Vibration Characteristics of an Experimental Wind Turbine with a 15 m Teetered Rotor*

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Vibration spectra of the experimental 15 m wind turbine of the Mechanical Engineering Laboratory were obtained in field operation to clarify the vibration characteristics of general teetered-rotor wind turbines. To investigate the causes of steady vibration, step response tests were also conducted, where excitations were made with the disk brake located at the high-speed shaft. As a result, a Campbell diagram for the system has been established. The tower-bending resonance with one-per-rev and two-per-rev excitations of the rotor, as well as the transmission-torsion resonance with two-per-rev excitation, has been observed. It has also been found that the one-per-rev gravitational force is predominant for the blade chordwise bending and that various n -per-rev components due to wind speed variation can be seen on the blade flapwise bending.

Key Words: Windmill, Resonance, Vibration of Rotating Body, Teetered Rotor

1. Introduction

More than 16 000 wind turbines are in operation in California, U. S. A., and the first wind farm in Japan was constructed in Hokkaido in 1989. Vibration of wind turbines is an important subject since many middle- or large-scale wind turbines are designed based on the concept of "soft tower". The concept implies that the first tower bending frequency is allowed to be lower than the fundamental excitation frequency of the rotor to suppress the tower weight against the increase in the size.

We can easily understand the relationship between the natural frequencies and the excitation frequencies with the aid of a Campbell diagram, which is also used for other general rotors. Regarding practical wind turbines, however, few reports have been published about comprehensive studies on the total vibration characteristics.

A comprehensive study on the vibration of the NASA MOD-0 wind turbine⁽¹⁾ revealed a resonance of the yaw mechanism, a torsion resonance of the transmission, a bending resonance of blades, and so on. As

for Japan, in a report about an experimental wind turbine with a 14 m rigid-hub rotor⁽²⁾, free vibration characteristics are mainly described. Dynamic wind tunnel experiments were carried out with a 0.8 m model for coupled rotor/tower vibration⁽³⁾ and with a 3 m model for rotor speed control⁽⁴⁾. Theoretical analysis for cross-wind response was conducted by Azuma et al.⁽⁵⁾ and analyses for wind shear response and for tower shadow response of a teetered rotor were done by Kondo and Yokoyama^{(6),(7)}.

In this paper the vibration spectra in field operation are presented for an experimental wind turbine with a 15 m teetered rotor (WINDMEL, Fig. 1) constructed on the premises of the Mechanical Engineering Laboratory under the Sunshine Project, Ministry of International Trade and Industry. By manipulating the disk brake located at the high-speed shaft, step response tests were also performed to investigate resonances. The results indicate that the first bending of the tower is excited by one-per-rev or two-per-rev of the rotor load and that the first torsion of the transmission is excited by two-per-rev. It was also found that the blade chordwise bending of one-per-rev is excited by gravitational force, that the flap bending is excited mainly by wind speed variation, and that the teetering motion occurs in a manner so as to maintain the tip-path plane in space.

* Received 18th July, 1991. Paper No. 89-1184B

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2. System Description

Major dimensions of the wind turbine system are listed in Table 1 and the sensor system is shown in Fig. 2. The blades are made of glass/polyester composite and the tower is composed of a steel shell.

The rotor is connected through a pin joint to the low-speed shaft without coning angle or delta-three angle and is allowed to teeter freely. To maintain the clearance between the blades and the tower the low-speed shaft is inclined by 6° from the horizontal plane. The present rotor is an upwind type; namely, it is located on the upwind side of the tower. The yaw control is performed through a tail fan which is located on a side of the nacelle and transmits the power of cross wind directly to the yaw gear. The generator is an asynchronous type with four poles, and the electricity is converted into 50 Hz AC through an AC-DC-AC converter. Therefore, the rotor speed is allowed to change from 50 % to 125 % of the rated speed. The

Table 1 Major dimensions of the experimental 15 m wind turbine

Rotor Diameter	15.0 m
Hub Height	14.7 m
Number of Blades	2
Rated Rotor Speed	81.4 rpm
Rated Generator Speed	1800 rpm
Generator Capacity	22 kW
Rated Wind Speed	8.0 m/s
Step-up Gear Ratio	80:17 (First Stage) 61:13 (Second Stage)
Blade Weight	54.6 kg/Blade
Blade Mass Moment	180 kgm/Blade
Blade Moment of Inertia	803 kgm ² /Blade
Generator Moment of Inertia	170 kgm ² /Low-Speed Shaft

Fig. 1 Experimental wind turbine with a 15 m teetered rotor

mechanical governor located at the rotor hub controls the blade pitch angle in the range over the rated speed to prevent overrevolution of the rotor. The obtained data were processed with a Fourier analyzer implemented with antialiasing filters.

