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TOWER AND ROTOR BLADE VIBRATION TEST RESULTS FOR A 100-KILOWATT WIND TURBINE

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16. Abstract

Because the steel truss tower and rotor blades are major structural subassemblies of the ERDA-NASA 100-kW wind turbine, the predominant natural frequencies and mode shapes for the tower and the rotor blades were determined by testing. The tests on the tower and the blades were conducted both before and after the rotor blades and the rotating machinery were installed on top of the tower. The tower and each blade were instrumented with an accelerometer and impacted by an instrumented mass. The tower and blade structure was analyzed by means of NASTRAN, and computed values agree with the test data.

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TOWER AND ROTOR BLADE VIBRATION TEST RESULTS FOR A 100-KILOWATT WIND TURBINE

by Bradford S. Linscott, William R. Shapton*, and David Brown†

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SUMMARY

The 100-kilowatt wind turbine consists of a 28.3-meter- (93-ft-) high truss tower, a nacelle, and 38.5-meter- (125-ft-) diameter rotor blades. The nacelle is located on top of the tower and contains the drive train and generator.

The natural frequencies of the tower alone, the rotor blades attached to the drive train, and the fully assembled wind turbine were determined by testing. Test results were obtained by instrumenting the tower and rotor blades with accelerometers and then impacting each structure with a measured force pulse.

The first bending modes of the tower in the north-south and east-west directions were found at 2.1 and 2.2 hertz, respectively, both for the fully assembled wind turbine. The first torsional mode of the tower was found at 9.8 hertz for the fully assembled wind turbine.

The tower structure was modeled and programmed for analysis on a computer program called NASTRAN. The tower natural frequencies determined by testing agree within 4 percent with the tower frequencies predicted by NASTRAN.

Frequency and mode shape test data are needed to assure accurate prediction of the dynamic response of the wind turbine. Because the NASTRAN predictions closely agree with the test data, the NASTRAN model can now be used with greater confidence to evaluate the dynamic response of the wind turbine. This effort is a key step in the program goal of predicting the dynamic response of the wind turbine.

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INTRODUCTION

Recent shortages in the supply of energy, coupled with increasing fuel costs, have forced our Nation to reassess all forms of energy. The power available from the wind is now being examined with renewed interest.

The Federal wind energy program is directed by the Energy Research and Development Administration (ERDA). The program includes research and development on a variety of applications and concepts for wind energy systems. Agreement was reached that, under the overall program management of ERDA, the NASA Lewis Research Center would provide project management for a portion of the overall program.

As part of this program, Lewis has designed and constructed a wind turbine large enough to assess the technology requirements and the associated operational problems of a large wind turbine. The 100-kilowatt wind turbine has been constructed at the NASA Lewis Plum Brook Station near Sandusky, Ohio.

The wind turbine consists of an open-truss steel tower, 28.3 meters (93 ft) high; a nacelle that houses the alternator, the gearbox, and the low-speed drive shaft; and two aluminum rotor blades, each 18.75 meters (62.5 ft) long. The wind turbine is designed to produce 100 kilowatts of electric power in an 29-kilometer-per-hour (18-mph) wind at a rotor speed of 40 rpm.

For proper design of a wind turbine, it is necessary to perform analyses to determine the various types, magnitudes, and frequencies of loads in the blades, the drive train, and the tower that result from operation. To gain confidence in wind turbine structural dynamic analyses, it is necessary to support these analyses with test data on the natural vibrations and mode shapes of the major wind turbine subassemblies. This report only discusses the natural measured frequencies of the tower and the blades and the natural frequencies predicted with the aid of a computer program called NASTRAN. It does not discuss the dynamic response of the tower, the drive train, or the rotor blades during actual operation of the wind turbine.

The reasons for conducting the tests include using the test data to compare with analytical predictions and gaining added insight on the natural structural vibration characteristics of the tower and the blades over and above those predicted by analysis. Present program plans include design and fabrication of one or more large 1500-kilowatt wind turbines. It is important, at this time, to verify that the analytical predictions agree with experimental results before the design of a larger wind turbine is started.

This report describes the design of the 100-kilowatt steel truss tower and its overall dimensions, member sizes, materials, and total weight. Certain details of the design of the steel-reinforced concrete foundation are also described. Test results were obtained by instrumenting the tower with an accelerometer and impacting the tower with a measured force pulse. This report presents the measured tower natural frequencies and mode shapes before and after the rotor blades and the nacelle were installed on top of the tower. The measured data are then compared with analytical predictions made at Lewis by using NASTRAN.

TOWER DESCRIPTION

Design

The tower, a steel open-truss structure, shown in figure 1, was designed so that the first-bending-mode natural frequency was at least 20 percent above the critical driving frequency of 1.33 hertz, for a two-blade machine operating at 40 rpm. The rotor blades are located downwind of the tower, as shown in figure 2. This design provides maximum safety from the potential hazard of a blade striking the tower. This blade and tower orientation subjects the tower to lower turbulent air loads. On the other hand, the tower causes turbulent air loads on the blades as each blade passes near the downwind side of the tower. The open-truss type of tower structure was selected in an effort to minimize turbulent airflow on the portion of the swept rotor disk downwind of the tower.

Structure

The four tubular legs shown in figure 1 are constructed from structural steel pipe (ASTM A501). Structural bracing uses standard channel sections and angles. Brace members are either bolted or welded to plates, which in turn are bolted or welded to the tubular legs or adjoining brace members. All steel shapes and plates are fabricated from ASTM A36. The typical diamond-shape brace at the 6.4-meter (21-ft) level shown in figure 1 (view A-A) provides torsional stiffness for the tower. Diamond-shape braces are also provided at 11.58, 16.46, 20.73, 24.69, and 28.35 meters (38, 54, 68, 81, and 93 ft).

A nacelle, as shown in figure 2, is attached to the tower at the 28.35-meter (93-ft) level. The nacelle contains the rotating machinery for the wind turbine, including a gear type of pitch-change hub, a gearbox, an a.c. generator, and an electrohydraulic power supply. Also shown in figure 2 are the rotor blades, 37.5 meters (125 ft) in diameter, that are attached to the hub contained within the nacelle. A stairway is provided to allow personnel access from the ground to the interior to the nacelle, as shown in figure 2.

The tower structure is estimated to weigh 19 158 kilograms (44 000 lb), excluding the stairway. The stairway weighs approximately 5443 kilograms (12 000 lb). The nacelle and interior equipment, less the rotor blades, is estimated to weigh 13 608 kilograms (30 000 lb). Each blade weight approximately 907.2 kilograms (2000 lb). The center of gravity of the nacelle, interior equipment, and blades is approximately 1.9 meters (6.25 ft) downwind from the tower vertical centerline, as shown in figure 2.

Two parallel structural members were added to one side of the tower. These two members serve as guide rails for an open elevator car. The elevator car is used to transport tools and equipment from the ground to the top of the tower.

Foundation

The foundation plan is shown in figure 3. The foundation consists of four identical steel-reinforced concrete piers and four connecting grade beams. The grade beams form a square, in the plan view, with the piers located at each corner of the square. The grade-beam cross section is 1.07 meters (3.5 ft) deep by 0.40 meter (1.33 ft) wide. The distance from the center of one pier to another is 9.14 meters (30 ft) as measured along the side of the square in the plan view.

Figure 4 shows an elevation view of a typical pier and one of the connecting grade beams. Each pier is cylindrical, having a diameter of 1.07 meters (3.5 ft). Each pier extends below ground level to a grey shale rock bed. The shale bed lies about 7.62 meters (25 ft) below ground level. Each pier is flared from 1.07 meters (3.5 ft) in diameter to 2.29 meters (7.5 ft) in diameter over a length of 1.22 meter (4 ft). The maximum pier diameter bears on sound rock.

Shown in figure 3 are four steel anchor bolts located at the top of each pier. The anchor bolts are used to attach each tower leg to the foundation. A shear key, also shown in figure 3, is provided between each tower leg and pier. The shear key is used to transmit horizontal shearing forces from the tower into the foundation.

Additional detail on the 100-kilowatt wind turbine is contained in reference 1.

PURPOSE OF TEST AND APPARATUS USED

The two main reasons for conducting the tests are

(1) To compare the test data with the natural frequencies and mode shapes for the tower structural model as predicted by NASTRAN and thereby to determine the adequacy of the model

(2) To gain further insight into the tower structural vibration characteristics over and above those predicted by analysis

Tower displacements and bending frequencies are planned to be monitored during future operational tests on the 100-kilowatt wind turbine. Further understanding of the vibrational characteristics of the tower, as a result of testing, will improve the ability of the analyst to interpret and analyze operational test data resulting from future tests of the wind turbine. This understanding is needed for the design of larger wind turbines that are planned as part of the Nation's energy program.

The vibration tests were performed for Lewis by a test team from the Department of Mechanical Engineering of the University of Cincinnati, Cincinnati, Ohio. The test team used the University of Cincinnati's Mobile Vibration Laboratory at the test site.

A force pulse was used to excite the tower structure. The input force and the resulting tower motion responses were then measured. A hand-held hammer, the size of a common sledge hammer, was first used to excite the tower. A load cell on the head of the hammer was used to measure the applied force.

Similarly, a large cylindrical weight (272 kg (600 lb)) was later used to excite the tower. A load cell located and protruding from the circular surface of the cylindrical weight was used to measure the applied force.

An accelerometer was used to measure the tower motion resulting from the applied force. The frequency content of the force and motion responses was measured by the equipment in the mobile laboratory and determined by using a Fourier analyzer. The frequency response (displacement per unit force) was obtained by dividing the response by the excitation.

The tower mode shapes, described in the next section, were determined by moving the response transducer about the structure and determining the cross-frequency response while the tower was impacted at a specified point. The motion per unit input force at each natural frequency was then determined from the cross-frequency response plots and the displacement at selected points for the given input. In determining the amplitude of the response at a given natural frequency, only the imaginary part (quadrature) of the response was used. This technique improves the modal presentation when the natural frequencies are close together.

The blade modes and frequencies were determined by using a small hand-held hammer for blade excitation. A load cell on the head of the hammer was used to measure the applied force. An accelerometer was used to measure the blade motion resulting from the applied force. Again, the frequency content of the force and motion responses was measured by the equipment in the mobile laboratory.

RESULTS AND DISCUSSION

Frequency Response and Mode Shapes of the Tower Alone

The frequency response of the tower was determined by applying a force at the 28.3-meter (93-ft) level. The excitation force was applied in both the north-south (N-S) and east-west (E-W) directions and the resulting frequency response plots are shown in figures 5 and 6. Both plots are dominated by the first bending mode of the tower, which is 4.7 hertz in the N-S direction and 5.1 hertz in the E-W direction. The higher frequency in the E-W direction is assumed to be the result of a stiffening effect in the direction of the staircase and the guide rails for the equipment elevator.

The plots shown in figures 5 and 6 are "driving point" frequency response plots. The plots present the displacement response in a specified direction due to a force applied at the same point and in the same direction. A sketch of the tower orientation defining north as used in this report and showing the points at which force was applied to obtain data in figures 5 and 6 is shown in figure 7.

The point of application for a third driving-point frequency response is also shown in figure 7 and plotted in figure 8. This off-center plot should be more sensitive to the torsion response of the tower. A comparison of figures 8 and 5 indicates that the 10.5- and 12.7-hertz natural frequencies were excited to a greater extent by the off-center impact.

The plots shown in figures 5, 6, and 8 were all obtained by impacting the tower at the 28.3-meter (93-ft) level with a hand-held hammer. An impact with higher force levels was obtained by swinging a weight into the tower from a crane, as shown in figure 9. The frequency response of the tower to this impact is shown in figure 10. This plot also reflects an off-center force applied in the E-W direction on the northeast corner of the tower. The mode shapes were obtained for the principal natural frequencies in this plot and with the same excitation.

In summarizing the frequency response plots shown in figures 5, 6, 8, and 10, it is evident that the tower's response is dominated by its 4.7- and 5.1-hertz modes. However, numerous other modes can also be identified, and these include modes at 8.5, 9.4, 10.5, 17.3, 23.5, and 24.6 hertz. Mode shapes were run at these and several other frequencies in an effort to identify the tower's fundamental frequencies.

