DOE/NASA MOD-0 100KW WIND TURBINE

TEST RESULTS

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ABSTRACT

The Mod-0 100kW Wind Turbine was designed and fabricated by the NASA under the direction of the U.S. Department of Energy to assess technology requirements and engineering problems of large wind turbines. The machine became operational in October 1975 and has demonstrated successful operation at 40 rpm while producing power on resistive load bank and while synchronized with power grids. The Wind Turbine has also demonstrated the capability of automatic unattended operation, including startup, achieving synchronism, and shutdown as dictated by wind conditions. During the course of these operations, a wealth of engineering data has been generated. This paper presents some of this data which is associated with rotor and machine dynamics problems encountered and the machine modifications incorporated as a solution. These include high blade loads due to tower shadow, excessive nacelle yawing motion, and power oscillations. The results of efforts to correlate measured wind velocity with power output and wind turbine loads are also discussed.

INTRODUCTION

The Mod-0 100 kW Experimental Wind Turbine is a part of the National Wind Energy Program under the direction of the U.S. Department of Energy. The NASA Lewis Research Center has designed, built and erected this machine near Sandusky, Ohio and is currently testing it to obtain engineering data on large horizontal axis wind turbines.

The wind turbine described in reference 1 has a 125 foot diameter two bladed rotor which drives a 100 kW capacity synchronous generator through a step up gear box. The rotor is positioned downwind of a 100-foot steel truss tower as pictured in figure 1. The rotor is designed to operate at a constant speed of 40 rpm and it drives a 480 volt 60 Hz three phase generator at 1800 rpm. Rotor speed or output power level is maintained by controlling rotor blade pitch angle with an active feedback control system. The rotor, generator, transmission and associated equipment are mounted in a nacelle, figure 2, which can be yawed to align the rotor with the wind. Power, instrumentation and control connections to the ground are made through slip rings.

The turbine was designed to begin generating power in winds of 10 mph (at 100 ft) and produce 100 kW at a wind velocity of 18 mph. In winds above 18 mph, the generator continues to operate at 100 kW output by adjusting the pitch of the rotor to spill excess wind energy. When the wind velocity exceeds 30 mph the generator is taken out of synchronism with the power network, the blades are feathered to bring the rotor to a halt and the machine is shut down to await the return of lower velocity winds.

Final assembly of the machine was completed in September 1975 and since that time successful operation of the wind turbine has been demonstrated for each of its design operating modes at 40 rpm; Manual operation on a resistive load and while synchronized to a large power grid and a simulated small power grid, and unattended automatic synchronization and operation on a large power grid.

In keeping with the primary objective of the Mod-0 program, a considerable amount of engineering data has been generated for use in the ongoing U.S. Wind Energy Program. On the Mod-0 project as with any research project, useful information is generated both from demonstrations of successful designs and operations and from designs which create engineering problems or unsuccessful operation. This paper discusses some of the engineering problems which pertain to rotor and machine dynamics and the design changes which have been incorporated to eliminate or reduce their undesirable effects. Also included is a short discussion on techniques which are being used to correlate wind turbine power output and loads with measured wind velocity.

Instrumentation

The Mod-0 research data system provides approximately 100 channels of information. This data is recorded on magnetic tape at the request of an operator or at specific time intervals. The data is processed off-line for analysis. Selected instruments are displayed on Brush recorders for real time monitoring and review. Most of the data presented in this paper is from the Brush recorders and the transducers which produced the data are listed below.

1. Nacelle wind velocity and yaw angle of nacelle relative to the wind.
2. Nacelle accelerations $\ddot{x}$, $\ddot{y}$, and $\ddot{z}$ at the rotor shaft bearing support nearest the rotor.
3. Rotor blade pitch angle.
4. Rotor blade bending moments, indicating flatwise (Mm) and inplane (Mn) bending at two stations along the blade span.
5. Rotor shaft torque (Mz) and bending moments (Mx) and (My).
6. Rotor speed and position.
7. Alternator output in kW.
8. Yaw drive shaft torque.

Figures 3 and 4 give a schematic representation of these measurements, their location on the wind turbine, and the sign convention of each.

TOWER SHADOW

Initial operations of the Mod-0 wind turbine at 40 rpm resulted in blade and low speed shaft loads which exceeded design loads by a considerable margin. These results were presented in reference 2. Review of the data indicated two factors to be the primary cause of the high loads (a) tower shadow or low velocity air flow immediately downwind of the tower which affected the downwind Mod-0 rotor, and (b) excessive nacelle yawing motion. Nacelle yawing motion is discussed in a later section; tower shadow is discussed below.

The flapwise bending load experienced by a Mod-0 rotor blade near the root is presented in figure 5. The moment increases negatively as the blade moves from behind the tower and reaches a maximum value at approximately 35^{o} from the vertical down position indicating deflection toward the tower in response to the reduced air load in the tower shadow region. Also indicated in the figure are design values for this moment and a calculated value using a tower shadow value which would reproduce the measured loads.

After the initial Mod-0 40 rpm operation, wind tunnel tests were conducted to define the tower shadow for the Mod-0 tower in its original configuration and to evaluate various tower configurations designed to reduce tower shadow. The results of this investigation are reported in reference 3 and figures 6 and 7 show measured tower shadow values for the original Mod-0 with stairs and rails and for the tower with stairs and rails removed.

Based on the wind tunnel results the stairs were removed and Mod-0 operation at 40 rpm showed a marked reduction in flapwise bending loads as reported in reference 4 and shown in table 1. As indicated in the table, the flapwise bending moment for steady-state operation was reduced from 130,000 ft.lbs. to 70,000 ft.lbs. when the stairs were removed. While the load reduction attributable to reduced tower shadow was significant with respect to flapwise bending moment, very little improvement was seen in inplane moment and both flatwise and inplane moments remained high with respect to blade design load. Inplane bending moments have been observed to be affected more directly by lateral motion of the rotor which can be produced by lateral motion of the tower or by yawing of the nacelle. The major source of lateral motion at the rotor has been attributed to nacelle yawing which is discussed below.

Nacelle Yawing Motion

Data taken during early operation of the Mod-0 wind turbine at 40 rpm indicated high oscillatory torque loads on the low speed rotor shaft as the rotor speed varied between 37 and 40 rpm and the wind velocity indicated on the nacelle varied between 22 and 32 miles per hour. This data was presented and discussed in reference 2 and is shown in figure 8. When the data was first presented high drive train response indicated by the oscillatory load on the low speed shaft was attributed to a blade inplane mode being excited as the rotor speed varied between 38 and 42 rpm. Since that time it has been demonstrated that the primary cause of the conditions encountered in figure 8 was nacelle yawing motions which produces an oscillatory lateral motion at the rotor. Tests were run in 1976 after the stairway was removed with a locked yaw mechanism. This locked the nacelle to the tower and increased the resonant frequency in yaw from approximately twice the rotor speed, 2P, to over 5 times the rotor speed as indicated in table 2. Comparison of data taken with and without the yaw drive locked indicated a reduced tendency for low speed shaft bending response with the yaw drive locked and reduced moments on the rotor blades and low speed drive shaft, which indicated a definite connection between nacelle yawing motion and the low speed shaft response.

Reducing tower shadow also had an effect in reducing the low speed shaft torque response at 4P as was indicated by the inability to reproduce the drive train torque response shown in figure 8b after the tower was modified to reduce tower shadow. Repeated attempts to reproduce the condition in winds of similar magnitude failed to excite the condition to the amplitudes originally encountered. This was true for both single yaw drive and locked yaw tests. Also, the rotor vertical motion as indicated in figure 8c, bearing "B" acceleration, $\ddot{Y}$, was reduced by an order of magnitude after the stairway was removed indicating a strong connection between vertical motion of the rotor or nacelle "nodding" and tower shadow.

After the test results for locked yaw were obtained a dual yaw drive and yaw brake were installed on the Mod-0 wind turbine. It was predicted that the dual yaw drive with a preload to remove free play would eliminate the problems associated with nacelle yawing motion. The single yaw drive permitted some free play and the drive system stiffness resulted in a nacelle yawing natural frequency approximately equal to twice the rotor speed. The dual yaw drive was designed to raise this frequency to 2.5 times the rotor speed, 2.5P, and decouple the machine in yaw. The yaw brake was added as a backup system which would provide capability for additional yaw restraint if this was required. The revised system is depicted in figure 2.

Tests with the dual yaw drive at 40 rpm indicated that more restraint was needed to prevent excessive nacelle yawing motions which resulted in high blade flapwise and inplane bending loads, low speed shaft bending loads and loads on the yaw drive mechanism. The yaw brake was used on subsequent operations and with the nacelle locked to the tower with a brake clamping pressure of 1500 psi, the frequency of occurrence of the high blade and shaft bending moments was greatly reduced.

The results of tests with the dual yaw drive and the yaw brake demonstrated the need for the yaw brake to keep machine loads within acceptable limits and the brake was incorporated as a part of the yaw control system. The yaw system was designed to provide a clamping pressure of 1500 psi on the yaw brake when the yaw drive motors were off and a drag pressure of 100 psi when the yaw motors were on to change nacelle azimuth.

Operations with this system proved to be unsatisfactory. High blade and shaft loads occurred frequently as the yaw brake clamping pressure was relieved to permit a nacelle azimuth change. This effect is depicted in figure 9 showing a rapid buildup in low speed shaft bending as the yaw brake is released. Yaw brake release is indicated by activity on the yaw drive torque trace. Raising the yaw brake drag pressure from 100 psi to 300 psi reduced the undesirable effects resulting from brake release.

As stated above, locking the nacelle to the tower with the yaw brake reduced the frequency of occurrence of high blade and shaft loads. The yaw brake did not eliminate these high loads and a typical occurrence is indicated in figure 10 for load bank operation. In this figure the wind turbine is operating on the resistive load bank and electrical load has been removed and replaced in a period of approximately 30 seconds. Rotor motion has been reduced as indicated by the rotor bearing accelerations in figure 10a. However, as the wind velocity measured on the nacelle increases, rotor blade and low speed shaft loads increase above desirable levels (fig. 10b). A comparison of the rotor bearing accelerations with those of figure 8c clearly indicates that rotor motion has been greatly reduced, however, high blade and shaft loads continue to occur as wind velocity varies. The condition has been observed to be a transient response to variable wind speed rather than a condition which occurs at a particular wind velocity, and little correlation exists between low speed shaft bending and instantaneous nacelle wind velocity.

Future operations of the Mod-0 wind turbine will evaluate the potential of yaw brake as a yaw damper. In these tests, the preload will be removed from the dual yaw drive to permit some free play in yaw and a constant pressure will be applied to the yaw brake providing a constant restraint in yaw throughout the operation, yaw motors on or off. The yaw damping force can be varied by changing the yaw brake pressure and the effect of this variable on wind turbine response can be evaluated.

Power Oscillations During Synchronous Operation

Initial tests of the Mod-0 for synchronous operation were conducted at a 20 rpm rotor speed. This rotor speed was chosen because of the high loads encountered at 40 rpm with the single yaw drive, mentioned above. The blade loads and nacelle yawing response were reduced at 20 rpm and it permitted the operations to continue while the dual yaw drive and brake were being fabricated.

Obtaining synchronism with a large power grid or with a small diesel generator set presented no difficulty, the normal deviations from rotor speed set point being sufficient to provide enough variation in generator speed to permit synchronism with the aid of a commercially available synchronizer. Synchronization of the Mod-0 is discussed in detail in reference 5. However, once synchronous operation was obtained the rotor, drive train and generator experienced a high amplitude resonant response at 40 CPM or 2P, as indicated in figure 11.

The resonant response was identified as a first mode vibration of the drive train and rotor as described in reference 6 which predicts this mode to occur between 0.27 Hz and 0.62 Hz, or .8P to 1.86P (for 20 rpm operation) as the generator load is varied between 0 and 100 kW. The driving force for the mode is the tower shadow which creates a defect in rotor torque as each blade passes behind the tower. The analytic value for this forcing function for 40 rpm operation is shown in figure 11. Synchronous operations were conducted at 26.3 rpm and 40 rpm and representative samples of the results are shown in figures 12 and 13. As shown by the figures, operation at 26.3 rpm did not relieve the resonant response observed at 20 rpm but the 40 rpm rotor speed improved the situation significantly. However, operation at 40 rpm still left a ±15 to ±20 kW power oscillation at 80 CPM or 2P.

To reduce the power oscillations, a fluid coupling was installed on the high speed shaft and was run at 20 and 40 rpm as shown in figure 2. The results are shown in figures 15 and 16. As indicated, a large reduction in power oscillations was achieved by the fluid coupling at 20 rpm and a somewhat less significant improvement is shown at 40 rpm. The 20 rpm test was run with a 4% slip at a 60 kW load and the 40 rpm test was run with a 2% slip at 100 kW load. The oscillations can be reduced still further by increasing the slip in the coupling.

The use of a fluid coupling in the drive train provided an additional benefit in permitting the use of larger amounts of proportional gain in the power control system. The power control system was highly unstable when proportional gain was used with a rigid drive train, but the fluid coupling removed the instability and proportional gain considerably improved control system response.

Correlation of Wind Turbine Response with Measured Wind Velocity

Since the beginning of Mod-0 operations, efforts have been under way to develop methods which can be used to describe wind turbine performance and load response as a function of wind velocity. As a result of these investigations, methods have been developed which permit the desired correlations of power versus wind speed and loads versus wind speed to be made. A report describing Mod-0 performance will be available in the near future and the method used to obtain this correlation is described briefly below. A method for describing loads versus wind speed is also presented along with some preliminary results using these methods.

