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U.S. DEPARTMENT OF ENERGY
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SUMMARY

The performance and loading of a large wind turbine rotor, 38.4 m in diameter and composed of two low-cost steel spar blades has been examined. Two blades were fabricated at Lewis Research Center and successfully operated on the Mod-0 wind turbine at Plum Brook. The blades were operated on a tower on which the natural bending frequency had been altered by placing the tower on a leaf-spring apparatus. It was found that neither blade performance nor loading were affected significantly by this tower softening technique. Rotor performance exceeded prediction while blade loads were found to be in reasonable agreement with those predicted. Seventy-five hours of operation over a five month period resulted in no deterioration in the blade.

INTRODUCTION

An important part of the NASA Wind Energy Project involves research efforts directed toward reducing wind turbine hardware costs. The ultimate objective of this work is to reduce wind energy costs to a point that is financially competitive with current costs of other forms of energy production. To date, a variety of innovative concepts have been considered and several have shown excellent potential for attaining the desired reductions.

Among the most promising are several that are associated with reductions in the costs of wind turbine blades. For example, recent attention has been focused on the design and construction of low-cost blading that will have long life and will require little maintenance. Wood, transverse filament tape, fiberglass composite and steel-fiberglass composite blades all are currently being considered.

Moreover, tests on an experimental wind turbine using novel concepts such as fixed pitch blades, a teetered hub, and, most recently, tip-controlled blading have been performed and each has shown certain operating advantages that will be reported elsewhere.

The purpose of the present report is to evaluate the performance of another blade cost reduction concept. In particular, the performance of a wind turbine blade known as a steel spar blade will be presented. The evaluation will be based on field test results that were obtained from the Mod-0 wind turbine located at the NASA Plum Brook facility near Sandusky, Ohio pictured in Figure 1.

The design and construction of this type of blade have been discussed in Ref. (1). Basically, the blade is formed by surrounding a tapered steel pole (similar to the steel poles used for lighting along highways or for support of electric transmission lines, known as utility poles) with an airfoil shape which is formed out of lightweight wood ribs overwrapped by a fiberglass cloth. Figure 2 depicts the fabrication process of the blade. Of primary importance, cost of constructing the blades that were eventually tested was approximately one fourth that of the aluminum blades originally flown on the Mod-0 wind turbine, and described in Refs. (2) and (3). Moreover, it has been estimated that these costs can be reduced by implementation of mass production techniques; it may be possible to construct such a blade for less than $20,000 (1980 dollars).

To be sure, such cost savings are very attractive. However, these financial advantages mean little unless the proposed blading possesses the qualities of long life, good aerodynamic performance and low maintenance. Then too, these blades will be attractive only if they demonstrate adequate performance when used in concert with other proposed cost reduction concepts.

One such concept is that of the "firm" tower. A tower may be termed soft, firm or stiff depending on the value of its first bending frequency. If the first bending frequency is less than the rotor speed, "P", the tower is said to be soft; if the first bending frequency is between one and two P, the tower is said to be firm; and if the first bending frequency is greater that 2P, the tower is said to be stiff. The Mod-0, Mod-0A and Mod-1 wind turbine towers all have first bending frequencies that exceed 2P and consequently are termed stiff. One reason for desiring a firm tower is that it offers savings in amount and cost of material without incurring performance penalties. As a demonstration and investigation of the firm tower concept, the existing Mod-0 stiff tower was softened by placing the tower on a leaf-spring apparatus. This work was reported by Winemiller <u>et</u> <u>al</u>. in Ref. (4).

In the following, the performance of steel spar blades on both stiff and firm towers will be examined. Blade loadings will also be examined and compared to predicted values. However, before proceeding to these examinations, brief descriptions of the wind turbine facility, the steel spar blade and the tower (both stiff and firm) used in the test program will be given.

TEST FACILITY AND EQUIPMENT

All tests were performed on the Mod-0 wind turbine located at the NASA Plum Brook facility. The period of testing was between September 1978 and February 1979. During this period, the blades were operated for 75 hours. The data upon which this report is based represent 7 hours of operation.

The Facility

The experimental wind turbine located at Plum Brook is a two-bladed, horizontal axis machine having a rotor diameter of 38 m (125 ft); it is rated at 100 kW when run in an 8 m/s (18 mph) wind at a rotor speed of 40 RPM. The wind turbine consists of: two rotor blades 19.1 m (62.5 ft) long, a nacelle that houses the alternator, gearbox and low-speed drive shaft, and an open truss steel tower 28 m (93 ft) high. The tower has a 9 m (30 ft) square base, but tapers to a 2 m (7 ft) square at the top. When the tower is situated on a spring base, simulating a "softened" tower, the rotor centerline is 31 m (103 ft) above the ground. A more detailed description of the Mod-0 facility is given by Thomas and Richards in Ref. (5).

