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DESIGN, FABRICATION, AND INITIAL TEST OF A FIXTURE FOR REDUCING THE NATURAL FREQUENCY OF THE MOD-0 WIND TURBINE TOWER

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SUMMARY

Operation of the Mod-0 wind turbine with a tower first bending frequency less than twice the rotor speed was desired. This would provide an opportunity to study system dynamics for a "soft" tower as well as provide data for the system passing through resonance. The method selected to reduce the frequency was to place the original Mod-0 tower on a set of springs. The fixture fabricated to do this was designed so that the spring stiffness could be varied in the field to provide a range of tower frequencies. Design requirements and fixture fabrication details are given. Actual operation of the Mod-0 with the softening fixture showed that the desired tower natural frequencies were obtained. Only moderate fixture deflections were observed when the system passed through resonance.

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INTRODUCTION

A major goal of the wind energy program is the design and development of cost-effective wind turbines. Although it has been possible to construct wind turbine generators that produce desired operating results, the machines to date have not been cost-competitive with other forms of available energy. One reason for the non-competitive posture is that present-day wind turbines are supported atop stiff towers. That is, for turbine systems with two-bladed rotors, the first bending frequency of the tower is made greater than twice the rotor speed to avoid resonance. Consequently, the size of the main tower members is usually dictated by stiffness requirements rather than by strength requirements. This results in the use of more construction materials than would be required by strength requirements alone.

One obvious means of reducing material is to support the turbine on a soft tower, i.e., one for which the first bending frequency is less than twice the rotor speed. Wind turbines currently being designed plan to use towers with a first bending frequency of about 1.5 times the rotor speed. In order to gain confidence in the soft tower concept, it was decided to modify the Mod-0 wind turbine tower (ref. 1) to reduce its natural frequency to about 1.5 times the rotor speed. The purpose of this was three-fold. First, operating experience with a soft tower system could be obtained and the effect on system components of passing through resonance could be determined. Secondly, it would provide additional check cases for computer codes used to predict blade and system loads. And finally, any psychological effects due to increased tower movements could be explored.

This report examines the concepts considered for softening the Mod-0 tower. The concept chosen required a softening fixture and the design and fabrication of this fixture are described in detail. In addition, a comparison is made of predicted softened tower frequencies with those measured. The behavior of the fixture during initial operation with Mod-0 is reported.

SOFTENING CONCEPTS

The Mod-0 wind turbine (fig. 1) is an experimental, two-bladed, horizontal axis machine with a downwind rotor. The rotor diameter is 125 ft. The rotor and machinery sit atop a 93 ft. steel latticed tower. The tower is 30 ft. square at its base and tapers to about 7 ft. at the top. The rotor centerline is at 100 ft. A more detailed description of Mod-0 is given in reference 1.

Several schemes for softening the stiff Mod-0 tower were explored. Initially it was thought that removing some of the diagonal braces would lower the bending stiffness. However, to meet the desired bending frequency, all the diagonals in the four uppermost bays had to be removed. Consequently, the structure lacked sufficient shear and torsional resistance.

The addition of coil springs between the nacelle and the tower was also considered. While this scheme would not actually soften the tower itself, the effect of the springs upon the system behavior would approximate that of a soft tower. This scheme was rejected, however, because of design difficulties, space limitations, and an anticipated long delivery time for the springs.

The concept finally chosen was to provide leaf springs at the base of the tower. This scheme was selected because the design was relatively simple, it provided lateral stability, material delivery would be of no consequence, and perhaps most importantly, adjustments for fine-tuning the natural frequency of the system could be built into the springs. A schematic of this concept is shown in figure 2.

The deflections and rotations provided by this concept are an approximation of those obtained for a truly soft tower. An indication of the accuracy of this approximation was determined with a finite element stick model of the tower. Results can be seen in figure 3. For a representative load at the top of the tower, deflections for a truly soft tower are compared with those obtained using the chosen softening concept. At the top of the tower the deflections produced by a force or moment are reasonably close. However, the rotations for a truly soft tower are substantially greater. In spite of these differences, it was decided that the chosen softening concept would provide the desired system response.

DESIGN REQUIREMENTS

The design of the springs involved satisfying two conflicting criteria: (1) the springs had to be strong enough to withstand a sizeable wind load;

and (2), the springs had to be soft enough to give a first bending frequency for the complete turbine system as low as 0.8 Hz. The load cases considered in the design of the softening fixture are given in this section.

The springs were sized to safely withstand a 60 mph wind statically applied with the rotor blades in the powered position (broadside to the wind). The 60 mph wind velocity was assumed to occur at the 30-foot elevation. Because of wind shear the corresponding velocity at the centerline of the rotor is 73 mph. This load would cause greater stresses in the springs than any operating load. As a safeguard, the strains and deflections of the springs would be continuously monitored when operating the turbine in the soft mode. In addition, adjustable limit stops were provided at the four corners to limit strains and deflections.

Design loads are shown in figure 4. Figure 5 is a plan view of the turbine defining the direction of the "side-wind" loading and the "skew-wind" loading. Stresses in the springs were investigated for both wind directions. Note that in both cases the longitudinal axis of the nacelle is assumed to be parallel with the wind direction.

Except when the turbine was operating in the soft mode, the adjustable limit stops were used to lock the four corners of the tower to the foundation. A 97 mph wind loading was used to design the limit-stops. This wind velocity represents a once-in-50-years wind at the site (ref. 2), includes a 20 percent increase for gusts, and was used for the original design of the Mod-0 wind turbine. The wind directions were assumed the same as shown in figure 5 for the 60 mph wind.

FIXTURE DESCRIPTION AND STRESS ANALYSIS

Design Description

The fixture designed to meet the previously described load and natural frequency requirements is shown in figure 6. The fixture consists principally of two tiers of W12 x 53 beams at each face of the tower. The beams are reinforced with partial length coverplates. Each of the four beams forming the top tier is supported off the lower beams at two intermediate points. Each beam of the bottom tier spans 30 feet and is supported at its ends by the concrete foundation.

