Analysis of the Vibrational Properties of Wind Turbines Utilizing a Gravity Speed Regulating Mechanism

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In order to investigate the vibration characteristics and optimize the design of the gravity return type wind turbine, this study analyzes the influence of the length of the tail rod on the vibration characteristics of the wind turbine in the yawing process using the wind tunnel test method. The test was carried out with a retractable tail rod structure at a high wind velocity of 10 m/s. The results indicate that with an increase in the yaw angle of the wind turbine, both the vibration frequency and the amplitude of vibration acceleration decrease; the first-order axial vibration frequency of the tower exceeds the radial vibration frequency for yaw angles ranging from $0°$ to $45°$, whereas the converse holds for yaw angles between $45°$ and $60°$. It is further found that when the length of the tail rod is 1.1 m, the first-order axial vibration frequency and amplitude of the tower are at a lower level, while the first-order radial vibration frequency and amplitude are reduced by a larger amount of 10.95 % and 34.48 %, respectively, which shows a better vibration reduction effect. This study offers both a theoretical foundation and experimental support for the structural design of gravity return type wind turbines, while also having a significant application for enhancing the operational stability of wind turbines.

1. INTRODUCTION

As the development of wind energy continues, the cumulative installed capacity of onshore wind power in China is 360 million kilowatts, with onshore wind power accounting for 92.3 % of all cumulative installed capacity.[1] Recent years have seen a global intensification of research focused on optimizing wind turbine performance, particularly in material innovation and structural improvement. Agarwal et al.[2] demonstrated that boron-aluminum metal matrix composites (Boron-Al MMC) can markedly diminish the equivalent stress and deformation of vertical axis wind turbines. Additionally, attention needs to be paid to the critical speed to avoid resonance, offering a new idea on optimizing the dynamic performance of wind turbines. Similar material innovation, the optimization of structural design is an important way for enhancing the dynamic performance of wind turbines.

Natural winds change all the time, which means that small wind turbines need to be equipped with an efficient speed control mechanism.[3] In order to better utilize the undirected wind energy between the city and the valley, a gravity return type wind turbine was designed.

Researchers both domestically and internationally have undertaken relevant research on the gravity speed control mechanism. In investigating the gravitational speed regulating mechanism of gravity return type wind turbines, Liu Xiongfei et al.[4] analyzed the aerodynamic performance of wind turbine blades and tail fins for the derivation of theoretical moment formulae in the process of side deflection of small wind turbines with speed limiting mechanisms, revealed the mechanism of the generating side deflection of a wind turbine, deflection of tail fins and gravitational return moments of the speed limiting mechanism, and deduced the precise expression formulae of the moments. Sun Feng and colleagues[5] analyzed the generation mechanism of lateral deviation in gravity return wind turbines, including tail aerodynamic force and gravitational return. They derived an accurate torque calculation formula and proposed a design methodology for the wind turbine speed control mechanism. Wang Jianwen and colleagues[6] carried out an experimental study on the optimization of the main characteristic parameters of the gravity speed control mechanism of a wind turbine. The study was carried out only by using on-board experiments without sufficient consideration of other disturbing factors. Audierne et al.[7] proposed a gravity-controlled Lagrangian side deflection system dynamics model to evaluate the side deflection effect of a wind turbine at a given incoming wind speed by adjusting the design parameters, such as the length of the tail rod and the inclination angle of the inclined hinge axis, providing an initial method for the design of the side deflection system. Marwan Bikdash et al.[8] from the University of North Carolina, USA, reconsidered the traditional gravity side-biased speed governing mechanism and proposed a mathematical model for the side-biased mechanism under low wind conditions through careful analysis and redesign, enabling simulation based on an aerodynamic model. Lubitz, WD et al.[9] from the University of Guelph, Canada, conducted experiments on wind farms, revealing an upper and lower branch in the fluctuation of side-biased wind turbine output power relative to wind speed.