The modes at 4.7 and 5.1 hertz are essentially identical except that in the 4.7-hertz mode the tower deflects in the N-S direction and in the 5.1-hertz mode it deflects in the E-W direction. Movement of the tower at the 28.3-meter (93-ft) level for each mode is depicted in figure 11. Insufficient data were taken to establish the tower deflection in the N-S direction for the 4.7-hertz mode. However, the tower deflection in the E-W direction was measured and is shown for the 5.1-hertz mode in figure 12. Although this is clearly the first bending mode of the tower in the E-W direction, a mode exists at about the 4.9-meter (16-ft) level, and deflections below this level are in the negative direction.

In figures 12 to 18 the plots portray deflection of the east side of the tower as if it were viewed standing south of the tower. The deflection of the near leg (southeast) is shown as a solid line and that of the far leg (northeast) is shown as a dashed line. (Assume the force to be applied from west to east at the 28.3-m (93-ft) level and on the northeast corner of the tower.) Each mode shape has been normalized by dividing it by its maximum deflection.

The second N-S mode of the tower is not as clear as the first but is probably at 8.5 hertz, and the second E-W mode is at 9.4 hertz. A combined mode appears at 7.8 hertz and is shown in figure 13. The 8.5- and 9.4-hertz second bending modes are shown in figures 14 and 15, respectively. The first torsional mode is at 10.5 hertz and is shown in figure 16. The third bending mode of the tower in the E-W direction appears at 17.3 hertz and is shown in figure 17. The final tower mode plotted is the 23.5-hertz mode and appears to be a second torsional bending mode. This mode is shown in figure 18.

The higher tower modes shown are not simple modes but are complex system modes and are influenced by individual members and their natural frequencies. The result is a complex deformation pattern and frequency response plots that indicate the presence of many local modes. A great deal of time would be required to trace each of these local modes and determine its source.

One local mode that was detected and evaluated was the local bending of the cross members, which results in torsion of the individual tower legs. The driving-point frequency response of one cross member is shown in figure 19, and the leg is identified in figure 2. Although the overall structure's natural frequencies are not apparent in this plot, local natural frequencies at 5.4, 6.0, and 6.6 hertz are. The 6.0-hertz mode shape for the lower half of this member is shown in figure 20. The direction of motion of the cross member is perpendicular to the plane parallel to the side of the tower (fig. 2). In summary, there are a great number of natural frequencies present in the tower in the 1- to 25-hertz range investigated in this study. However, many are the result of local resonances and are not significant structural modes. The natural frequencies of the most important modes identified are listed in table I.

The tower structure was modeled by Lewis and programmed for analysis by using the NASTRAN computer code. The first bending mode frequencies in the N-S and E-W directions were calculated at 4.76 and 5.19 hertz, respectively. The first-torsional-mode natural frequency was calculated at 10.1 hertz. The calculated values are shown in table I and agree very closely with the values obtained experimentally. Details of the NASTRAN analysis that was conducted on the 100-kilowatt wind turbine are reported in reference 2.

Frequency Response and Mode Shapes of Tower with Nacelle and Blades

The nacelle-and-blade assembly was mounted on the tower for evaluation of the dynamic characteristics of the entire system. The tower mode shapes for this configuration were again determined by impacting the tower with the 272-kilogram (600-lb) weight suspended from the crane. The impact was applied in the N-S direction on the northeast corner, as depicted in figure 21. The resulting driving-point frequency response plot obtained at the 28.3-meter (93-ft) level is shown in figure 22. A cross-frequency response plot showing the E-W motion due to the N-S impact is given in figure 23. The two most important natural frequencies are evident from these plots; they are

(1) 2.1 Hertz - tower first bending mode in the N-S direction

(2) 2.2 Hertz - tower first bending mode in the E-W direction

These modes are essentially identical and are shown in figures 24 and 25.

The remaining modes are complex interactions of the blades and the tower, and their description in terms of common simple mode shapes may be an oversimplification. With this in mind the tower mode shapes for the most significant peaks are simply plotted in figures 26 to 36.

Figures 27 to 36 show the deformations of the tower legs from three views. The first shows Z-axis motion as if the tower were viewed from the south looking north. The deflections of the near legs (south side) are shown as solid lines and those of the far legs as dashed lines. The second view shows the tower as viewed from the east looking west and shows X-axis motion. Again deflections of the near legs are shown as solid lines and those of the far legs as dashed lines. The sketch on each figure shows the tower as if seen from above and gives the X- and Z-axis deflections of the 28.3-meter (93-ft) level.

Referring again to figures 24 and 25, which are assumed to show the tower first bending modes, it can be seen from the 28.3-meter (93-ft) level view that because the two modes are close together and both excited, the actual mode shapes are translations along the tower diagonals. In fact, whether these modes are actually bending perpendicular to the sides or along the diagonals is open to debate.

The 4.4-hertz mode shown in figure 26 appears to be torsion, with the blades and the nacelle twisting more than the tower, which also has some N-S first mode bending present. In fact, the blades actually are twisting out of phase with the nacelle, and a slight deformation of the blade end of the nacelle is evident.

Figure 27 shows the 5.0-hertz mode, in which the tower is in very pure first mode bending in the E-W direction. Not shown is the presence of a large inplane blade bending that occurred at this frequency. (The blades were feathered during this test and the inplane blade motion was in the E-W direction.) The tower motion may be the result of the blade whipping.

The 9.8-hertz mode shown in figure 28 is a torsional mode. The actual torsional mode may well be at 8.5 hertz but was not determined to be significant in the driving-point frequency response plot. The 10.4- and 10.9-hertz modes shown in figures 29 and 30 are torsional-bending modes in which the nacelle and the blades follow the tower. In the 11.6-hertz mode of figure 31, the blades show no movement, but there is a large torsional displacement at the lower levels of the tower. In this mode, the tower seems to be in a first bending mode on the south side, with a second bending mode on the east and west.

The 12.4-hertz mode in figure 32 is again torsion with something like second mode bending of the tower walls. The 13.0-hertz mode shown in figure 33 is torsion with the nacelle out of phase with the tower. The 13.7-hertz mode shown in figure 34 contains large distortions at the third tower level, but the nacelle does not move to follow the tower for this mode. Figures 35 and 36 show the 14.6- and 15.1-hertz modes, which have large tower second-bending-mode deformations in the east and west walls.

The complete wind turbine was modeled by adding the structural components and the nonstructural mass of the nacelle and the rotor blades to the tower model previously described. The tower first-bending-mode frequency in the N-S direction was predicted by NASTRAN to be 2.15 hertz. The tower and first-bending-mode frequency in the E-W direction was calculated at 2.28 hertz, and the first-torsional-mode frequency at 9.56 hertz. The structural model simulated the actual test configuration in that the rotor blades were oriented in a horizontal position (parallel to the ground) and the blade pitch angle was set at full feather. The calculated values are shown in table II and agree closely with the experimental results.

Rotor-Blade Natural Frequencies and Mode Shapes

In reference 3 the design of the rotor blade for the 100-kilowatt wind turbine is described. Also the blade vibration characteristics determined by both analysis and testing are presented.

Vibration tests were conducted on the rotor blades when the blades were attached to the rotating machinery. These blade tests were conducted before and after the blades were positioned on top of the tower.

A summary of the blade natural frequencies determined by the University of Cincinnati is presented in table III. The mode shapes described in table III are interpreted as being similar to the modes expected for a cantilever beam. The blade frequencies calculated and established by testing were taken from reference 3 and are presented in table III for ease of comparison. A special blade-supporting test fixture was used to simulate the stiffness of the wind turbine structure for the tests described in reference 3. The blade test data as determined by the University of Cincinnati agree closely with the test data taken from reference 3.

SUMMARY OF RESULTS

The vibration characteristics of the tower for the ERDA-NASA 100-kilowatt wind turbine were determined by testing before and after the rotor blades and the nacelle containing the rotating machinery were installed on top of the tower. The vibration characteristics of the rotor blades were determined by testing while they were attached to the rotating machinery. The blade vibration characteristics were measured before and after the blades were mounted on top of the tower. The following results were obtained:

1. Before the nacelle was installed on the tower the first bending mode occurred at 4.7 hertz in the north-south direction and at 5.1 hertz in the east-west direction. The first torsional mode was found at 10.5 hertz.

2. After the nacelle was installed on the tower the first bending mode occurred at 2.1 hertz in the north-south direction and at 2.2 hertz in the east-west direction. The first torsional mode was found at 9.8 hertz.

3. The tower frequencies and mode shapes predicted analytically, by using the NASTRAN computer code, in general compare very closely with the test data.

4. The blade frequencies and mode shapes, as measured by testing at Plum Brook Station, compare quite closely with the values measured by the Lockheed Aircraft Company.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 19, 1976,
778-24.

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TABLE I. - SUMMARY OF TOWER NATURAL FREQUENCIES WITHOUT

NACELLE AND ROTOR BLADES

Tower frequency, Hz		Tower mode
Test values	NASTRAN values	
4.7	4.76	First bending, in north-south direction
5.1	5.19	First bending, in east-west direction
7.8	-----	Second bending, in north-south direction, and a combined mode
8.5	-----	
9.4	9.16	Second bending, in east-west direction
10.5	10.1	First torsional
17.3	-----	Third bending
23.5	-----	Second torsional

TABLE II. - SUMMARY OF TOWER NATURAL FREQUENCIES

WITH NACELLE AND ROTOR BLADES MOUNTED ON TOWER

Tower frequency, Hz		Tower mode
Test values	NASTRAN values	
2.1	2.15	First bending, in north-south direction
2.2	2.28	First bending, in east-west direction
9.8	9.56	First torsional

TABLE III. - SUMMARY OF BLADE FREQUENCIES

AND MODE SHAPES

Blade mode	Blade frequency, Hz			
	University of Cincinnati test data		Reference 3 data	
	Off tower[a]	On top of tower[b]	Analysis values	Test values
First beamwise	1.75	1.73	1.64	1.73
Second beamwise	5.03	3.6	4.76	4.99
	5.27	----	-----	-----
Third beamwise	9.76	(c)	10.17	10.38
	10.4	----	-----	-----
First chordwise	2.7	3.0	2.38	2.66
Second chordwise	9.2	(c)	9.3	9.8
Third chordwise	(c)	(c)	(c)	(c)
First torsional	(c)	(c)	34	32.8

[a]Blades horizontal in powered position.
[b]Blades horizontal in feathered position.
[c]Value not determined by testing or by analysis.

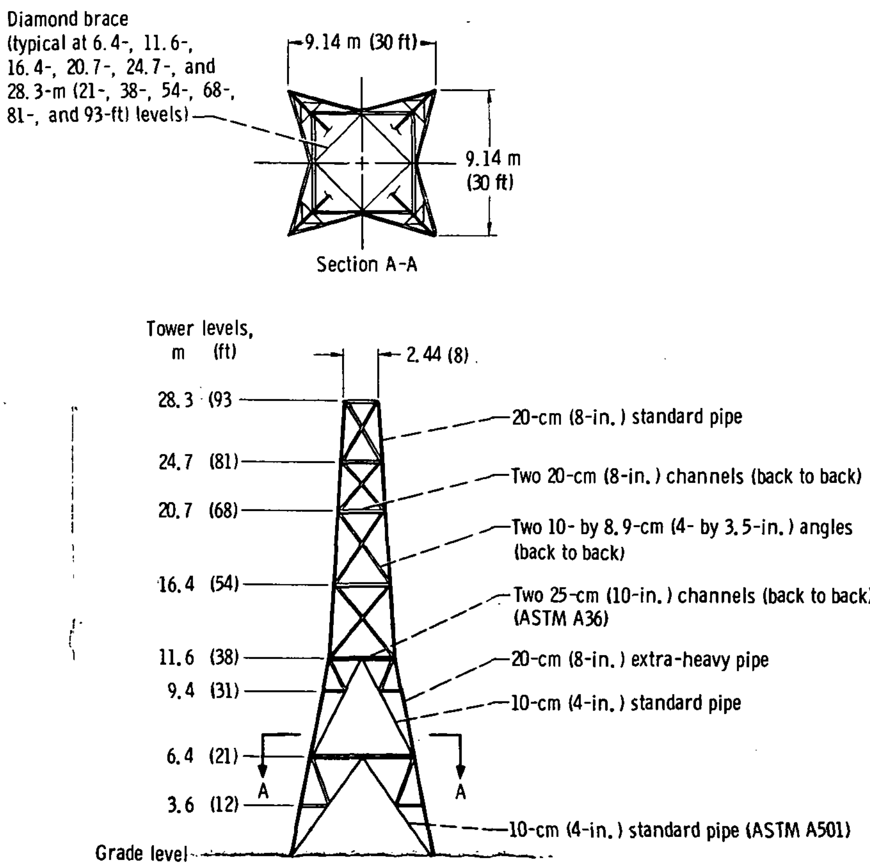


Figure 1. - Tower structure.