The Blade

Figure 3 depicts the steel spar blade design. It should be noted that the steel spar was bolted to a high strength steel tubular extension section that was in turn attached to the hub flange, Figure 3a. This union was dictated by hub geometry and the geometry of standard utility poles. In addition, to reduce the steady flatwise blade loads, it was necessary to reduce the pre-cone angle from the 7^0 built into the Mod-0 hub to 3^0. Therefore, the steel spar is at a 4^0 angle to the extension piece as shown in Figure 3a. The steel spar is made in two sections so as to permit the use of thinner wall material in the outboard section of the blade.

The blade planform and typical cross section are shown in Figure 3b. The leading edge of the airfoil shape is formed with foam, whereas the trailing edge shape is formed with wooden ribs. The blade skin is made of fiberglass cloth. Further design and fabrication details have been reported by Sullivan et al., Ref. (1). Table I presents additional rotor information. Physical details of the original Mod-0 aluminum blades are also presented for purposes of comparison.

Examination of these data suggests that the steel spar blade is a much simpler blade form: it has no twist, has a constant thickness ratio and has a greater root cutout. Also, the steel spar blade is slightly longer. For the tests, two blades were fabricated. The blade weight and balance data for each of the two blades are summarized in Table II. As may be seen, the weights of the two blades are within 13 kg (28 lb) of each other (approximately 1 %). The total weight of each blade is about 1,640 kg (3,615 lb) compared to 910 kg (2,000 lb) for a Mod-0 aluminum blade.

The blades were instrumented with strain gage bridges to provide flatwise and chordwise loads during operation. These bridges were located at Stations 45, 159, and 540.

The Tower

As mentioned previously, Ref. (4) describes the design, fabrication and testing of a softened tower. Briefly, the tower flexibility was altered from 2 Hz to 0.83 Hz by inserting a leaf-spring fixture under the base of the tower. It was demonstrated that this method provided lateral stability as well as a means of adjustment in order to create the desired natural frequency of the system. A schematic of the softening simulation is shown in Figure 4. It was found that the deflections produced by a force or moment were in close approximation to those obtained for a truly firm tower; apparently, the technique of softening the tower at its base adequately simulated a firm tower having flexibility distributed more uniformly.

RESULTS AND DISCUSSION

During the tests of the steel spar blade, the Mod-0 wind turbine was operated with its supporting tower in two different configurations: the first was the stiff tower mode in which the tower exhibited a first bending frequency of 1.6 to 1.7 Hz (3.0 to 3.2 P); the second was the firm tower mode in which the tower had a first bending frequency of approximately 0.8 Hz (1.5 P). From the measured performance and loads, it was found that the tower natural frequency had very little effect on either blade performance or blade loading at the operational speed of 31 RPM. Furthermore, it was found that there was no apparent increase in blade loads when passing through resonance (22 to 26 RPM). Each of these topics, resonance response of the rotor and tower, aerodynamic performance and blade loads, are discussed below.

Rotor and Tower Resonance Response - Startup and Shutdown

The response of the rotor and the tower while passing through the resonance point during startup and shutdown is the focus of considerable interest to designers of wind turbines with softened towers. The softened Mod-0 tower had a first cantilever bending frequency of 0.8 Hz which produced a peak response point at a rotor speed of 24 RPM; this speed must be passed through during each startup and shutdown of the wind turbine. Typical response of the Mod-0 when passing through resonance can be seen in Figure 5, Case I and II, which shows a time sequence of tower deflections, acceleration measured at the rotor support bearing and blade chordwise and flatwise bending. Case I shows the response for a slow passage through resonance typical of a low wind startup and Case II shows a response for a faster startup. In Case I, 55 seconds were required to pass from 20 RPM to 30 RPM while 58 seconds were required to drop from 30 RPM to 20 RPM. Corresponding times for Case II were 35 seconds during startup and 14 seconds during shutdown.

Blade bending loads were not affected by the passage through resonance as indicated in Figure 5. An apparent increase in flatwise bending does occur during shutdown in Case II, Figure 5b, but the buildup in flatwise loads is due to the high blade feather rate (1^o per second) used in the test rather than to any load increase associated with the tower response.

As indicated in the Figure 5, the rate of passage through the resonance point has a significant impact on the amplitude of the tower response as reflected in the tower deflections and in the rotor bearing block acceleration, with the slower rate of passage through the resonance producing significantly higher response. (Unfortunately, the data system clipped the tower deflection signal; the dashed line on the figure indicates the probable envelope of the tower deflection.). The rotor bearing accelerometers indicate that the predominant response is lateral, or perpendicular to the rotor axis, with the response in the axial direction being only one half that in the lateral direction.

Figure 6 presents the variation in tower displacement and in rotor support bearing acceleration as the rotor speed varied for both increasing and decreasing rotor speed. The plot demonstrates the time required for resonance buildup in a system of this type, with the peak response occurring above the resonance rotor speed for increasing rotor speed and below it for decreasing rotor speed.

Tables III and IV tabulate the results for purposes of comparison. Table III presents the chordwise and flatwise loads before, during and after passing through resonance for the slow passage through resonance and Table IV presents the peak tower deflections and rotor support bearing acceleration for increasing and decreasing rotor speeds. Table III indicates that the passage through tower resonance, if anything, reduces blade bending loads in both the flatwise and chordwise directions. Table IV points out the advantages to be gained in reduced tower response by a rapid passage through tower resonance.

