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# A Vibration-Based Structural Health Monitoring System for Transmission Line Towers

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**Abstract:** In this paper, we present a vibration-based transmission tower structural health monitoring system consisting of two parts that identifies structural changes in towers. An accelerometer group realizes vibration response acquisition at different positions and reduces the risk of data loss by data compression technology. A solar cell provides the power supply. An analyser receives the data from the acceleration sensor group and calculates the transmission tower natural frequencies, and the change in the structure is determined based on natural frequencies. Then, the data are sent to the monitoring center. Furthermore, analysis of the vibration signal and the calculation method of natural frequencies are proposed. The response and natural frequencies of vibration at different wind speeds are analysed by time-domain signal, power spectral density (PSD), root mean square (RMS) and short-time Fouier transform (STFT). The natural frequency identification of the overall structure by the stochastic subspace identification (SSI) method reveals that the number of natural frequencies that can be calculated at different wind speeds is different, but the 2nd, 3rd and 4th natural frequencies can be excited. Finally, the system was tested on a 110 kV experimental transmission line. After 18 h of experimentation, the natural frequency of the overall structure of the transmission tower was determined before and after the tower leg was lifted. The results show that before and after the tower leg is lifted, the natural frequencies of each order exhibit obvious changes, and the differences in the average values can be used as the basis for judging the structural changes of the tower.

Keywords: transmission line tower; accelerometers; modal identification; natural frequency

# 1. Introduction

Transmission line towers are important parts of the power system, but due to the special nature of their operating environments, some accidents can occur, such as collapse and breakage [1,2]. Although tower structures have been improved, the risk of damage cannot be avoided [3]. Accidents are caused by abnormal stresses, and inclination and settlement are the causes of abnormal forces [4].

To better understand the mechanical distribution characteristics of towers and the ability of towers under various conditions to undergo disasters, many scholars have analysed tower forces through calculation methods. Including the structural capacity of transmission towers under wind load and corrosive conditions [5], failure analysis is carried out by finite element simulation in freezing rain, snow and wind load [6,7]. Some people have obtained the static wind load coefficient of transmission towers and transmission lines through wind tunnel experiments and have calculated an iron tower's load by combining meteorological parameters to calculate the failure probability of the tower [8].

Compared with various calculation methods, state monitoring technology can directly obtain the structural state of a tower by measuring the iron tower. Condition monitoring based on tilt sensors was

an early method used to give alarm information when a tilt angle exceeded a standard threshold [9]. Differential synthetic aperture radar interferometry has also been attempted for monitoring tower tilt [10]. This method is mainly used to detect significant changes in the overall structure of towers, and local deformation and damage are not applicable. There are also studies of health monitoring of towers in special areas, such as tower foundations in permafrost regions that may become unstable with a rise in temperature, and some people have monitored the temperature of frozen soil to achieve structural health monitoring [11].

The visual method is a better way to monitor the structure of iron towers. Deformation and structural state can be measured by images [12], especially with the application of robotic total station and unmanned aerial vehicles (UAVs) in the power industry, which provides a better platform for this method [13,14]. Reference [15] uses a point cloud model to implement viewpoint optimization, which can improve the accuracy of UAV monitoring.

Structural health monitoring using modal analysis is a common method and is often used in large structures such as bridges and offshore platforms. There are also some studies on transmission lines. In [16], a modal identification method without cable was studied in a laboratory environment, but in practice, cable is not negligible. Reference [17] established a finite element model for the health monitoring of the tower structure of a 131-metre large transmission tower and obtained the conclusion that the ladder, steel plate and bolt have no influence on the overall stiffness of the tower. Reference [18] proposed an optimization method for the installation position of an acceleration sensor.

In this paper, a vibration-based tower structure health monitoring system is designed. This system is mounted on an accelerometer tower and transmits to an analyser through Zigbee. The analyser recognizes the natural frequency and gives an alarm based on the change in the natural frequency. The modal parameters of the tower are then identified. Finally, through the change in the modal parameters, whether the tower is settled is judged. Based on analysis of the vibration response of a tower, the response and natural frequency of vibration at different wind speeds and different positions are analysed by time-domain signal, power spectral density (PSD), root mean square (RMS) and short-time Fourier transform (STFT). The natural frequency identification of the overall structure is performed by the stochastic subspace identification (SSI) method. The system was tested on a 110 kV transmission tower, and the variation in the natural frequency of the tower was analysed before and after the deformation caused by lifting tower legs.