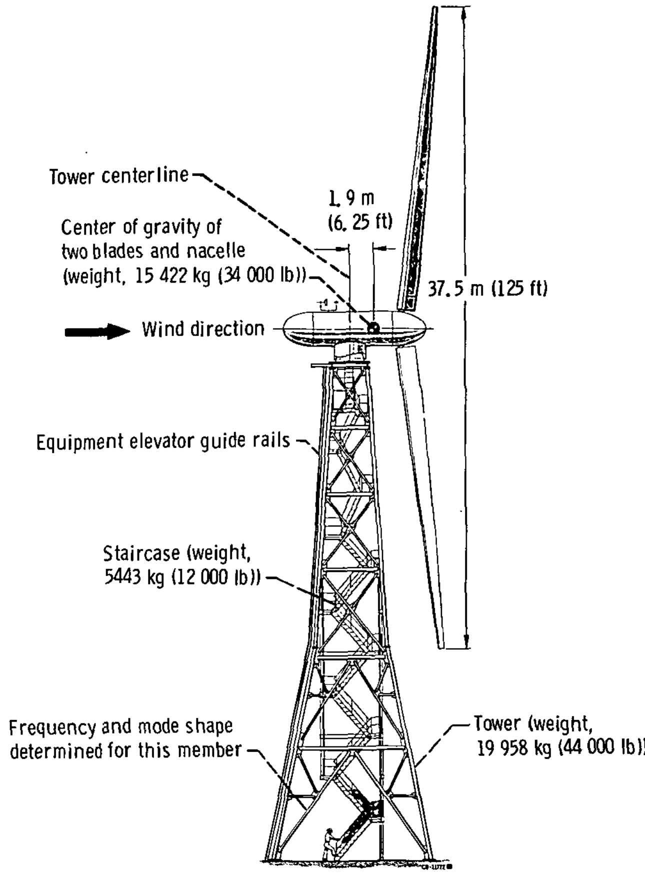


Figure 2. - 100-Kilowatt wind turbine assembly.

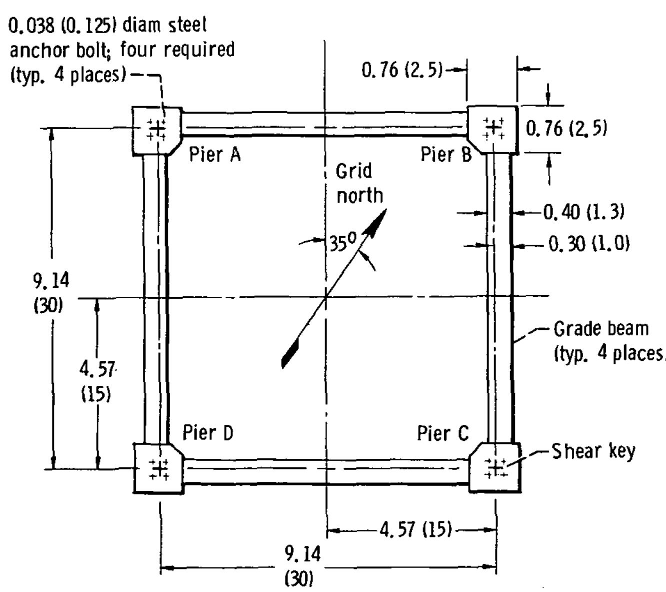


Figure 3. - Foundation plan for 100-kilowatt wind turbine tower. (Dimensions are in meters (ft).)

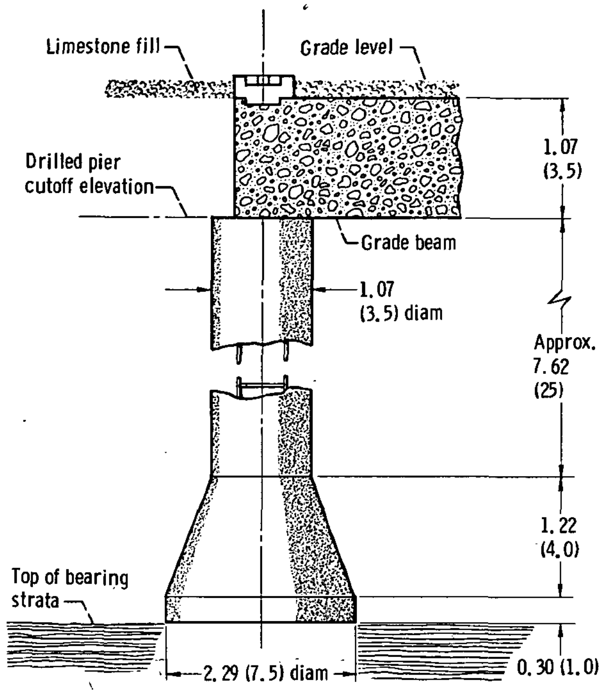


Figure 4. - Elevation view of typical pier and grade beam. (Dimensions are in meters (ft).)

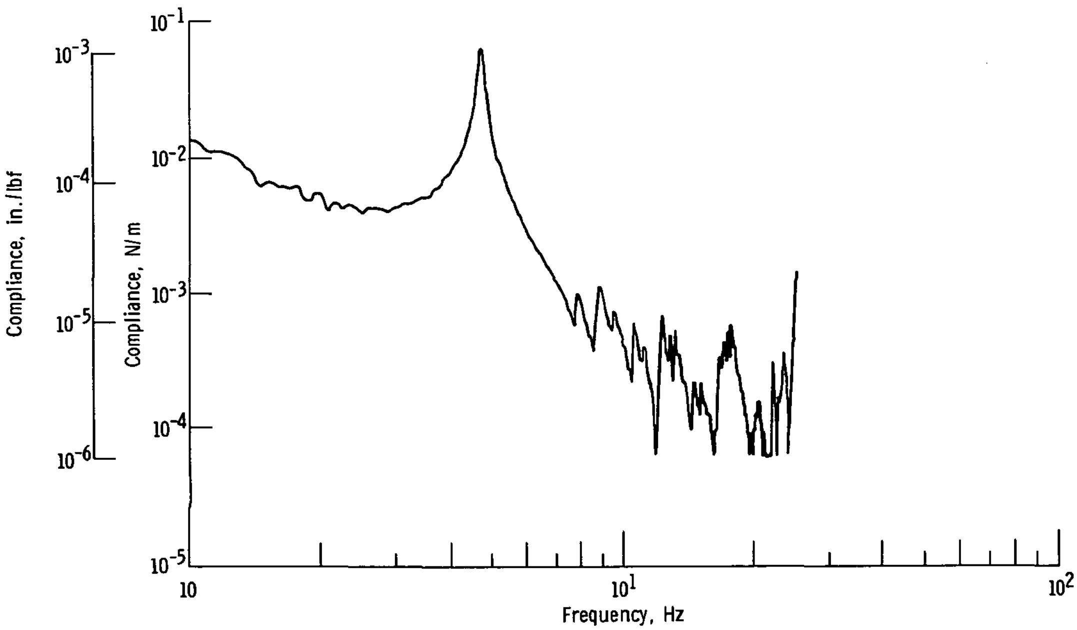


Figure 5. - Tower frequency response in north-south direction.

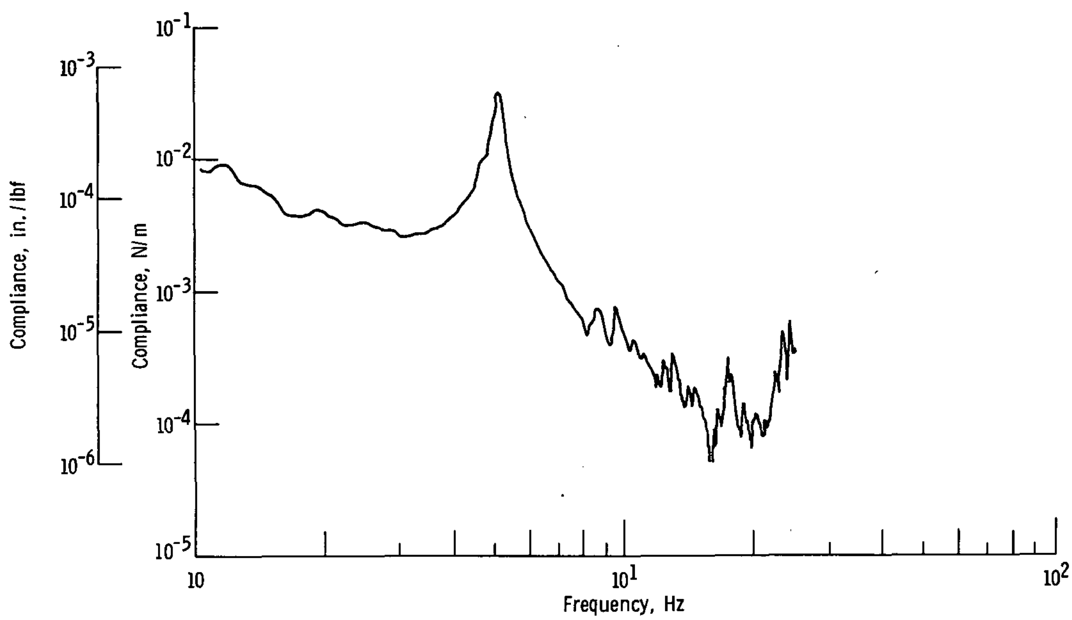


Figure 6. - Tower frequency response in east-west direction.

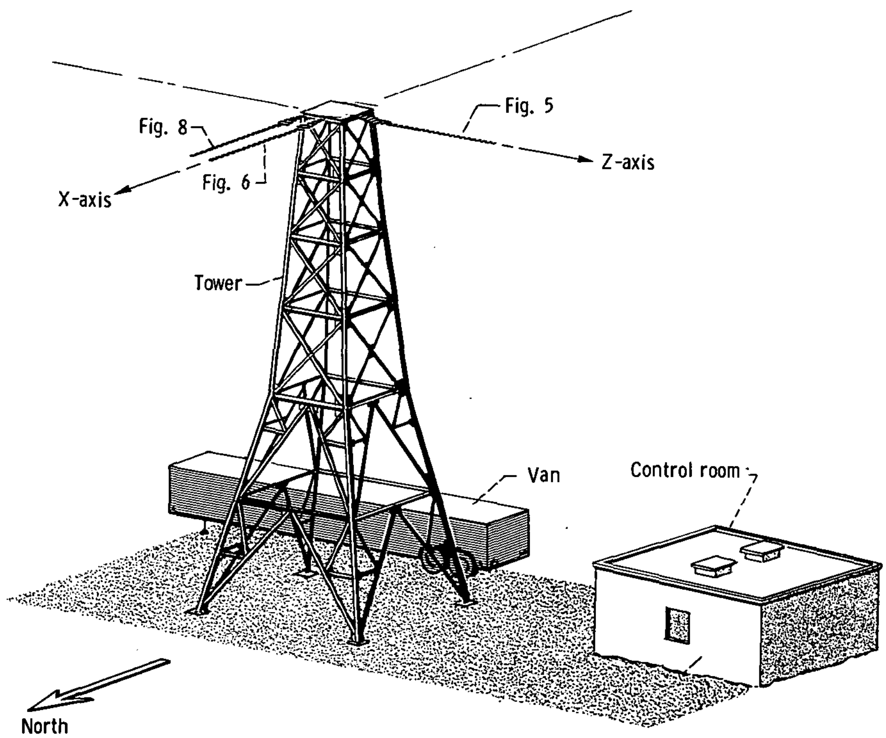


Figure 7. - Sketch defining coordinate directions and points at which force is applied to obtain data in figures 5, 6, and 8.