Wind measurements for the Mod-0 wind turbine are taken at two locations, on the wind turbine nacelle and on a 195 foot meteorological tower located 650 southwest of the wind turbine as depicted in figure 17. Wind turbine response is measured in terms of alternator power output and load measuring instrumentation described previously.

The process of correlating wind turbine performance with measured wind speed is complicated somewhat by the method of wind measurement. Measurements made on the nacelle correlate well with wind turbine response but are subject to inaccuracies due to flow disturbances created by the rotor and the nacelle. Measurements taken on the meteorological tower are relatively free of flow disturbances but are hampered by the distance between the wind turbine and the tower. To account for these complications it was necessary to first obtain a relationship between nacelle wind speed and alternator power and then correct nacelle wind speed to an undisturbed value based on meteorological tower data taken over the same time period.

To obtain the relationship between alternator power output and nacelle wind speed, simultaneous measurements of power output and nacelle wind speed are taken over a broad speed range. A typical set of simultaneous data is shown in figure 18. These data are then sorted into 1 mph speed increments and a region averaged value is obtained for each speed range. The average values are then used to produce a power versus nacelle wind speed plot as shown in figure 19.

Wind speed measurements taken on the meteorological tower are curve fitted to obtain a wind speed at the nacelle height. Two minute averages of the nacelle wind speed and the derived meteorological tower wind speed are taken to smooth the data and the simultaneous averages are cross plotted to obtain a relationship between nacelle wind speed and free stream wind speed as shown in figure 20. The relationship thus derived permits the correction from nacelle wind speed to free stream wind speed to be made.

Analysis to describe Mod-0 performance using this method is presently underway and results will be published as they become available.

The method used in describing wind turbine loads is similar to that employed in describing performance. Fatigue is a primary concern in the design of wind turbines and cyclic loads are the major source of fatigue. Loads measured on Mod-0 are therefore described in terms of mean and cyclic values.

Loads data is first broken down into mean and cyclic values and the component parts along with the simultaneous wind speed are stored and sorted into wind speed ranges. The loads data contained in each wind speed range is then averaged and a standard deviation of the set is obtained. The results of limited samples of data processed in this manner is shown in figure 21 for rotor blade flatwise bending at station 40, near the blade root. The data indicates a trend increasing with increasing wind speed and provides a means of quantifying a highly variable set of data. A relatively small sample of data has been processed in this manner at this time but the results obtained thus far indicate that this approach is a good one for describing wind turbine loads and vibratory response.

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4. Linscott, B. S.; Glasgow, J. C.; Anderson, W. D. and Donham, R. E.: Experimental Data and Theoretical Analysis of an Operating 100 kW Wind Turbine. Proceedings of the 12th Intersociety Energy Conversion Engineering Conference, Aug. 1977.

5. Gilbert, Leonard J.: Synchronization of the DOE/NASA 100 kW Wind Turbine Generator With a Large Utility Network. NASA TM-73861.

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DISCUSSION

Q. In view of the blade flapwise bending response and low speed shaft bending phasing, it would appear a teetered rotor would reduce 2P yawing motion. Why did NASA drop teetered hub?

A. Early in the Mod-0 program a teetered rotor was considered to relieve tower shadow problems. The idea was not pursued when Mod-1 studies indicated that teetering was not worth the added cost and complexity.

Q. Could you elaborate on the interesting observation made that damping the yaw drive tends to eliminate the 4P torsional oscillations of the low speed shaft?

A. Increasing yaw stiffness did not remove the 4P torsional drive train oscillations. They can be seen on figure 10b with the yaw brake applied. However, after the stairs were removed to reduce tower shadow the condition depicted in figure 8b could not be reproduced at any significant magnitude. Yaw stiffness did not seem to have as much effect on the condition as reduced tower shadow.

Q. Where should you measure the wind speed on which you base your performance?

A. As a first choice, I would prefer a point 1 rotor diameter upwind of the rotor at hub height.

Q. Do you use an average of the wind velocity cubed?

A. Harold Neustadter: No, at constant rotor speed power is linear with wind speed and averaging is performed on velocity to the first power.

Q. Don't you think that the yaw drive stiffness has been worked to the point that the tower has now been made the critical tuning problem?

A. I would have to agree with your statement insofar as we have tested a flexible, 2P yaw drive, a 2.5P yaw drive and a locked yaw mechanism at 5P in yaw. The locked yaw was the best of the three in terms of rotor loads but I do not feel that additional yaw stiffness will improve matters. We feel that damping may offer the best solution and plan tests for the near future using the yaw brake as a damping device.

Q. What was the magnitude of the actual tower shadow before and after the stairs were taken out of the Mod-0 tower?

A. Tower shadow was never measured on the wind turbine. Wind tunnel test results indicate velocity reductions near 100% for certain conditions with stairs in place. Maximum velocity reductions were reduced to about 40% with the stairs removed.

Q. Would a three bladed rotor help the "yaw" motion problem?

A. Yes, I feel that it would.

Q. Have you made a comparison of power output solely with an upwind anemometer?

A. Yes, these correlations are currently being investigated and will be reported in the near future.

Q. Do you impose a time delay between the anemometer data from the upwind meteorological tower and the power output? Time delay to correspond to transit time of wind and transfer through WECS to produce power.

A. We have seen some improvement in the meteorological tower-vs-nacelle wind speed correlation when the data from the two sites are time-shifted and a correlation calculated. The correlation coefficient increases from .4 to .7. However, this has negligible effect on the 2-minute averaged results.

Q. Rather than comparing instantaneous power output vs. instantaneous point wind data with the results of steady-state theory, shouldn't an effort be used to derive a dynamic system transfer function from data measured over time?

A. I think a system of the type you describe will develop as wind energy develops further. There are some shortcomings with the technique we have developed at Lewis but it appears to be satisfactory for our purposes at this point in time.

TABLE 1. - COMPARISON OF BLADE LOADS WITH AND WITHOUT STAIRWAY FOR STEADY STATE OPERATION

CONFIGURATION	BLADE BENDING MOMENT AT STA 40 (FT-LBS)	
	FLAPWISE PEAK TO PEAK	INPLANE PEAK TO PEAK
WITH STAIRS	130,000	108,000
WITHOUT STAIRS	70,000	103,000
DESIGN	58,000	75,000

TABLE 2. - MOD-0 WIND TURBINE NACELLE YAWING RESONANT FREQUENCIES

SINGLE YAW DRIVE	1.2 - 1.4 Hz	2P
DUAL YAW DRIVE	1.7 Hz	2.5P
LOCKED YAW (PREDOMINANT LATERAL MOTION)	2.2 Hz	3.3P
LOCKED YAW (TORSION)	3.4 Hz	5.1P

Figure 1. - Mod-0 100-kW wind turbine.

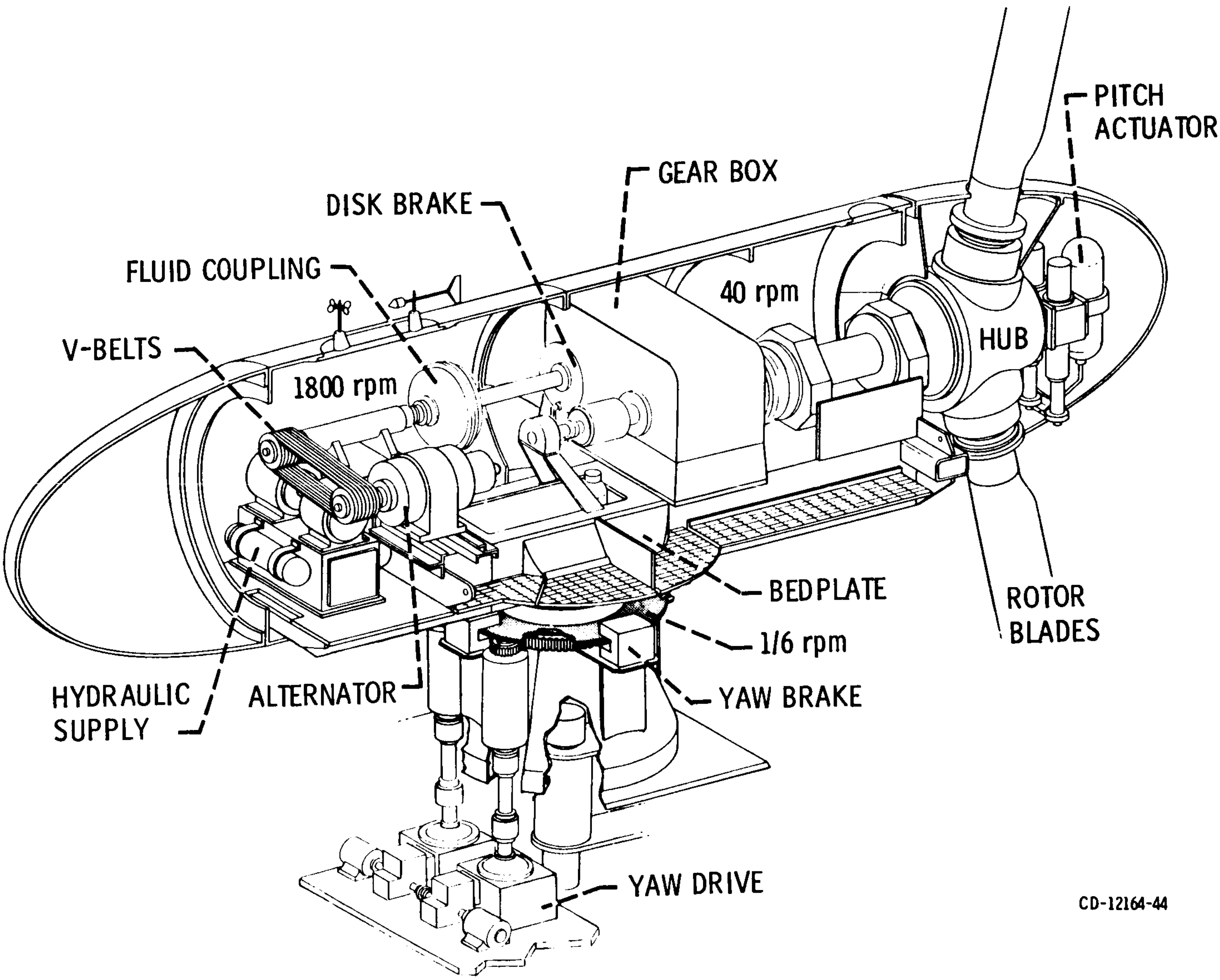


Figure 2. - Cutaway drawing of Mod-0 wind turbine nacelle interior.

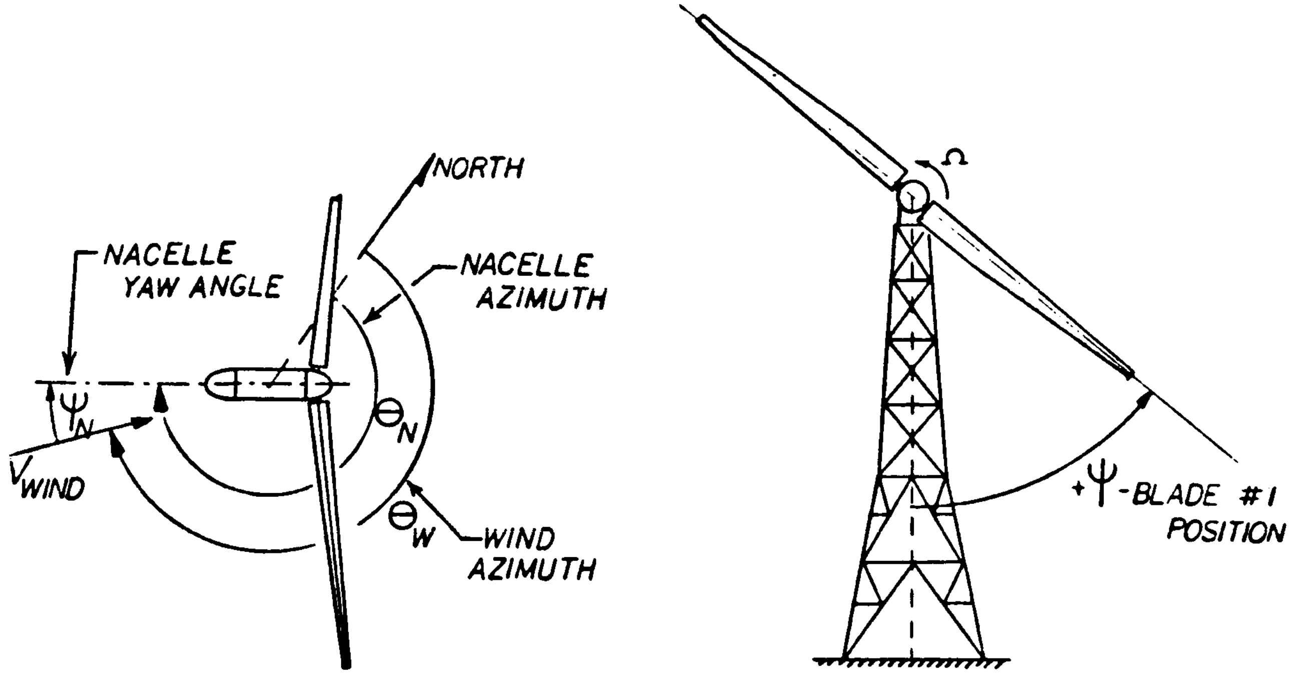


Figure 3. - Instrumentation sign convention.