Aerodynamic Performance

Figure 7 presents the measured aerodynamic performance of the steel spar rotor. More specifically, this figure provides a plot of the measured alternator power output versus the measured wind speed as recorded by a wind anemometer located at the top of the wind turbine nacelle. As may be seen the performance for firm and stiff tower operation are not appreciably different.

Also shown in Figure 7 is the predicted performance as computed by the Wilson PROP code, Ref. (6). The predicted results were corrected for drive train losses using the following empirical relationship

$$P_G = 0.95\ (P_R - 0.075\ P_E)$$

where P_G is the generated electrical power, P_R is the power produced by the rotor and P_E is the rated electrical power. The constants appearing in the relationship were established from previous wind turbine tests.

From Figure 7 it can be seen that the steel spar blades performed slightly better than predicted. The PROP code underestimates the median power produced both near cut-in and at rated wind speeds. Precise reasons for these differences are at present not fully understood. The PROP code is currently being reviewed in an attempt to resolve this difficulty. In particular, assumptions made concerning blade roughness and blade stall are being carefully examined, as are limitations of the momentum theory upon which the PROP code is based.

It is of some interest to compare the performance of the steel spar blades with that of the original Lockheed aluminum blades. This comparison complements the comparison of physical differences presented earlier in the form of Table I. Figure 8 displays the experimental performance data for the two blade types. The steel spar blades were found to produce approximately 15% more power at a given wind speed below rated. At present, the reason for this somewhat better performance is not fully understood. It was hypothesized that the differences could be attributed to the fact that the steel spar blade has a slightly larger rotor diameter and a reduced coning angle. However, further investigation revealed these physical differences could only account for a 1.3% increase in power. The better performance of the steel spar blade was also unexpected because the blade has no twist and has a greater percentage of root cut-out.

Blade Bending Loads

Besides an examination of blade performance, it is of equal importance that some attention also be given the blade bending loads. For, as is well known, in large wind turbines operating at relatively low shaft speeds, blade bending loads are of much greater concern than are centrifugal tension loads. As a matter of general practice, these bending loads are resolved into flatwise and chordwise components at stations along the blade span, with the chord line as the flatwise axis. Hence, flatwise bending produces stresses on the pressure and suction surfaces of the blade while chordwise bending produces stresses at the leading and trailing edges.

Figure 9 shows the variation of the flatwise bending component at blade station 45 against wind speed. Results for steady and cyclic loads are presented. The steady moment load is defined as one-half the sum of the maximum and minimum loads during one revolution of the rotor, whereas the cyclic moment load is defined as one-half the difference between the maximum and minimum loads. Results are presented for both stiff and firm towers. And, as in the case of the performance data, the reduced tower natural frequency is seen to have very little effect on blade bending loads.

For comparative purposes, the design blade bending loads as obtained from use of the MOSTAB-WT computer code, Ref. (7), are also shown in Figure 9. It can be seen that, in general, the design cyclic values are in good agreement with measured results. Differences that occur at the higher wind speeds are attributed to the fact that the computer code overestimates wind shear at higher wind speeds, and consequently, tends to predict cyclic loads that exceed the measured values. On the other hand, the difference between the design and measured steady component of the flatwise bending load is due to differences between the design and fabricated blade weight and center of gravity (CG) location. The design weight and CG are 1,565 kg (3450 lbs) and 8.3 m (27.3 ft), respectively, while the actual weight and CG are 1,640 kg (3615 lb) and 7.2 m (23.8 ft). In addition, the actual rotor speed was not used in the code. The design rotor speed was 33 rpm, while the actual rotor speed was 31 rpm.

Measured and predicted chordwise steady and cyclic bending moments are compared in Figure 10. It should be noted that the steady component of the chordwise load is the torque producing component. From the figure it can be seen that the predicted cyclic load is slightly greater than that measured. The difference is again due to the difference between design and actual blade weight and CG location. At least a portion of the difference between measured and predicted chordwise steady load can again be attributed to the difference between the actual rotor speed and the design speed used in the calculations.

The steel spar blades were operated on the Mod-0 wind turbine over a period of 5 months, including the most severe part of the winter. Blades were then removed from the machine and inspected. The fiberglass skins showed no signs of deterioration and dye-penetrant check of the spar-to-flange weld revealed no cracks. As further evidence of durability, the in-board section of the blade is still being utilized in various wind turbine tests.

CONCLUDING REMARKS

In this investigation it was determined that the Mod-0 wind turbine could be successfully operated using wind turbine blades fabricated with a low-cost steel spar as the primary structural member. In addition, it was found that:

(1) the passage through tower resonance during startup and shutdown resulted in no adverse effects on blade loads;

(2) neither rotor performance nor blade loading was affected significantly when the steel spar blades were operated on a tower that had its natural frequency lowered to 1.5 times the rotor speed when compared with data taken with the tower frequency above 2 times the rotor speed;

(3) the aerodynamic performance both exceeded that predicted as well as that of the aluminum blades originally flown on Mod-0;

(4) the blade loads were in reasonable agreement with the calculated loads used in designing the blades; and

(5) no structural deterioration in the blades was detected during or after the test program.