The intermediate supports between the two tiers are movable within certain limits and are capable of resisting uplift as well as downward loads. By increasing or decreasing the distance between the intermediate supports, the stiffness of the springs, and hence the bending frequencies of the tower, can be varied.

Horizontal loads acting on the tower are transmitted to the foundation through a shear lug located at the centerline of each beam. The lugs carry no vertical loads.

Located as close to the ends of the beams as possible are limit-stops. These are simply threaded rods welded into the web of the bottom beams and passing through sleeves in the top beams. The stops serve a dual purpose. First, loads produced by winds in excess of 60 mph are too great for the structural capability of the springs. Therefore, whenever the turbine is parked in a non-operating mode, the top tier of springs is clamped between nuts on the limit-stops. The vertical load path is then from the tower through the limit-stops into the foundation. In effect, the springs are short-circuited. Second, prior to operating the turbine, the nuts on the limit-stops are backed-off a pre-determined amount to allow the springs to deflect. If the tower were to tilt excessively or the springs were to yield due to operating loads, catastrophic failure would be averted by the springs coming to bear against the nuts on the limit-stops.

Stress Analysis

The springs were constructed of A36 steel for which the basic allowable bending stress is usually taken as 60 percent of yield strength. For design of the springs, however, the maximum allowable bending stress was established at 27,500 psi (76 percent of yield) because of the failure-safe nature of the design.

Throughout the design, extensive use was made of the NASTRAN computer code. Both the stress analysis and frequency predictions were made using that code. A plot of the finite element model is shown in figure 7.

Maximum stress in the springs will always be greater for a skew-wind than for a side-wind of the same velocity. This is primarily true because a skew-wind impinges on a greater tower area than a side-wind.

For both wind directions, the maximum stress will always occur in the bottom tier of springs. One very obvious reason for this is that the bottom springs support a slightly greater dead weight. In addition, the local moment produced by the horizontal shear-lug load is additive to the vertical-load moment in the bottom beams, but subtracts from the vertical-load moment in the top tier.

For the range of intermediate support spacings most likely to be used during operation, it can be shown that the maximum stress for the side-wind condition will occur in the bottom side beams, that is, in the two beams parallel to the wind direction. Likewise, it can be shown that the maximum stress for the skew-wind condition occurs in the vicinity of the leeward corner.

With the intermediate supports spaced at 114 inches from the tower centerline, the maximum computed stress in the springs is 24,990 psi for the 60 mph side-wind loading and 25,810 psi for the skew-wind loading. These maximum stresses occurred in the bottom beams at a section just outside the outermost end of the coverplates.

Figure 8 shows the variation in computed stresses as a function of the intermediate support spacing. Figure 8(a) is for the 60 mph side-wind loading condition and figure 8(b) is for skew-wind loading. From figure 8(b), note that for values of L greater than 112 inches, the maximum stress occurs at a section outside the outer end of the coverplate, (Pt. A). For L less than 112 inches the point of maximum stress shifts to a point inside the inner end of the coverplate, (Pt. B). Because of increased section properties, the maximum stress never occurs at the support point, (Pt. S). Note also that the intermediate support spacing must be greater than 108 inches if the stresses are not to exceed the 27,500 psi allowable.

Computed stresses in the tower, springs, and limit stops were below the allowable stress when the "locked-up" structure was subjected to a 96 mph wind.

The finite element model predicted that a first bending natural frequency as low as 0.80 Hz (1.5 times the rotor frequency for 32 rpm operation) could be achieved without exceeding the fixture stress allowable for the 60 mph skew wind case. More details concerning natural frequencies and comparison with measured values are given in a subsequent section.

FABRICATION AND ERECTION

Fabrication of the fixture was performed at the Lewis Research Center. Welding was visually inspected and, in addition, welds at the ends of each coverplate were radiographically examined. All welds met the quality requirements of the Structural Welding Code of the American Welding Society. Views of the intermediate supports, shear lugs, and limit-stops are shown in figures 9(a), 9(b), and 9(c), respectively.

Field erection was performed by a local contractor and involved the following steps:

1. The existing tower was removed from its foundation by cutting through the four legs at the top surface of the baseplates and placed aside using a mobile crane.

2. The softening fixture was assembled on the left-in-place baseplates.

3. The tower was placed on the fixture and its legs rewelded to baseplates on the fixture.

Photographs taken during assembly are shown in figure 10. Figure 10(a) is an overall view of the leaf spring base during erection, figure 10(b) shows the tower being moved for placement on the springs, and figure 10(c) is a photo of the completed Mod-0 wind turbine generator with the softened tower.

NATURAL FREQUENCIES

Frequency predictions are shown in figure 11. This figure shows the variation in first bending frequency versus half the distance between the intermediate supports. Natural frequencies were computed for both the tower alone and for the completely assembled turbine system, although the latter is the one of real interest. When computing the frequencies of the complete system, the effect of the non-structural nacelle and the rotor masses was approximated by simply lumping one-fourth of their total mass at the top of each tower leg.

The frequencies as measured in the field are also shown in figure 11. To measure the frequencies, the tower was excited by either pulling on it with a rope and then suddenly releasing the force or by jacking it up and releasing the load. The resulting response was measured by an accelerometer and fed into a spectrum analyzer. For the complete machine, a range of measured frequencies is obtained. This range of values is caused by changes in the rotor position and nacelle azimuth angle and is not predicted analytically because of the manner in which the rotor and nacelle masses were modeled

Agreement between the measured and computed frequencies for the complete turbine is quite good. For the tower alone, however, there is a definite difference between the measured and computed values of about 0.3 Hz. This difference is most likely due to the difficulty in accurately modeling the connection between the intermediate supports and the beams. It was modeled as a pinned joint whereas in reality the connection lies somewhere between pinned and fixed. The test data show that the accuracy of this connection is less important for the complete system model.