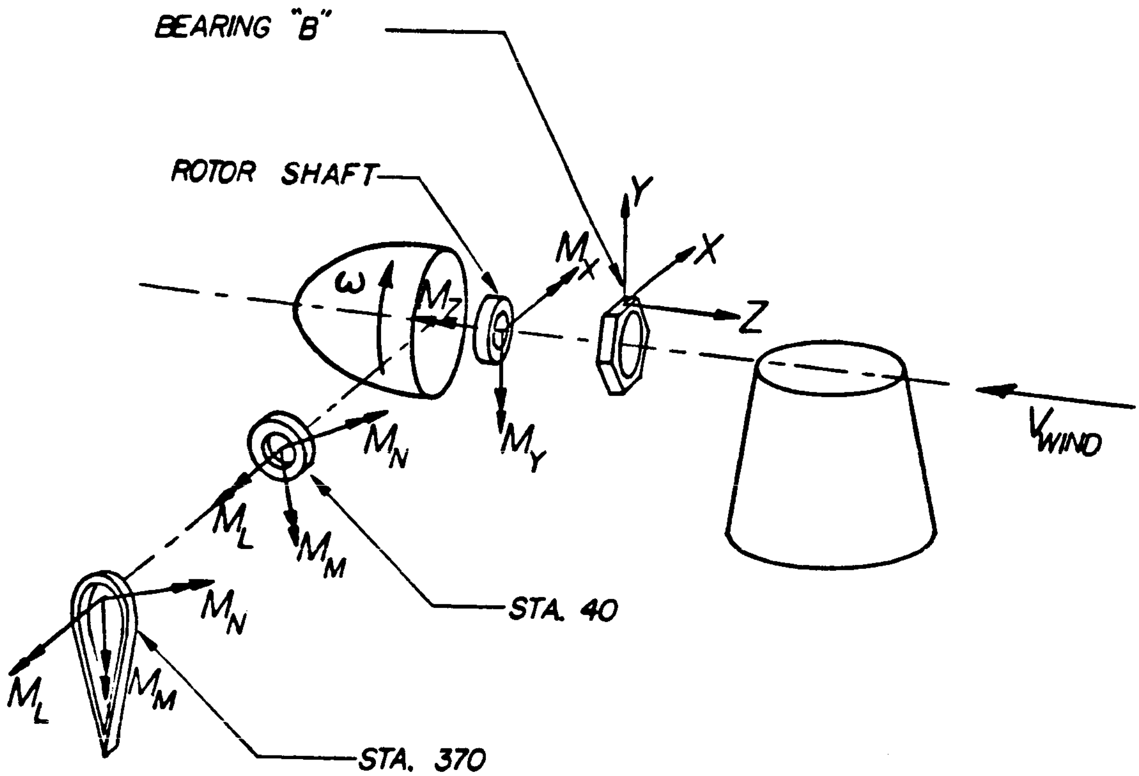


Figure 4. - Instrumentation sign convention.

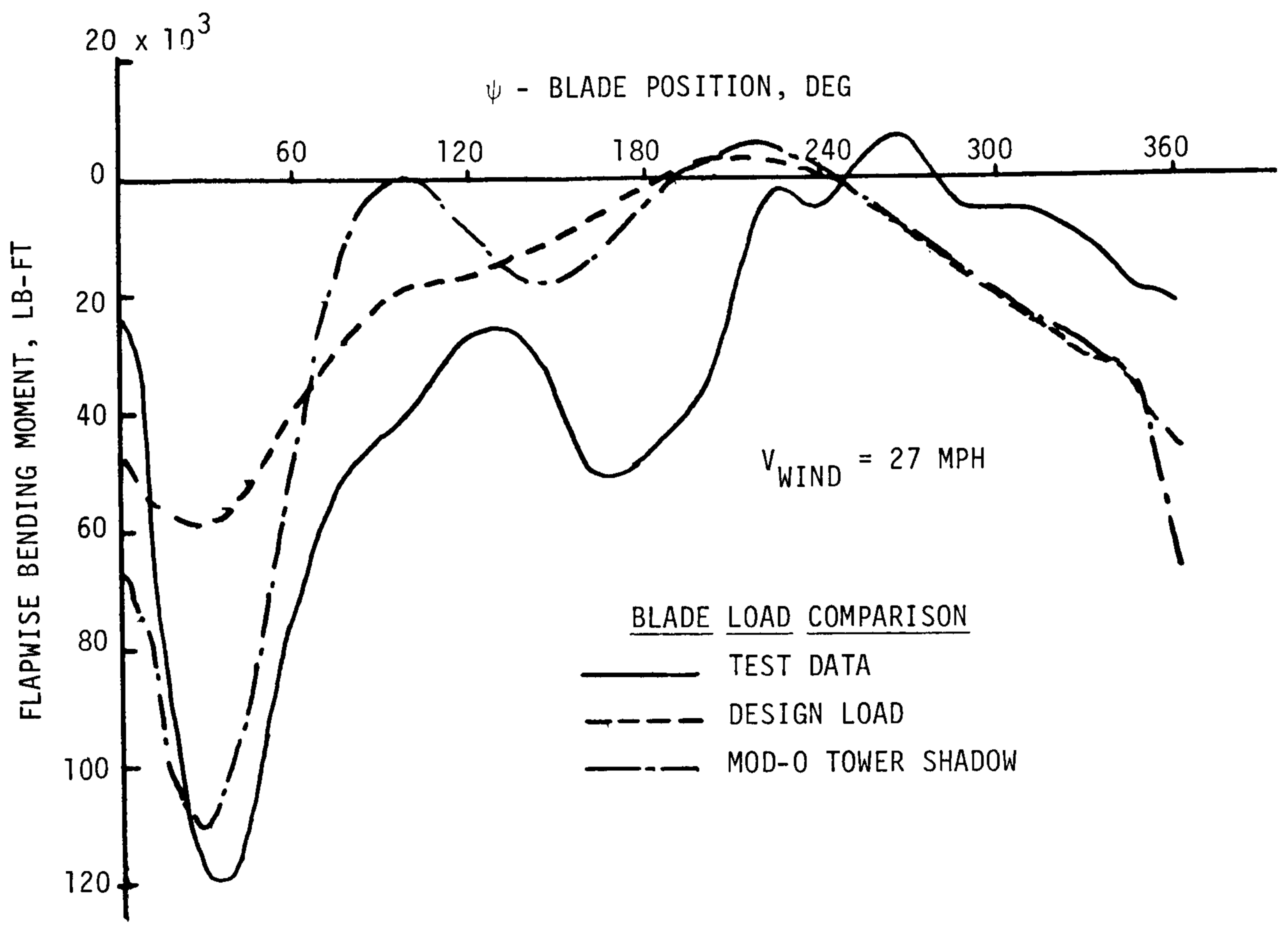


Figure 5. - Blade root flapwise bending with stairs - 40-rpm operation.

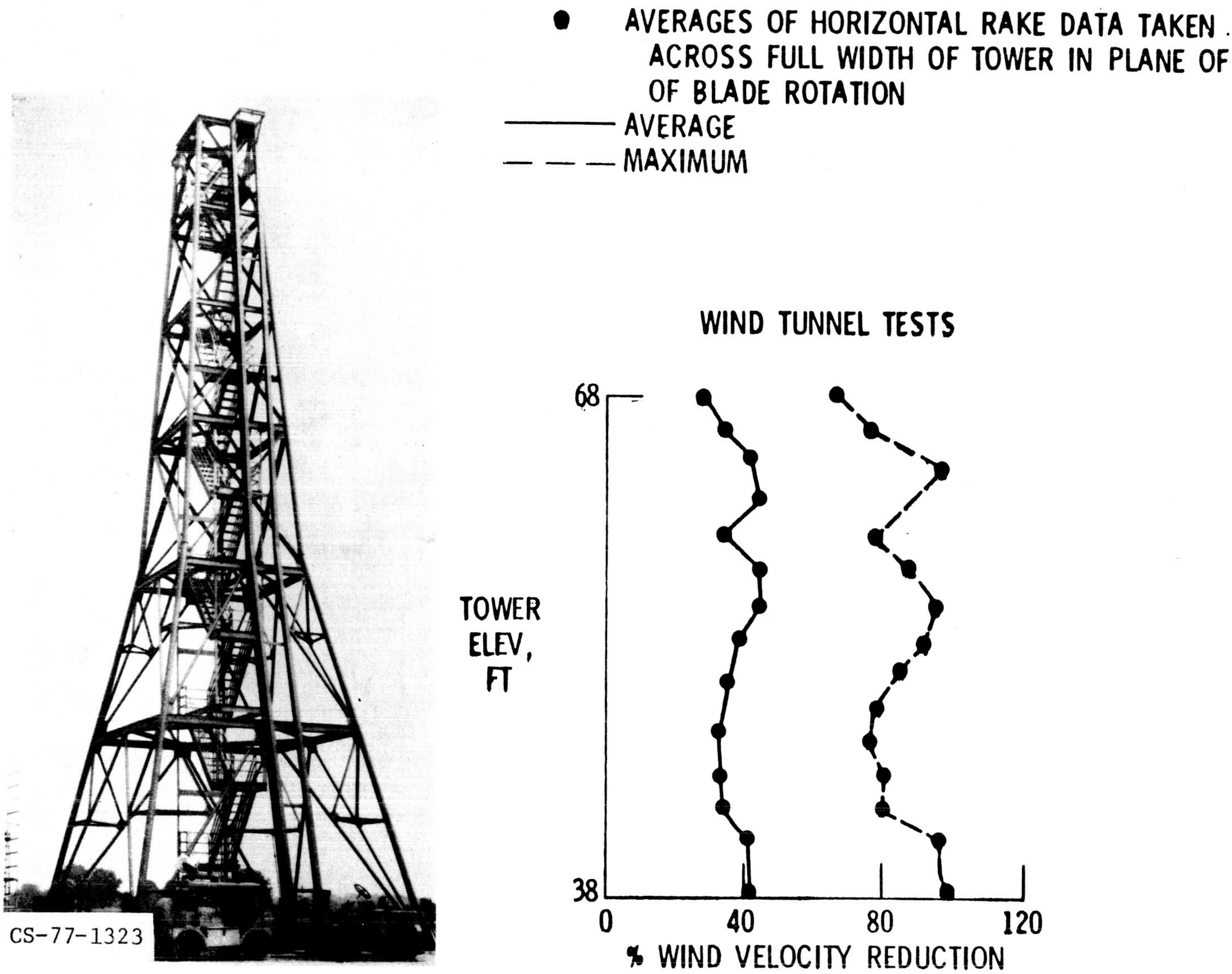


Figure 6. - Mod-0 tower wind velocity reduction - with stairs and rails.