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TABLE I. Comparison of Rotor Characteristics
(NASA 230XX Series Airfoil)

	Steel Spar Blade	Aluminum Blade
Rotor diameter, m (ft)	38.4 (126)	38.1 (125)
Root cutout, percent	23.0	6.4
Root chord, m (ft)	1.9 (6.3)	1.4 (4.5)
Tip chord, m (ft)	0.6 (2.1)	0.5 (1.5)
Root thickness ratio	0.24	0.40
Tip thickness ratio	0.24	0.12
Solidity	0.033	0.031
Precone angle, deg.	3.8 (effective)	7.0
Total twist, deg.	0	34
Airfoil surface	rib stitched fiberglass cloth	riveted aluminum
Operating speed, rpm	31	40

TABLE II. Steel Spar Blade Weight and Balance

Item	Blade No. 1		Blade No. 2	
Blade weight, kg (lb)	1,116	(2460)	1,129	(2488)
Balance weight, kg (lb)	31	(68)	0	(0)
Extension weight, kg (lb)	494	(1089)	510	(1125)
Total weight, kg (lb)	1,641	(3617)	1,639	(3613)
Spanwise C.G., station, m (in)	7.24 (285)		7.24 (285)	
Chordwise C.G., percent chord	27		27	

TABLE III. Peak-to-Peak Blade Loads at Sta. 159
During Firm Power Operation (Case I)

Operating Condition	Blade Moment, 10^3 N-m (lb-ft) Flatwise	Chordwise
20 rpm	33 (45)	66 (90)
20-30 rpm	13-24 (17-33)	66-77 (90-105)
30 rpm	18-35 (24-48)	71 (96)
30-20 rpm	20-31 (27-42)	66-80 (90-108)
26 rpm (peak resonance, increasing rotor speed)	14 (19)	71 (96)
25 rpm (peak resonance, decreasing rotor speed)	24 (33)	68 (92)

TABLE IV. Influence of Rotor Acceleration on Tower Deflection and Pod Acceleration

Condition	Rotor Acceleration, rpm/sec.	Peak Tower Deflection, cm (in)	Peak Pod Acceleration, g
increasing rotor speed	0.18	6.6 (2.6)	0.21
	0.29	1.8 (0.7)	0.17
decreasing rotor speed	- 0.17	11.2 (4.4)	0.24
	- 0.71	1.0 (0.4)	0.11

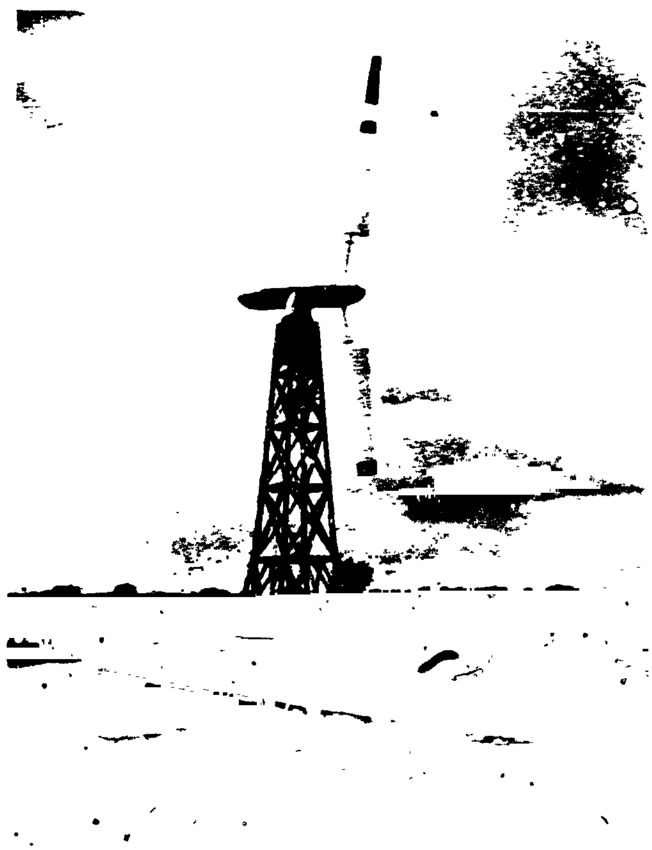

Figure 1. - Mod-0 wind turbine.

