

COMPARISON OF COMPUTER CODES FOR CALCULATING DYNAMIC LOADS IN WIND TURBINES

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INTRODUCTION

The development of computer codes for calculating dynamic loads in horizontal-axis wind turbines has been part of the Federal Wind Energy Program for almost four years.

During this period of time the Energy Research and Development Administration (ERDA) has sponsored the development of at least seven codes by NASA and its contractors. As might be expected in an area of new technology, these codes differ considerably in approach and technique. Because of the generally complicated nature of any structural dynamics analysis, a detailed comparison of seven computer codes is extremely difficult. Therefore, the objectives of this study have been limited to the following: (1) To present a brief overview of each code and identify sources for further detailed information, and (2) to compare the performance of each code against two sets of test data measured on the 100 kW Mod-0 wind turbine, an experimental machine in operation at NASA's Plum Brook Station near Sandusky, Ohio. Comparison on the basis of cyclic loads, peak loads, and harmonic contents was selected. The results of this study are given in detail in Reference 1.

DESCRIPTION OF CODES

The seven computer codes compared in this study are listed in Table 1. All codes are aeroelastic (i.e., air loads and blade deformations are coupled) and include loads which are gravitational, inertial, and aerodynamic in origin. Three of the codes (MOSTAB-WT, -WTE, and -HFW) analyze only rotor loads, while the remaining four codes (REXOR-WT, GETSS, F-762, and MOSTAS) are complete system codes which include rotor-tower interaction.

MOD-0 DATA CASES

For purposes of establishing reference test data, two sets of blade load data have been defined, which were measured on the Mod-0 wind turbine (Ref. 1). These data sets have been designated as Mod-0 Data Cases I and IV. The data sets contain time histories and harmonic analyses of bending moment loads measured in the Mod-0 blades by means of strain-gage load cells. Moment loads in the flatwise and edgewise directions at Station 40 (shank area, 5% span) and Station 370 (midblade area, 49% span) were measured. Additional data are also available for these two cases, including shaft bending and torque loads, nacelle accelerations, and tower deflections. However, for purposes of

comparing computer codes, blade moment loads were judged to be critical, so other measured data were not used in this study.

Operating Conditions

Data Case I, with single yaw drive and stairs in the tower, presents a high level of rotor-tower interaction. These data were measured on December 18, 1975. On the other hand, Data Case IV with the yaw drive locked (relatively rigid nacelle-to-tower connection) were measured on September 11, 1976, after the tower stairs were removed and therefore exhibit little rotor-tower interaction. Thus, these two cases represent relatively high and low levels of blade loading sustained by the Mod-0 wind turbine operating at nominal wind speeds between 25 and 28 mph.

Typical Time-History Curves

A typical cycle of flatwise bending load during one rotor revolution is shown in Figure 1. A positive flatwise moment bends the blade toward the tower causing tensile stresses on the low-pressure (downwind) surface. In Figure 1, flatwise moment M_y is plotted versus the blade azimuth ψ_b , which is zero and 360° when the blade points downward. As shown in the figure, the flatwise time history for a rotor located downwind of the tower is dominated by the impulse applied to the blade each time it passes through the tower's wake or "shadow." For purposes of stress and fatigue analysis it is convenient to define cyclic load δM and steady load \bar{M} , as shown in Figure 1.

Figure 2 illustrates a typical time history of edgewise load, M_z , measured during one revolution. A positive edgewise load on the blade tends to stop the rotor, causing tensile stresses on the blade's leading edge. An edgewise moment time history is usually composed of three components, as shown in Figure 2: (1) A relatively steady bending moment which produces shaft torque and power, (2) a sinusoidal moment caused by the blade's own weight plus a small wind shear effect (90° out of phase) and (3) high frequency dynamic loads attributable to motions of the nacelle and tower.