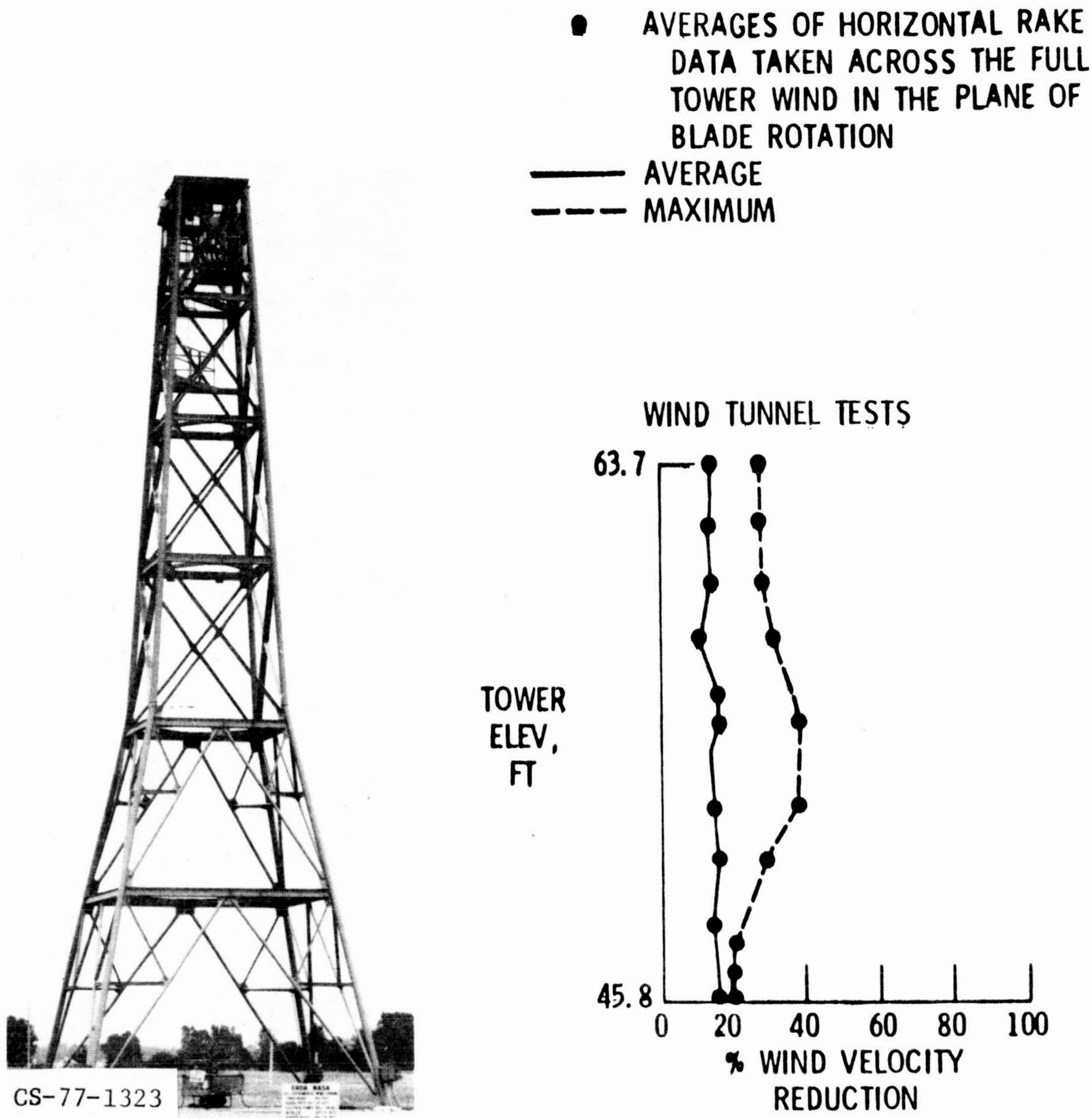
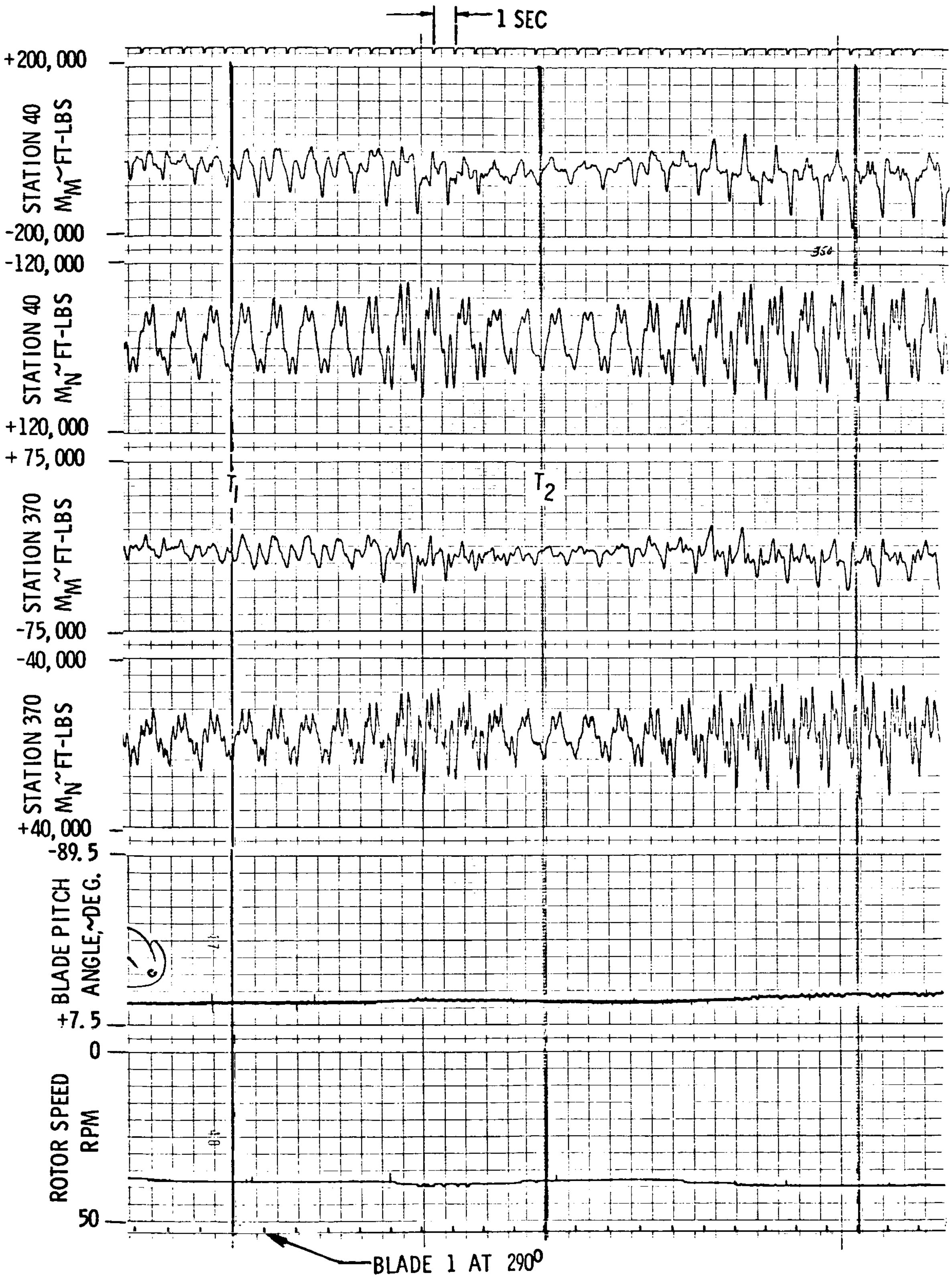
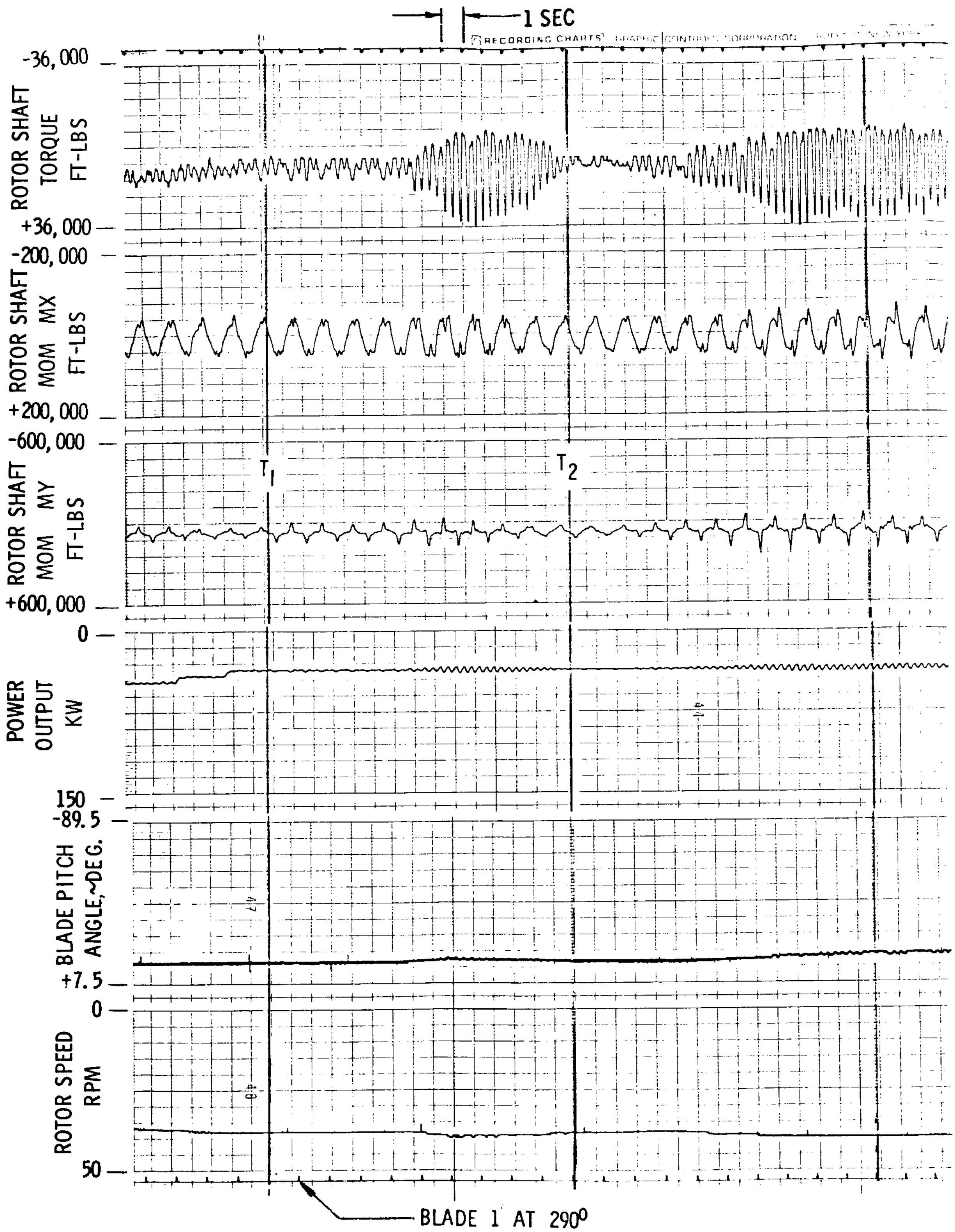


Figure 7. - Mod-0 tower wind velocity reduction with stairs and rails removed.



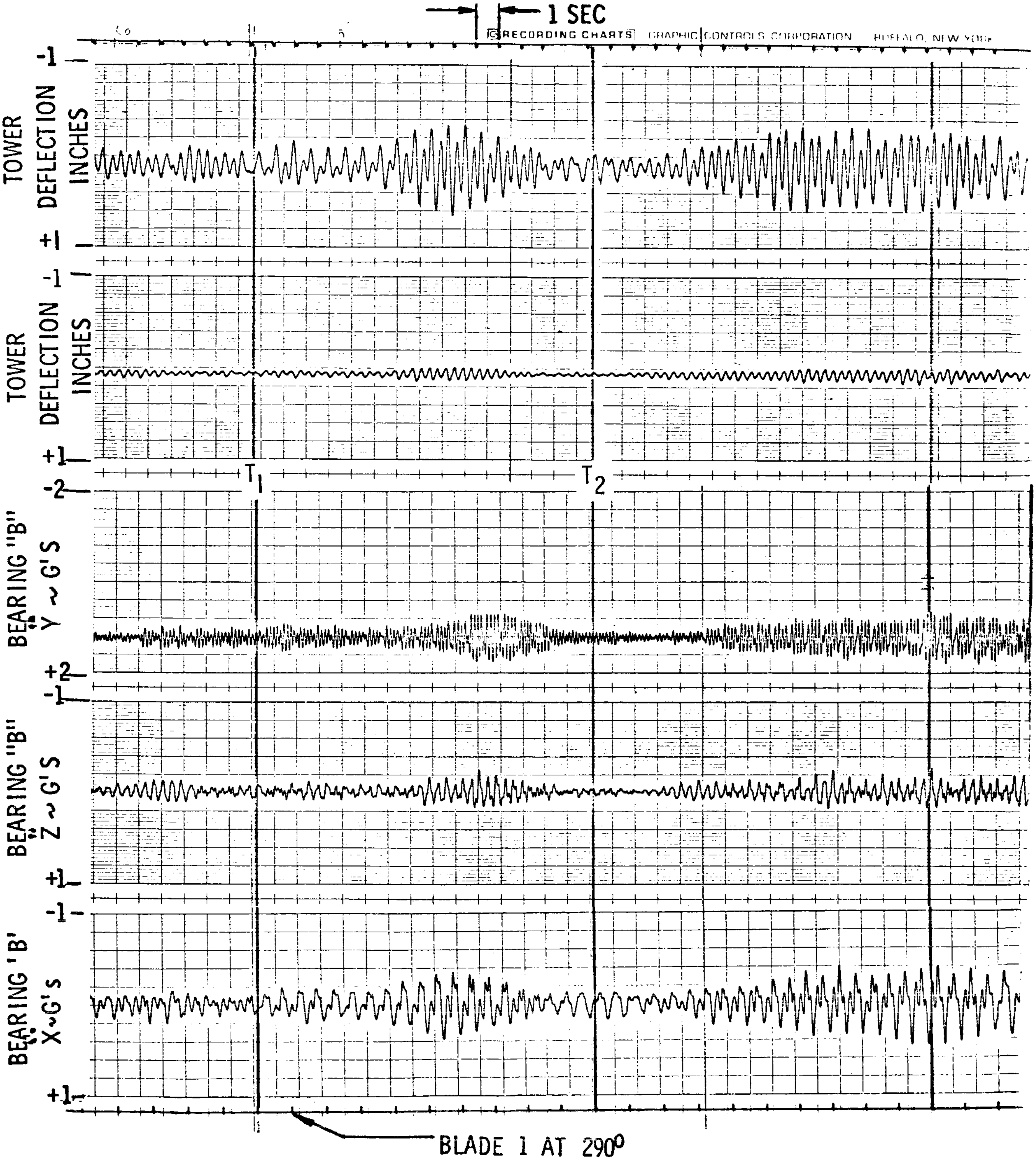
(a)

Figure 8. - Gust response with shaft oscillation.