# 2. Design and Specifications the Vibration-Based Monitoring System

# 2.1. System Specifications

To enable operation in strong magnetic and vibration environments, the system is designed to have the following specifications:

- Self-powered and low-power devices that can operate for at least 5 years because the solar cells can be charged in daylight conditions—even with continuous rainy days, the device can still run for 30 days depending on the battery.
- Wireless communication via Zigbee, which can transmit vibration data in real time or can easily connect to a computer of on-site inspection personnel.
- Data loss reconstruction function to reduce errors caused by wireless data loss.
- Due to its light weight and small size, it will not cause too much pressure on the tower.
- Highly waterproof with normal operation under continuous rain or heavy precipitation.
- Anti-electromagnetic interference, installed on the transmission line with a high voltage level, can continue to operate without interference.
- Fully considers the long-term operation under vibration conditions and will not cause damage due to wire vibration.
- Acceleration maximum measurement range ± 2 g and sensitivity of 0.1 mg.

The vibration-based structural health monitoring system designed in this paper includes an acceleration sensor, wind speed and direction sensor, analyser and monitoring center. As shown in Figure 1, the acceleration sensor is used to measure the vibration acceleration of the tower; the wind speed and direction sensor measures the wind speed and direction near the tower; the analyser receives the vibration data and analyses the modal parameters of the tower; and the monitoring center has the functions of alarm.



Figure 1. Block diagram of the system.

The number of accelerometers is determined by the tower type; accelerometers need to be installed at different locations, so they are designed as wireless sensors to transmit data via Zigbee. The components used in the sensors require very low power consumption, allowing the sensors to operate for a longer time. The MSP430F2955 microprocessor was chosen for its ultra-low power consumption and suitable operating speed. The MSP430F2955 microprocessor features a 16-bit RISC architecture with a maximum operating speed of 16 MHz and a minimum current of 0.7  $\mu$ A in low-power mode. The LIS3DSH is a digital output Micro-Electro-Mechanical System (MEMS) sensor with very low power consumption (0.63 mW) that transmits data to the MSP430F2955 via serial peripheral interface (SPI) and is used to measure acceleration. The control and management module includes a plurality of load switches for controlling the power of each module to achieve energy savings.

To make the sensor work for a long time and to avoid frequent replacement of the sensor battery, a small solar power source is used to power the acceleration sensor, as shown in Figure 2. This power source has a power of 1 Wh from the solar charging board, a solar charging efficiency of 200 mA/h and a battery capacity of 20,000 mAh.



Figure 2. Photo of the field installation.

The wind speed and direction sensor uses an ultrasonic sensor to transmit data to the analyser via RS485. The sensor model is NHFS47.

The analyser uses STM32F407 as the CPU, and the working frequency can reach 168 MHz with 192 Kbytes of SRAM, which is enough to complete the modal analysis algorithm. The analyser's power supply uses solar and battery power, 40 W solar panels and 40 Ah lead–acid batteries, allowing this power supply to work for more than 30 days without light. Figure 2 shows a photo of the field installation.

#### 2.2. Data Loss Reconstruction Function

Collecting data with wireless accelerometers is a common way to prevent signal degradation and increase installation flexibility. Wireless signal transmission is usually affected by distance, and data loss occurs. The overall structure of a lattice tower is not large. For example, the height of a 110 kV transmission tower in the plain area generally ranges from 15 m to 27 m. However, the lattice structure hinders wireless signals and makes it inevitable to lose some data during data transmission. To ensure the integrity of the data and improve the overall reliability of the system, this paper adopts a data recovery method based on compressed sampling (CS) to solve the problem of data loss in the wireless data transmission process. The key of this method is that the compressed data are sparse. According to preliminary experiments, the vibration response of the transmission tower does not have the characteristics of the coefficient matrix in the time domain. However, in the frequency domain, we are more concerned with the natural frequency. The vibration is a sparse matrix in the frequency domain.