RESULTS AND DISCUSSION

Cyclic Moment Load Comparisons

Figures 3(a) and (b) illustrate how cyclic moments calculated using the seven codes compare not only with the specific data cases defined but also with the trend of data measured over a period of time on the Mod-0 wind turbine. This trend is represented by a nominal variation of load with wind speed plus a band of variation which is estimated to be $\pm 1\sigma$ in width, thereby containing loads for about 70% of the machine's revolutions. This band is approximately equal to $\pm 20\%$ of the nominal loads with the exception of Case IV edgewise loads. Variations are caused by changes in wind direction and velocity, control changes, and unsteady factors not yet identified.

The empirical constants used in the MOSTAB-WTE code were selected to place its results at the top of the variation band, as shown in Figures 3(a) and (b).

Data Cases I and IV do not necessarily represent the nominal loads. Other general observations concerning the results shown in Figures 3 are as follows:

1. Loads calculated by all codes fall within the data variation band, with the exception of edgewise loads for Case I which were calculated using the MOSTAB-WT and MOSTAB-HFW codes. MOSTAB codes are able to predict only the gravity component of cyclic edgewise load because shaft motion is absent in these codes.
2. REXOR-WT results generally coincide with nominal loads.
3. Results for the remaining codes tend to be mixed, falling both above and below nominal load values.

Table 2 presents data for a more complete comparison of measured and calculated cyclic loads.

Peak Moment Load Comparisons

A second comparison of calculated and measured moment loads will be made on the basis of their peak values, defined as the maximum absolute value occurring during one revolution. Measured and calculated peak moment loads are listed in Table 3. Inspection of the normalized results shows a wide range of values, from 0.57 to 1.30. With the exception of the empirical code MOSTAB-WTE, all the codes exhibit load ratios both larger and smaller than unity, without any significant trends being apparent.

Summary of Load Ratios

All the load ratios listed in Tables 2 and 3 for cyclic and peak loads, respectively, were averaged and appear in Table 4. These average ratios signify the general level of loading calculated using the various codes in comparison with a blend of high and low nominal loads. MOSTAB-WTE, with its empirical constants selected to place calculated loads well above nominal, was found to have an average load ratio of 1.15, slightly lower than expected. Of the remaining codes, all produced average load ratios within $97\% \pm 3\%$ of nominal. Load ratios obtained with the REXOR-WT code showed significantly less deviation than ratios for all the other codes.

Load Predictions

The MOSTAB-WTE and REXOR-WT were used to predict the effect on blade loads of a new dual yaw drive system for the Mod-0 wind turbine (Ref. 2). The results are shown in Figures 4(a) and (b). The MOSTAB-WTE code provided an estimate of nominal + 1 σ cyclic flatwise moment (Fig. 4(a)) in good agreement with data obtained later. Prediction of edgewise loading using MOSTAB-WTE (Fig. 4(b)) appears to be somewhat conservative, at least in comparison with load bank data. Additional synchronized operation data are required before the level of conservatism can be judged.

SUMMARY OF RESULTS

1. Six of the seven codes studied (MOSTAB-WT and -HFW, MOSTAS, REXOR-WT, GETSS, and F-762) calculated loads which on the average were within 4% of nominal loads measured on the Mod-0 wind turbine.
2. Loads calculated using an empirical code (MOSTAB-WTE) were 18% above nominal levels, in accordance with the objective of this code to provide load margin.
3. Among the four system codes evaluated (MOSTAS, REXOR-WT, GETSS, and F-762), the REXOR-WT code appeared to be the most consistent in producing calculated loads close to nominal loads.
4. All codes except MOSTAB-WT and -HFW satisfactorily calculated the general pattern of both flatwise and edgewise loads for the two cases studied. These two codes contain the assumption of rigid rotor support which eliminates some edgewise load harmonics.
5. The empirical code MOSTAB-WTE was verified on the basis of comparisons with the results of the system codes and test data obtained from the Mod-0 wind turbine with dual yaw drive.

CONCLUSIONS

1. WTG load prediction codes are in an advanced state of development.
2. Present system codes tend to predict nominal loads, so load margins must be explicitly introduced into input or output data.
3. System codes have been validated for "stiff" WTG systems, but are not yet validated for "flexible" systems.

REFERENCES

1. Spera, D. A.: Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines. NASA TM (to be published).
2. Spera, D. A.; Janetzke, D. C.; and Richards, T. R.: Dynamic Blade Loading in the ERDA-NASA 100 kW and 200 kW Wind Turbines. NASA TM-73711, 1977.