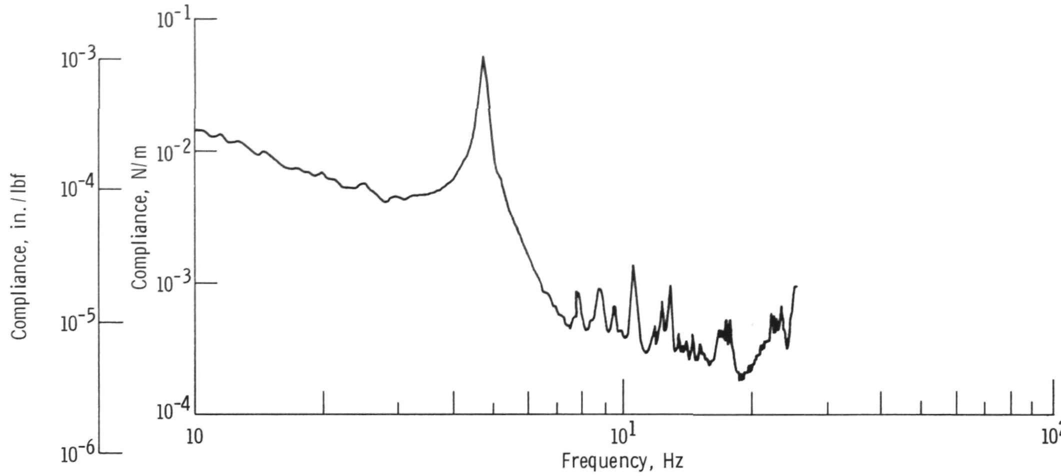


Figure 8. - Off-center tower frequency response in north-south direction.

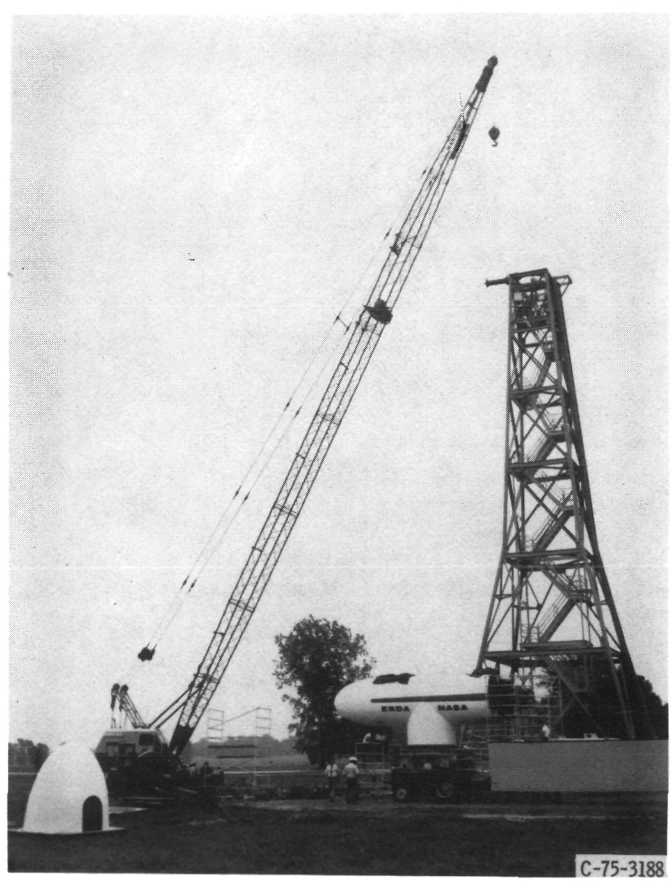


Figure 9. - Test setup.

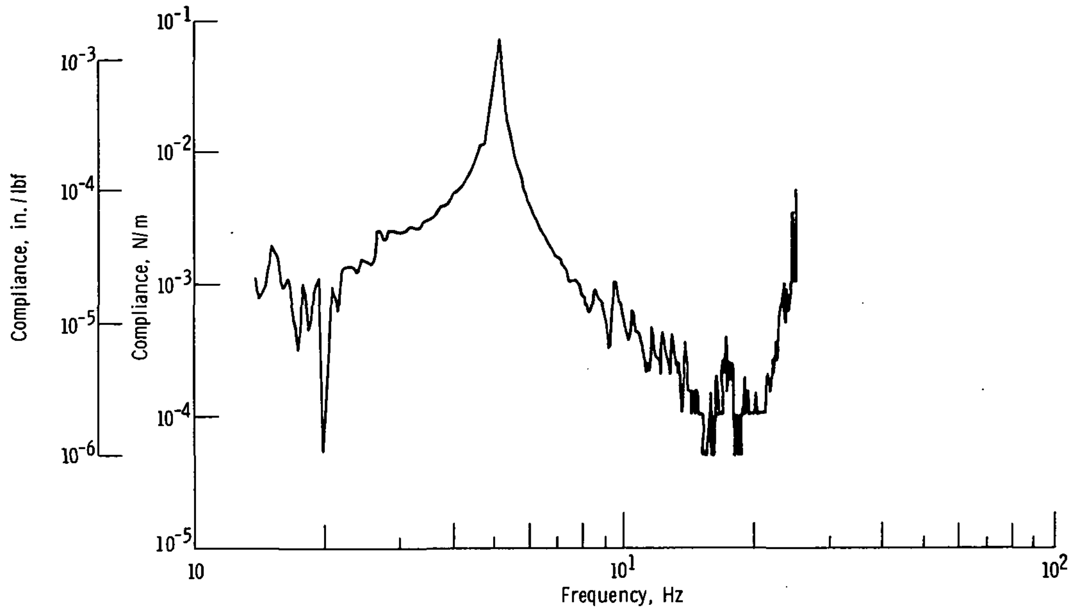
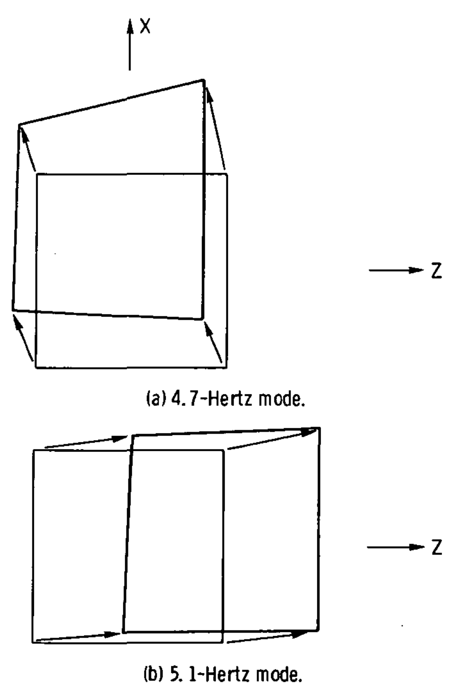


Figure 10. - Driving-point frequency response of tower at 28.3-meter (93-ft) level.



(a) 4.7-Hertz mode.

(b) 5.1-Hertz mode.

Figure 11. - Mode shape at 28.3-meter (93-ft) level for 4.7- and 5.1-hertz modes.

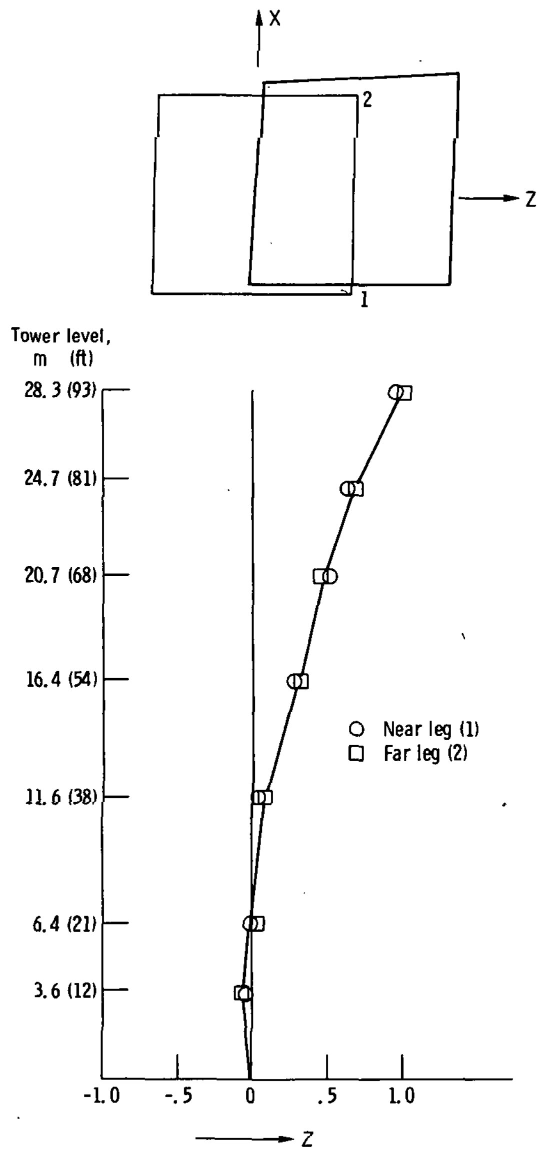


Figure 12. - 5.1-Hertz tower bending mode.

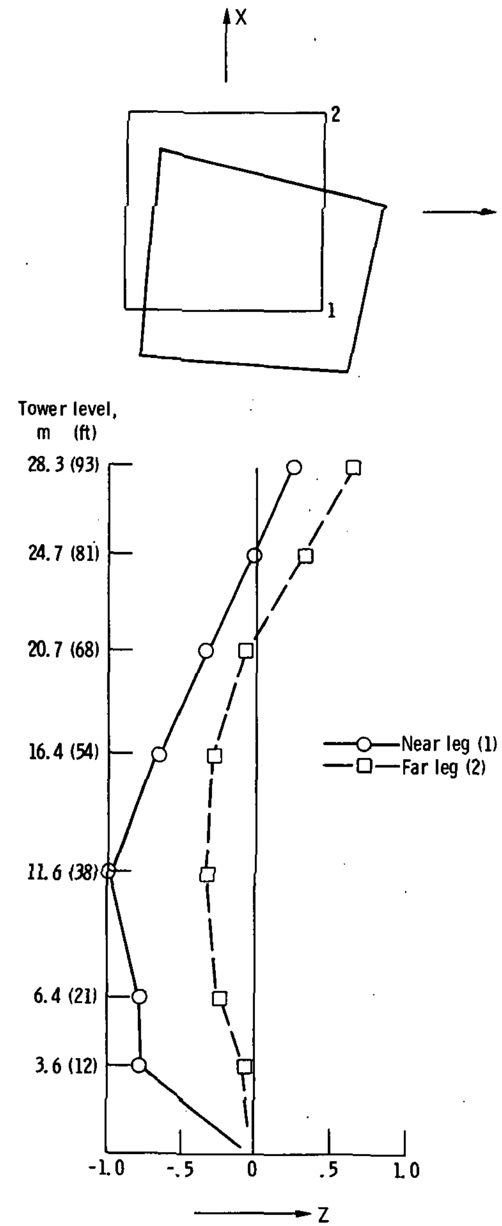


Figure 13. - 7.8-Hertz tower bending mode.

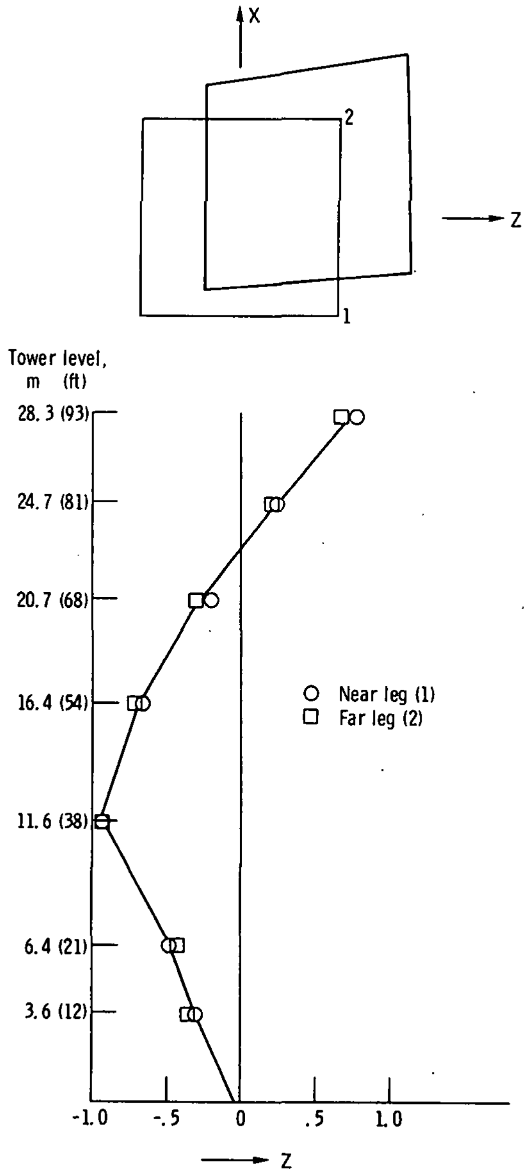


Figure 14. - 8.5-Hertz tower bending mode.

