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FREE VIBRATIONS OF THE ERDA-NASA

100 KW WIND TURBINE

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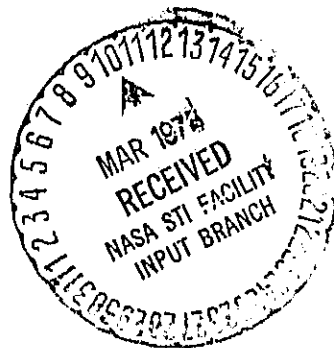
Lewis Research Center

ABSTRACT

The ERDA-NASA wind turbine (windmill), which consists of a 93-foot truss tower, a bed plate that supports mechanical and electrical equipment, and two 62.5-foot long blades, was analyzed to determine its free vibrations using NASTRAN. The finite element representation of the system consisted of beam and plate elements. The free vibrations of the tower alone, the blades alone, and the complete system were determined experimentally in the field. These results were obtained by instrumenting the tower or blades with an accelerometer and impacting the components with an instrumented mass. The predicted results for natural frequencies and mode shapes were in excellent agreement with measured data.

Key words

Windmill, wind turbine, structural analysis, natural frequencies, mode shapes, NASTRAN, experimental data

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INTRODUCTION

In order to study some of the technical and economic problems involved in generating electricity from wind energy, a 100 kW wind turbine generator (windmill) has been constructed at NASA-Lewis Research Center's Plum Brook facility near Sandusky, Ohio. The project is a cooperative effort between NASA and the Energy Research and Development Agency (ERDA). The wind turbine consists of a 93-foot tall square open truss steel tower; a bed plate that sits on top of the tower; generator, mechanical equipment and drive shafts which rest on the bed plate; and two 62.5-foot long aluminum blades. The blades are downwind of the tower and inclined at an angle of 7° from the vertical plane. The wind turbine is designed to produce 100 kW of electrical power in an 18-mph wind.

Spera (ref. 3) performed a preliminary analysis comparing dynamic loads and stresses in two types of rotors for this wind turbine, under static, rated, and overload conditions. Blade vibrations were limited to the first beamwise mode. Closed-form equations were derived for the natural frequency in this mode. Donham, Schmidt, and Linscott present a detailed analysis and measured data for the wind turbine blade in reference 1. In the present investigation the complete wind turbine as well as individual components were analyzed using NASTRAN to determine their free vibrations. The free vibrations of the tower alone, one blade alone, the blades mounted on the bed plate, and the complete system were determined experimentally in the field by the Mobile Vibration Laboratory of the Department of Mechanical Engineering, University of Cincinnati (ref. 2). Briefly, these results were obtained by instrumenting the tower or blades with an accelerometer and impacting the components with an instrumented mass. Fast Fourier transform techniques were used to reduce

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the measured data to free vibration results. The objective of this investigation was to verify the NASTRAN finite element representation with measured data. Then the model can be used with confidence to further evaluate the dynamic response of the wind turbine.

The finite element representation, the results obtained and comparison of these results with measured data are described and discussed in detail in this paper.

DESCRIPTION OF THE WIND TURBINE

For purposes of describing the wind turbine (fig. 1) it will be divided into three major sub-assemblies. These are (1) tower, (2) bed plate and machinery, and (3) blades. This section describes in detail these sub-assemblies.

Tower

The tower (fig. 2(a)) is a 93-foot tall welded open truss constructed from steel pipe (the four vertical columns), angle, channel, and wide flange beam sections. It is square and ranges from 30 feet wide at the base to 6.7 feet wide at the top. The tower weight is approximately 44,000 pounds. It is bolted to a steel-reinforced concrete foundation. Inside the tower a stairway runs from ground level to the top of the tower. The stairway weight is approximately 12,000 pounds. On the outside of one side of the tower two beams run from ground level to the top of the tower. These serve as tracks for a self-propelled elevator (spider) used to transport tools and equipment from the base to the top of the tower.

The transition between the tower and the bed plate is made with a 4-foot rib-stiffened conical transition section, the lower part of which is bolted to the top of the tower. A motor driven gear drive within this cone orients the bed plate and blades with respect to the wind. The yaw plane is at the 97-foot level.