DISCUSSION

- Q. How broadly applicable are the empirical corrections in MOSTAB-WTE?
- A. The empirical equations apply to two-bladed hingeless rotors. However, the two empirical constants have been evaluated only for stiff or semi-stiff towers, to date.
- Q. What accuracy is associated with the experimental bending moment data?

- A. About 5% accuracy for cyclic bending moments. However, zero errors can be significant (see Ref. 1, Table 7).
- Q. Has the yaw brake dramatically improved rotor/tower coupling effects in the Mod-0 WTG?
- A. Yes. Blade loads are definitely lower when the yaw brake is on.
- Q. What causes the significant variation in blade loads for the same nominal wind speed?
- A. Variations in wind direction, control changes, yaw maneuvers, and other factors we don't understand.
- Q. What is the frequency distribution of load variations?
- A. Both normal and log normal distributions have been observed. More data are definitely needed.
- Q. Have these codes been used to calculate stress levels?
- A. No. The output of these codes is loads. Auxiliary stress codes are used subsequent to these codes.
- Q. Please comment on costs per case and input/output format for the various codes.
- A. I don't have specific information for all the codes but the contact persons listed in Table 1 do. For MOSTAB-WT and -WTE, typical input would consist of about 50 cards, running time would be two minutes (IBM 1110 computer) and typical output would be tabular listings of three moments and three shear forces at up to a dozen blade stations at each of 24 azimuthal blade positions. Parametric studies are conveniently and economically performed by non-specialists. My general comments about the remaining codes are that personnel must be well trained, running times of 30 to 60 minutes (or more) are to be expected, and your organization must be ready to provide dedicated support.
- Q. During preliminary design, predicting load frequencies may be more important than predicting amplitudes. Do you plan to compare these programs on the basis of predicted frequencies?
- A. Yes. The harmonic contents of the predicted loads are compared in Reference 1.
- Q. Your experience has shown that softness in the Mod-0 yaw drive induced undesirable cyclic loads. How then can flexibility in future systems reduce costs?
- A. Flexibility can lead to lighter, less costly structures only if resonances can be avoided. Unfortunately, softness in the Mod-0 yaw drive placed it at a resonance, leading to the undesired cyclic loads.

TABLE 1. - COMPUTER CODES PRESENTLY USED FOR AERO-ELASTIC ANALYSIS OF DYNAMIC LOADS AND DEFORMATIONS IN HORIZONTAL-AXIS WIND TURBINES

Code	Type (domain)	Source for Information
MOSTAB-WT	Single blade; 1 DOF ^a (time)	Barry Holchin Mechanics Research Incorporated 9841 Airport Boulevard Los Angeles, CA 90045
MOSTAB-WTE	Same, plus empirical constants	David A. Spera NASA-Lewis 49-6 21000 Brookpark Road Cleveland, Ohio 44135
MOSTAB-HFW	Rotor; 4 DOF plus gimbaling (time)	John A. Hoffman Paragon Pacific Incorporated 1601 E. El Segundo Boulevard El Segundo, CA 90245
REXOR-WT	System; multi-DOF (time)	Robert E. Donham Dept 75-21, Bldg. 360, Plant B-6 Lockheed-California Company Burbank, CA 91520
GETSS	System; multi-DOF (freq.)	Clyde Stahle General Electric Space Division Box 8661 Philadelphia, PA 19101
F-762	System; multi-DOF, (time)	Richard Bielawa United Technologies Research Center East Hartford, CT 06108
MOSTAS	System; multi-DOF, (time/freq.)	John A. Hoffman Paragon Pacific Incorporated 1601 E. El Segundo Boulevard El Segundo, CA 90245

^aDegrees of freedom

TABLE 2. - COMPARISON OF RELATIVE CYCLIC MOMENT LOADS,
NORMALIZED WITH RESPECT TO NOMINAL CYCLIC LOADS

Source	Relative cyclic moment loads			
	Flatwise ^a		Edgewise ^b	
	Sta 40	Sta 370	Sta 40	Sta 370