When the tower is locked-up, that is, the top-tier springs are clamped between the nuts on the limit-stops, the computed first bending frequency of the complete system is 1.72 Hz. This value was computed assuming that the intermediate supports coincide with the limit-stops at 160.5 inches from the centerline. Note that this is the hardest the leaf-spring structure can be made without the use of supplemental devices and represents a reduction of 20 percent from the first bending frequency of the original Mod-0 machine. If the tower is supported directly beneath its legs (L = 180 inches), the computed first bending frequency is 2.17 Hz., which agrees with the value for the original hard Mod-0 tower.

With the data of figure 8, it is possible for a user to select an intermediate support spacing to produce a desired first bending frequency and then to determine, for that support spacing, the magnitude and location of the maximum stress due to a 60 mph wind.

Based on the data of figure 11, the intermediate supports were positioned at a distance of 114 inches from the centerline of the springs to provide a first tower bending frequency of 0.83 Hz.

FIXTURE INSTRUMENTATION AND INITIAL TEST

The springs were instrumented to measure strains and displacements. Eight strain gages were attached to the top flange of the bottom-tier beams at a point just inside the innermost end of each coverplate. To measure vertical deflections, four displacement transducers were mounted between the two tiers directly below the legs of the tower. When operating the turbine, measurements from the gages were continuously tracked on a strip chart recorder.

Initial testing with the softening fixture was conducted with the intermediate supports set at 114 inches. Samples of the strain and displacement readings are shown in figures 12(a) and 12(b), respectively. The charts clearly indicate resonant conditions at a rotor speed of about 25 rpm, which as expected, corresponds to a forcing frequency of 0.83 Hz.

The maximum recorded strain range at resonance was about 460 microinches per inch. This is equivalent to a stress range of 13,400 psi for Young's modulus of 29×10^6 psi. In accordance with Appendix B of the American Institute of Steel Construction (AISC) Specification for the Design, Fabrication and Erection of Structural Steel for Buildings (ref. 3), the construction detail at the gage locations falls under Category C. For that category, the allowable stress range is 17,000 psi for 100,000 loading cycles or less and 12,000 psi for 100,000 to 500,000 cycles. Assuming the fixture is subjected to 25 high stress cycles when passing through resonance, this would allow more than 2000 start up, shut down cycles. This number is sufficient to complete all testing planned using the fixture in its soft mode. Nevertheless, periodic inspection of the beams at the ends of each coverplate will be conducted to insure that no failure occurs due to fatigue.

At resonance, the maximum vertical displacement was about 0.8 inch peak to peak. A close examination of figure 12(b) reveals that two springs may have "bottomed-out" on the limit -stops. This is indicated by the flattened lower portion of the resonant balloon for gage nos. 1 and 3.

Motion pictures taken while testing show that tower movement is clearly evident as the rotor speed passes through the resonance frequency during startup and shutdown. However, the magnitude of the movement was not excessive. When the turbine operated at a speed removed from the resonance frequency, tower motion was indiscernible.

CONCLUDING REMARKS

Placing the Mod-0 tower on leaf springs proved to be a satisfactory means of reducing the bending frequency of the tower. The design had the added advantage of allowing adjustment of the tower bending frequencies. The major findings of the program are as follows:

1. Predicted natural frequencies obtained from a finite element model of the tower and softening fixture were in good agreement with measured frequencies.

2. Operation of the Mod-0 showed that the softening fixture was effective in reducing the tower bending frequency. The desired system response was obtained.

3. Fixture strains and deflections were not excessive when the system passed through resonance.

REFERENCES

1. Thomas, R. L.; and Richards, T. R.: ERDA/NASA 100-Kilowatt Mod-0 Wind Turbine Operations and Performance. ERDA/NASA-1028/77/9, NASA TM-73825, 1977.

2. Wind Forces on Structures. Paper No. 3269, Trans. Am. Soc. Civil Eng., vol. 126, part II, 1961, p. 1124.

3. Manual of Steel Construction. Seventh ed. American Institute of Steel Construction, 1970.

Figure 1. - Mod - 0 wind turbine before installation of softening fixture.

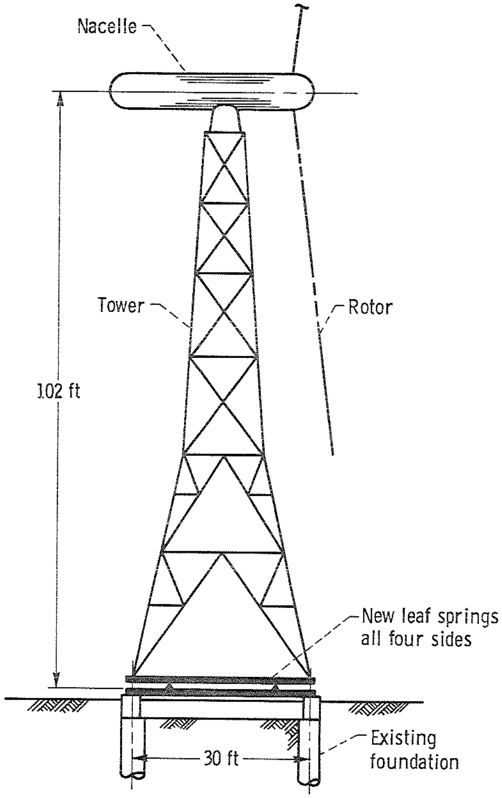
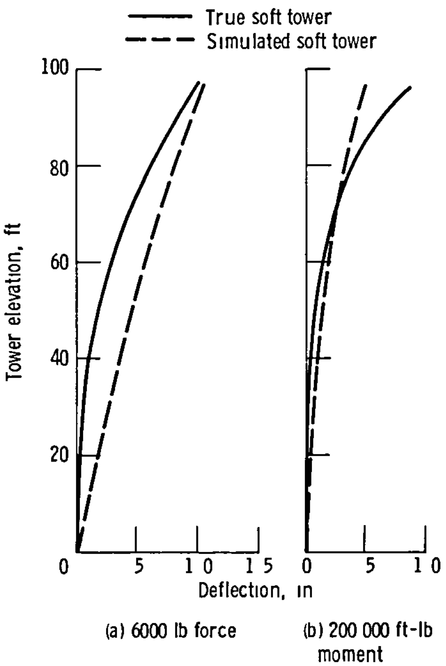


Figure 2. - Tower softening concept.