3. Free Vibration Characteristics

Under the condition of low wind speeds, step response tests were conducted. The responses were measured just after the rotor stopped the revolution by manipulating the disk brake located at the high-speed shaft. This method did not necessitate any wire or hammer to excite the free vibrations.

First, Fig. 3 shows the FFT spectra for the flap bending and chordwise bending strains measured at the blade flange under the condition where the high-speed shaft is clumped with the disk brake. In the spectrum of the chordwise bending strain, torsional oscillation of the transmission due to the rotor inertial moment, S1, and the chordwise oscillation of the rotor

Fig. 2 Sensor system

Fig. 3 Step response spectrum showing blade natural frequencies (Generator armature is clumped with disk brake.)

blade, C1, can be seen. In the spectrum of the flap bending strain, peaks of the first and the second flapwise bendings, F1 and F2, can be seen as well as the peaks of S1 and C1. The peak at about 40 Hz can be regarded as the first torsional frequency of the blade based on the analysis described later.

Secondly, Fig. 4 shows FFT spectra of shaft torque and tower longitudinal acceleration in the case where the disk brake was released just after the rotor stopped. The peak of T1 corresponds to the first bending frequency of the tower. Though the natural frequency for the horizontal blade configuration differs from that for the vertical blade configuration, their discrepancy is less than 0.005 Hz for this system. The peak of S2 is estimated to be the vibration mode where the generator armature oscillates freely at the end of the power train.

The above results were obtained with the sampling rate of 10 ms and sampling time of 10 s. More precise data for the natural frequencies were obtained through the measurements with longer sampling time, as is shown in Table 2.

The natural frequencies of the blades in rotation were estimated analytically using the Holzer-Mykles-tad finite-element method implemented with flapwise

Table 2 Measured natural frequencies (for stationary rotor)

Notation	Natural Vibration Mode	Natural Frequency
S1	Transmission Torsion (Parking Condition)	0.52 Hz
T1	1st Tower Bending	1.28
S2	Transmission Torsion (Free-Free Condition)	1.98
F1	1st Blade Flapwise Bending	2.70
C1	1st Blade Chordwise Bending	4.70
F2	2nd Blade Flapwise Bending	8.08

Fig. 4 Step response spectrum showing transmission and tower natural frequencies (Generator armature is released from disk brake.)

and chordwise bendings in the centrifugal force field⁽⁸⁾. Figure 5 denotes the data of the blade stiffness and mass distribution used in the analysis. The result coincides well with the experimental data, as is shown in Fig. 6, in the case where the rotor is stationary.

4. Steady Vibration Characteristics

Under the conditions of power generation, vibration at each component was measured next. Figures 7 and 8 list the spectra for all the measuring items in two cases: the rated power condition (rotor speed of 79 rpm and wind speed of 5-7 m/s) and the partial power condition (rotor speed of 50-53 rpm and wind speed of 3-4 m/s). The measurements were conducted at stable rotor speeds where the speed variation was less than $\pm 5\%$. For comparison, the abscissas are in the same scale and the ordinates are in linear scales. Moreover, the bias (DC) components were deleted from the data. The numbers of 1, 2, ... in the figure show the harmonics of n -per-rev oscillation (nP , where P corresponds to angular velocity of the rotor).

Fig. 5 Blade mass and stiffness distribution used in the analysis

Fig. 6 Predicted blade natural frequencies in rotation

4.1 Wind speed

The spectra of wind speed variation, which is one of the excitation sources of the system, are shown in Fig. 7. The spectra were obtained with the ultrasonic anemometer located at the same height as the rotor hub, 23 m away from the tower. During the measurement, wind came from approximately the direction of the anemometer. The wind speed variation is larger for higher wind speeds, and the range of the spectrum seems to be restricted to less than 5 Hz.

4.2 Torque

The shaft torque varies with wind speed. Though the peak of $2P$ appears for low rotor speeds, it cannot be seen near the rated speed. Figure 9 clearly shows that the height of the $2P$ peak decreases as the rotor speed increases. The following points were assured:

- The $2P$ oscillation has a weak correlation with the teetering motion.
- It also has a weak correlation with the rotor azimuth angle, namely, with the direction of gravity.
- It disappears while the generator operates at the rated speed.

Therefore, the $2P$ oscillation can be regarded as a response of the transmission with the natural frequency of 2 Hz, which is excited by the rotor load. The transmission of the present wind turbine system

Fig. 7 Steady vibration spectra in power generation (1)

adopted the concept of “quill shaft”, which is composed of a torque tube and a shaft as a bending moment sustainer. Though a damping component is added, the oscillation still remains on the shaft.