(a) Data Case I

Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	1.02	0.97	0.87	0.95
MOSTAB rotor codes	-WT	1.00	1.00	0.60	0.50
	-WTE	1.20	1.20	1.20	1.20
	-HFW	1.00	0.99	0.66	0.58
REXOR-WT		0.96	1.00	0.94	0.87
GETSS		1.19	1.16	0.80	1.05
F-762		1.08	1.03	0.78	0.77
MOSTAS		0.92	0.97	0.82	0.78

(b) Data Case IV

Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	0.83	0.96	1.05	0.93
MOSTAB rotor codes	-WT	1.20	1.20	0.94	0.93
	-WTE	1.20	1.20	1.04	1.07
	-HFW	1.17	1.17	1.00	1.04
REXOR-WT		0.97	0.92	0.98	0.96
GETSS		0.92	0.86	0.98	1.01
F-762		0.87	0.91	1.05	1.11
MOSTAS		1.22	1.23	0.97	1.01

^a $\delta M_y / \delta M_{y,nom}$

^b $\delta M_z / \delta M_{z,nom}$

TABLE 3. - RELATIVE PEAK MOMENT LOADS, NORMALIZED WITH
RESPECT TO NOMINAL PEAK LOADS

Source	Relative peak moment loads			
	Flatwise ^a		Edgewise ^b	
	Sta 40	Sta 370	Sta 40	Sta 370

(a) Data Case I

Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	1.01	0.98	0.89	0.96
MOSTAB rotor codes	-WT	1.01	1.12	0.66	0.57
	-WTE	1.12	1.25	1.13	1.17
	-HFW	1.02	1.13	0.78	0.73
REXOR-WT		0.96	1.05	0.89	0.85
GETSS		0.98	0.96	0.72	1.11
F-762		1.11	1.19	0.84	0.95
MOSTAS		0.88	0.98	0.86	0.94

(b) Data Case IV

Test data	Nominal	1.00	1.00	1.00	1.00
	Actual	0.76	0.97	1.03	0.94
MOSTAB rotor codes	-WT	1.23	1.30	0.94	0.96
	-WTE	1.23	1.30	0.94	0.96
	-HFW	1.22	1.30	1.06	1.13
REXOR-WT		1.02	0.99	0.96	0.93
GETSS		0.76	0.67	0.77	1.17
F-762		0.92	0.92	1.01	1.27
MOSTAS		1.03	1.05	0.99	1.07

$$^a \left| M_y \right|_{\max} / \left| M_{y, \text{nom}} \right|_{\max}$$

$$^b \left| M_z \right|_{\max} / \left| M_{z, \text{nom}} \right|_{\max}$$

TABLE 4. - SUMMARY OF LOAD RATIOS OBTAINED USING VARIOUS COMPUTER CODES AND MOD-0
WIND TURBINE TEST DATA

Code Type and Name	Goal of Calc. Load	Blade Load Ratio ^a		
		Average	RMS Dev. ^b	
Rotor Codes	MOSTAB-WTE MOSTAB-HFW MOSTAB-WT	Nom. + 1 σ	1.15	± 0.10
		Nom.	1.00	± 0.20
		"	0.95	± 0.24
System Codes	F-762 MOSTAS REXOR-WT	"	0.99	± 0.14
		"	0.98	± 0.12
		"	0.95	± 0.05
	GETSS	"	0.94	± 0.16

^a Calculated to nominal measured; based on 16 ratios combining 2 data cases, 2 blade stations, flatwise and edgewise directions, and cyclic and peak bending moments.

^b Root-mean-square deviation; includes approximately 11 of 16 ratios.