(a) 6000 lb force (b) 200 000 ft-lb moment

Figure 3 - Comparison of deflections for a truly soft tower and a simulated soft tower due to a load applied at top of tower

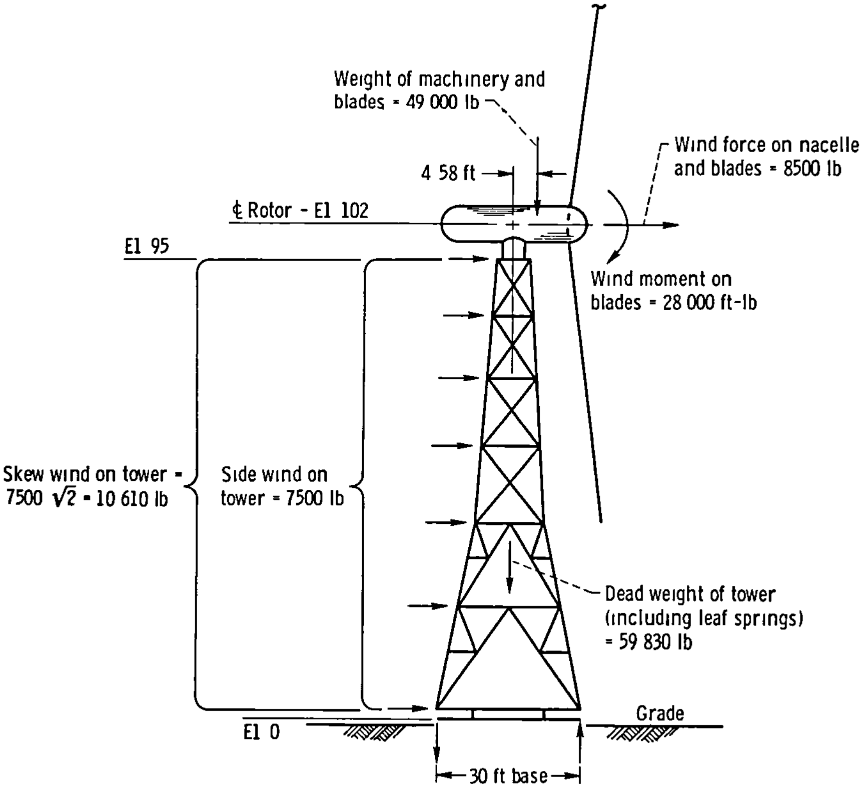


Figure 4 - Design loading for a 60 mph wind

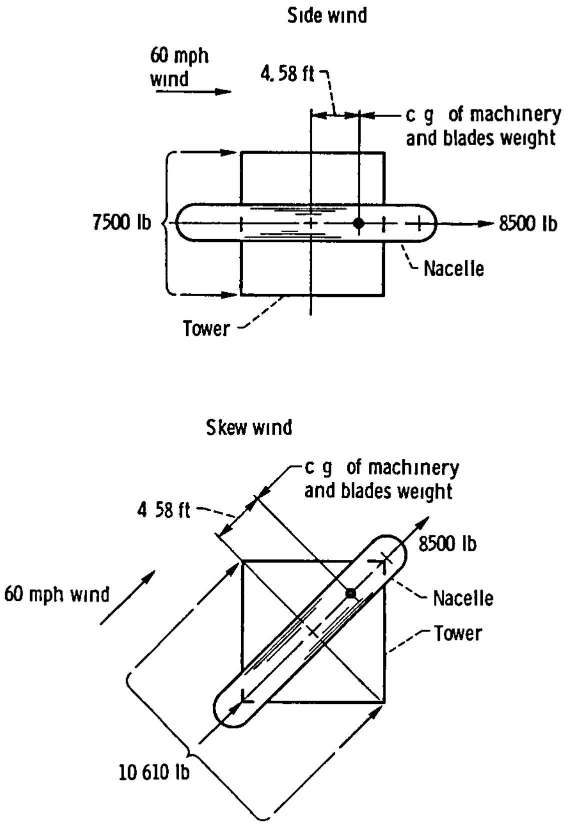


Figure 5 - Plan view of loadings

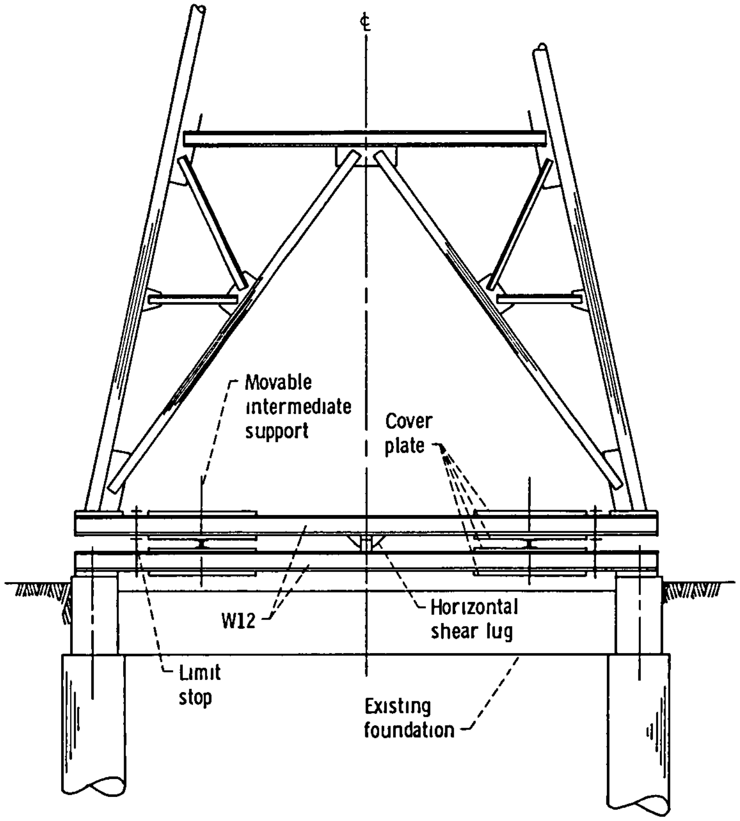


Figure 6 - Soft tower fixture details.