As for the research field of vibration characteristics of wind turbines, Dai Yuanjun et al. performed wind turbine experiments in the wind tunnel laboratory of Xinjiang College of Engineering, focusing on the modified blade tip as the subject of their research.[10] Ashim Khadka et al. from Kettering University, USA, performed non-contact vibration monitoring of rotating wind turbines utilizing semi-autonomous uncrewed aerial vehicles (UAVs) to acquire the vibration characteristics of wind turbine blades. These data may ultimately facilitate structural health monitoring of these structures, enabling engineers to conduct remote assessments of wind turbine integrity during operation in offshore and inland wind farms.[11] Xu Q. et al. investigated a trailing edge flap wind turbine and determined its favorable compatibility for blade vibration amidst constant variations in wind speed.[12] Wang et al. utilized dynamic frequency curves to examine the influence of blade triplets on the dynamic frequency of wind turbines.[13] Zhang Z investigated the performance of using roller dampers in rotating wind turbine blades to reduce the along-direction vibration of the blades.[14] Ma Jianlong did vibration experiments on the S-type blade tip winglets wind turbine and found that the blade tip plus winglets can effectively reduce the first-order and second-order vibration frequency so that the wind turbine can get out of the resonance area as soon as possible.[15]John Arrigan investigated changes in the intrinsic frequency of wind turbine blades due to centrifugal stiffening, and the role of semi-active tuned mass dampers (STMDs) in reducing flap directional vibration that varies with parameters was studied.[16] The dynamic response analysis model of the combined wind turbine-damper system is established and the time-dependent analysis is carried out.[17] Structural modal analysis of a 5MW horizontal axis wind turbine blade was performed by Tarfaoui to evaluate the effect of mass reduction on its vibration modes.[18]

Existing research mostly focuses on the analysis of traditional wind turbines, while there is a lack of systematic research on the vibration characteristics of gravity return type wind turbines. The theoretical analysis and experimental comparison of the scholars of Nei Gong University found that the gravity speed regulation mechanism is simple and reliable, and has great market potential. Vibration is the most important factor of damage to the wind turbine, and the tail rod and tail fin play an indispensable function in the speed regulation mechanism. When the gravity speed regulation mechanism acts, the gravity of the tail rod and the tail fin becomes the main force to push the wind turbine back to the initial equilibrium state. If the tail is too heavy, the gravity speed regulation mechanism may fail, resulting in a wind turbine performance that is no different from the performance of an unmodified wind turbine. Therefore, adjusting the tail rod length through the lever principle is a more appropriate method. In this paper, the effect of tail rod length on the vibration characteristics of wind turbines will be investigated.

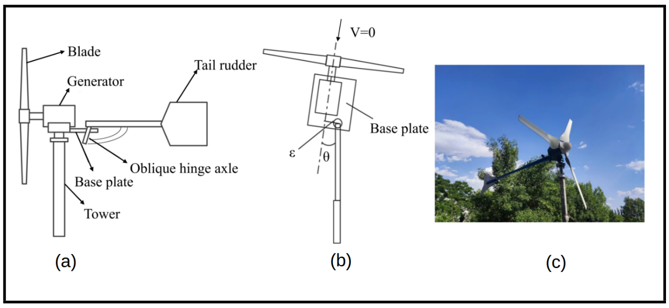

Figure 1. Gravity return type wind turbine (a) Front view (b) Top view (c) Actual installation view.[19]

The effect of the tail bar length in the gravity speed governing mechanism on the vibration characteristics of the wind turbine was investigated using a 300W gravity return type wind turbine. The dynamic vibrational properties of the wind turbine rotor and tower were evaluated. The organization of the paper is as follows: Section 2 describes the principles of the speed governing mechanism and the methodology of the vibration analysis; Section 3 elucidates the scenario and equipment employed in the trials; Section 4 examines the outcomes of the data analysis; and Section 5 encapsulates the conclusions drawn from the research investigations.