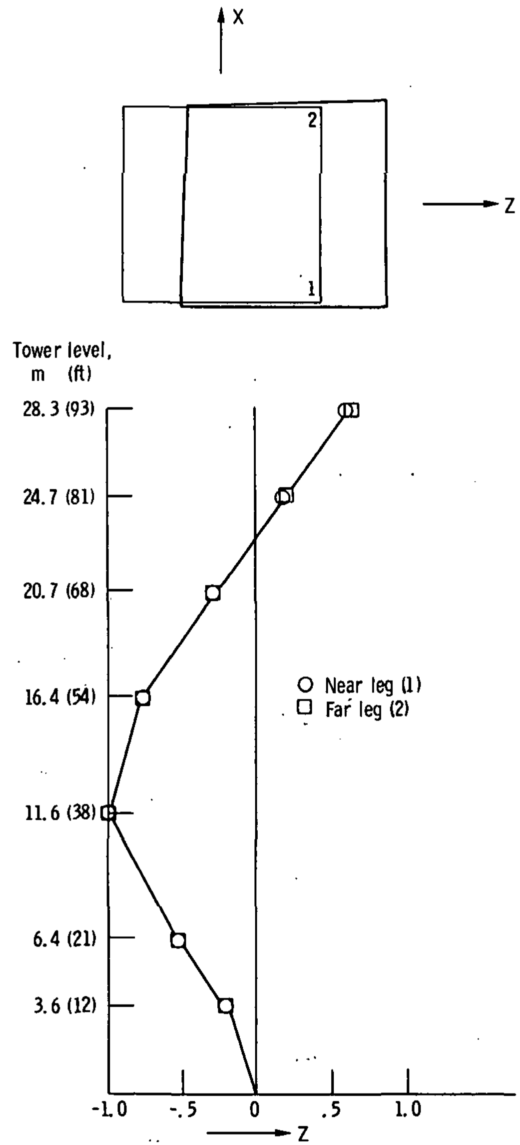


Figure 15. - 9.4-Hertz tower bending mode.

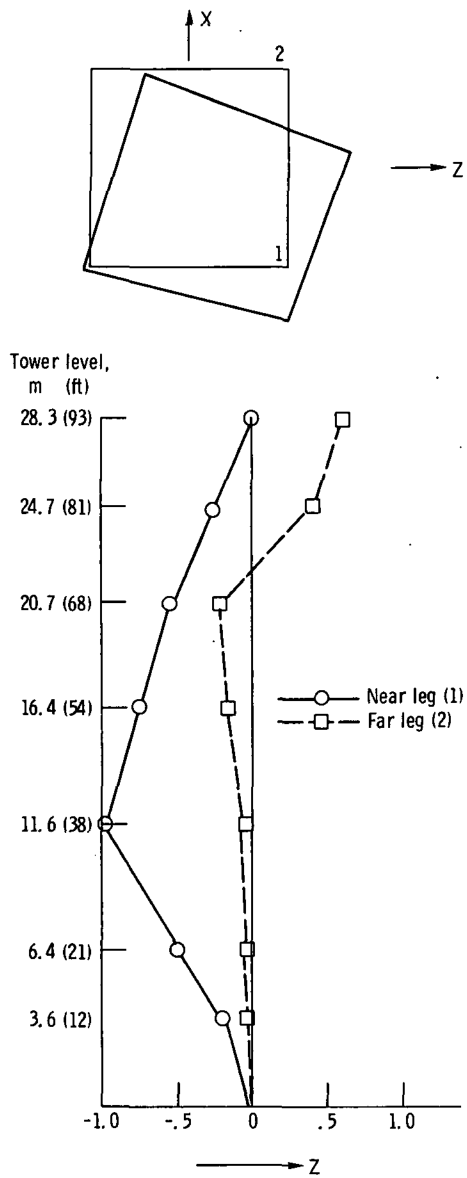


Figure 16. - 10.5-Hertz tower torsional mode.

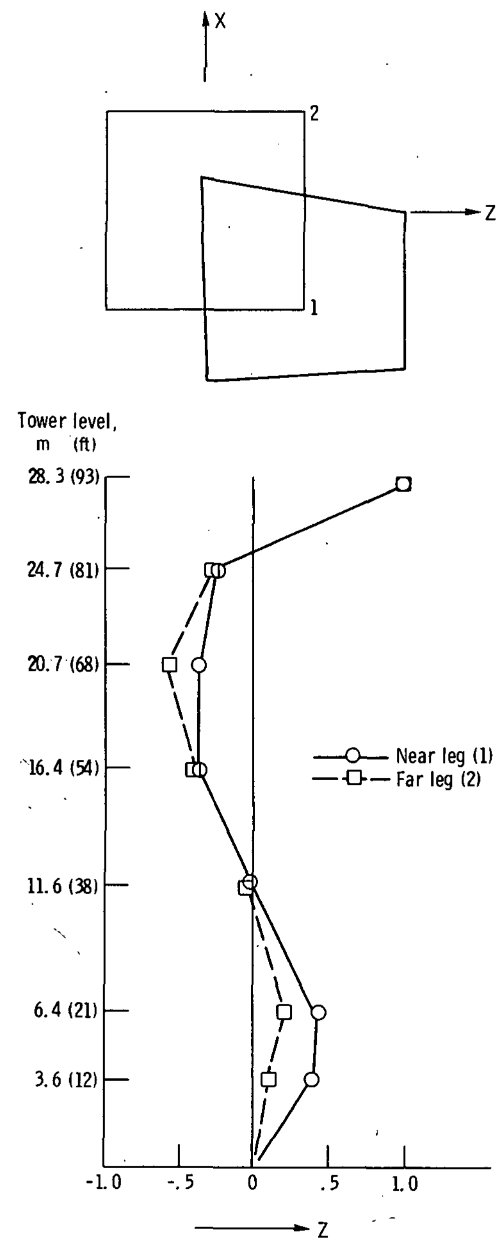


Figure 17. - 17.3-Hertz tower bending mode.

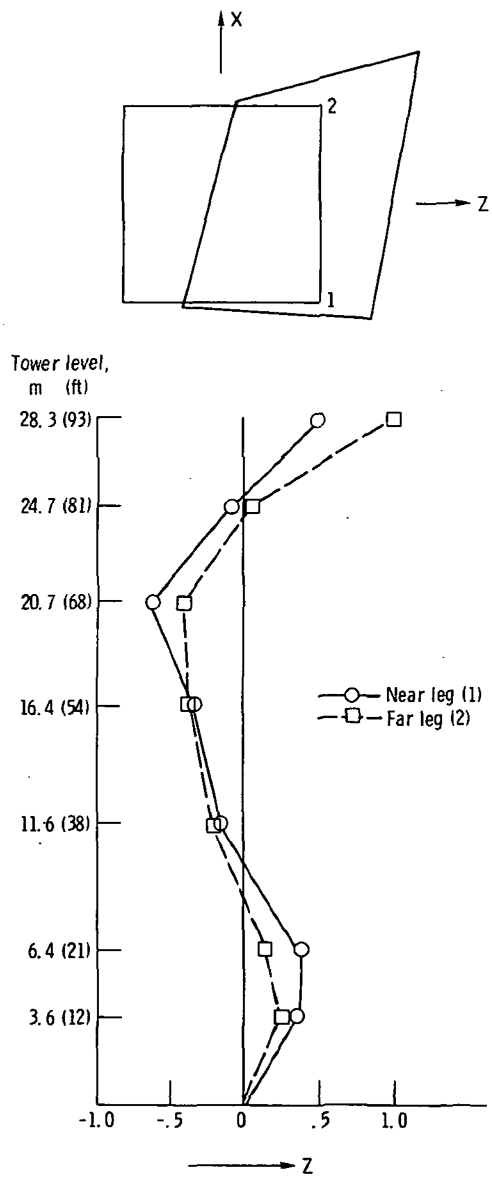


Figure 18. - 23.5-Hertz tower torsional mode.

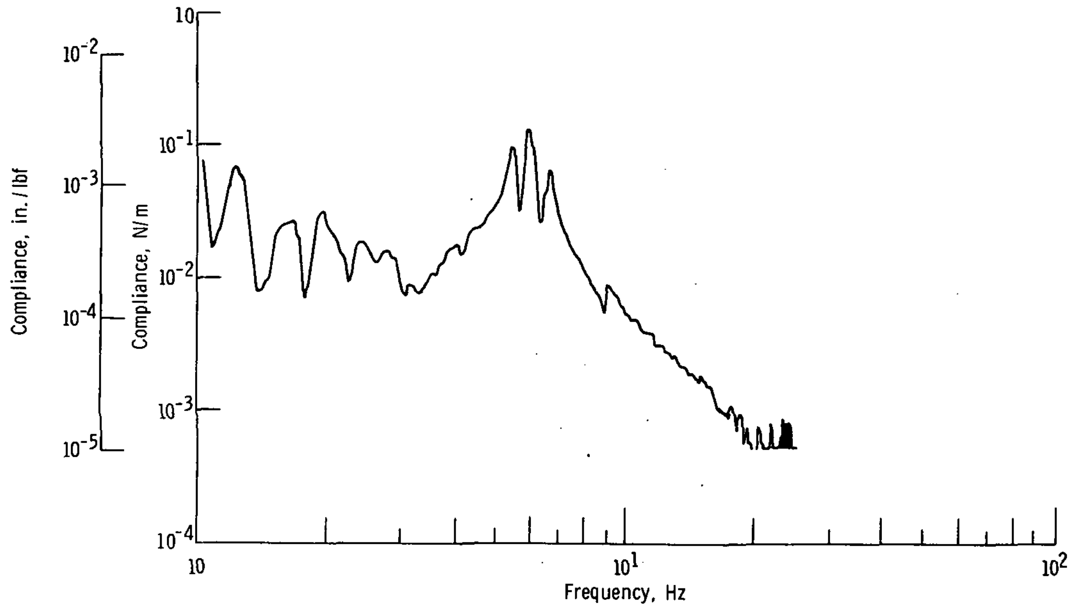


Figure 19. - Frequency response of lower structural member of tower.

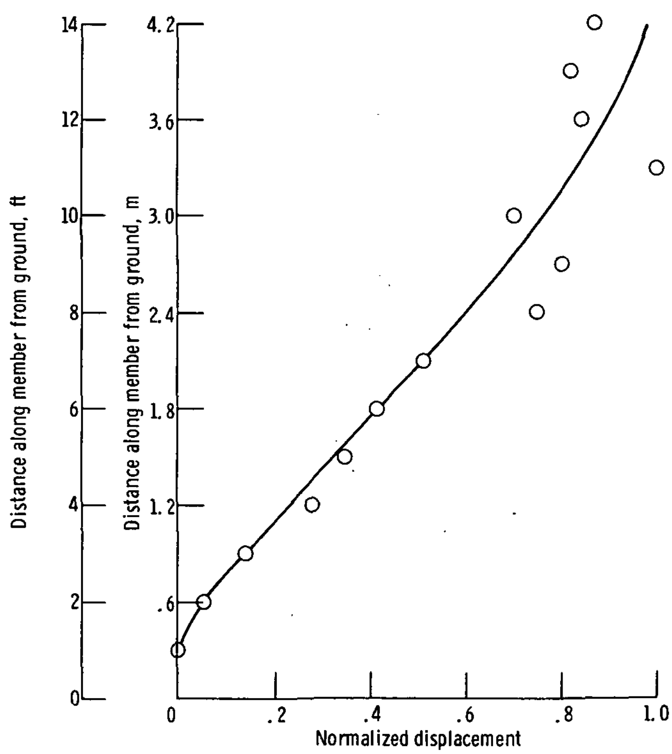


Figure 20. - 6.0-Hertz mode of lower structural member shown in figure 4.