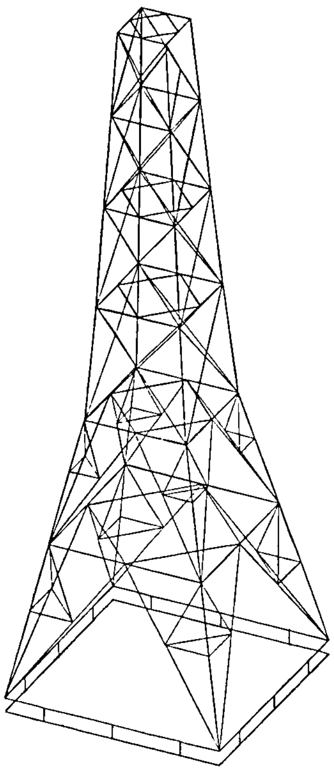
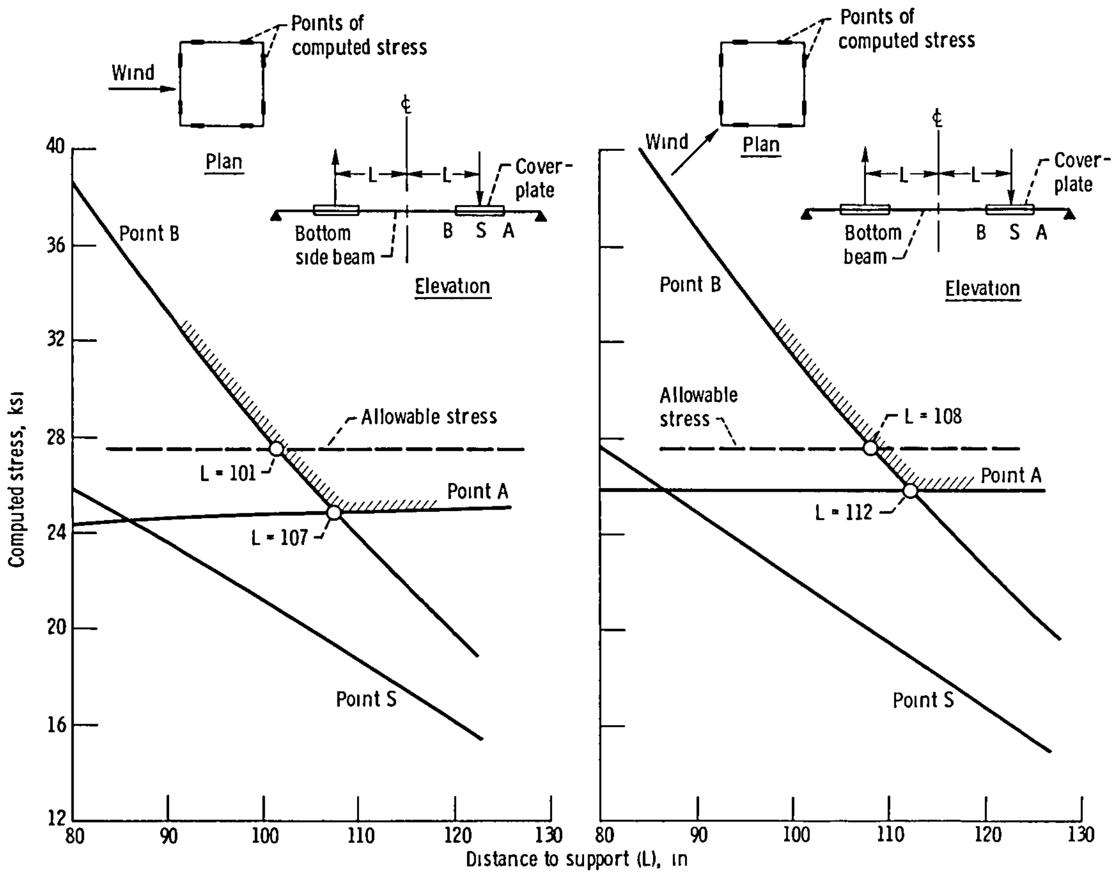


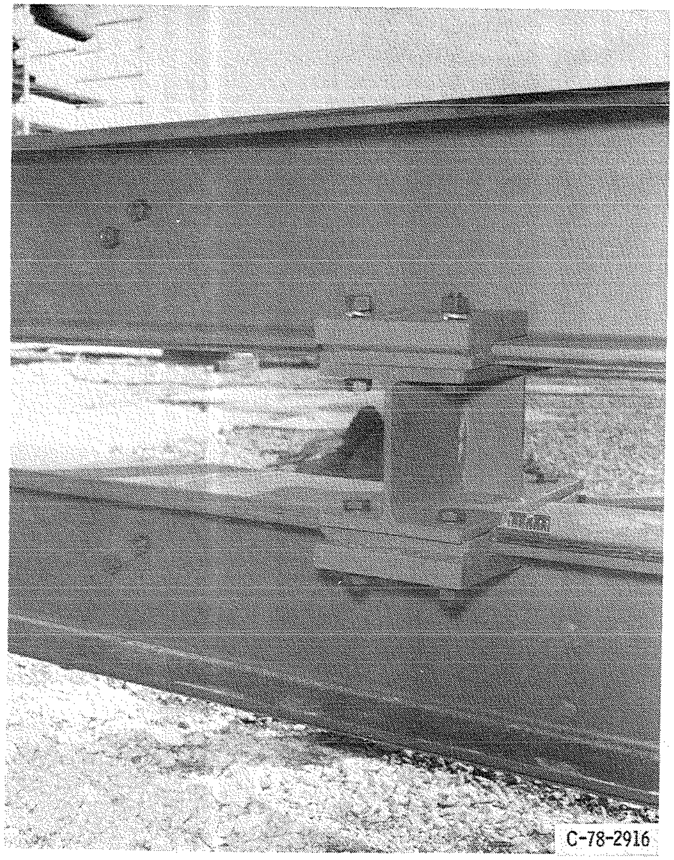
Figure 7 - Finite-element model of soft tower