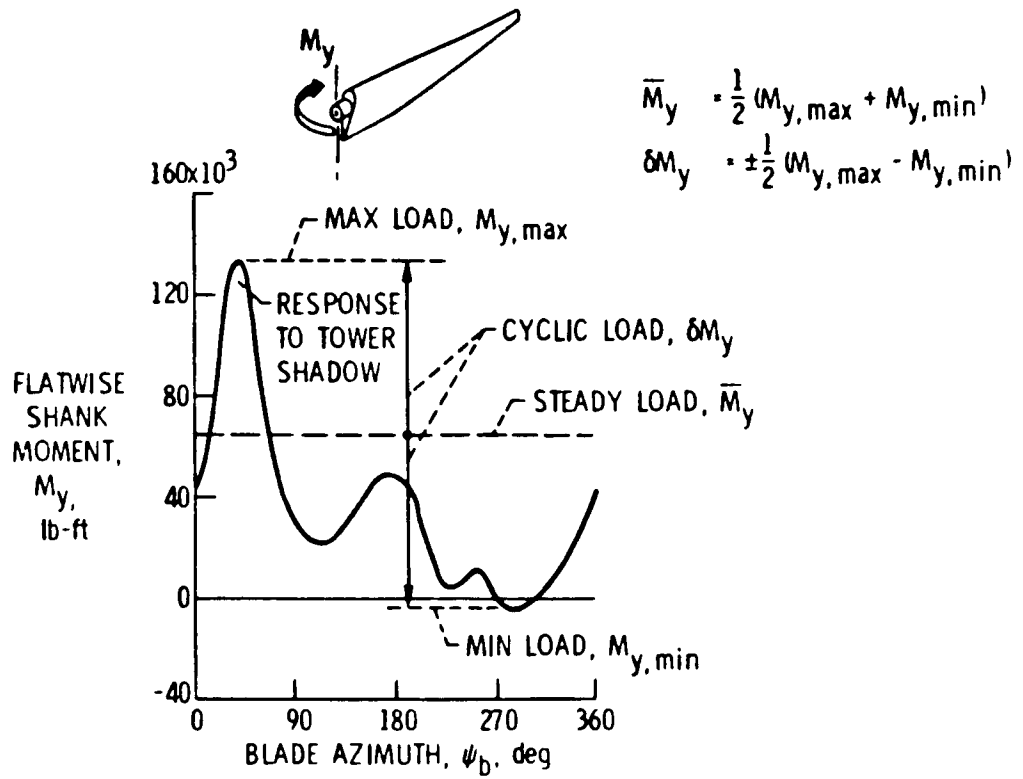


Figure 1. - Typical cycle of blade flatwise moment measured on ERDA-NASA 100-kilowatt Mod-0 wind turbine.