First, the data collected by the sensor are compressed,

$$A_0 = \Psi_0 \cdot a + e \tag{1}$$

where

 $A_0$  represents the acceleration data after compression. It is an m-order vector.

 $\Psi_0$  is the compression matrix. It is an m × n–order matrix.

*a* is the data collected by the sensor and is an n–order vector.

e is random noise.

Then, the compressed data  $A_0$  are sent to the analyser, and the data  $A_1$  received by the analyser after packet loss are determined according to the sampling frequency and the time label, the positions of the lost data are determined and the column corresponding to  $\Psi_0$  is removed to obtain a new compression matrix  $\Psi$ . The CS method can be used to reconstruct and recover lost data.

$$A_1 = \Psi_1 \cdot a + e = \Psi_1 x + e \tag{2}$$

where

*H* is the wavelet basis matrix,

*x* is the base transform coefficient.

By calculating *x*, data a can be reconstructed, and *x* can be solved by solving 1-norm optimization.

$$\begin{cases} \min \|x\|_1 \\ s.t. \quad \|\Psi_1 H x - A_1\| \le \varepsilon \end{cases}$$
(3)

The online monitoring system designed in this paper is for a 110 kV transmission tower experiment at the Lintong Campus of Xi'an Polytechnic University. The sampling frequency of the acceleration sensor is 200 Hz, and data are collected for 20 minutes. The data loss rate is 5%, and the graph shows a

typical packet loss situation. As shown in Figure 3, the error caused by data loss can be reduced by data reconstruction.



Figure 3. Data loss and reconstruction: (a) Data loss of 5%; (b) Data reconstruction result.

## 3. Signal Processing and Natural Frequency Calculation

Acceleration is the main concern of the structural health monitoring system. However, the magnitude of acceleration does not directly reflect structural changes. After the structure of the transmission tower changes, it directly shows the change in the modal parameters. The relationship between acceleration and the modal parameters can be clearly seen from the equation of motion.

#### 3.1. Equation of Motion of a Transmission Tower

Transmission towers are typical lattice towers that vibrate under the influence of wind. The structure of the transmission tower can be regarded as a multi-degree-of-freedom vibration system, and its differential equation of motion can be written as:

$$[\mathbf{m}]\{\dot{\mathbf{x}}(t)\} + [c]\{\dot{\mathbf{x}}(t)\} + [k]\{\mathbf{x}(t)\} = \{f(t)\}$$
(4)

where

- [*m*] is the mass matrix,
- [*c*] is the damping ratio,
- [k] is the stiffness matrix,
- ${f(t)}$  is an externally applied force (wind load),
- $\{\ddot{x}(t)\}$  is the acceleration,
- $\{\ddot{x}(t)\}$  is the velocity,
- $\{x(t)\}$  is the displacement.

Under normal circumstances, the external force generated by the wind is similar to white noise. When the structure of the tower changes, the damping ratio and stiffness change, and the acceleration, velocity and displacement also change. Changes in structure and stiffness also result in changes in the natural frequency. Often, structural health monitoring techniques are the inverse of the equation of motion. First, the vibration acceleration is measured and the modal parameters, such as the natural frequency, the damping ratio and the mode shape, are analysed by the acceleration spectrum. The structural change is judged according to the change in the modal parameters.

#### 3.2. Modal Identification of Transmission Towers

As expressed in Equation (4), the acceleration of a tower is related to parameters such as mass, stiffness and damping ratio. Modal recognition technology is a technique for solving modal parameters by acceleration signals. In this paper, the transmission tower structure health monitoring system is

designed to install four accelerometers in a 21 m high 110 kV transmission line cat-head tower, and the vibration response is collected every 2 hours.

Figure 4 shows the time-domain signal of the sensor acceleration. It can be seen from the figure that the vibration acceleration of sensor 2 is the largest, which reaches 21.2 mg. That of sensor 3 is slightly smaller, and the maximum value reaches 7.3 mg. Other sensors have smaller acceleration amplitudes. It can also be seen from the RMS value shown in Figure 5 that the responses of sensor 2 and sensor 3 are larger, while the responses of sensors 1 and 4 are smaller. This result is because the tower legs are partially bolted and have certain constraints. At the same time, the tower head is restrained by the force of the transmission wire, and the vibration response is not large.