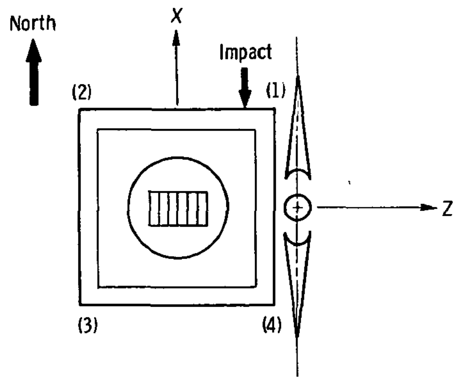


Figure 21. - Sketch of test setup for wind turbine system evaluation. (Numbers in parentheses denote legs of tower.)

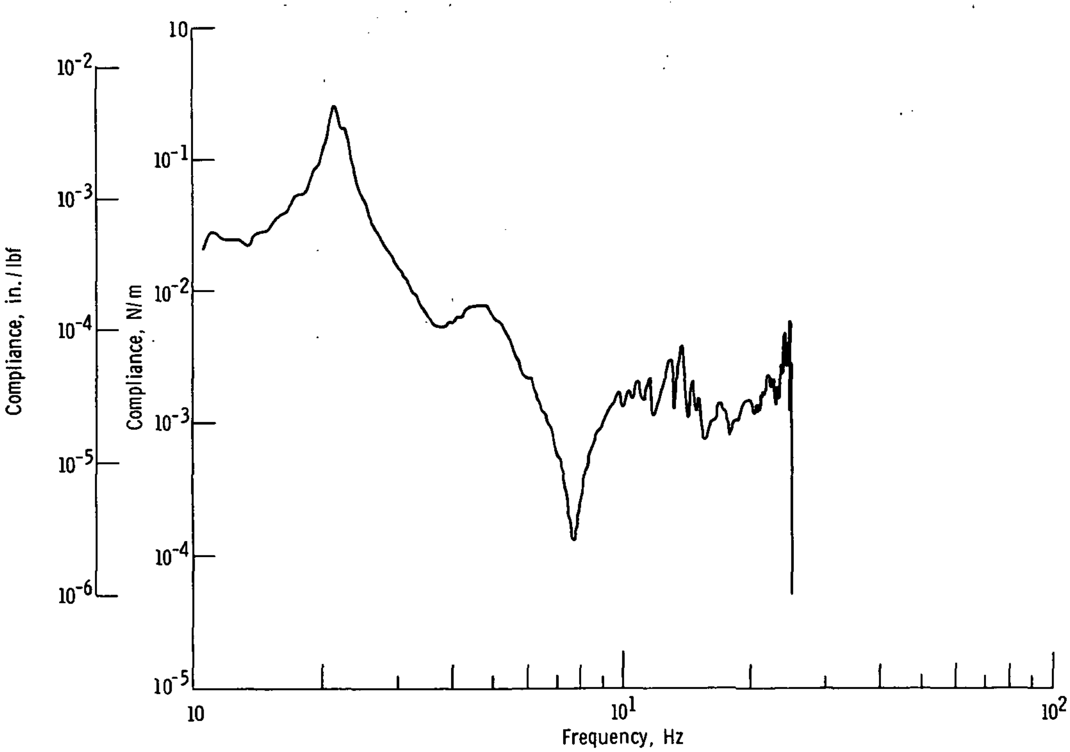


Figure 22. - North-south driving-point frequency response of tower at 28.3-meter (93-ft) level.

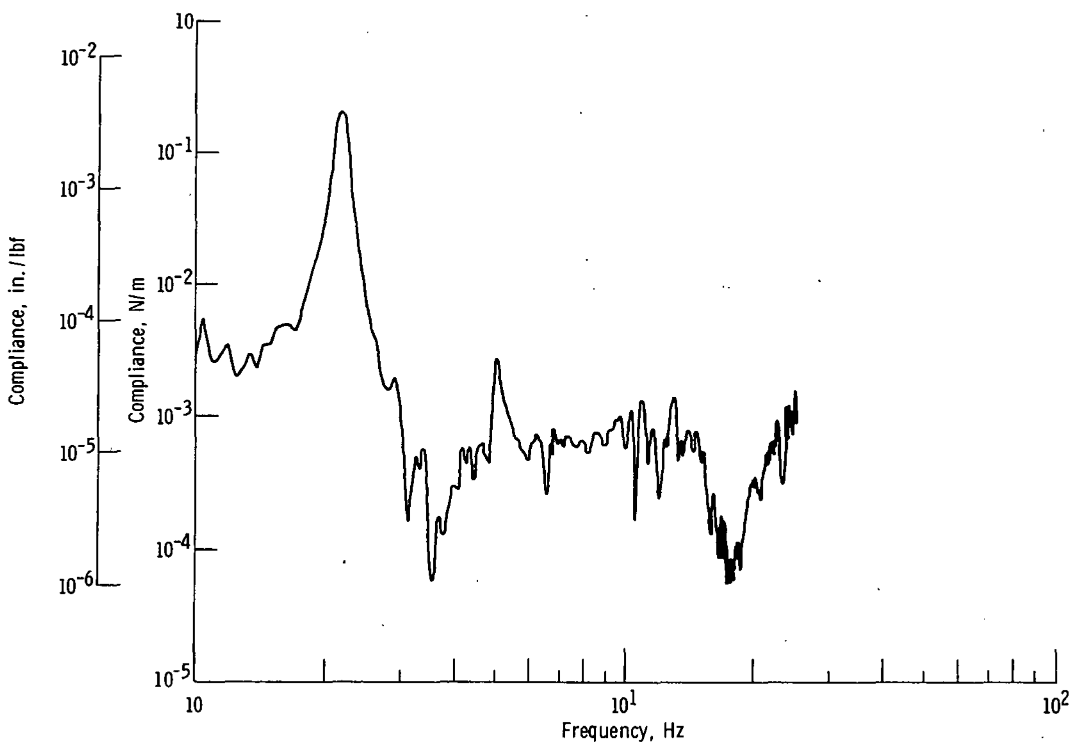


Figure 23. - East-west response of tower at 28.3-meter (93-ft) level due to north-south impact.

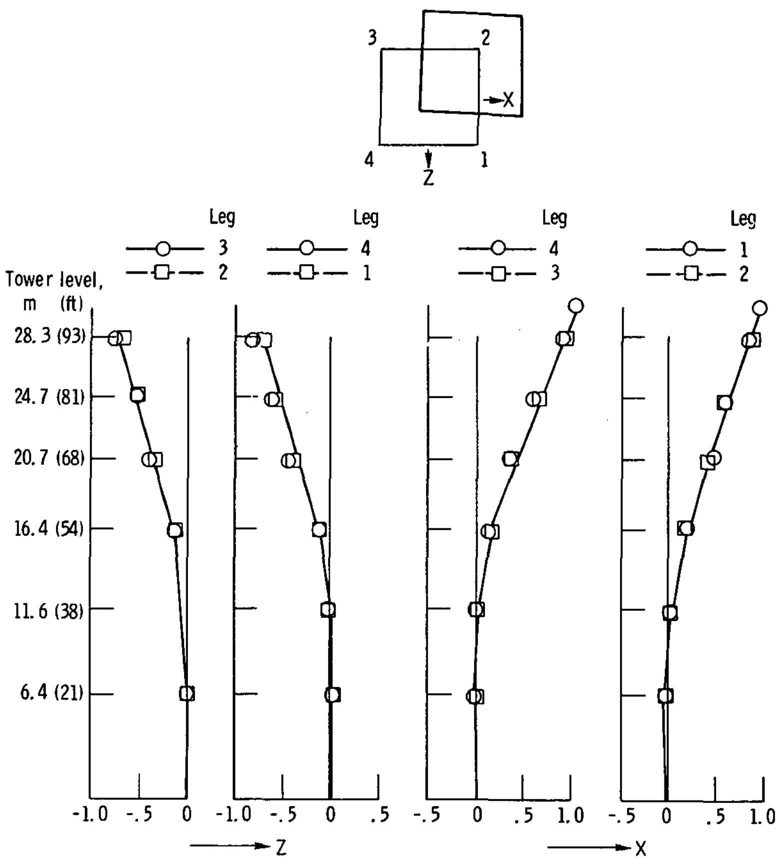


Figure 24. - 2.1-Hertz first bending mode of wind turbine system in north-south direction.

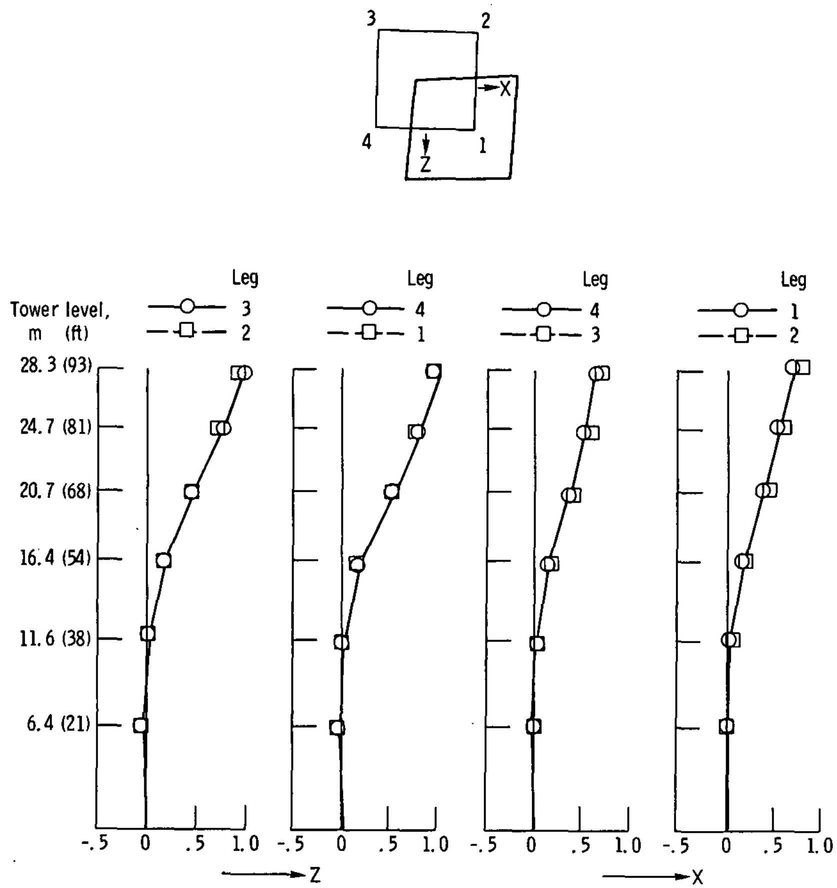


Figure 25. - 2.2-Hertz first bending mode of wind turbine system in east-west direction.

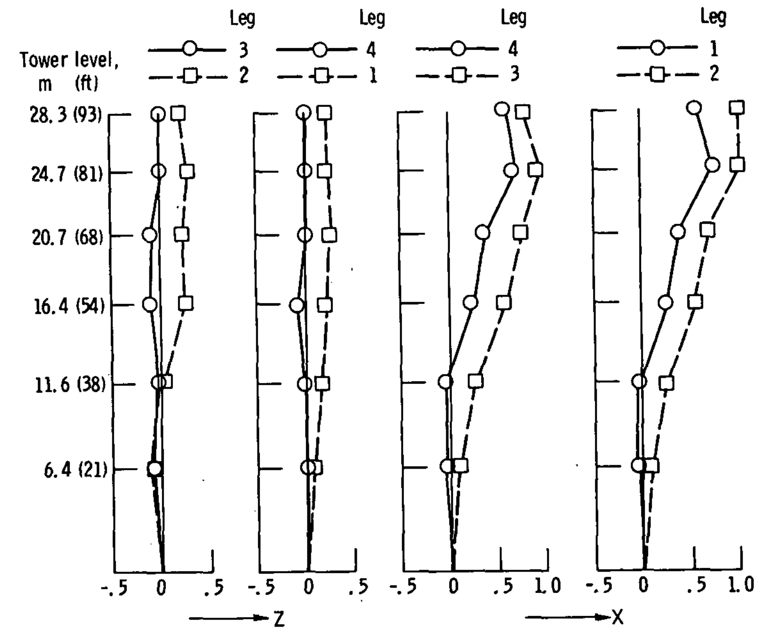


Figure 26. - 4.4-Hertz torsional mode of wind turbine system.