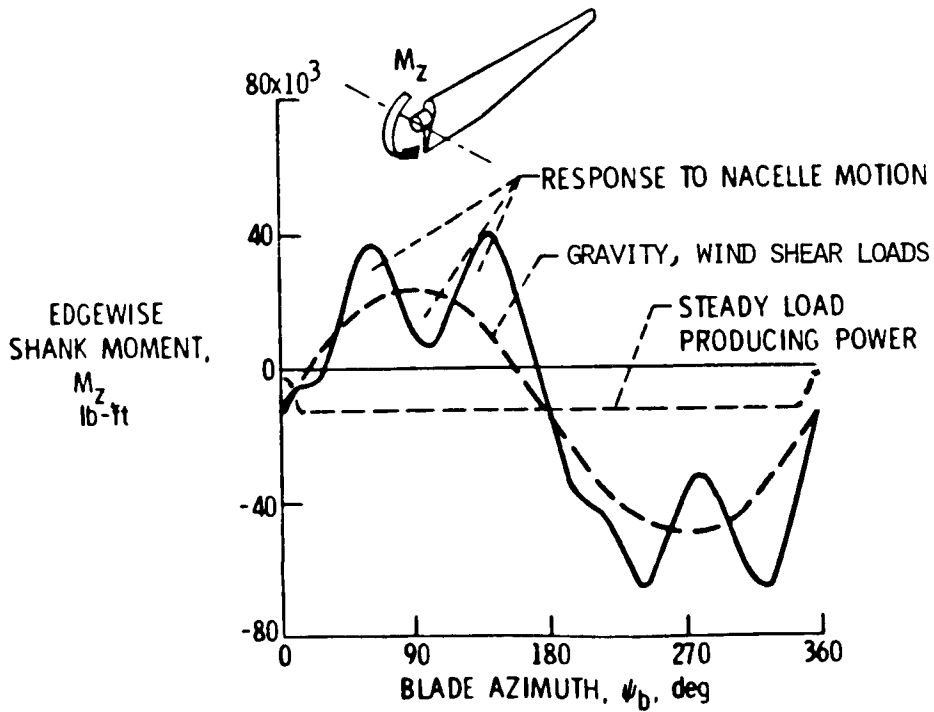
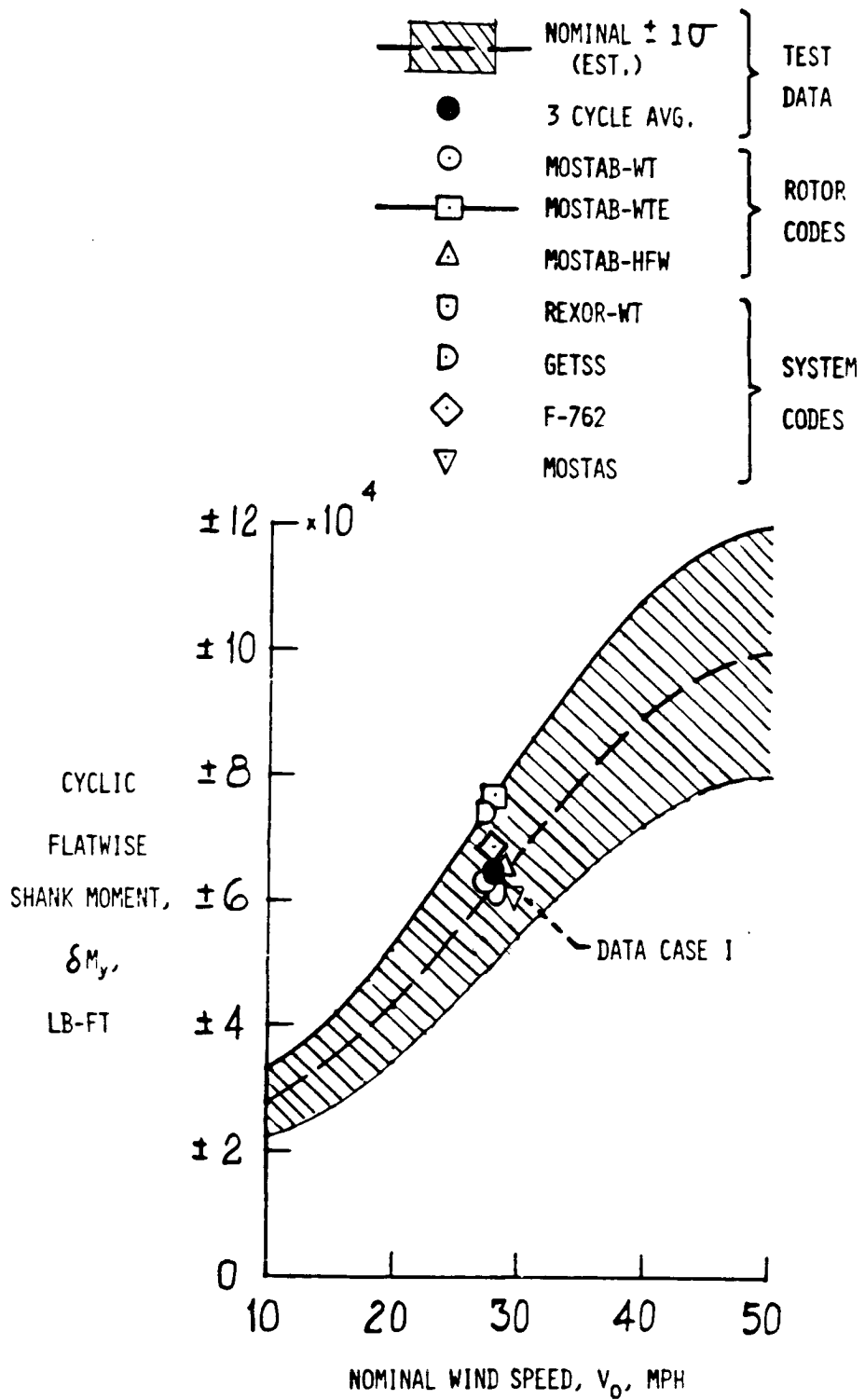