**Figure 4.** Acceleration responses of sensors: (a) Acceleration response of sensor 1; (b) Acceleration response of sensor 2; (c) Acceleration response of sensor 3; (d) Acceleration responses of sensor 4.



Figure 5. Root mean square (RMS) of sensor acceleration.

Figure 6 shows the self PSD of the four sensors. Although the acceleration responses of sensors 1 and 4 are small, the response at certain frequencies is indeed outstanding, especially at 3.891 Hz, 10.171 Hz and 11.786 Hz. Considering that the frequency of wind is broadband, similar to white noise, the frequencies marked in the figure may be natural frequencies of the tower. However,

the wind continues to fluctuate and the vibration response of the tower is also changing. We need further time–frequency analysis to explain the vibration of the tower.



Figure 6. PSD of the sensors: (a) sensor 1; (b) sensor 2; (c) sensor 3; (d) sensor 4.

Figure 7 shows the vibration response of sensor 2 at different wind speeds. The greater the wind speed is, the greater the acceleration response. At a wind speed of 1.9 m/s, the maximum amplitude of the acceleration response is only 3.2 mg, while the maximum amplitude is 15.3 mg at a wind speed of 5.4 m/s. Obviously, the dynamic response of the tower is unstable, which is related to the constant fluctuations in wind speed.



Figure 7. Acceleration of sensor 2 under different wind speeds.

Therefore, the analysis of the vibration signal of the tower should include a method for processing time information. In this paper, the STFT is applied to the vibration response of each node measured by the sensors (seen in Figure 8). A rectangular window with the length of 512 samples was used for the STFT. We also show the PSD plot on the left side of the spectrum and the time-domain waveform above the map. The time-domain waveform shows that the vibration response of the tower is very unstable, which is caused by the fluctuations in wind speed. At the same time, we found that the stronger the vibration response is, the deeper the colour in the spectrum, further indicating that the vibration intensity is stronger. The map also shows that although the response intensity fluctuates greatly, the dark position in the spectrum is nearly straight. As seen in the PSD diagram on the left, the dark lines

correspond to the natural frequencies. As is apparent from Figure 8b, when the response decrease is more pronounced, the colour in the map is obviously lighter. For example, when the response is strong, the position at 19.5 Hz can be seen, and the colour in the map is darker, indicating that the corresponding wind speed excites this mode. Figure 8d shows that the mode with a frequency value of approximately 6 Hz is sometimes excited when the response is strong.



**Figure 8.** Spectrograms of frequencies, accelerations and power density functions of the sensors: (a) sensor 1; (b) sensor 2; (c) sensor 3; (d) sensor 4.

From the above analysis, the change in wind intensity causes the response of the transmission tower to change, which has a significant impact on the solution of the modal parameters. In addition, the above methods provide a corresponding analysis of the individual sensors. For the overall modal identification of the tower structure, the SSI method driven by covariance is used to solve the modal parameters for solving the vibration of the tower, and the natural frequency and damping ratio at different wind speeds are obtained, as shown in Table 1.

Wind Speed	1.9 m/s		3.6 m/s		5.4 m/s	
	Freq. (Hz)	Diff (%)	Freq. (Hz)	Diff (%)	Freq. (Hz)	Diff (%)
1 <sup>st</sup>	-	-	-	-	6.6279	0.0770
2 <sup>nd</sup>	10.5609	0.0110	10.5706	0.0091	10.6118	0.0089
3rd	14.3911	0.0118	14.3883	0.0129	14.3876	0.0119
4 <sup>th</sup>	16.6740	0.0155	16.6705	0.0171	16.6195	0.0121
5 <sup>th</sup>	-	-	20.0668	0.0262	20.1792	0.0269

Table 1. Tower modal frequencies and damping ratios at different wind speeds.

It can be seen from the table that all the modal parameters cannot be obtained for different wind speeds, but the 2nd, 3rd and 4th natural frequencies are all present. On the other hand, the natural frequency does not change much at different wind speeds, but the damping ratio varies greatly. Therefore, we use these natural frequencies as the standard of measurement.

### 4. Experimental Results

The vibration-based transmission tower structure health monitoring system designed in this paper was tested in the experimental transmission line at Xi'an Polytechnic University. The test transmission line is a three-tower, two-speed structure with a voltage rating of 110 kV. The cat-head tower in the middle of the transmission line was tested, and the acceleration sensor was installed in the same position as described in Section 2.