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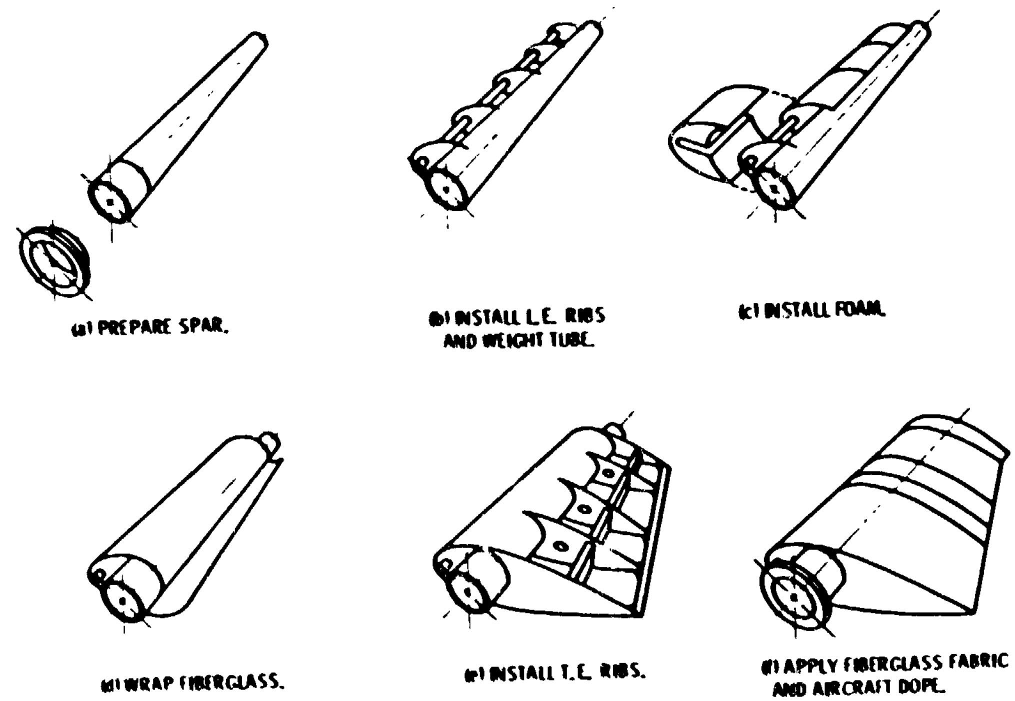


Figure 2. - Steel spar blade fabrication process.

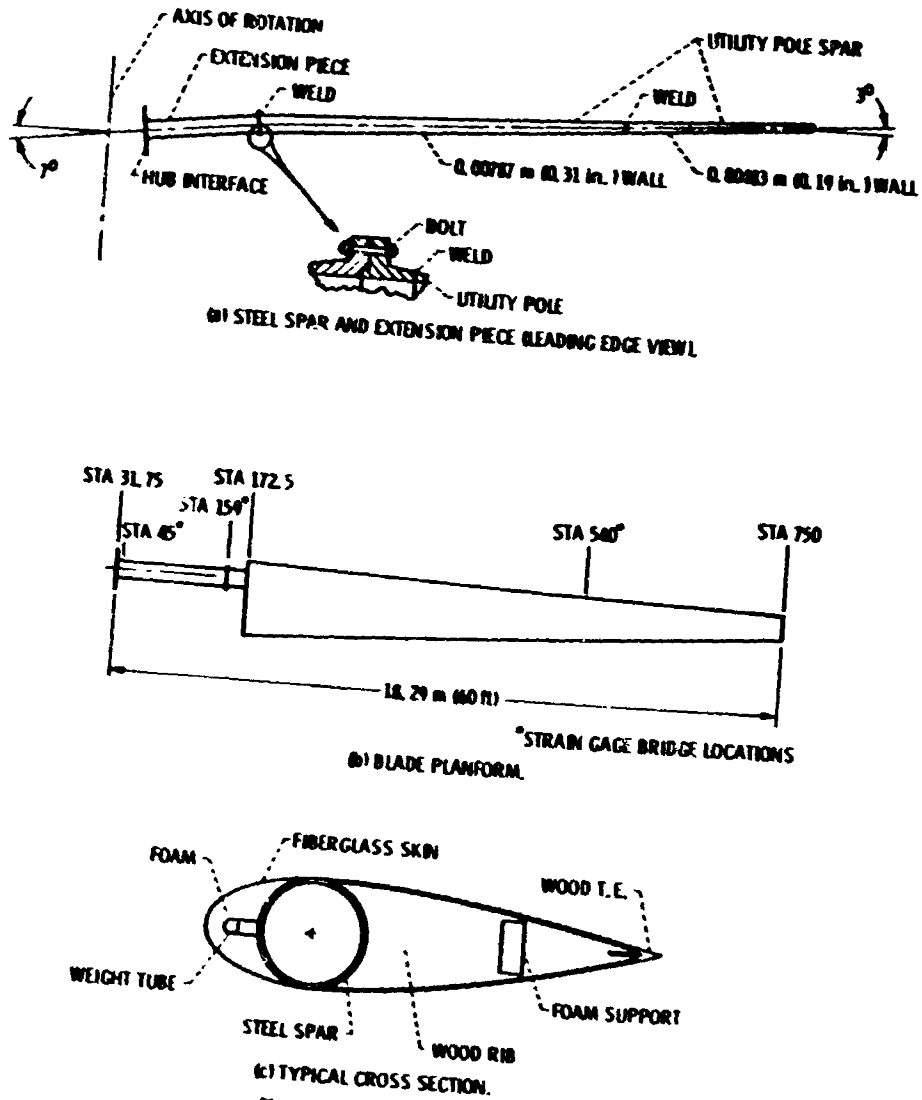


Figure 3. - Steel spar blade design.

