	1.928	1.938
Second Flatwise Symmetric	2.241	2.250
Second Blade Out-of-Plane	2.329	2.328
Second Blade Anti-Symmetric	2.396	2.391
Third Tower In-Plane	3.084	3.101
Third Flatwise Symmetric	3.564	3.563

As indicated earlier, the objective of this modal test was to verify the finite-element model. The comparison between the predicted frequencies and those from the test are shown in Table 2. Very fine agreement exists, which establishes the accuracy of the model. The average deviation between the test and analysis frequencies is <2% for modes 2 through 13. This is extremely close agreement. The first mode (propeller) was deleted from this comparison because the turbine brakes had to be engaged during testing, and the locked brake stiffness was not adequately represented in the model.

Table 2. Analytically Predicted Modal Frequencies, Experimentally Measured Modal Frequencies, and Measured Damping Factors

Mode Shape Description	Anal. Freq. (Hz)	Exper. Freq. (Hz)	Damping Factors (%)
Propeller	0.52	0.42	—
First Tower Out-of-Plane	0.63	0.63	0.2
First Tower In-Plane	0.75	0.74	0.5
Second Tower Out-of-Plane	0.92	0.93	0.3
Blade Flatwise Anti-Symmetric	1.27	1.30	0.8
Blade Flatwise Symmetric	1.29	1.32	0.4
Second Tower In-Plane	1.42	1.38	0.4
Blades Bending Out-of-Plane	1.61	1.55	1.1
Third Tower Out-of-Plane	1.76	1.79	0.1
Rotor Twist (Dumbbell)	1.96	1.93	0.2
Second Flatwise Symmetric	2.20	2.24	0.3
Second Blade Out-of-Plane	2.34	2.33	0.2
Second Blade Anti-Symmetric	2.38	2.40	0.2

Included in Table 2 are the measured damping values for each of the modes. These values, since they are measured, include both structural damping and aerodynamic damping (nonrotating). There were no analytical predictions of damping to compare. The measured data show the very low values of damping that are typically observed for wind turbines. Of the three measured quantities—the modal frequencies, the mode shapes, and the modal damping factors—the damping is most difficult to estimate accurately from the measurements. Consequently, these damping factors should be considered fairly approximate.

Conclusions

Both wind and step-relaxation testing methods worked extremely well and yielded virtually the same mode shapes and frequencies. Step-relaxation methods required the following: significant pretest analysis for sizing of excitation hardware, unusual hardware such as explosive cable cutters and a winch capable of applying 135 kN, expensive fixturing, and significant ground support. Both methods required a crane and personnel to mount the accelerometers. Step-relaxation testing required 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, in spite of high winds. However, it would not be possible to obtain meaningful wind-response measurements during completely calm days.

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