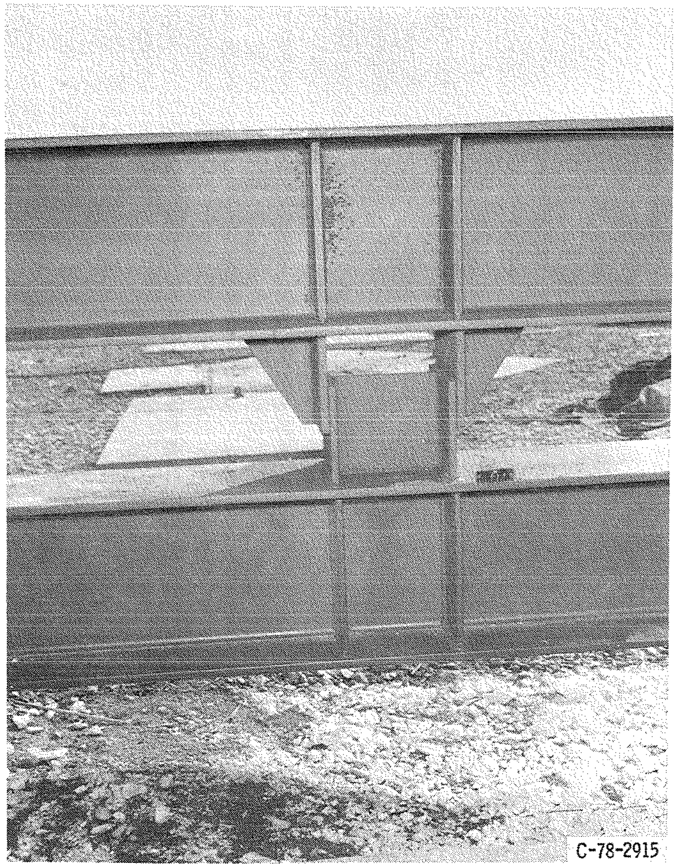
(a) 60 mph Side wind

(b) 60 mph Skew wind

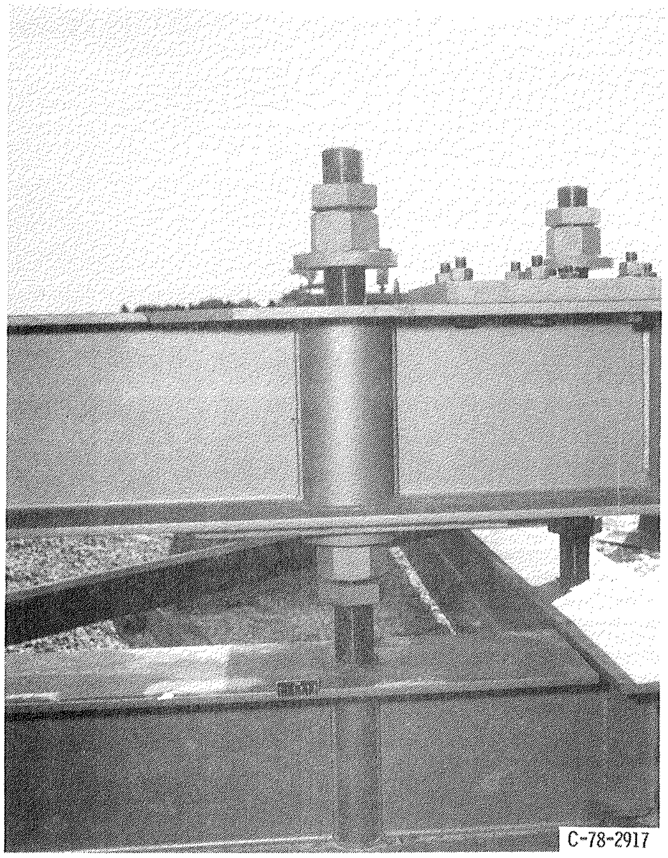
Figure 8. - Fixture stress as a function of support position



(a) MOVEABLE INTERMEDIATE SUPPORT.
Figure 9. Photographs of softening fixture details.

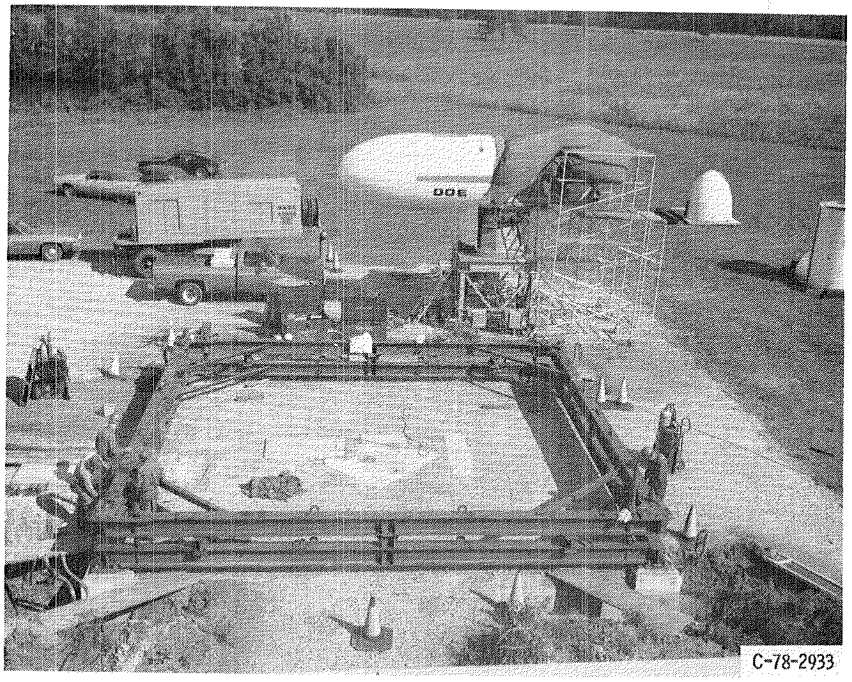


(b) SHEAR LUG.
Figure 9. Continued.