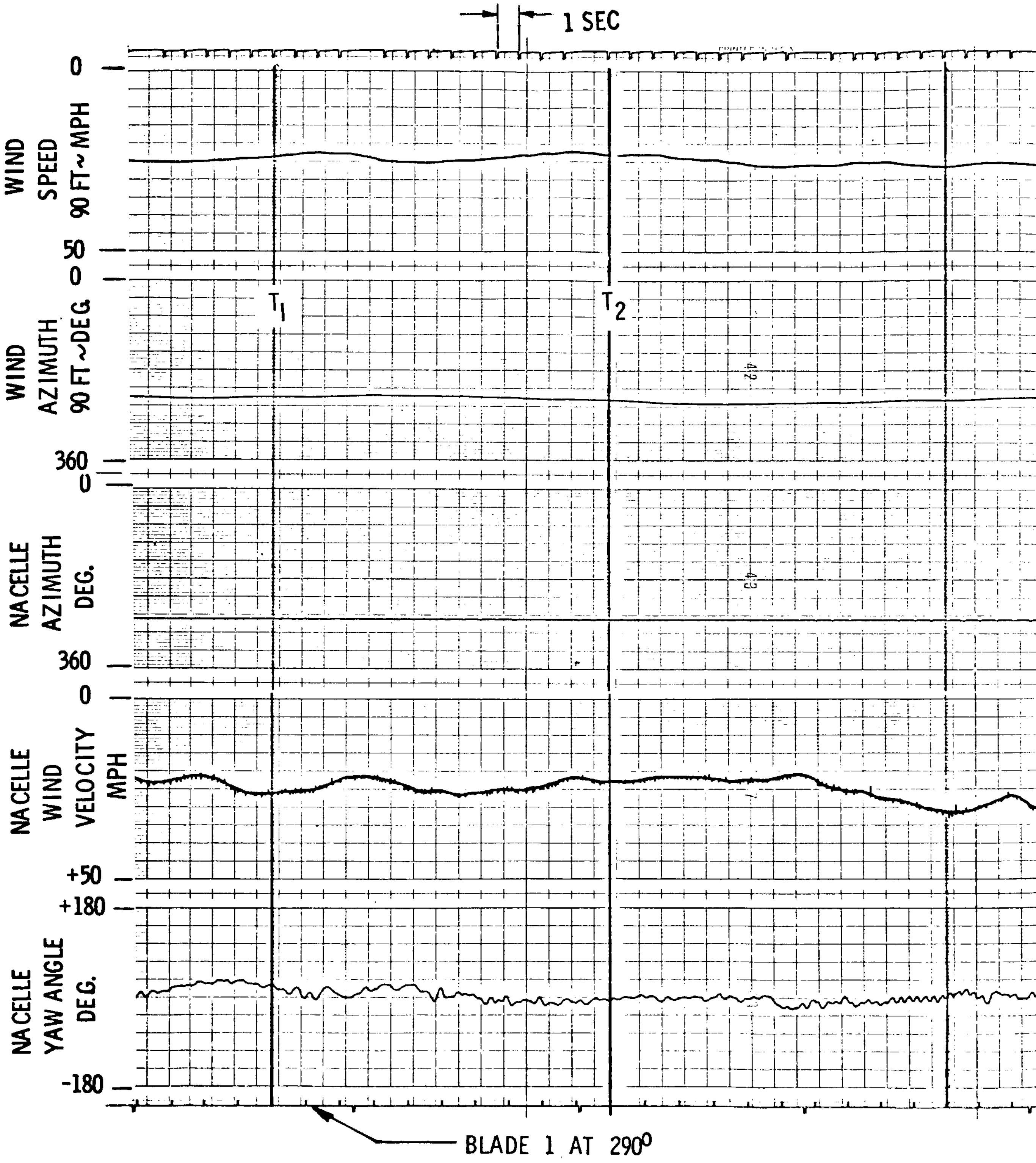
(b)

Figure 8. - Continued.



(c)

Figure 8. - Continued.



(d)

Figure 8. - Concluded.

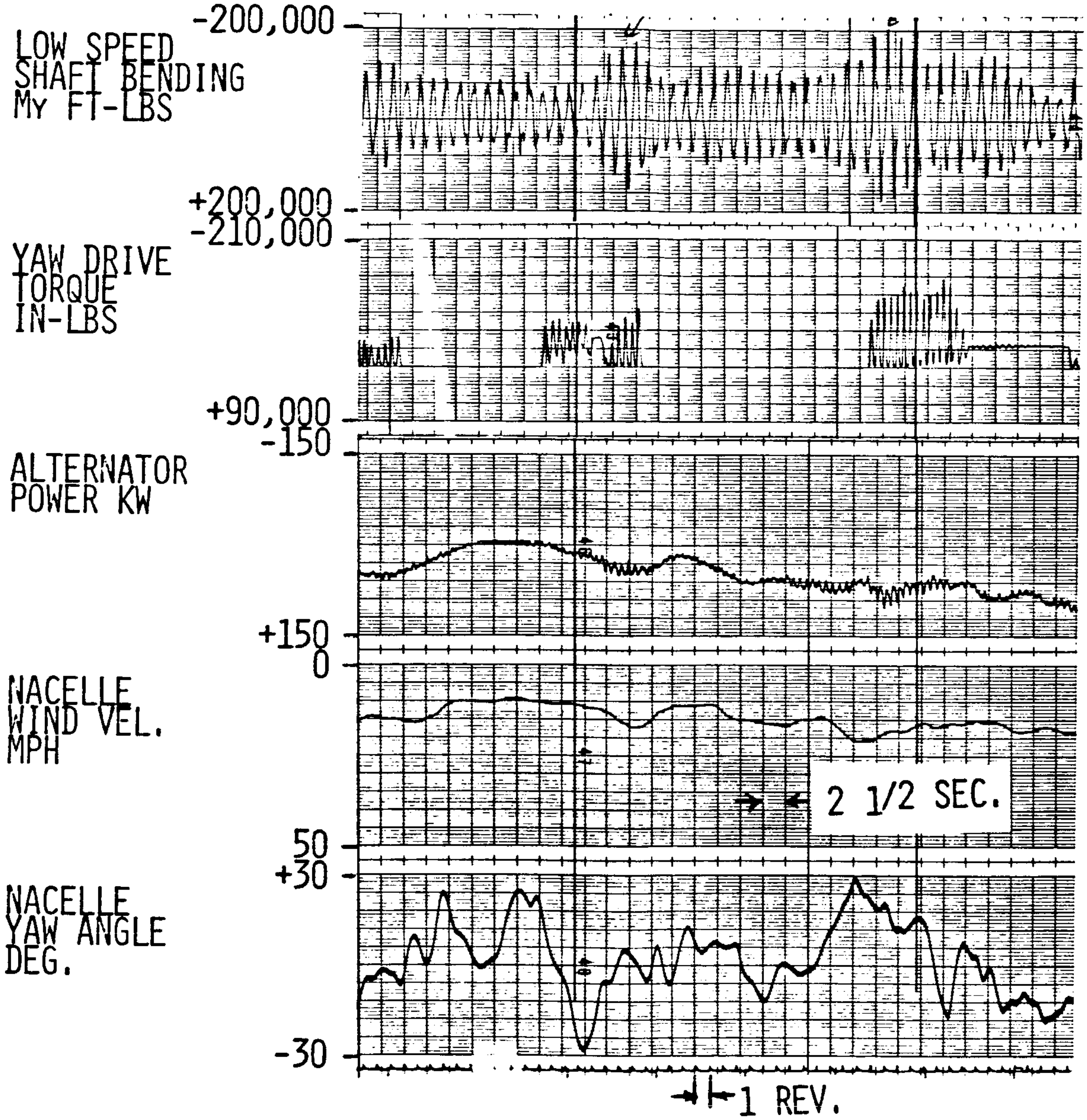
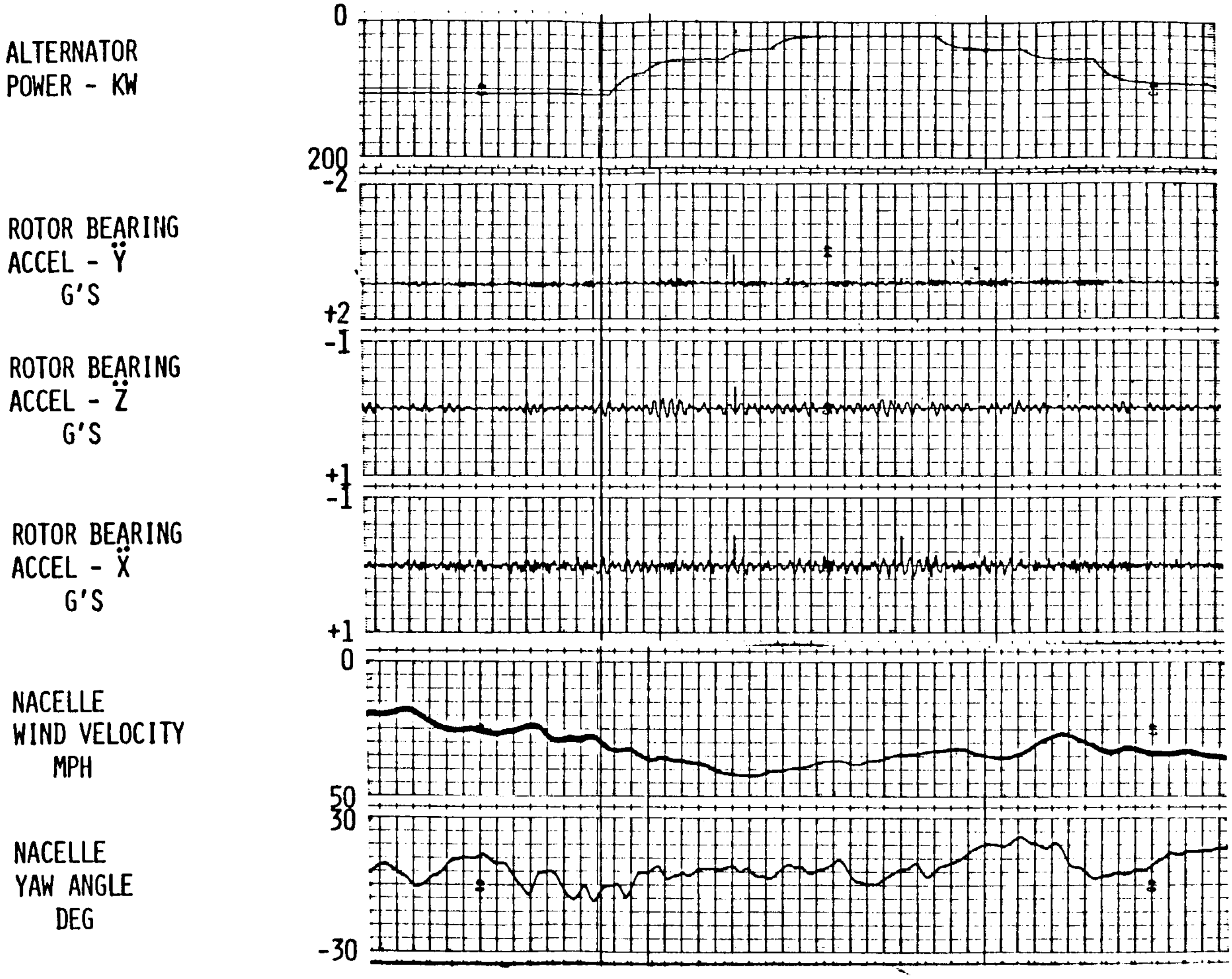
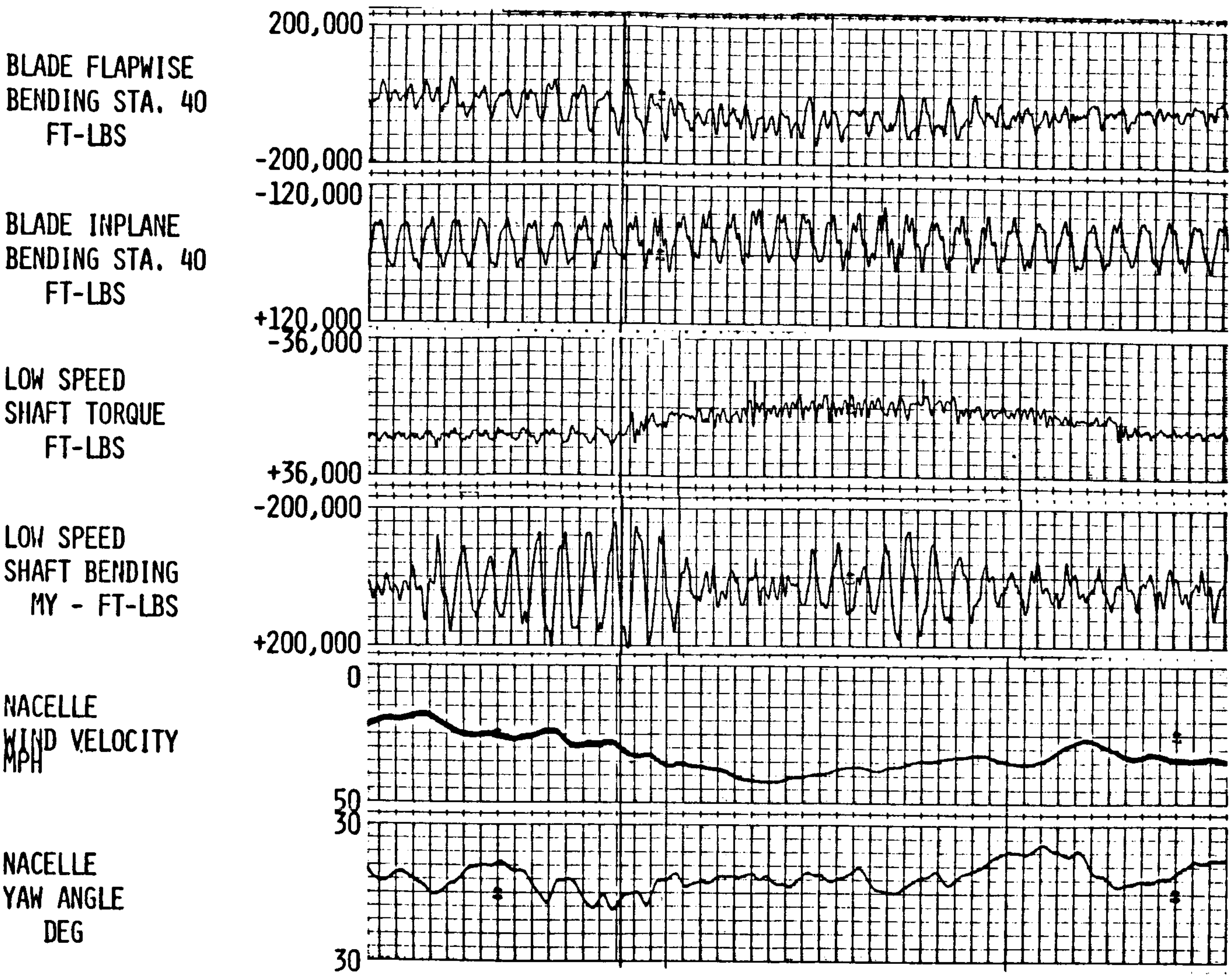


Figure 9. - Low-speed shaft bending with yaw brake release.