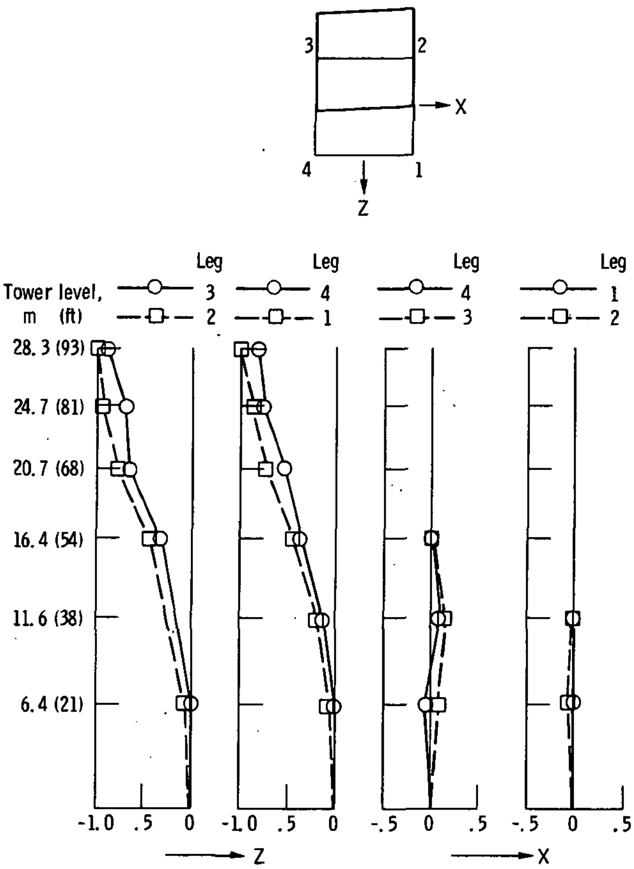


Figure 27. - 5.0-Hertz bending mode of wind turbine system.

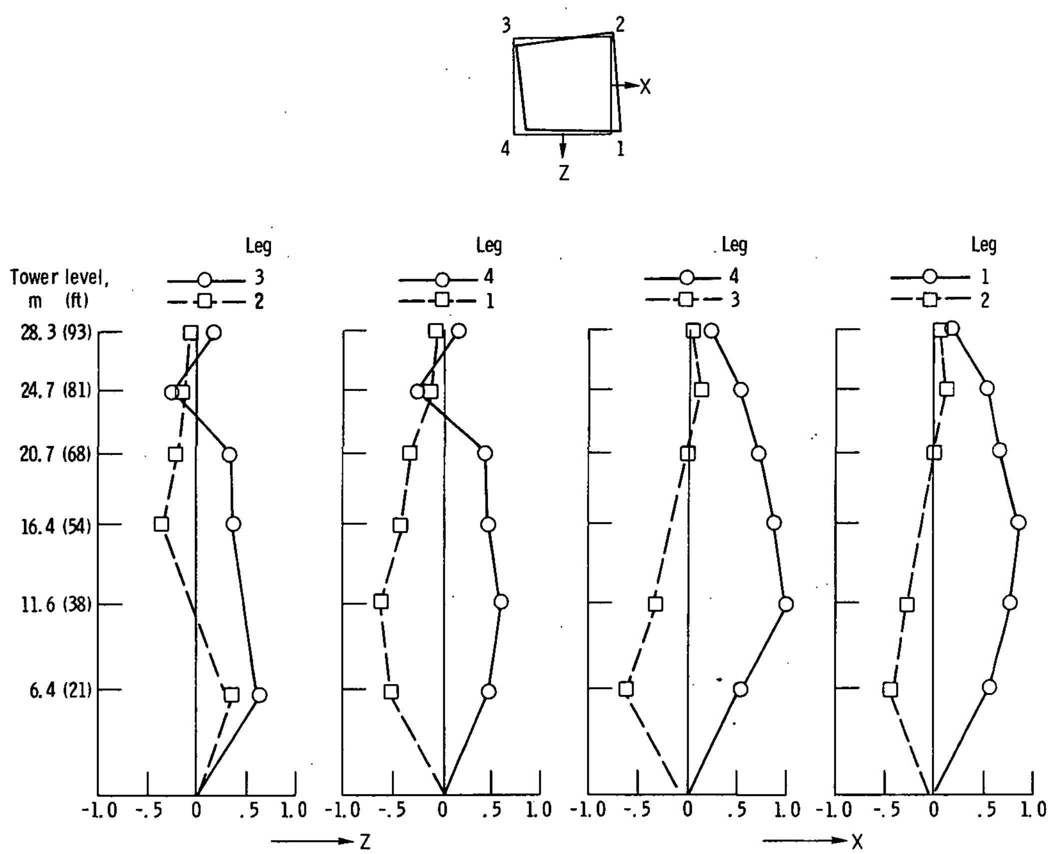


Figure 28. - 9.8-Hertz torsional mode of wind turbine system.

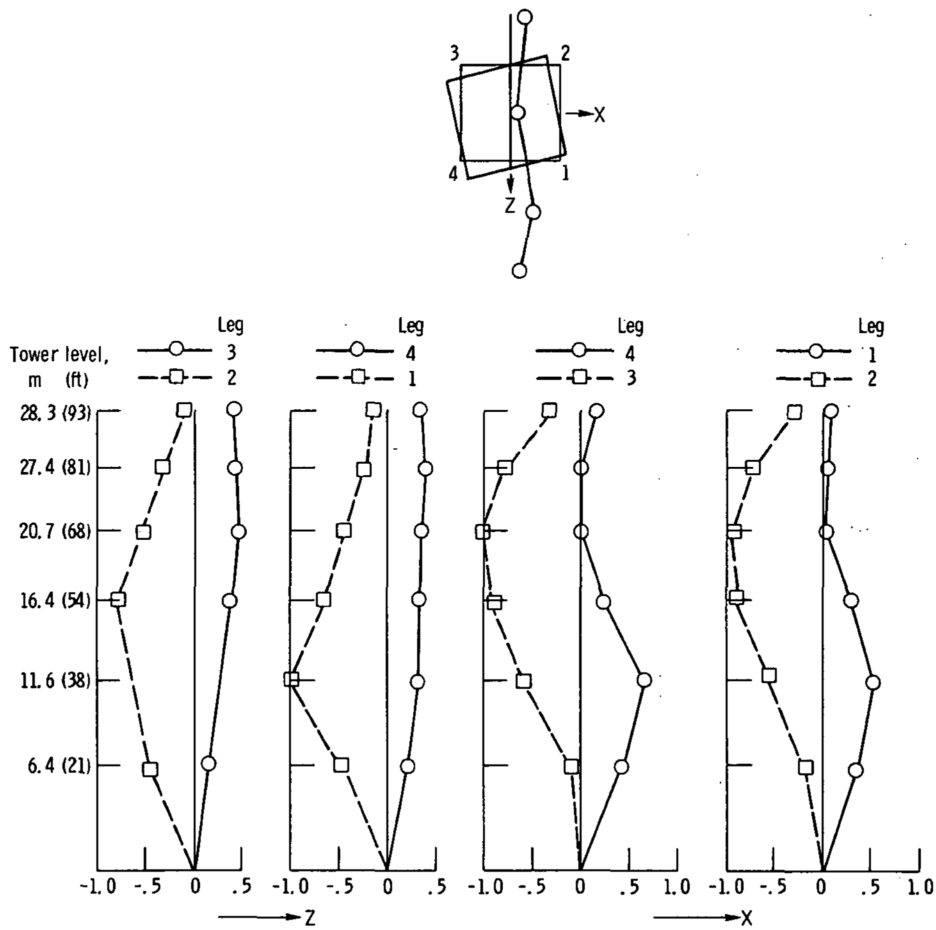


Figure 29. - 10.4-Hertz torsional-bending mode of wind turbine system.

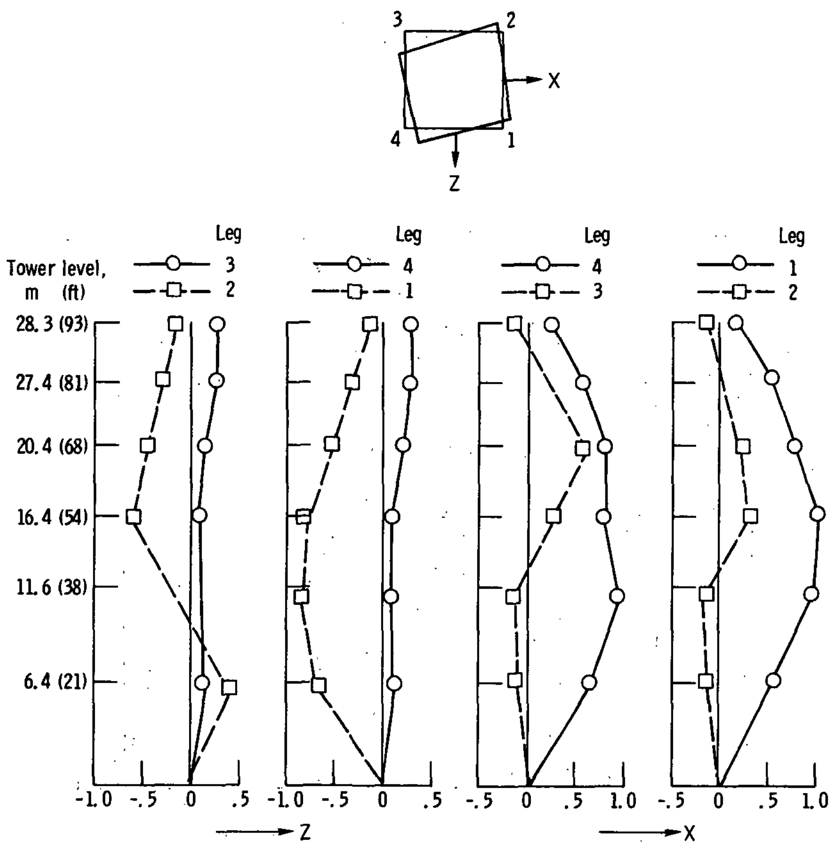


Figure 30. - 10.9-Hertz torsional-bending mode of wind turbine system.

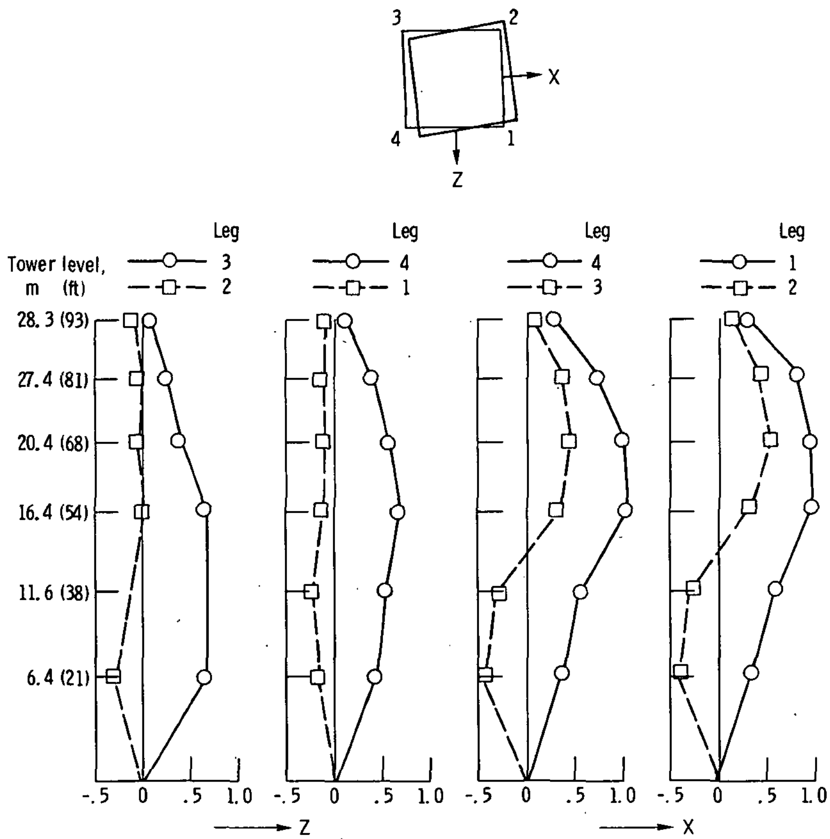


Figure 31. - 11.6-Hertz torsional-bending mode of wind turbine system.