Bed Plate and Machinery

A schematic of the bed plate and machinery is shown in figure 2(b). The bed plate is a welded box beam and is attached through a large diameter bearing

to the top of the conical transition section. The bed plate supports the elements necessary for transforming rotary energy into electrical energy. These elements are a hub, drive shafts, bearing supports, gear box, generator, and hydraulic power supply. The bed plate and machinery weigh approximately 30,000 pounds.

The hub contains the hydraulically actuated gear mechanism that controls the blade pitch angle. It is connected to a drive shaft which is supported by two bearings. The center line of the rotor shaft is at the 100-foot level. The shaft is connected to a 45:1 gear box to increase the rotational speed from 40 to 1800 rpm. The high-speed output shaft from the gear box is connected to the generator with V-belts.

Blades

The blades (fig. 2(c)) are fabricated from aluminum except for the root fitting which is steel. The blades are bolted to the hub. Blade fabrication was based on aircraft structural technology. Briefly, each blade consists of thick aluminum leading edge skins and a large number of formed ribs that support the thinner trailing edge skins. Each blade conforms to a prescribed aerodynamic shape which has a large amount of twist and taper. Total twist is 34°. Blade chord length varies 4.5 feet at the root to 2 feet at the tip. Blade thickness varies from 1.5 feet at the root to 2 inches at the tip. Each blade weighs approximately 2000 pounds. A more detailed description of the blades can be found in reference 1.

DESCRIPTION OF THE NASTRAN MODEL

The windmill was modeled using NASTRAN beam (CROD and CBAR) and plate (CQUAD2) elements. A schematic of the model is shown in figure 3. It consists of 307 elements and 170 nodes with each node having 6 degrees of freedom. This section describes in detail how the system was modeled.

Tower

The tower was modeled entirely with CROD and CBAR elements. The tower members were all common structural members and the section properties used (moments of inertia about principal axes, torsional constant, and cross sectional area) were handbook values. The tower model included the spider tracks that ran from the base to the top of the tower. The model included the weight but not the stiffness contribution of the stairway.

Top of Tower

Plate elements (CQUAD2) in combination with bar elements (CBAR) were used to model the top of the tower. The thickness used for the plate elements was that of the actual structure.

Conical Transition

This section connects the top of the tower with the bed plate. It was modeled with plate elements (CQUAD2). The element thickness was selected to provide bending stiffness equivalent to that of the actual structure.

Bed Plate, Bearing Supports, and Drive Shaft

The bed plate, bearing supports and drive shaft were modeled with bar elements (CBAR). The properties for these elements were obtained by calculating the moments of inertia and cross sectional area for the various component sections. The weight of the machinery on the bed plate was included as nonstructural mass in the appropriate finite element.

Blades

The blades were modeled with bar elements (CBAR). Blade stiffness, twist and weight distribution are shown in figure 4. They were provided by the manufacturer of the blades.

DISCUSSION OF RESULTS AND COMPARISON WITH MEASURED DATA

NASTRAN vibration results for one blade, blades mounted on bed plate, tower alone and the combined system are presented below and compared with measured data.

Blade

The vibration free frequencies for one blade are summarized in Table I for the first five natural frequencies. Note that each frequency is identified as beamwise mode, chordwise mode, or combined mode. The beamwise mode shape is a predominantly out-of-plane vibration motion with the plane taken parallel to the chord at the 3/4 blade span radius. "Chordwise" denotes the direction parallel to this plane (fig. 4). The measured data shown in Table I were obtained by Lockheed-California Co. and are reported in reference 2. Also included in Table I are analytical results from references 1 and 3. As can be observed from the results in Table I, the NASTRAN predicted first natural frequency is within 2 percent of the measured value with "no" tip weight. The corresponding higher frequencies (2 through 5) are within 5 percent. It is interesting to note that the predicted fourth and fifth natural frequencies are practically equal to the measured values with tip weight. This may be due to the fact that the blade has relatively large local variations along the span in both mass and stiffness that are not accounted for in the model. These large local variations tend to influence the higher frequencies especially when the wave lengths approach the length of the local variation.

The predicted mode shapes for the first and second natural frequencies (first beamwise and first chordwise modes) are plotted in figures 5(a) and (b) where measured data (ref. 2) are also shown. As can be observed, the predicted dynamic mode shapes provide a good fit to the measured data. The predicted mode shape for the third natural frequency (second flap) is plotted in figure 5(c) where the corresponding measured data are also plotted. For this case the predicted mode shape is in excellent agreement with the measured data.