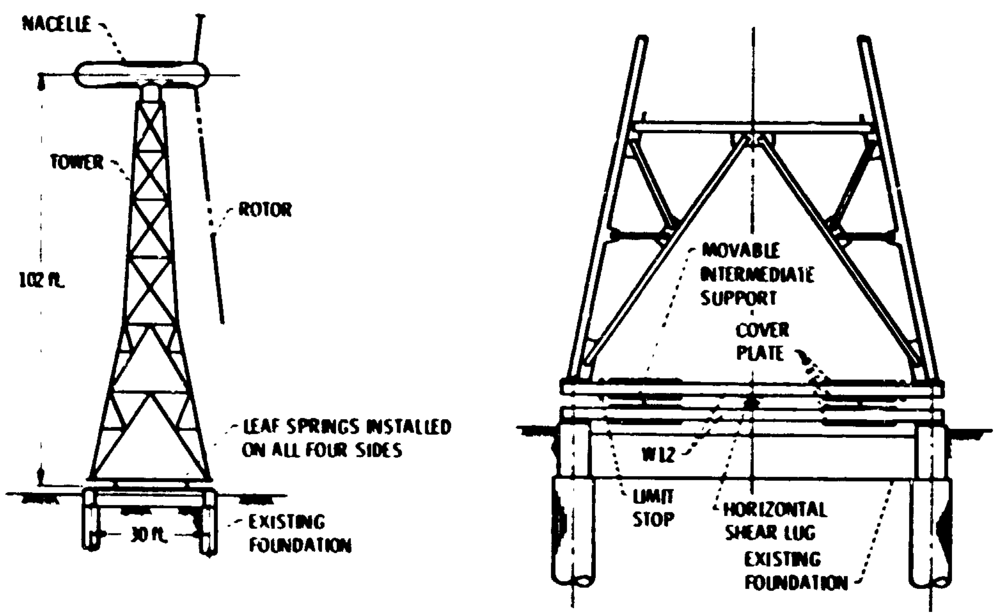
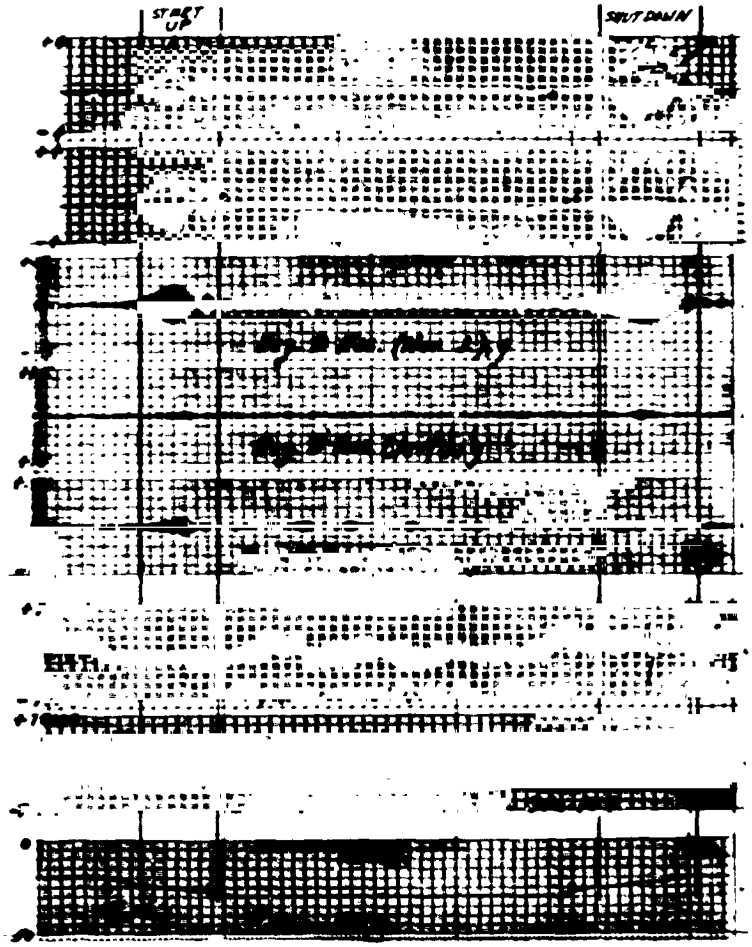


Figure 4. - Firm tower fixture (figure from ref. 4).



(a) Case 1.

Figure 5. - Response of Mod-0 with firm tower.