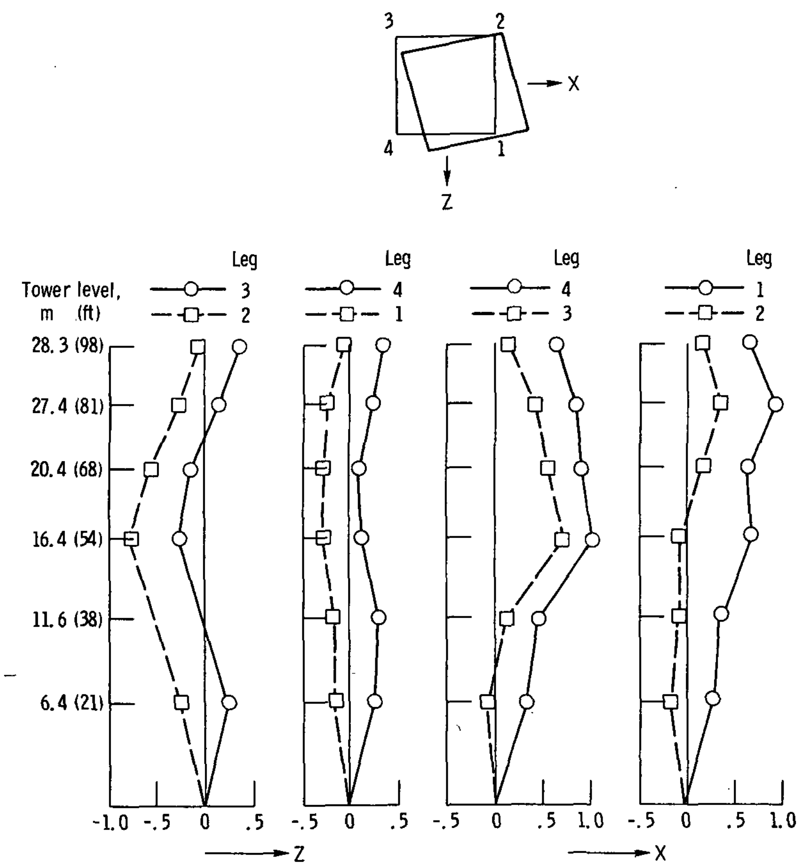


Figure 32. - 12.4-Hertz torsional-bending mode of wind turbine system.

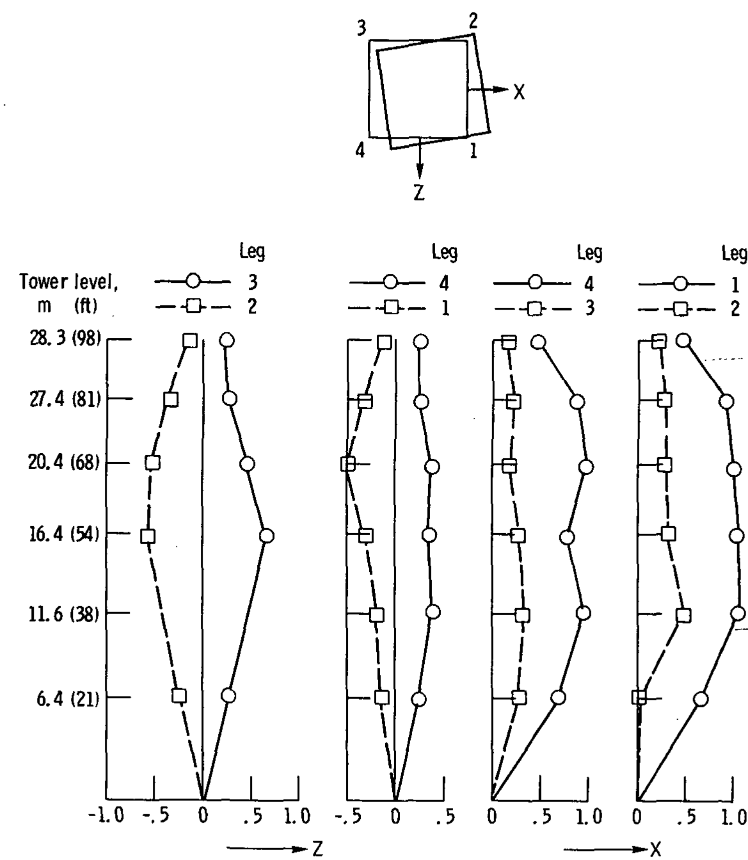


Figure 33. - 13.0-Hertz torsional mode of wind turbine system.

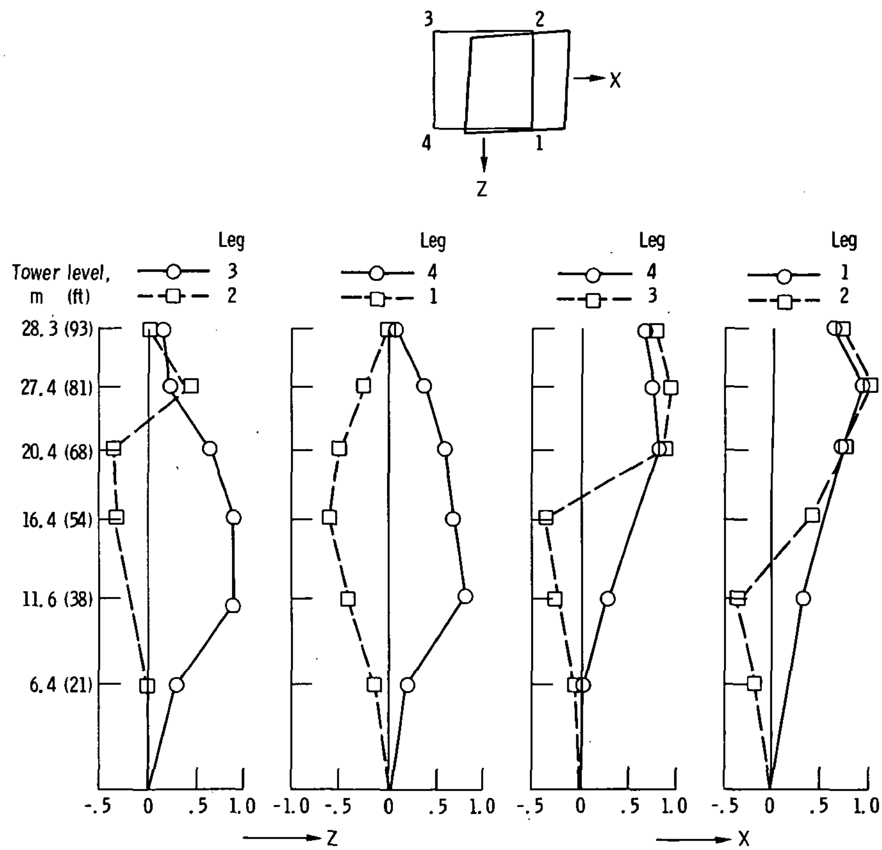


Figure 34. - 13.7-Hertz bending mode of wind turbine system.

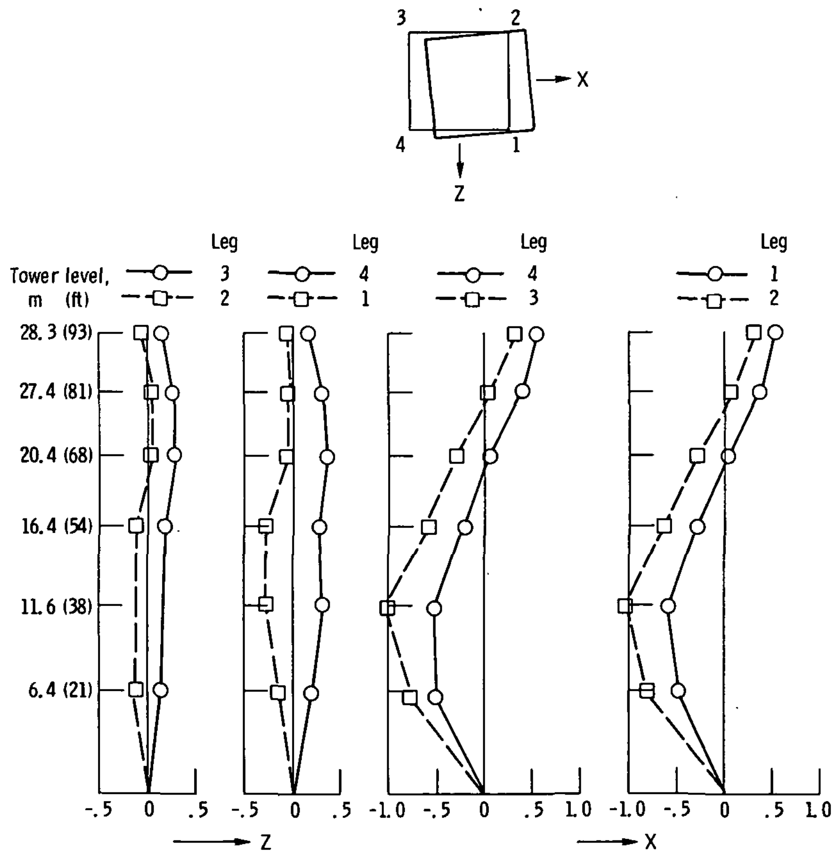


Figure 35. - 14.6-Hertz bending mode of wind turbine system.

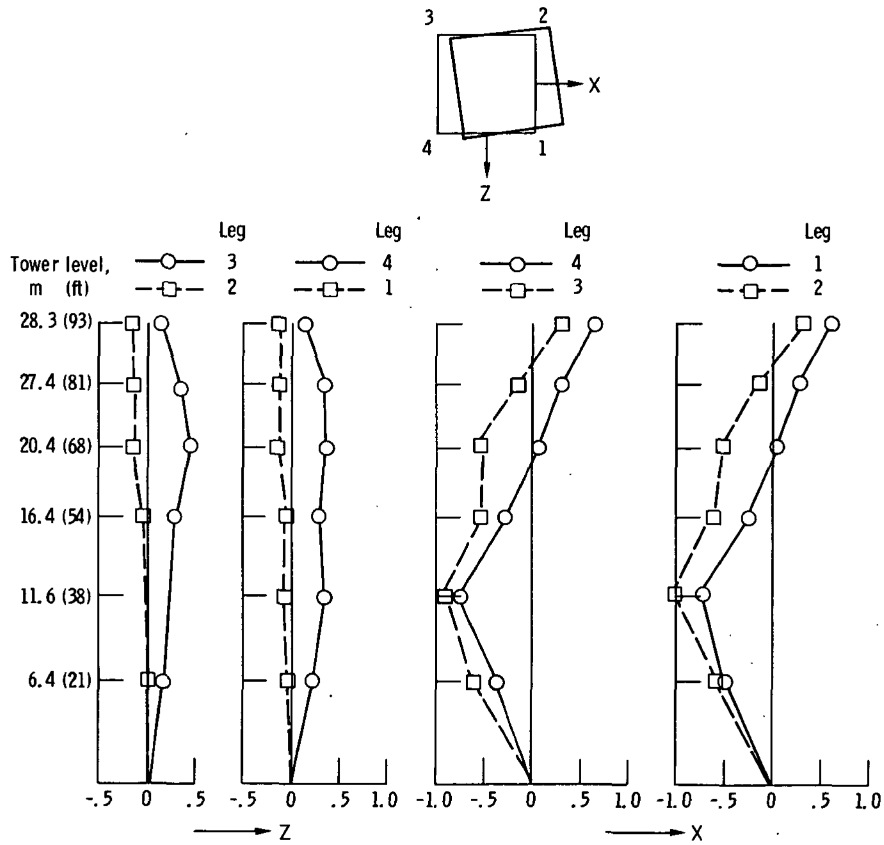


Figure 36. - 15.1-Hertz torsional-bending mode of wind turbine system.

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