(a)

Figure 10. - 40-rpm Load bank operation with yaw brake.



(b)

Figure 10. - Concluded.

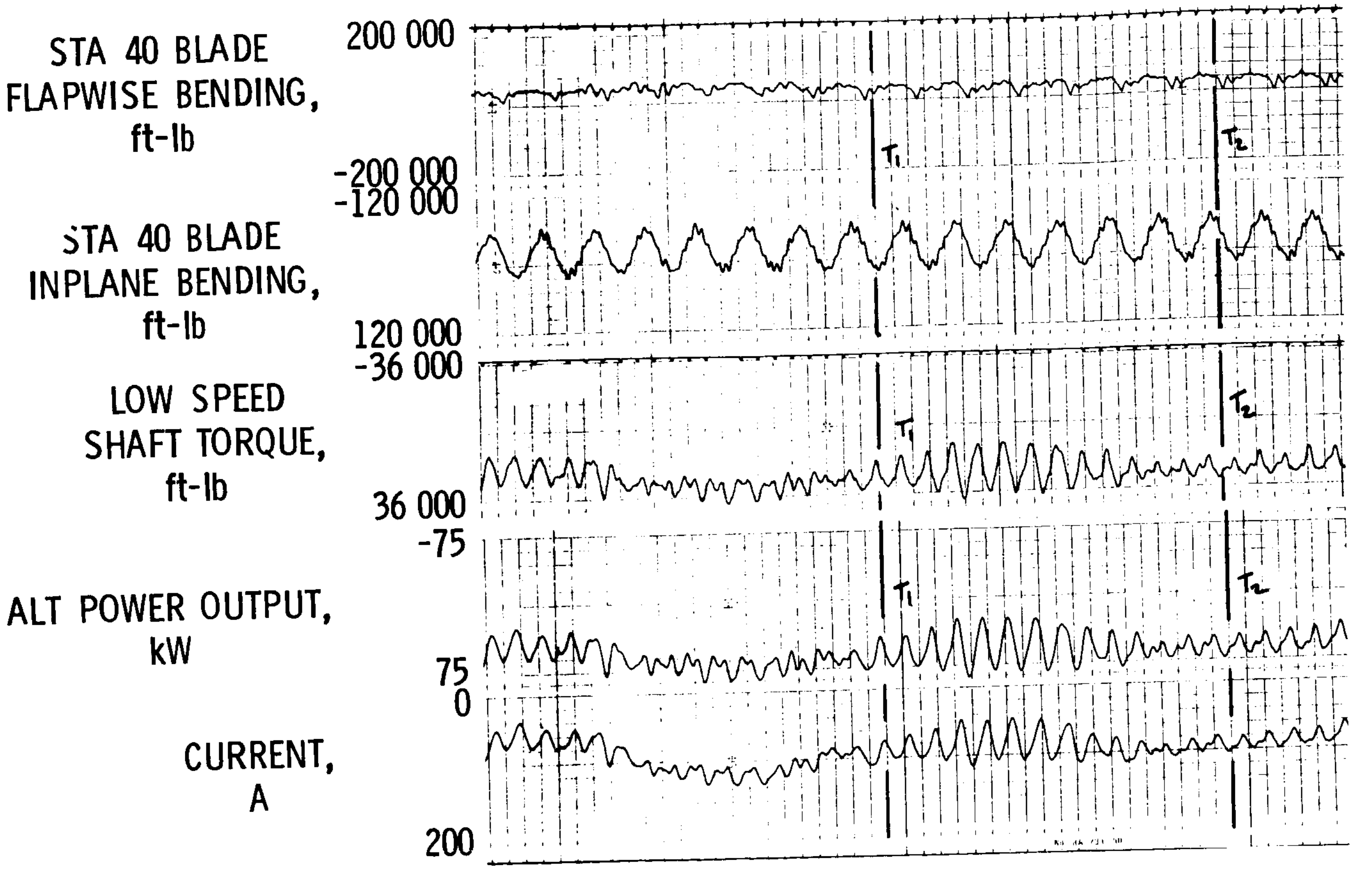


Figure 11. - 20-rpm Synchronous operation - 60-kW set point.

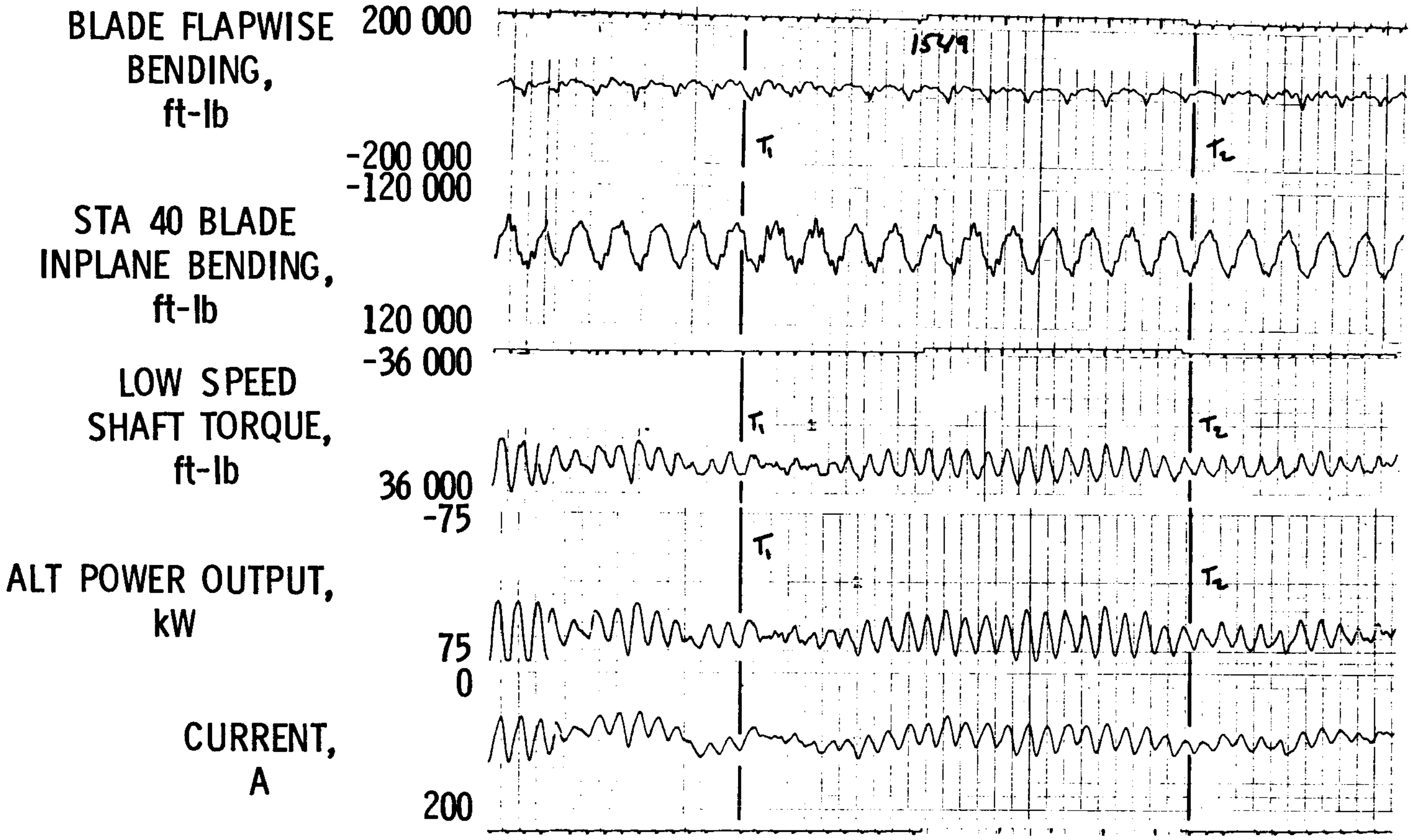


Figure 12. - 26.3-rpm Synchronous operation - 60-kW set point.

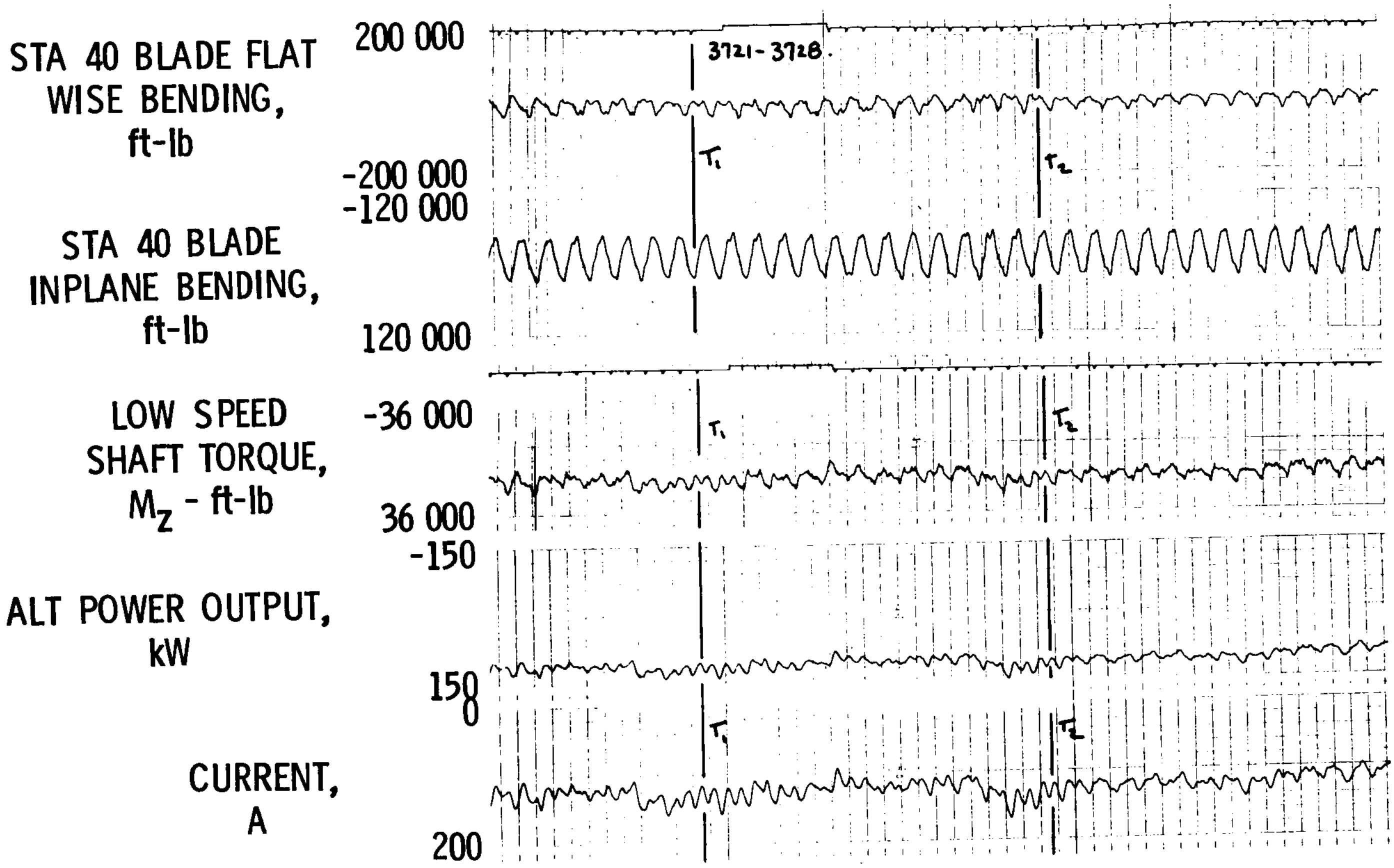


Figure 13. - 40-rpm Synchronous operation - 100-kW set point.