2. NUMERICAL ANALYSIS METHODS

2.1. Principle Of Gravity Return Type Speed Control Mechanism

The small wind turbine equipped with a side deflection speed limiting mechanism utilizes the principle of mechanics in the working process and has excellent deflection performance, and the basic structure is shown in Fig. 1 (a). As shown in Fig. 1 (b), the gravity speed governing mechanism has the following characteristics:

1. The wind turbine tail is mounted offset and has a certain side deviation distance from the main axis of the wind turbine, i.e., the eccentricity distance ϵ;

2. When the wind speed is 0, the wind turbine has a precession angle θ relative to the direction of the incoming wind speed.

Figure 1 (c) exhibits the actual installation of the gravity speed control mechanism.

2.2. Methods For Characterizing Vibration

The vibration characterization of wind turbines is typically conducted through experimental tests both domestically and internationally, offering a more direct and comprehensive understanding of their vibration properties. Analyzing low-order resonance in towers is essential, as tower vibrations in many environmental conditions impact wind turbines, demonstrating a strong association between the two.[20] This test evaluated the vibration characteristics of a gravity return wind turbine under various operation situations utilizing a relevant three-way acceleration sensor from B&K. The data undergo post-processing via the Fast Fourier Transform (FFT) analysis module in DEWESoft X. The FFT analysis is a widely employed analytical technique in the vibration assessment of wind turbines. The FFT, is a technique that allows periodic voltage and current signals to be represented as a combination of sinusoids (or cosoids) of varying frequencies. The frequency, amplitude, and phase of these sine waves collectively define the attributes of the original signal.[21] Assuming the function is a product function and meets the necessary Dirichlet condition, its FFT transform may be articulated as Eq. (1):[21]

$$F(w) = \int_{-\infty}^{+\infty} f(t)e^{-jwt}dt; \tag{1}$$

where t represents time and w denotes angular frequency. The process of obtaining incoming signals through a rectangular window and extending their duration into an infinitely long sequence, assuming the acquired vibration signals are either discretized or continuous, is called the Discrete Fourier Transform (DFT). It is articulated as Eq. (2):[21]

$$F(m) = DFT\{f(k)\} = \sum_{k=0}^{N-1} f(k)e^{-2\pi mk/N}. \tag{2}$$

Let $f(k)$ represent the collected discrete signal, N denote the number of sample points, k signify the number of time-domain discrete signals, and m indicate the number of frequency-domain signals. If the collected data are extensive, i.e., the value of N is tremendous, this arithmetic process is very complicated, so the fast Fourier Transform is widely used to process the collected discrete signals.[22] It significantly enhances the conversion rate of discrete signals. To minimize error and data leakage during the FFT transformation of the collected vibration signal and to ensure the accuracy and reliability of the processing results, it is essential to incorporate the Hanning window into the FFT. Its time domain window function is Eq. (3)[21]

$$wM^{(n)} = 0.5 - 0.5\cos\frac{2\pi n}{N}; \tag{3}$$

where n assumes the value of a natural number, specifically 1. The obtained signal is processed using a Hanning window, characterized by the following spectral function Eq. (4):[23]

$$W(\omega) = \{0.5T(\omega) + 0.25[T(\omega - \frac{2\pi}{N}) + T(\omega + \frac{2\pi}{N})]\}\exp(-j\frac{N}{2}\omega); \tag{4}$$

where $T(w)\sin\left(\frac{Nw}{2}\right)/\sin\left(\frac{w}{w}\right)$ represents the spectrum function of the rectangular window and denotes the signal period. Given that the obtained vibration signal is discretized, the spectral resolution is Eq. (5):[23]

$$\Delta\omega = \frac{2\pi}{N}k. \tag{5}$$

The Fourier variables are as follows Eq. (6):[23]

$$\omega = k \times \Delta\omega = \frac{2\pi}{N}; \tag{6}$$

where it is taken as a natural number, take until $N - 1$.