The important conclusion to be drawn from the above discussion is that the finite element representation of the blade properly accounted for the

physical characteristics of the blade. This is a necessary requirement before the combined system can be modeled satisfactorily using finite elements.

Blades Mounted on Bed Plate

Before the blades and bed plate were lifted to the top of the tower, measured data were obtained with the blades horizontal and in the powered position (ref. 2). These data are compared to NASTRAN results for the same condition in Table II. For comparison purposes NASTRAN results for the blades and hub only are included in this table.

Characterization of the NASTRAN results as "second chordwise" and "third beamwise" is only approximate as these are again combined modes. Note that NASTRAN predicts two first beamwise (and subsequent) modes. In one, the blade tips more in opposite directions (cyclic) and in the other, the blade tips move in the same direction (collective). There were insufficient measured data to determine if a mode was cyclic or collective.

The predicted and measured results are in good agreement. There were insufficient measured data to characterize the 12.6 Hz mode. The NASTRAN results indicated that this mode contained significant bed plate bending. The effect of the bed plate mass and stiffness on blade frequency can be seen by comparing the two sets of NASTRAN results. It can also be seen that the bed plate effect tends to induce a slight reduction in the blade frequencies.

Tower

The vibration free frequencies of the tower predicted by NASTRAN are summarized in Table III where measured field data (ref. 2) are also shown. The (N-S) and (E-W) refer to tower directions as noted in figure 2(a). As can be observed from the results in Table III, the predicted and measured data are in excellent agreement.

The tower mode shape corresponding to the first (E-W) natural frequency is shown in figure 6 where measured data are also shown. As can be observed from the plots in figure 6(b), the tower undergoes slight N-S motion as well. Note that the tower does not deflect laterally (fig. 6(a)) like a simple canti-lever. It deflects slightly in the reverse direction initially and then crosses

over at about elevation 31 feet. The important observation from the results
in figure 6 is that the predicted mode shape is identical to that measured.

The tower mode shape for the second (E-W) natural frequency is plotted
in figure 7. As can be observed in figure 7(b) the predicted results show con-
traction of the tower top in both directions. This contraction is the sum of
both "rigid body" tilting of the tower top plane due to tower vertical motion
and elastic deformation in the members connecting the tower legs at the top.
The experimental data shows motion only along the E-W direction. This
difference may be caused in part by: (1) the stiffness of the stairway which
is not accounted for in the NASTRAN model and which will tend to support the
stairs weight and (2) the lack of measured data for tower vertical motion. The
important point to be noted from figure 7 is that the predicted tower second
(E-W) mode shape is in reasonably good agreement with the field measured
data.

The important conclusion from the above discussion is that the NASTRAN
finite element representation of the tower properly accounts for the physical
characteristics of the tower. This again is a necessary requirement for ob-
taining satisfactory results from the finite element representation of the
combined system.

Combined System

The NASTRAN vibration frequency results for the combined system and
those measured in the field (ref. 2) are summarized in Table IV for the blades
in the horizontal and feathered position. The orientation of the blades and
shaft with respect to the tower for the results is shown in figure 8. As can
be observed from the results in this table, for the most part, the agreement
between predicted and measured results is good. The lowest frequency predic-
ted was 1.59 Hz for the blades horizontal and in the powered position.

There is some difference between the predicted and measured mode shapes
for the modes with frequencies between 2 and 3 Hz. The NASTRAN mode
shapes were primarily a combination of tower bending and blade chordwise
motion. The first two measured mode shapes were first bending modes along
the two diagonals, while the third mode was characterized as the blade first
chordwise mode. The diagonal motion is shown in figure 8(b) for the 2.2 Hz
mode. It is compared to the 2.28 Hz predicted mode shape. It is possibly the

influence of the stairway stiffness that causes the difference between the predicted and measured mode shapes although good agreement for the tower alone first bending mode shapes was obtained. Another possibility is an error in the mass distribution of the machinery on the bed plate Note in figure 8(a) the good agreement between predicted and measured mode shapes as observed from a south elevation.

The important conclusion to be drawn from the discussion of the combined system results is that both structural analysis and dynamic testing methodologies have advanced to the point where complex structural systems can be analyzed and field tested readily, reliably, and economically.