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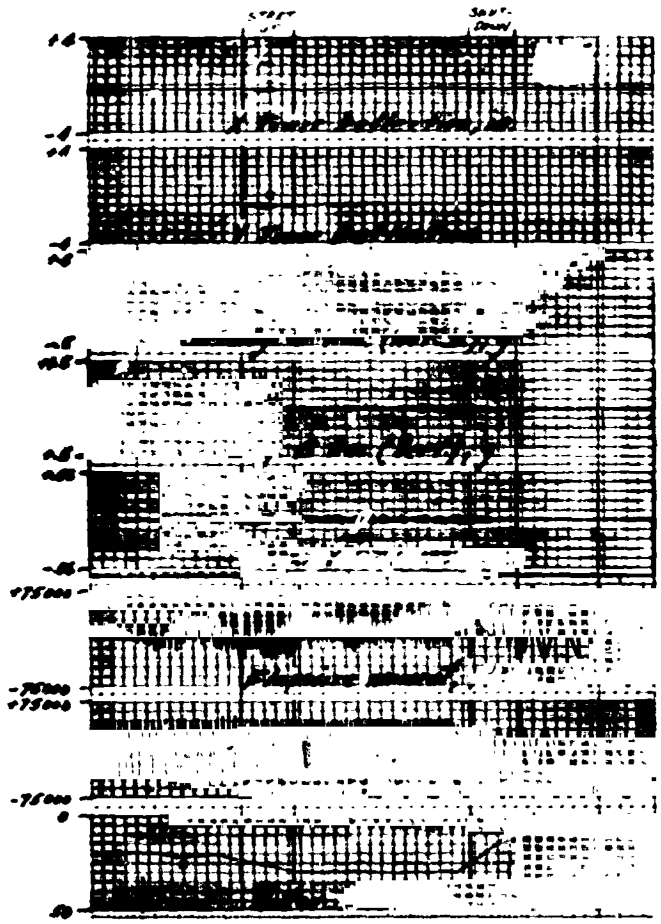
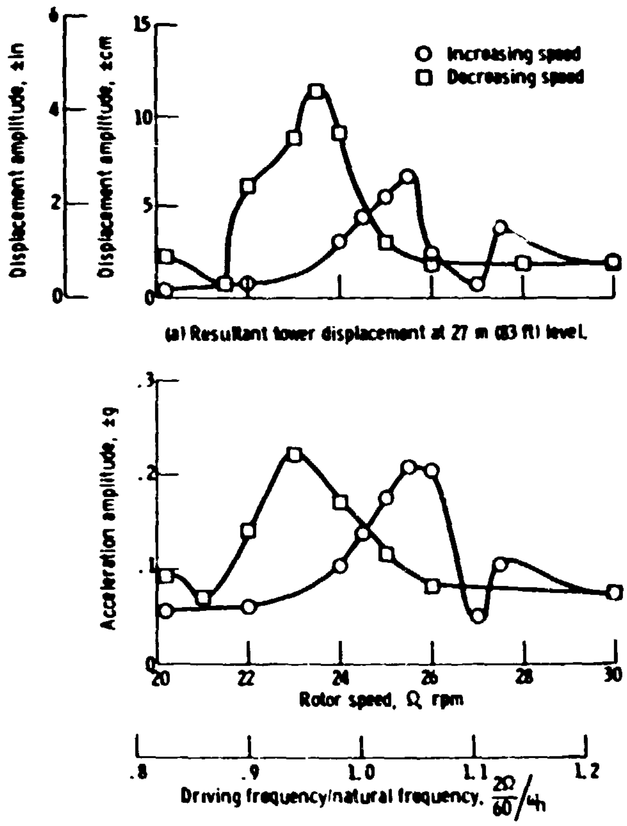


(b) Case II.

Figure 5. - Concluded.



(a) Resultant tower displacement at 27 m (83 ft) level.

(b) Resultant pod acceleration 3m (9 ft) aft of tower centerline.

Figure 6. - Variation of tower ... placement and pod acceleration with rotor speed (Case I).

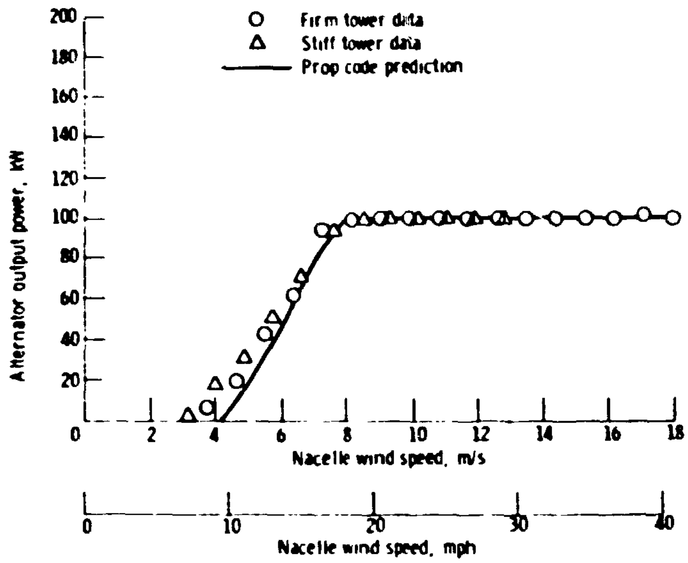


Figure 7. - Comparison of predicted and measured steel spar performance.