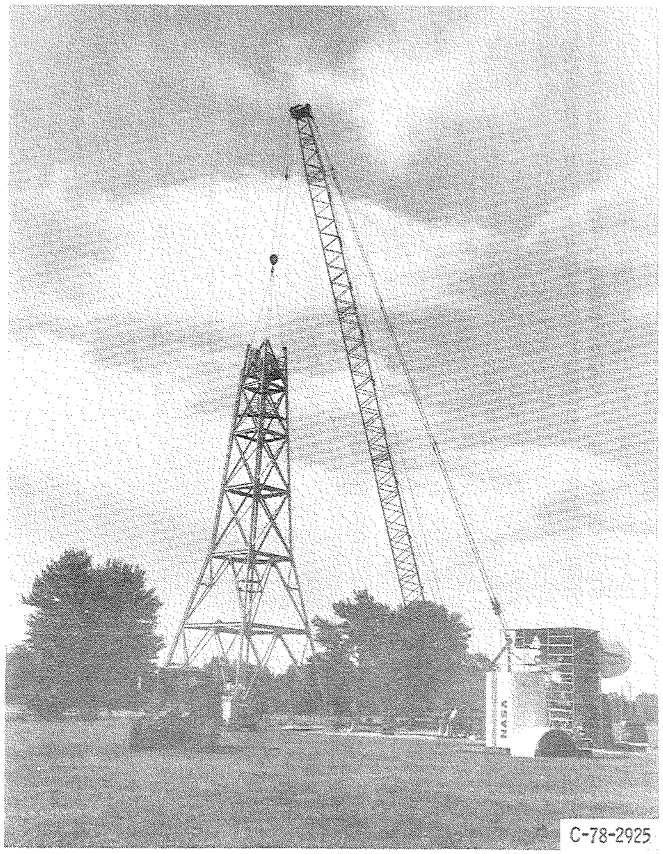
(c) LIMIT STOP.

Figure 9. Concluded.



(a) SITE INSTALLATION OF SOFTENING FIXTURE.

Figure 10. Assembly of soft tower.



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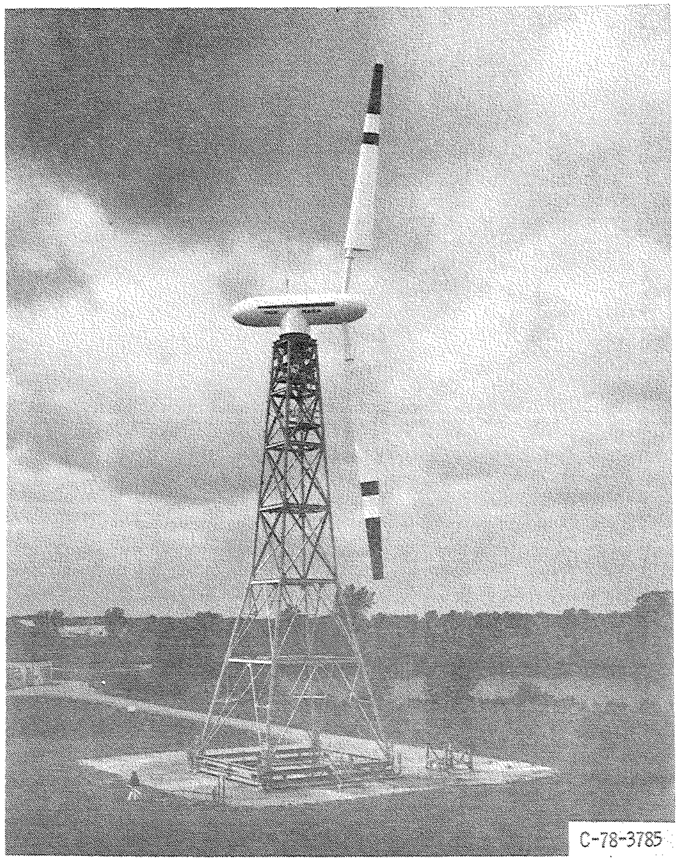
(b) TOWER BEFORE INSTALLATION ON FIXTURE.

Figure 10. Continued.



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(c) MOD-O WIND TURBINE WITH SOFT TOWER.

Figure 10. Concluded.