In actual transmission line operation, there are many situations that cause deformation of a tower. After the settlement of a transmission tower, a certain longitudinal displacement of the tower leg causes the force of the tower to change, and a certain deformation will occur. In response to this phenomenon, as shown in Figure 9, we lifted a tower leg with a hydraulic jack, which is a deformation of the transmission tower.



Figure 9. Photo of the experimental setup.

We performed continuous 9-hour experiments with and without deformation. The sampling frequency was 200 Hz, and the data were analysed every 10 minutes. The experimental results are shown in Figure 10. Although the tower legs are in the same state, the identified natural frequencies still have small fluctuations, which are due to the inherent recognition of certain errors, and temperature changes may also cause changes in the natural frequencies. However, after the tower leg is raised (5 mm in the experiment), the natural frequencies of each order are significantly reduced.



Figure 10. Changes in the natural frequencies of each order.

Table 2 shows that the natural frequencies exhibit significant decreases before and after the tower leg is lifted. In particular, the 2nd, 3rd and 4th natural frequencies are shown in this table. Furthermore, the differences between the minimum value before the tower leg is lifted and the maximum value after the lift for these natural frequencies are 0.2999 Hz, -0.19 Hz and 0.3798 Hz, respectively. These results indicate that although the frequencies before and after deformation have changed, as seen in Figure 10, if the analysis is performed with two measured values alone, it is not possible to determine whether deformation has occurred. However, from long-term monitoring, we found that the changes in the mean values of the 2nd, 3rd and 4th natural frequencies before and after the tower legs were raised were 0.7323 Hz, 0.473 Hz and 0.7491 Hz, respectively. Obviously, the third-order average natural frequencies as a basis by monitoring for several hours. According to the research results in Reference [4], 7 mm displacement of tower legs will cause damage to the members. The data in Table 2 are measured when the displacement of the tower leg is 5 mm. In practical application, the early warning information is given when the 2nd and 4th natural frequencies change to 0.7 Hz.

Fable 2. Numerical	statistics	of the	natural	freq	uencies.
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	Average		Maxii	num	Minimum	
	Undeformed	Deformed	Undeformed	Deformed	Undeformed	Deformed
2nd	10.7080	9.9757	10.9425	10.2503	10.5502	9.6681
3rd	14.1193	13.6463	14.4591	13.9622	13.7722	13.3812
4th	16.7380	15.9889	16.9942	16.2113	16.5911	15.6324

## 5. Conclusions

In this work, a system for health monitoring of transmission tower structures was designed and built, and the structural design and functional modules of the system were studied in detail. A field test was carried out on a transmission line spanning 105 m at Xi'an Polytechnic University.

An accelerometer is designed. Data compression technology reduces the influence of the lattice tower on signal transmission and realizes the vibration response of the transmission tower. Solar cells also solved the problem of power supply to the sensor.

The vibration response is analysed. From the time-domain signal, PSD and RMS analysis, it can be seen that the natural frequencies calculated by the responses at different positions are different. Combining the STFT time-domain signal and PSD analysis, it can be seen that the response strength caused by different wind speeds is different, and the number of natural frequencies excited also changes. In addition, from the SSI analysis of the overall structure, the 2nd, 3rd and 4th natural frequencies are excited at different wind speeds.

The system was implemented on a 105 m experimental transmission line at Xi'an Polytechnic University. From the long-term monitoring, we found two issues. Firstly, Measuring error, temperature effect and the micro-change of a structure will lead to errors in repeated measurements. However, the tower structure will not suddenly change dramatically, unless damaged, so it can be measured many times to find the average value to reduce this error. Secondly, changes in the mean values of the 2nd, 3rd and 4th natural frequencies before and after the tower legs were raised were 0.7323 Hz, 0.473 Hz and 0.7491 Hz, respectively. Therefore, in practical applications, the average value of the natural frequency is used as the basis for judgment. In practical application, the early warning information is given when the 2nd and 4th natural frequencies change to 0.7 Hz.

Further work will focus on how to identify the specific conditions of ice coating, bending of members, etc. by natural frequencies.

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