The FFT analysis in this work corresponds with established vibration theory models. Furthermore, the Lagrangian model examined by Audierne et al.[7] anticipated the influence of tail rod length on moment equilibrium, while the current experiment validated the leverage effect through the adjustment of tail rod length, thus expanding the model's application in dynamic response analysis.

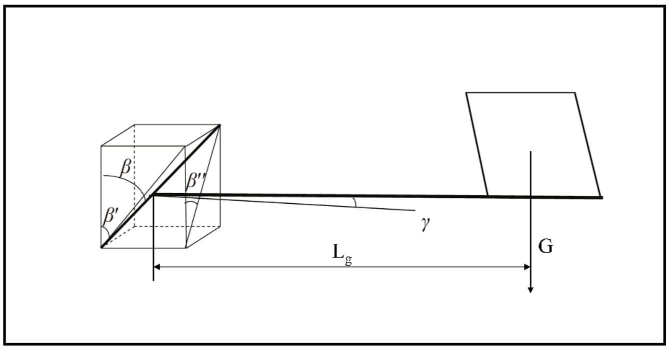

Figure 2. Schematic diagram of tailplane oblique hinge axis mechanism.[24]

2.3. Theoretical Assumptions

For gravity return type wind turbines, when the incoming wind speed exceeds the rated wind speed, the tail will deflect around the oblique hinge axis, making it deviate from the lowest position and the center of gravity rises, and the gravitational potential energy becomes larger until a new equilibrium is reached with the lateral deflection moment generated by the wind turbine. The principle of gravity return moment generation is shown in Fig. 2. In the gravity speed mechanism, the tail rod length directly affects the moment balance and vibration coupling relationship of the system. According to the lever principle, the tail rod length is positively correlated with the gravity return moment M_b:[24]

$$M_b = GL_g(\sin\varphi\sin\beta' + \cos\varphi\sin\beta''); \tag{7}$$

where G is the gravity of the tail, L_g is the distance from the center of gravity of the tail to the center of the tilt-hinge axis, β' is the rearward inclination of the tail's tilt-hinge axis, and β'' is the lateral inclination of the tilt-hinge axis.

According to the principle of leverage and the theory of dynamic equilibrium of moments, an increase in the length of the tail rod L will alter the ratio of the force arm of the tail in the gravity speed control mechanism, thereby optimizing the balance between the lateral deflection moment of the wind turbine and the gravitational return moment. Specifically, when the length of the tail rod is moderate, its leverage effect can effectively reduce the frequency and amplitude of axial and radial vibration of the tower; while too long or too short tail rod may exacerbate the vibration due to the moment imbalance. This hypothesis is verified by adjusting the length of the tail rod on the dynamic response mechanism.

3. DESIGN OF EXPERIMENTAL PROGRAM

This test is carried out at a high wind speed of $10m$ m/s, mainly to study the effect of the vibration characteristics of gravity return type wind turbine under the action of gravity speed governing mechanism with the change of the length of the tail rod. This experiment is conducted at the Yinchuan College of Science and Technology's Microgrid Wind and Solar Complementary Experimental Center. The wind turbine will yaw under specific dynamic conditions influenced by the wind tunnel. A multifunctional test system is employed to acquire raw vibration signals, enabling the analysis of corresponding frequency and acceleration amplitude to investigate their patterns. To ensure the reliability of the experimental results, the experiments were repeated five times under the same wind

Table 1. Wind turbine parameters.[25]

Parameters	Numerical value	Parameters	Numerical value
Power [w]	300	Blade tip ratio	5.23
Wheel Diameter [m]	1.7	The rearward inclination of the tail's tilt-hinge axis [°]	22
Length of blade [m]	0.585	The lateral inclination of the tilt-hinge axis [°]	16
Rated wind speed [m/s]	8.5	Composite inclination [°]	27
Rated speed [r/min]	500	Eccentricity [m]	0.15
Blade number	3	Tail Rod Length [m]	0.9-1.4