SUMMARY AND CONCLUSIONS

The predicted frequency and mode shape results obtained using NASTRAN for one blade alone, the blades mounted on the bed plate, the tower and the combined system were in good agreement with the measured data. The finite element representation properly accounts for the combined system's physical characteristics and can, therefore, be used with confidence to further evaluate its dynamic response. The results of this investigation demonstrate the versatility of NASTRAN for determining the free vibrations of complex structures. In addition, dynamic testing methodologies for determining free vibrations have advanced to the point where complex structural systesm can be field tested readily, reliably. and economically.

REFERENCES

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2. Linscott, B. S.; Shapton, W. R.; and Brown, D., "Tower Vibration Test Results for the ERDA/NASA 100 kW Experimental Wind Turbine," NASA-Lewis Research Center, Cleveland, Ohio, TM X in progress.
3. Spera, D. A., "Structural Analysis of Wind Turbine Rotors for NSF-NASA Mod-O Wind Power System," TM X-3198, NASA-Lewis Research Center, Cleveland, Ohio, Mar. 1975.

TABLE I. - SINGLE BLADE FREE FREQUENCIES, HZ

	1	2	3	4	5
NASTRAN	1.75(b)	2.73(c)	4.84(b)	9.54(a)	10.1(a)
Analysis (ref. 3)	1.77(b)	------	------	------	------
Analysis with no tip weight (ref. 1)	..65(b)	2.38(c)	4.77(b)	9.30(c)	10.2(b)
Measured with tip weight (ref. 1)	1.63(b)	?.35(c)	4.68(b)	9.56(c)	10.0(b)
Measured with no tip weight (ref. 1)	1.73(b)	2.66(c)	4.99(b)	9.80(c)	10.4(b)

(a) Combined mode.

(b) Beamwise mode.

(c) Chordwise mode.

TABLE II. - FREE FREQUENCIES OF BLADES MOUNTED ON BED

PLATE, HZ (BLADES HORIZONTAL IN POWERED POSITION)

Mode		NASTRAN[1]	NASTRAN	Measured[2]
1st Beamwise	Cyclic	1.73	1.68	1.75
	Collective	1.75	1.74	
1st Chordwise	Cyclic	2.67	2.4€	2.7
	Collective	2.73	2.70	
2nd Beamwise	Cyclic	4.78	4.63	5.03
	Collective	4.83	4.83	5.27
2nd Chordwise	Cyclic	9.43	8.74	9.2
	Collective	9.45	8.94	
3rd Beamwise	Cyclic	10.0	9.33	9.76
	Collective	10.1	9.85	10.4
Bed plate bending		------	11.9	12.6

(1) Blades and hub only.

(2) Ref. 2.

TABLE III. – TOWER ALONE FREE

FREQUENCIES, HZ

	NASTRAN	Measured[1]
1st Bending (N–S)	4.76	4.7
1st Bending (E–W)	5.19	5.1
2nd Bending (E–W)	9.16	9.4
1st Torsion	10.1	10.5

(1) Ref. 2.

TABLE IV. – COMBINED SYSTEM FREE FREQUENCIES, HZ

(BLADES HORIZONTAL AND FEATHERED)

NASTRAN		Measured[1]	
Mode	Fre-quency	Mode	Fre-quency
Blade 1st beamwise (cyclic)	1.69[2]		
		Blade 1st beamwise	1.73
Blade 1st beamwise (collective)	1.73		
	2.15	Tower diagonal bending (SE–NW)	2.1
Combined tower	2.28	Tower diagonal bending (SE–NE)	2.2
Bending and blade			
Chordwise modes	2.73		
		Blade 1st chordwise	3.0
	2.87		
Tower 1st torsion	9.56	Tower 1st torsion	9.8

(1) Ref. 2.

(2) The lowest frequency obtained for the combined system was 1.59 Hz for the
blades horizontal in powered position.

(a) TOWER (WEST ELEVATION).

Figure 2. - Major components of the wind turbine generator.

Figure 1. - ERDA-NASA 100 kw wind turbine generator.