4.3 Teeter angle

Though the amplitude of teeter angle varies with wind speed and with wind direction, the frequency always has a peak at $1P$. This means that the tip-path

Fig. 8 Steady vibration spectra in power generation (2)

Fig. 9 Variation of torque spectrum of the low-speed shaft

plane of the rotor is fixed in space. The data in Fig. 10 denote an example for mean amplitude of 2.3° . The teeter angle crosses zero when the blade is vertical (at azimuth angle of 0°) and the maximum teeter angle is attained in the horizontal plane. Though this seems to be caused by wind shear in this case, the maximum teeter angle can occur in the vertical plane on different occasions.

On the other hand, the blade pitch angle is affected slightly by gravity because of the antisymmetric pitch change mechanism.

4.4 Flapwise bending and chordwise bending

In the spectrum of the blade flapwise bending strain, the frequency components of $1P$, $2P$, $3P$ and $4P$ can be seen in Fig. 8 and the amplitude changes depending on wind speed and rotor speed. On the other hand, in the spectrum of the blade chordwise bending a single frequency component of $1P$ with constant amplitude is predominant. Since the amplitude of the peak is ± 1760 Nm and the gravitational bending moment calculated from Table 1 is ± 1960 to 1990 Nm, it can be concluded that the gravitational bending moment is predominant for blade chordwise bending. Moreover, the flapwise bending moment can be larger than the chordwise bending moment in the case of

Fig. 10 Example of teetering motion

Fig. 11 Spectra of tower longitudinal oscillation

high wind speeds.

4.5 Tower acceleration

Since the accelerometers are attached to the tower, the component along the rotor axis and the perpendicular component are denoted as "longitudinal" and "lateral", respectively. For low rotor speeds the longitudinal acceleration has a peak at $2P$ while the lateral acceleration has peaks at $2P$, $3P$ and $4P$. Around the rated rotor speed the accelerations in both directions have their peaks at $2P$, and the component of $1P$ due to the tower bending joins the spectrum. The longitudinal oscillation at 8 Hz can be seen and it has the following characteristics:

- Though the frequency is close to the second flapwise bending of the blade, no blade strain or pitch angle variation was detected (see Fig. 7 and Fig. 8).
- It appears only as a longitudinal oscillation.
- The oscillation could be excited by the wire connected to the tail fan.

Therefore, the oscillation can be regarded as being closely related to the tail fan.

Figures 11 and 12 compare the longitudinal and the lateral tower accelerations for different rotor speeds. The $2P$ resonance can be seen for rotor speed less than 42 rpm, and $1P$ resonance was observed for rotor speed over 70 rpm. Near the rated rotor speed, 76 rpm in the figure, the lateral oscillation is predominant and the longitudinal oscillation seems to be damped with aerodynamic forces.

High-frequency spectra of the tower acceleration up to 1 kHz for power-off conditions are shown in Fig. 13. In the case of the rated rotor speed, the first-stage gear meshing frequency, L , is 109 Hz and the second-stage gear meshing frequency, H , is 390 Hz. In the figure, harmonics of $1L$, $2L$, $3L$, $4L$, and $1H$, $2H$ can clearly be seen though the values of amplitude will not be discussed since the frequency range is over the cutoff frequency of the accelerometer, 90 Hz.

Fig. 12 Spectra of tower lateral oscillation

Fig. 13 High-frequency components of the tower acceleration (*L* and *H* denote gear meshing frequencies)

Fig. 14 Campbell diagram of the 15 m wind turbine (circle denotes the relative amplitude of oscillation)

4.6 Campbell diagram

Combining the results of the step response tests and the steady vibration tests in operation, a Campbell diagram for the system could be obtained as Fig. 14. Thick solid lines and dotted lines denote natural frequencies, and the radial lines of nP can be regarded as the excitation forces. The circles show the point where resonances were observed, and the diameter represents the relative amplitude of the same item.

5. Concluding Remarks

The experimental wind turbine with 15 m teetered rotor has been operating with no serious problems since its construction in March of 1987. By analyzing harmonic components of the steady vibration data

and comparing them with the step response tests, a Campbell diagram for the system has been established.

The measurement has revealed that the blades are exposed to $1P$ gravitational bending and to nP aerodynamic bending due to wind speed variation and that the teetering motion occurs to maintain the tip-path plane in space. The low-speed shaft sometimes shows the $2P$ torque variation due to the torsional frequency of the transmission though a small damping is applied. The tower shows a tendency to have $1P$ and $2P$ resonances, and the amplitudes are not small, especially for the lateral oscillations due to lack of aerodynamic damping. Since this oscillation occurs during the power-off or the partial-power conditions and might lead to some fatigue, vibration reduction is now under consideration.

Valuable experimental data have been obtained through this study for the structural design of general teetered-rotor wind turbines.

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