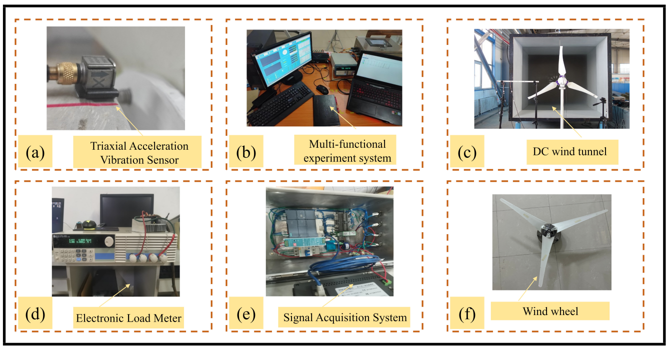

Figure 3. Test system (a) Triaxial Acceleration Vibration Sensor (b) Multi-functional experimental system (c) DC wind tunnel (d) Electronic load meter (e) Signal acquisition system (f) Wind wheel.

speed and yaw conditions for each group of tail rod lengths (1.0 m, 1.1 m, 1.2 m, 1.3 m).

3.1. Test Mode

This test utilized a gravity-return wind turbine with a rated power of 300 watts. The specifications of the wind turbine are presented in Table 1.

3.2. Vibration Characterization Assessment

3.2.1. Testing Apparatus And Procedures

To accurately replicate the conditions of the return-type wind turbine tail and tower in their natural environment, dynamic vibration characteristic studies employ wind tunnels to model real scenarios under diverse operating settings. The triaxial accelerometer is a B&K model 4524-B, with a sensor sensitivity of 9.589 mV/ms^{-2} and an acquisition range from 1 Hz to 6 kHz, as illustrated in Fig. 3 (a). Multifunctional test acquisition system for the Dewesoft X3 series, power analysis system utilizing M9700 software, original vibration signals from the data analysis software acquisition supporting Dewesoft X, as depicted in Fig. 3 (b). The experiment was conducted in a low-speed DC wind tunnel, as illustrated in Fig. 3 (c). Relative standard deviation of flow uniformity in the test section: $\leq$ 1.0 % (70 % of the airflow uniformity area, wind speed above 5.0 m/s). Relative deviation of flow rate stability in working section: $\leq$ 1.0 % (wind speed above 5.0 m/s); airflow deviation angle: $\leq 1.0°$. Data depicting the wind tunnel are presented in Table 2. As shown in Fig. 3 (d) for the programmable DC electronic load meter for the Melnor M9714B model, set to 8.9 Ω. The primary data acquisition system employed for the experimental test comprises a 0-20MA/4-20MA analog input module, the current acquisition MODBUS communication device (WP3082ADAM), the rectifier, control switches, among other components, as seen in Fig. 3 (e). The

Table 2. DC wind tunnel-related data.

Parameter name	Parameter value
Open the dimensions of the test section	2000 mm×2000 mm×500 mm
Dimensions of the enclosed testing portion	1400 mm×1400 mm×3000 mm
Flow rate spectrum for open test section	(0.5∼25.0) m/s
Velocity range of flow in the enclosed test segment	(0.5∼35.0) m/s

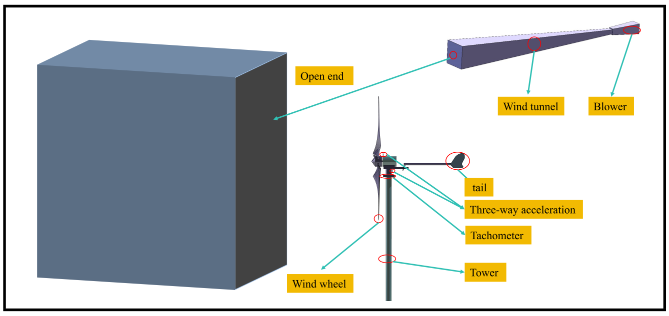

Figure 4. Configuration of experimental locations for the vibrational properties of a gravity return type wind force dynamo.