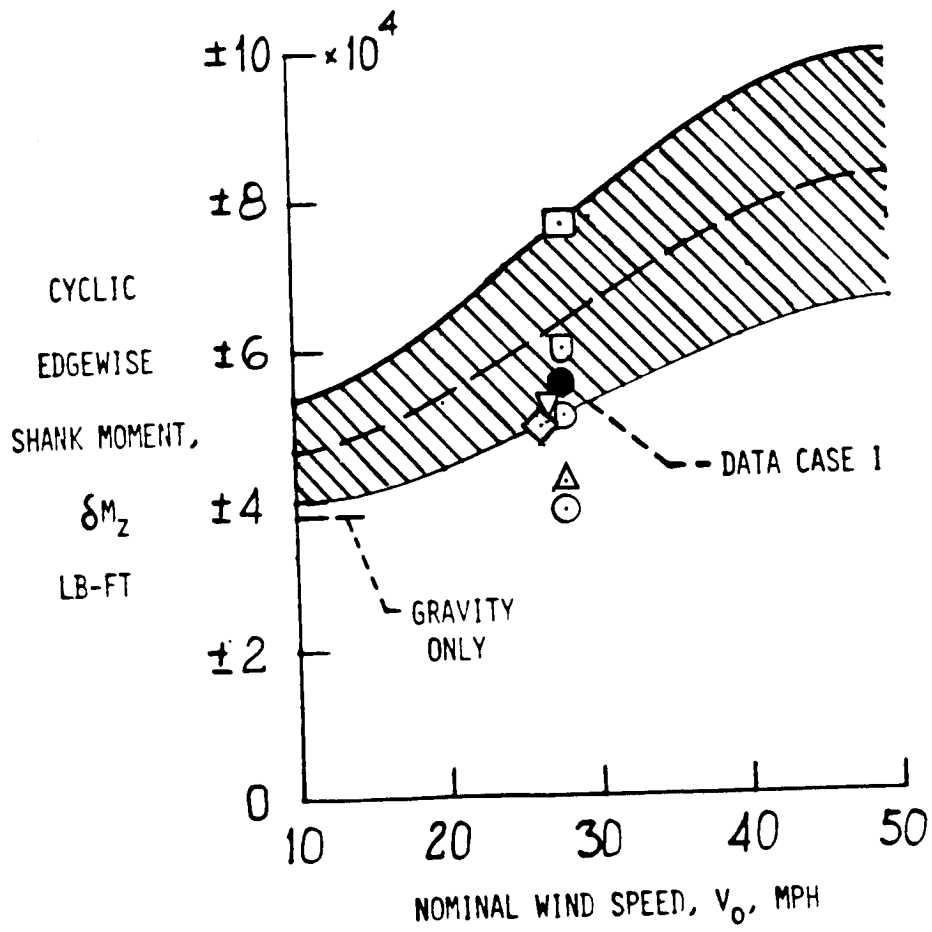