BEARING SUPPORTS AND
SHAFT - 4 ELEMENTS

BED PLATE - 14 ELEMENTS

CONICAL TRANSITION - 8 ELEMENTS

TOP OF TOWER - 40 ELEMENTS

BLADES - 24 ELEMENTS

TOWER - 217 ELEMENTS

62.5'

11'

8'

7'

7°

30'

93'
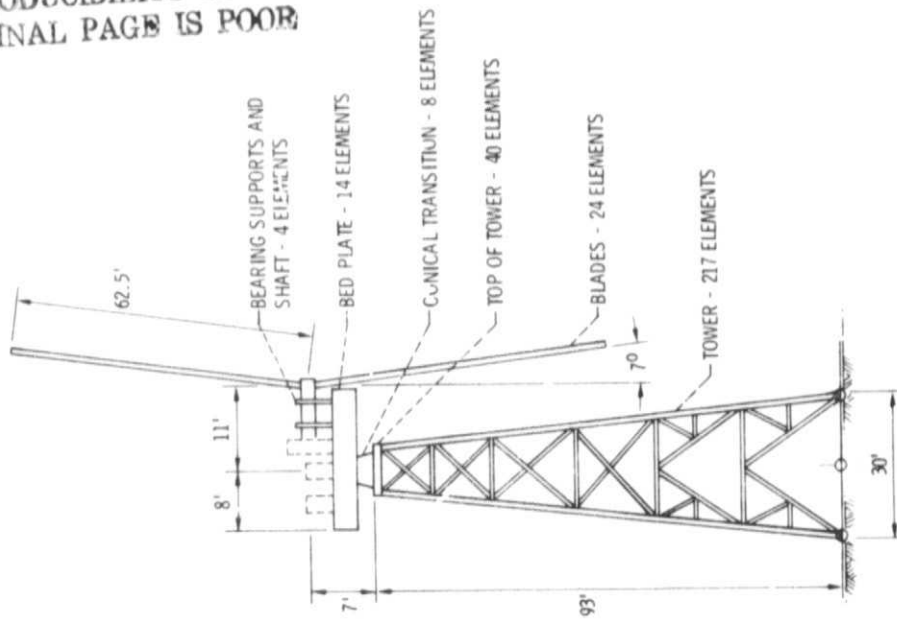
Figure 3. - Schematic of NASTRAN model.

HUB

BLADES

GEAR BOX

SLIP RINGS

BED PLATE

WEATHER INSTRUMENTS

FIBERGLAS HOUSING

BRAKE

HYDRAULIC

SYNCHRONOUS ALTERNATOR

YAW GEAR BOX

TOWER

(b) BED PLATE AND MACHINERY.

62.5'

CD-11767-03
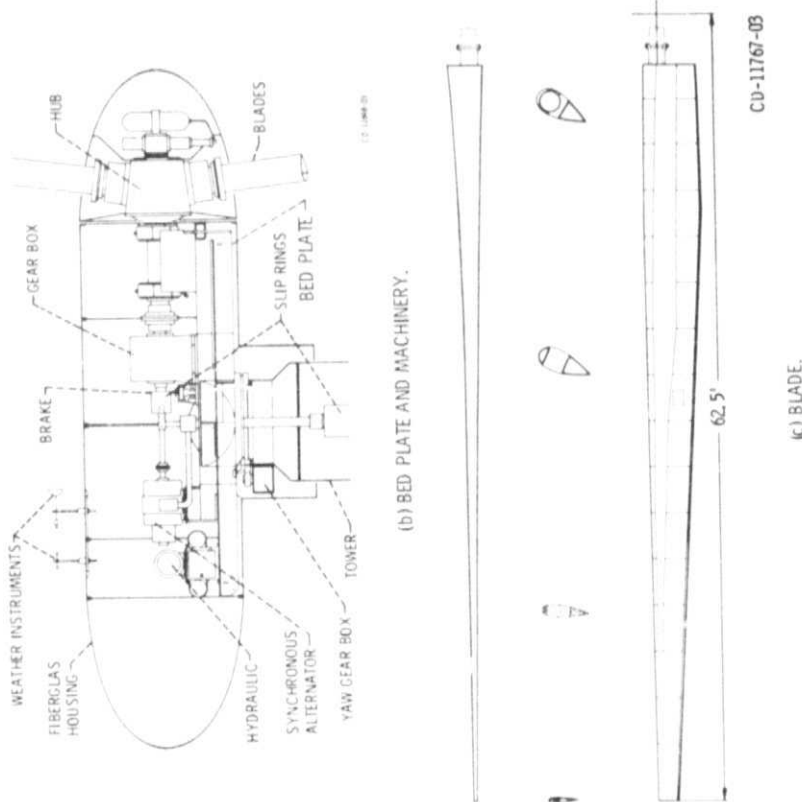
(c) BLADE.