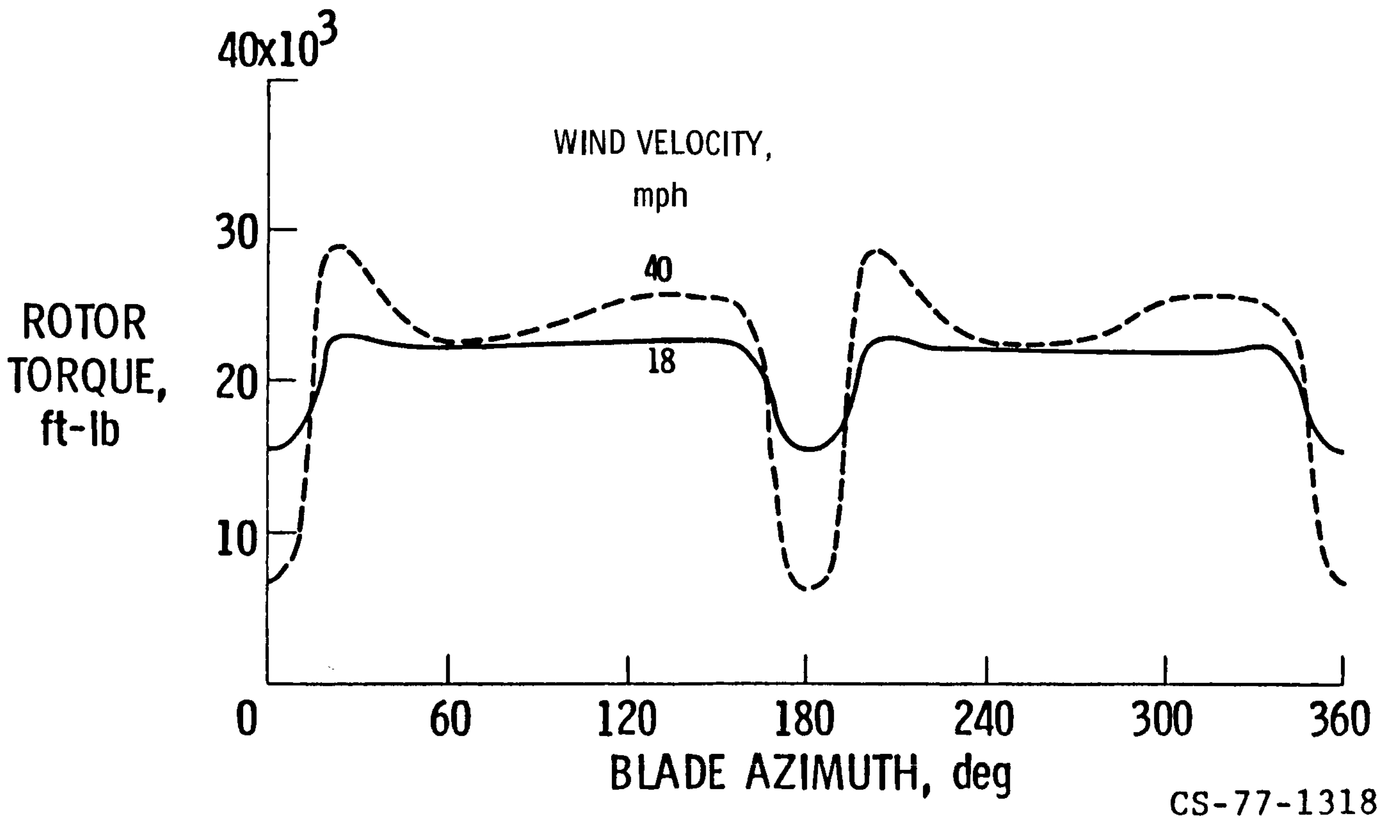


Figure 14. - Mod-0 rotor torque versus blade azimuth at 40 rpm.

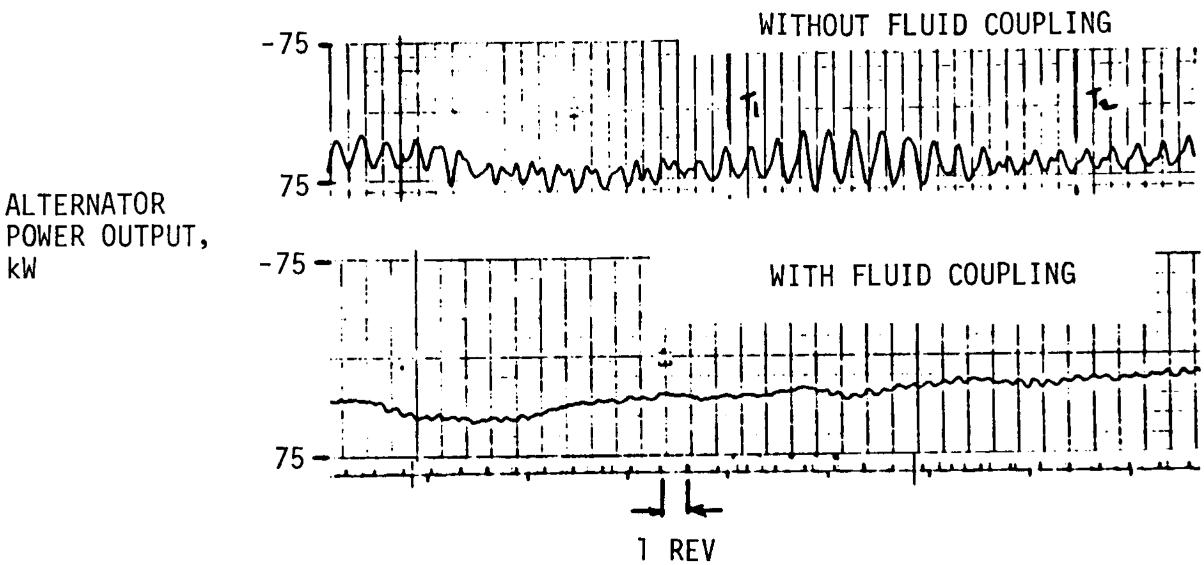


Figure 15. - Power oscillations with and without fluid coupling at 20 rpm.

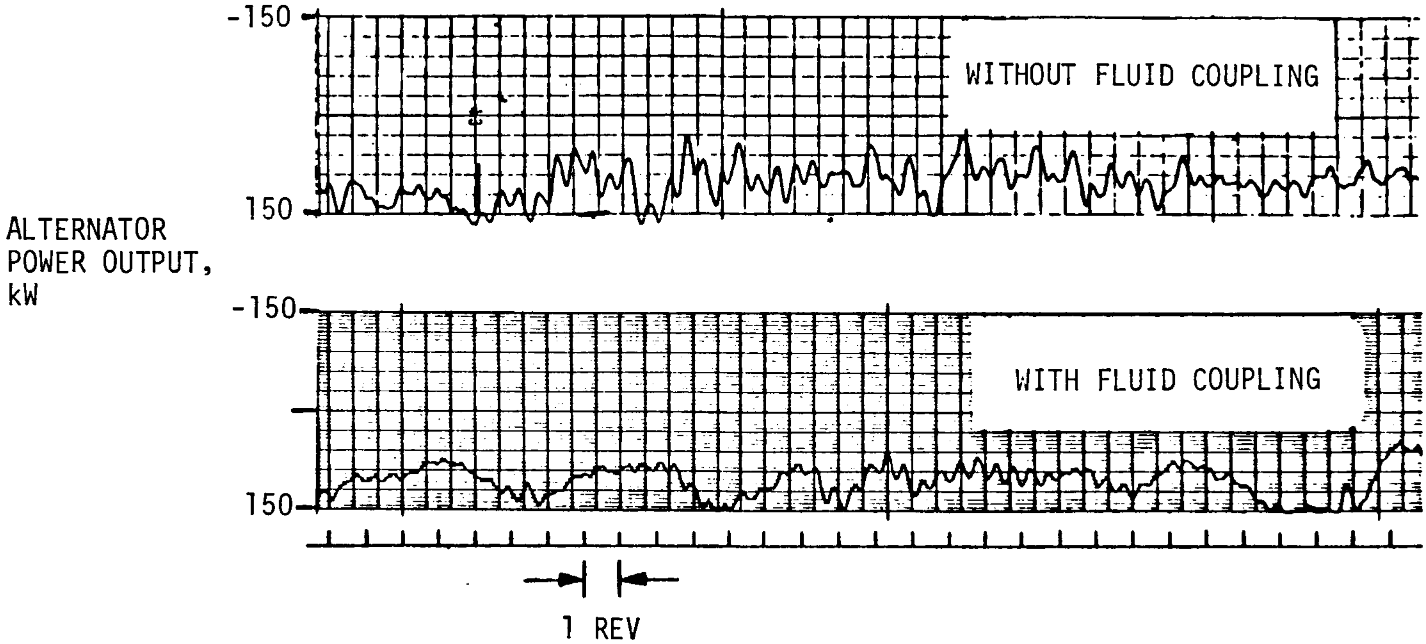


Figure 16. - Power oscillations with and without fluid coupling at 40 rpm.

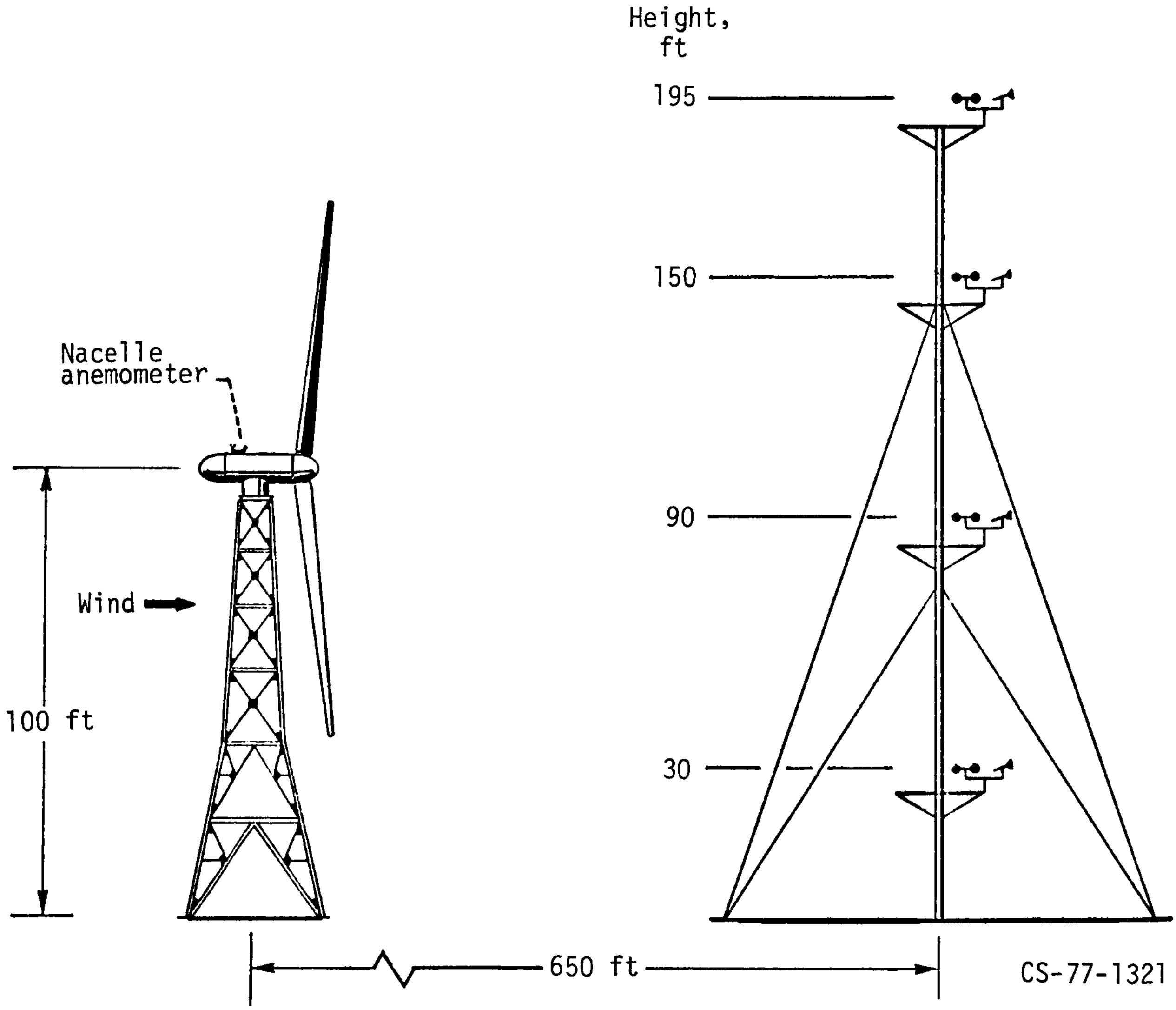


Figure 17. - Mod-O wind turbine and meteorological tower.

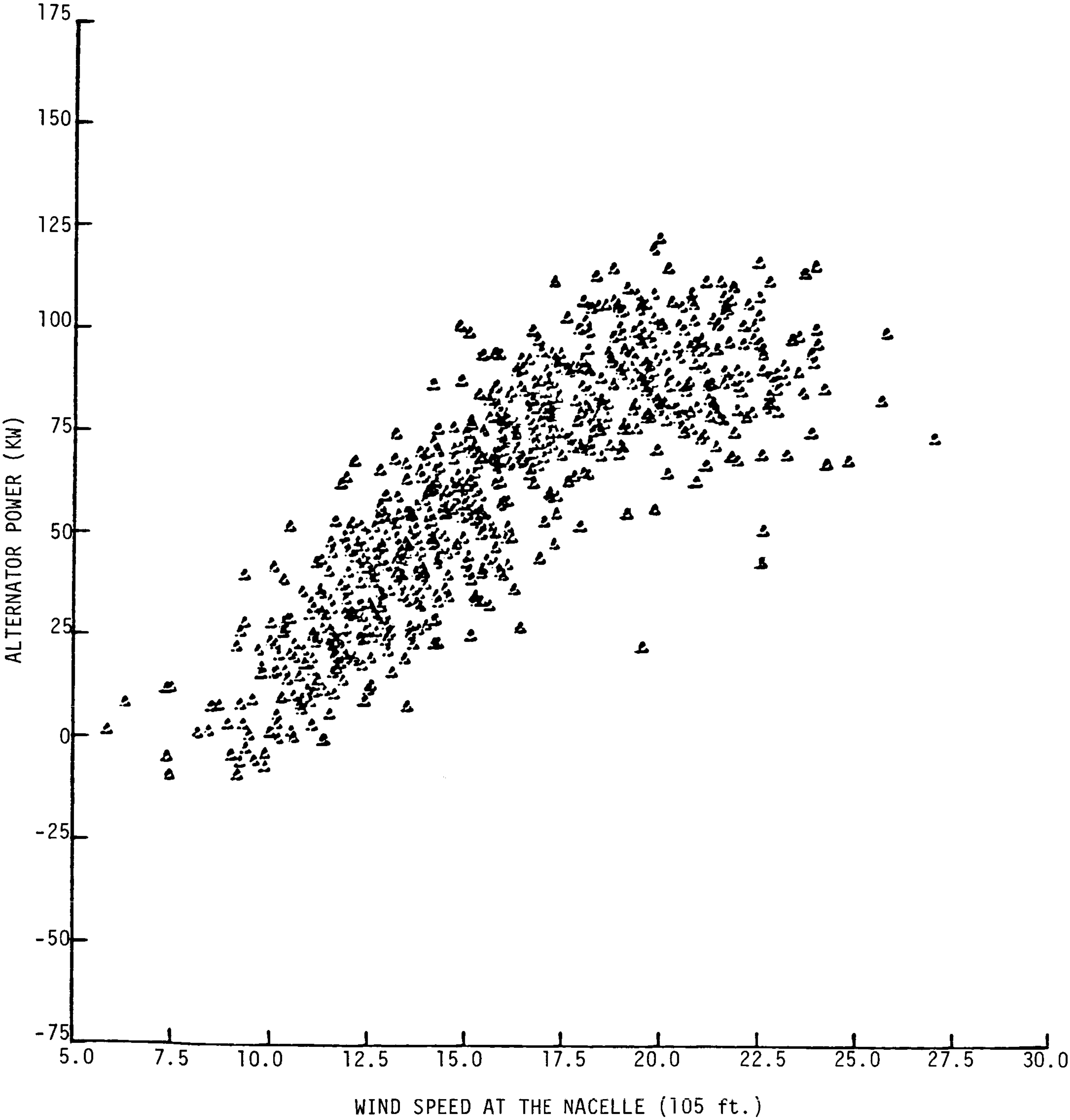


Figure 18. - Alternator power output versus nacelle wind speed - simultaneous measurements.