Figure 2. - Typical cycle of blade edgewise moment measured on Mod-0 wind turbine.



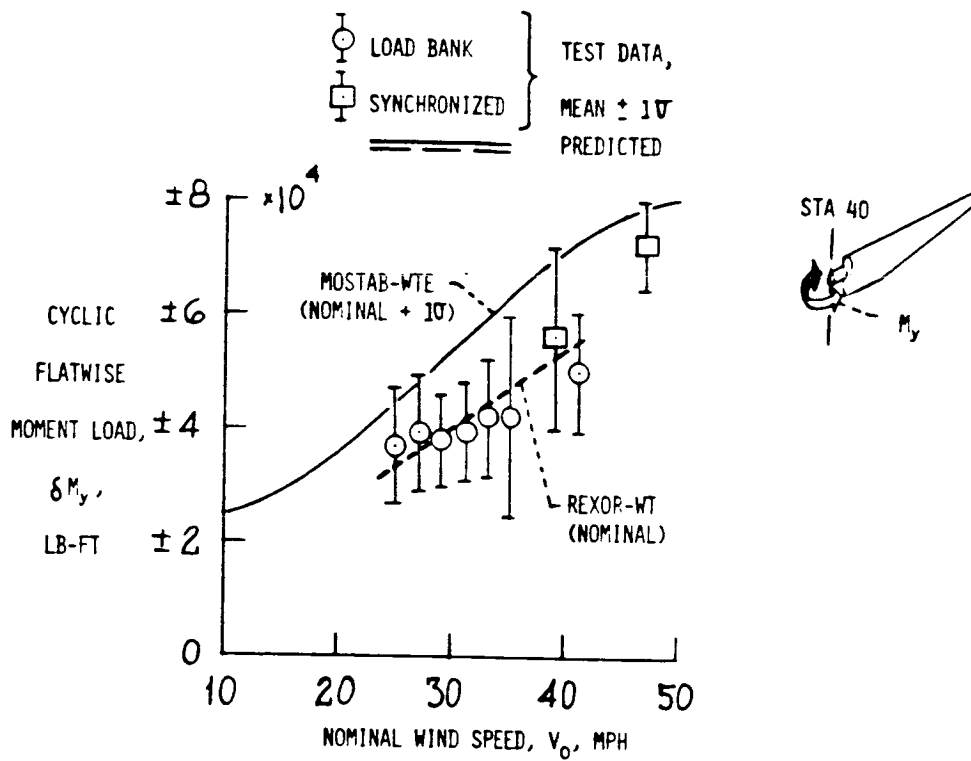
(a) Flatwise moment load.

Figure 3. - Comparison of measured and calculated blade moment loads for Mod-0 wind turbine at various wind speeds with stairs and single yaw drive. Station 40; 5-percent span.

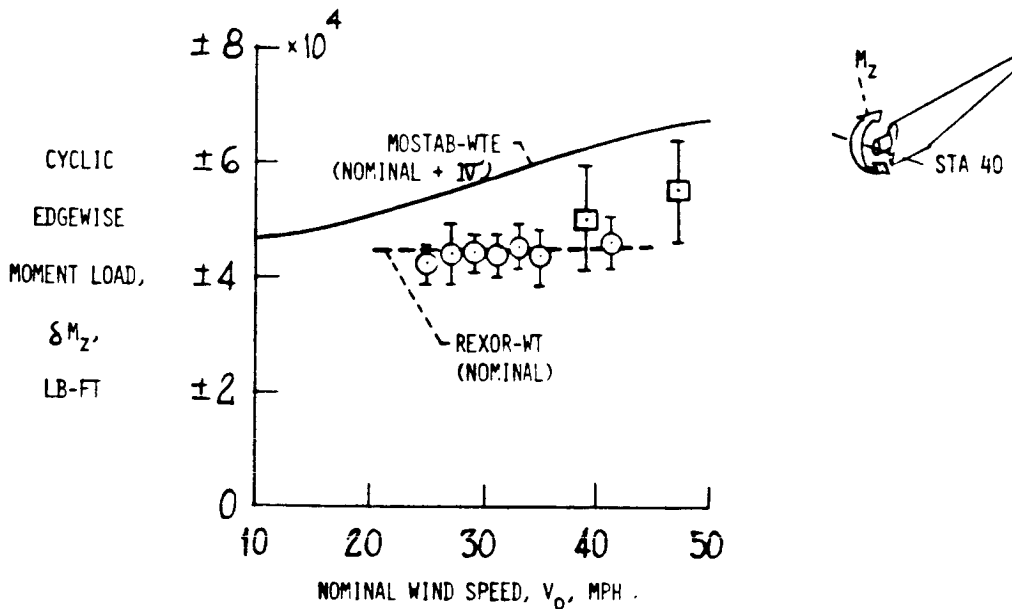


(b) Edgewise moment load.

Figure 3. - Concluded.



(a) Flatwise moment load.



(b) Edgewise moment load.

Figure 4. - Comparison of measured and calculated cyclic blade moment loads for Mod-0 wind turbine at various wind speeds with stairs removed and dual yaw drive installed. Station 40; 5-percent span.