Figure 2. - Major components of the wind turbine generator (continued).

(a) STIFFNESS DISTRIBUTION.

(b) WEIGHT DISTRIBUTION AND TWIST ANGLE.
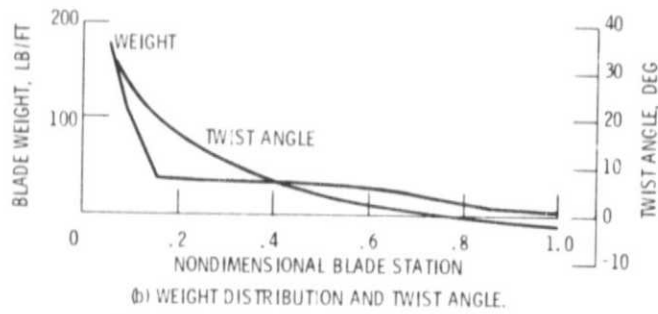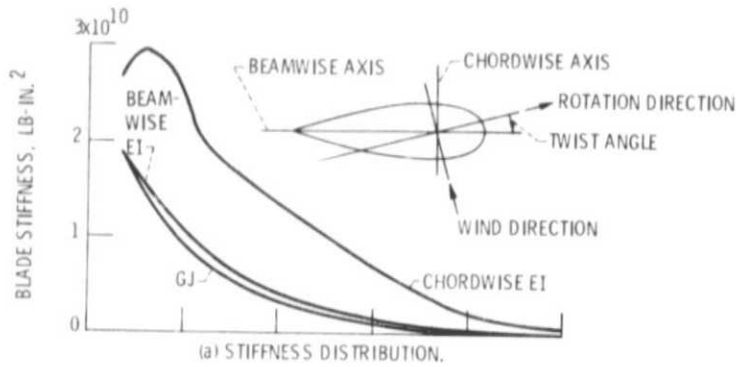
Figure 4. - Wind turbine blade local stiffness and weight distribution.

(a) FIRST BEAMWISE MODE.

(b) FIRST CHORDWISE MODE.

(c) SECOND BEAMWISE MODE.
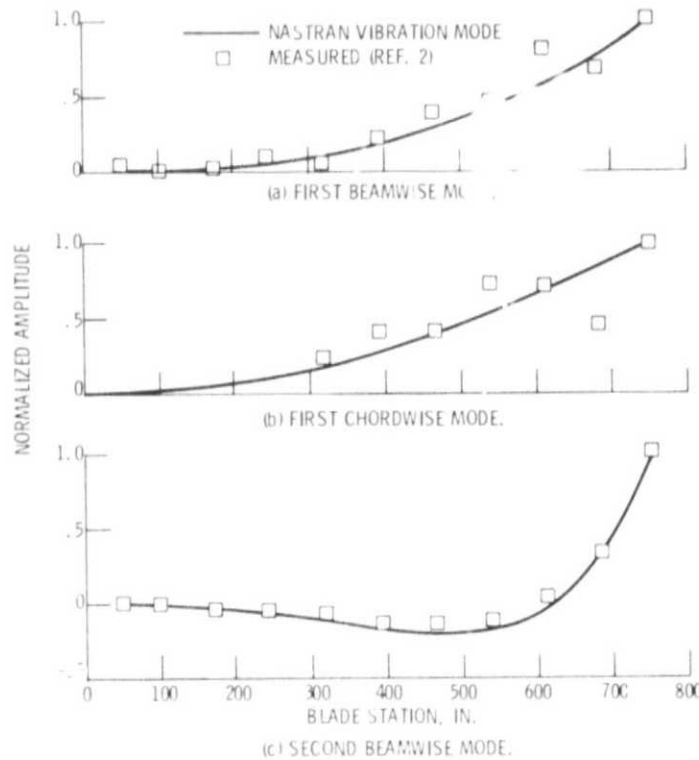
Figure 5. - Blade vibration mode shapes.