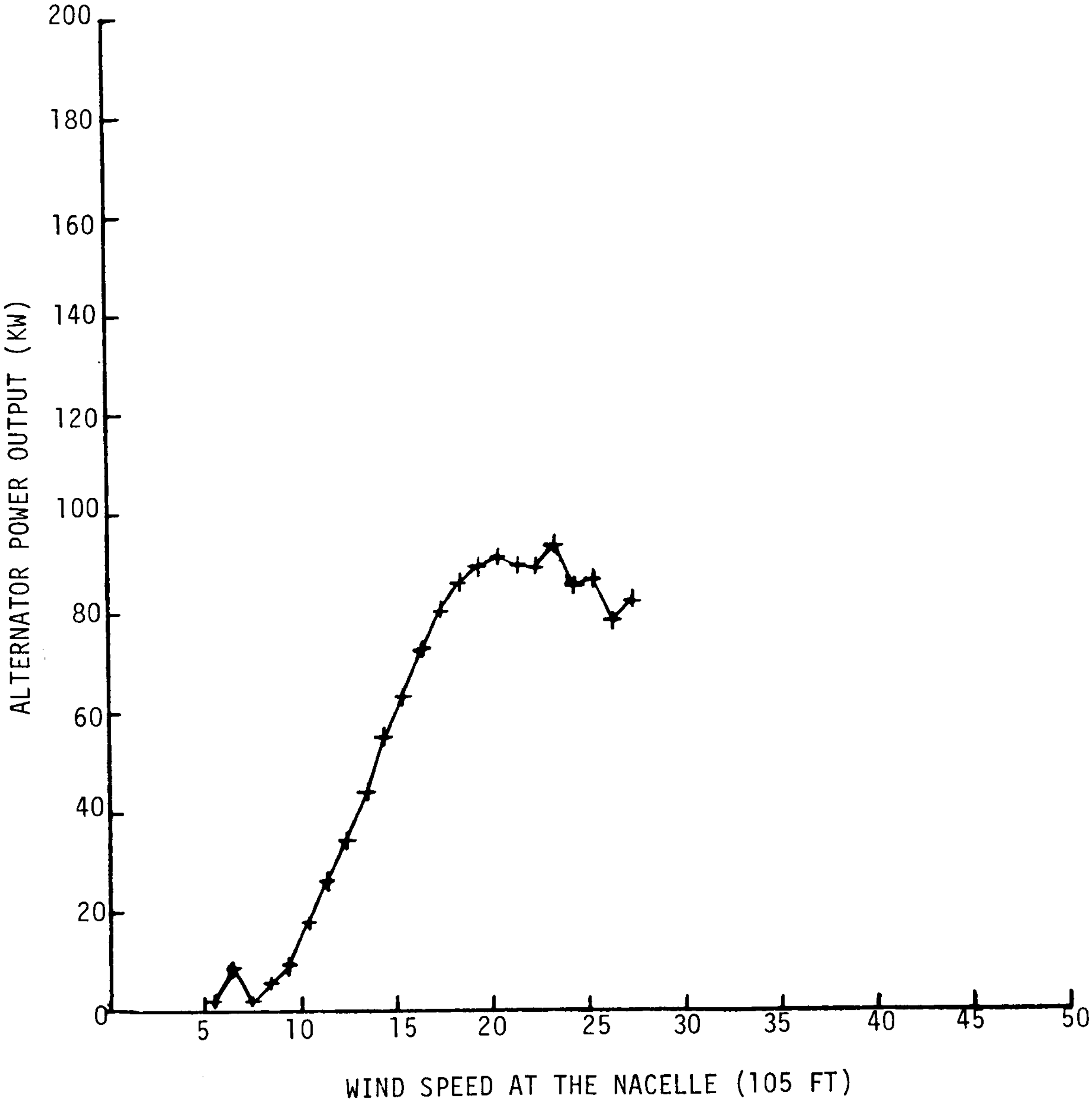


Figure 19. - Region-averaged alternator power output versus nacelle wind speed.

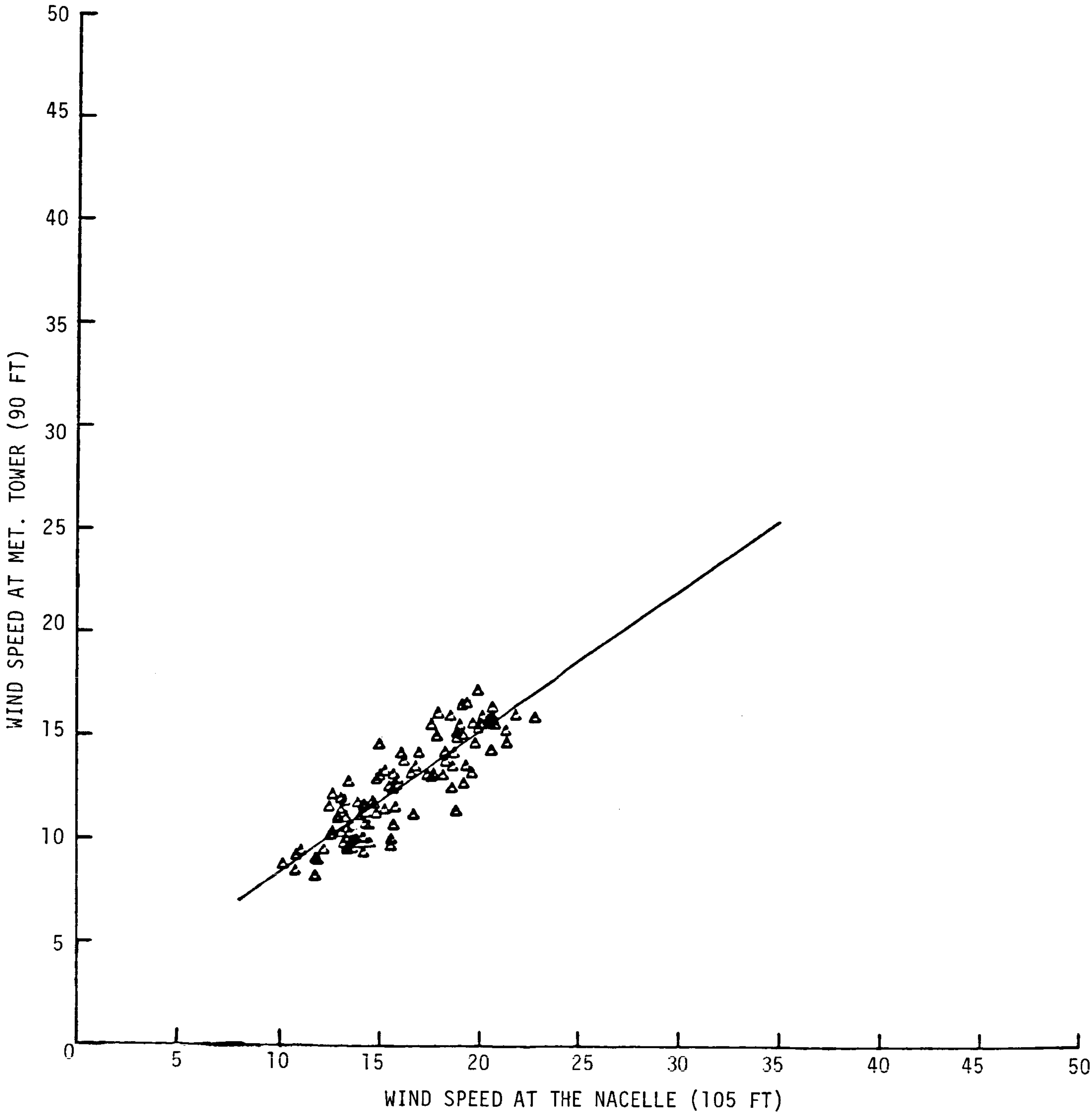


Figure 20. - Meteorological tower wind speed versus nacelle wind speed - 2-minute averages.

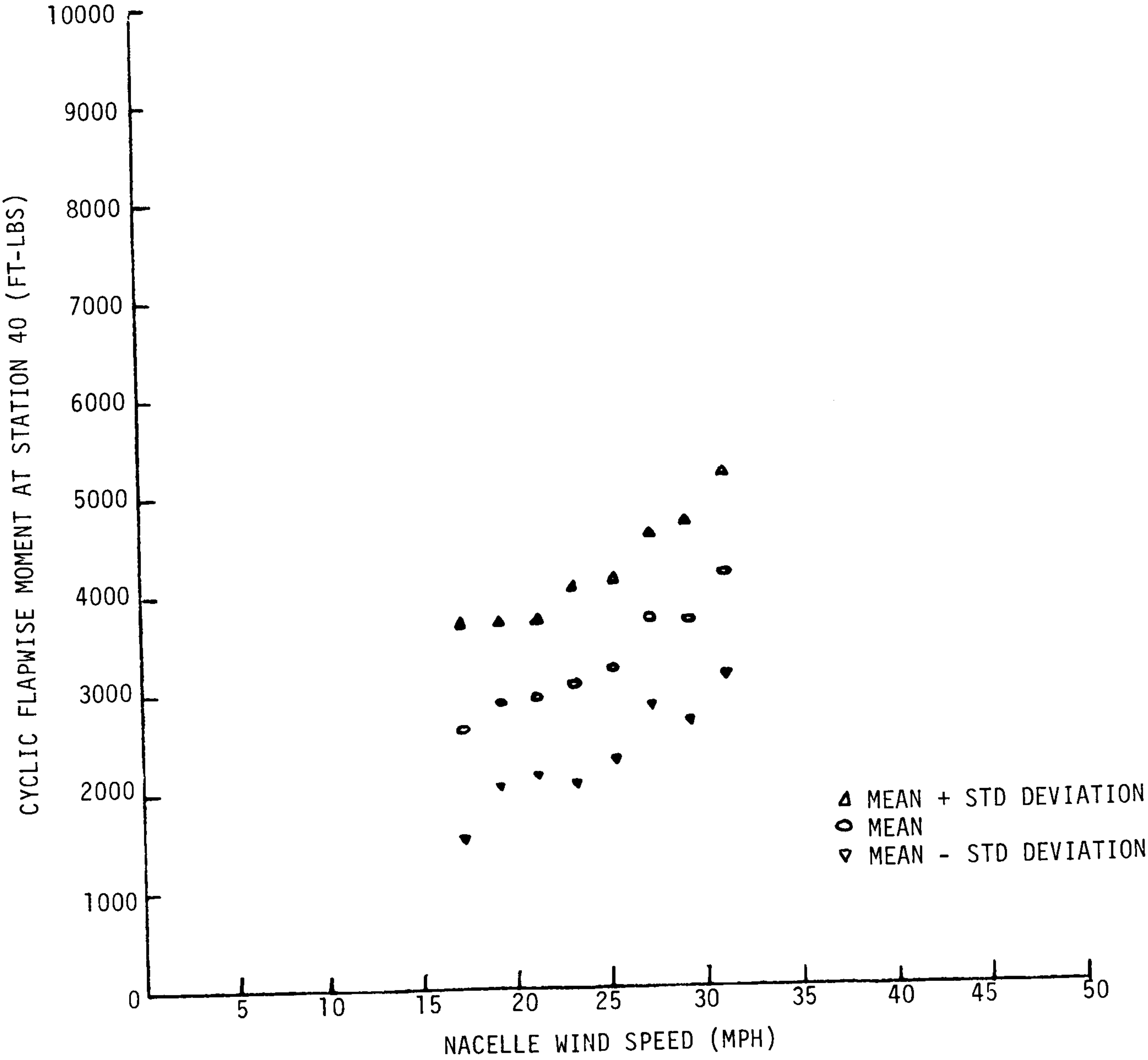


Figure 21. - Mod-0 cyclic loads versus nacelle wind speed - flatwise moment, station 40.