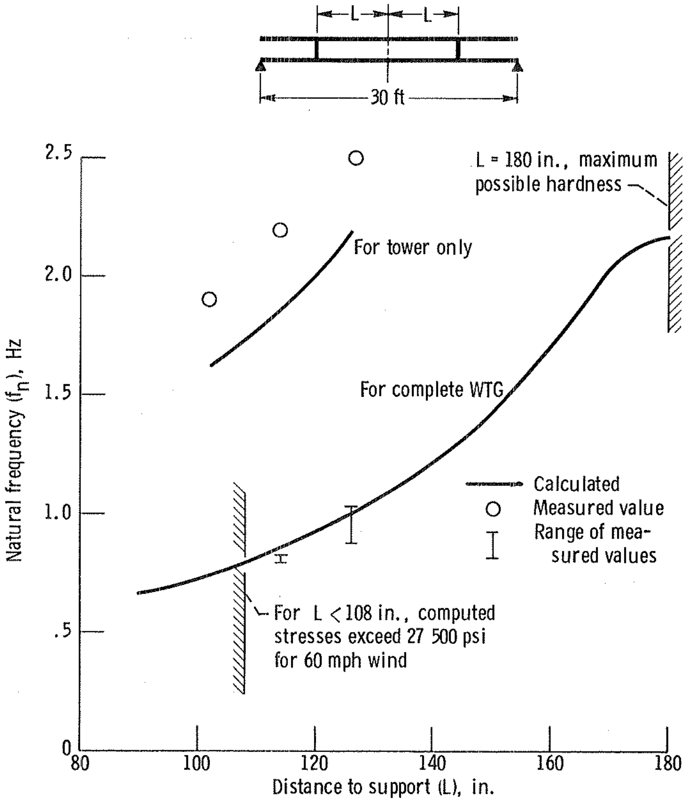
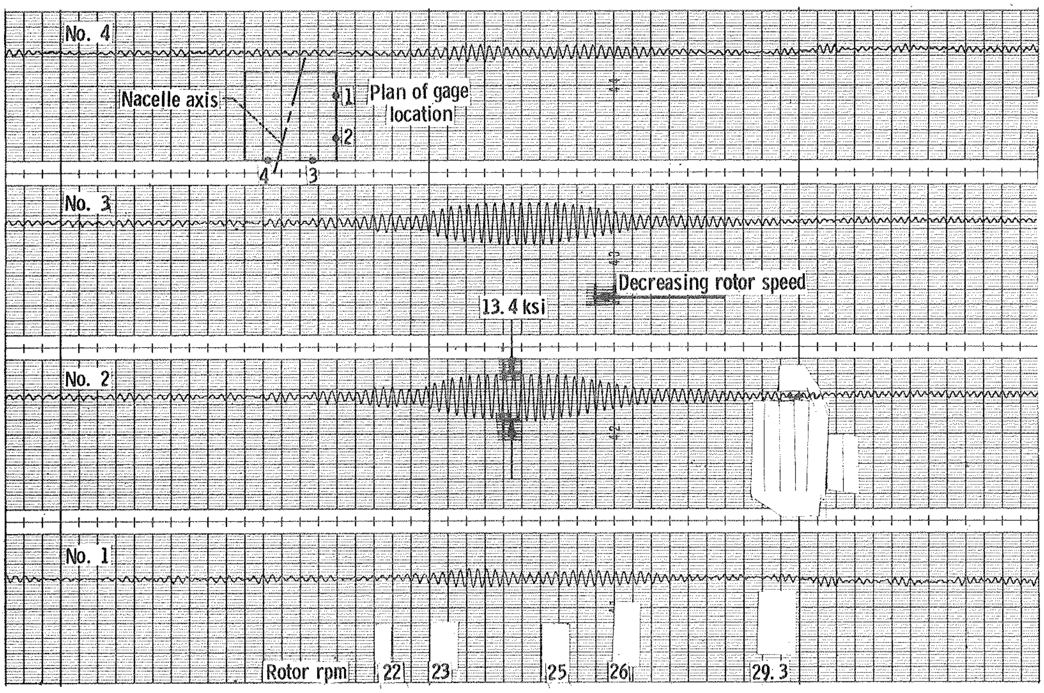
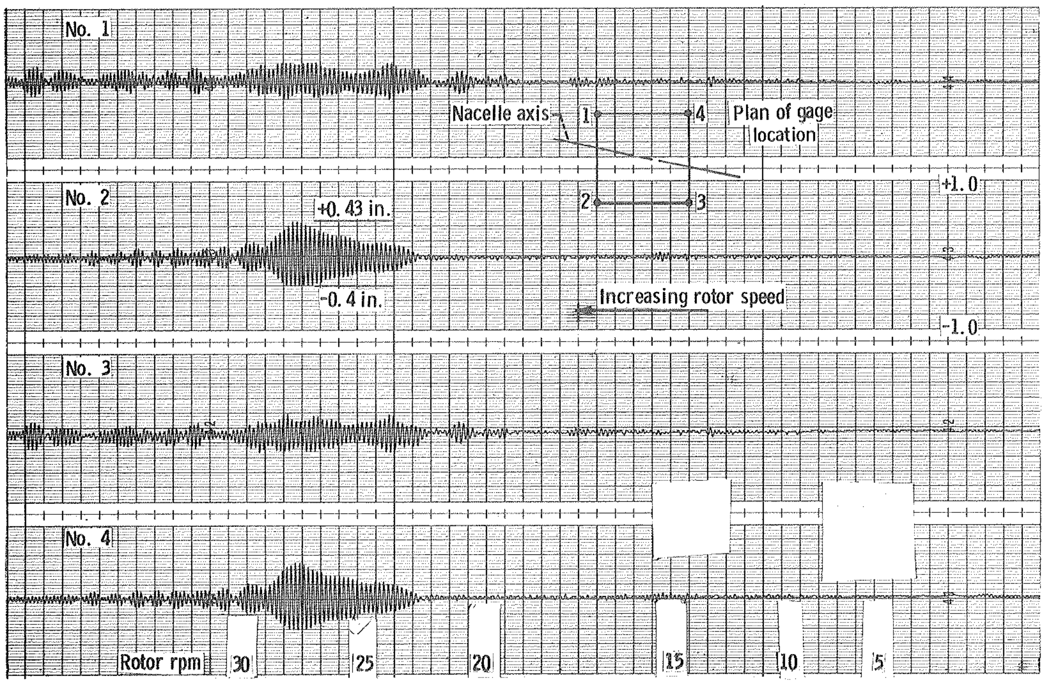


Figure 11. - Tower natural frequency as a function of support position.



(a) Beam top flange strains.



(b) Corner displacements.

Figure 12. - Fixture response when passing through resonance.

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16 Abstract

It was desired to observe the behavior of a two bladed wind turbine where the tower first bending natural frequency is less than twice the rotor speed. The system then passes through resonance when accelerating to operating speed The frequency of the original Mod-0 tower was reduced by placing it on a spring fixture. The fixture is adjustable to provide a range of tower bending frequencies. Fixture design details are given and behavior during initial operation is described

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