(a) SOUTH ELEVATION OF
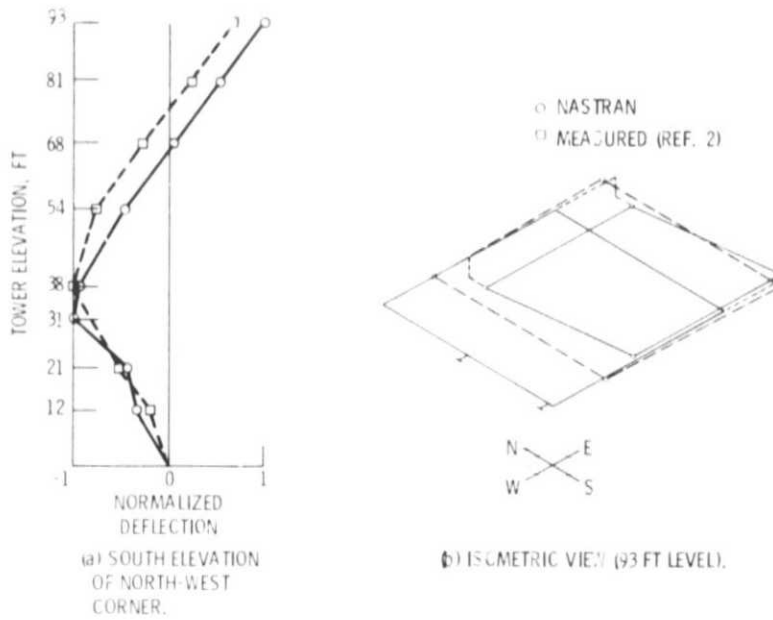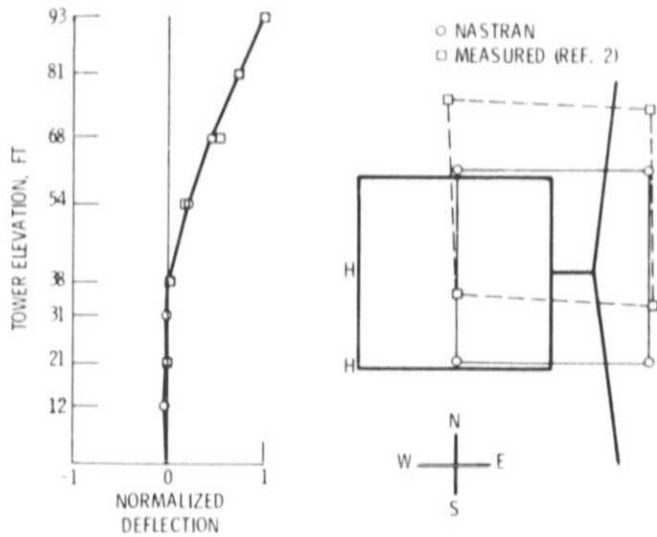NORTH-WEST COLUMN.

(b) PLAN VIEW (93 FT LEVEL).
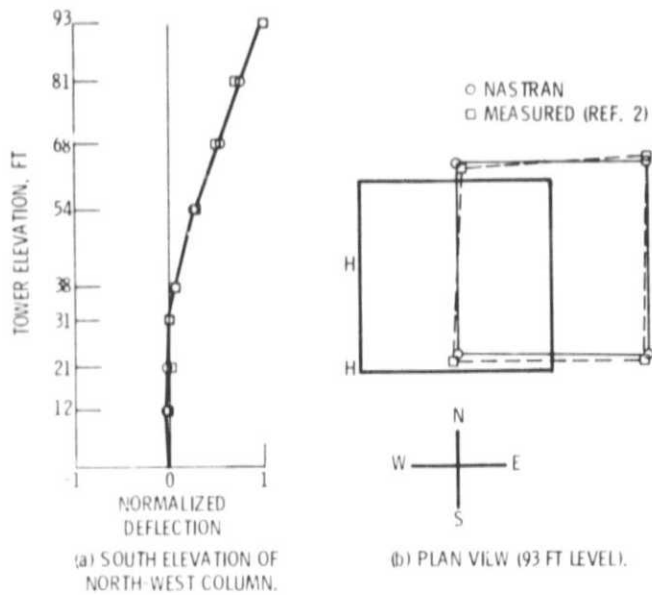
Figure 6. - Tower alone first bending vibration mode shape (E - W).

(a) SOUTH ELEVATION
OF NORTH-WEST
CORNER.

(b) ISOMETRIC VIEW (93 FT LEVEL).

Figure 7. - Tower alone second bending vibration mode shape (E - W).

Figure 8. - Combined system tower first bending vibration mode shape (SW-NE).