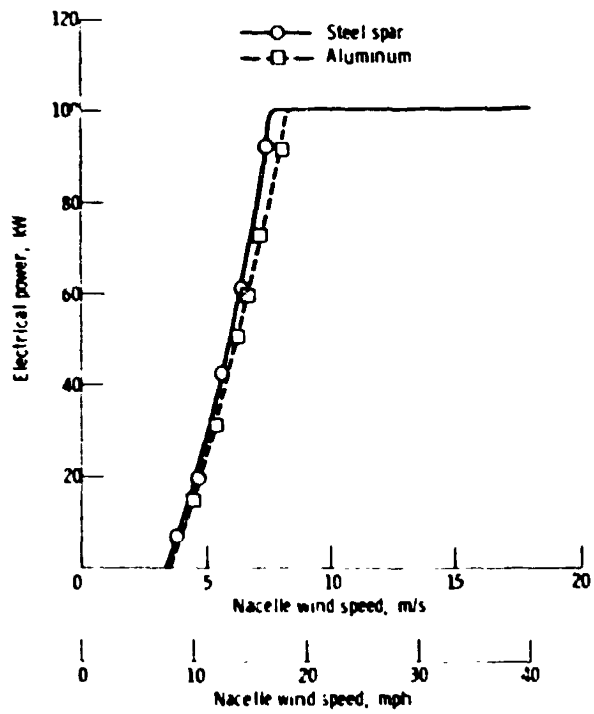


Figure 8. - Comparison of performance of two sets of Mod-0 blades.

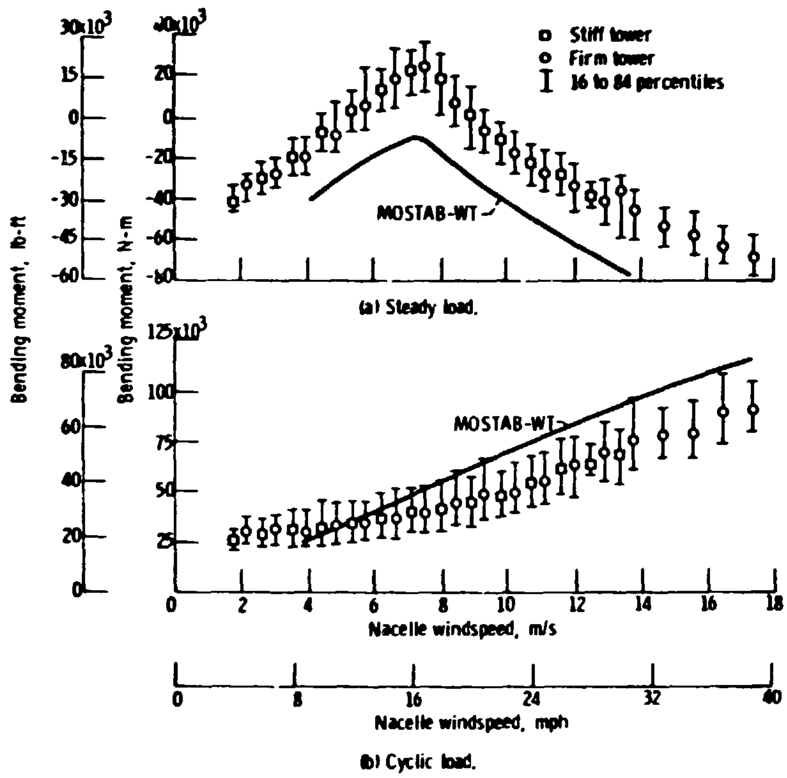


Figure 9. - Comparison of measured and design steel spar blade flatwise root loads (stiff and firm towers).

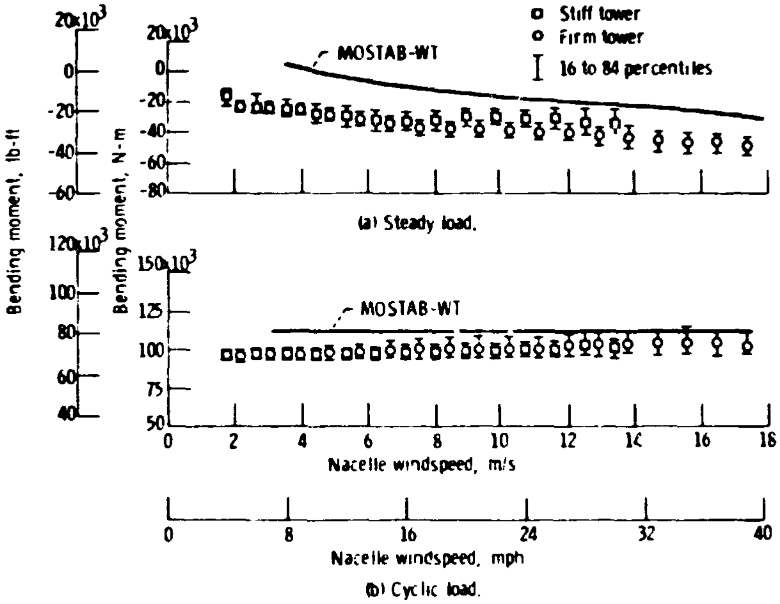


Figure 10. - Comparison of measured and design steel spar blade edgewise root loads (stiff and firm towers).