wind turbine blade utilizes a bionic design inspired by the wing of a sparrow hawk, as depicted in Fig. 3 (f). The designation QY-7305 indicates that 'QY' represents the initial letters of the Chinese term for sparrow hawk. At the same time, '7305' refers to the cross-section characterized by a reference plane, with a positional degree of -73.05 mm at the cross-section. The highest thickness of 10.14 % occurs at 10.1 % of the wing chord, whereas the maximum surface area of 10.92 % is located at 46.8 % of the wing chord. The goal of the test is to employ spectral analysis to investigate the influence of the gravity speed control mechanism on the vibration characteristics of the model, specifically in managing aerodynamic loads within a wind tunnel. Variations in wind speed induce lateral deviation in the wind wheel due to the inclined stranded axis and the gravitational effect at the tail, leading to a new equilibrium. A three-axis accelerometer sensor will capture the vibration signals from the gravity return-type wind turbine at the nacelle front and tower, which will be analyzed using spectral analysis and Fourier transformation. The DEWESoft X software's FFT analysis module enables spectrum acquisition during data post-processing, allowing for determining fundamental frequency and amplitude by basic numerical sorting and exploring its regularity.

3.2.2. Arrangement Of Test Points

Figure 4 illustrates the configuration of measurement points for the vibration characteristic test of the gravity return type wind turbine. The wind turbine rotor depicted in Fig. 4 is positioned on the tower 65 cm from the open end of the wind tunnel; the tower measures 142 cm in height and has a diameter of 4.5 cm, with the rotor's center of rotation being 175 cm above ground level. In the test, the meaning assigned to the three axes of the three-way sensor are as follows: entering wind speed corresponds to the positive X-axis; horizontal orientation towards the left of the wind tunnel corresponds to the positive Y-axis; and vertical orientation upwards corresponds to the positive Z-axis.

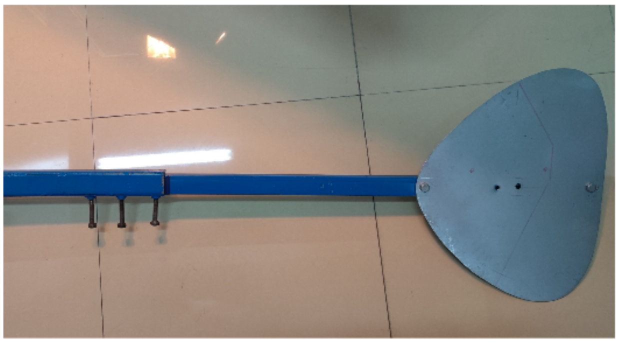

Figure 5. Retractable Tail rod.

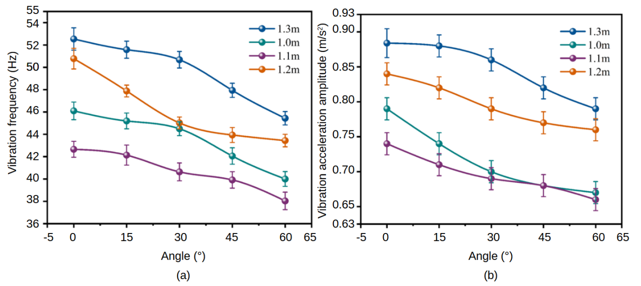

Figure 6. Diagram shows first-order vibration test parameters of a wind turbine about variations in tail rod length. (a) Frequency diagram shows the first rank vibration due to the wind force dynamo effect as the length of the tail rod varies. (b) Amplitude of vibration acceleration at Rank 1 due to wind force on the dynamo disc effect as the length of the tail rod varies.

4. ANALYSIS OF VIBRATION CHARACTERISTICS

Based on the design and calculation theories of the tailplane, the distance L from the support to the center of the tailplane is approximately 60 % of the wind turbine's diameter,[24] resulting in L being around 1.02 m. In order to determine a more suitable tail rod length, a retractable tail rod is designed as shown in Fig. 5, with the shortest length of 0.95 m and the longest length of 1.4 m. In the test, tail rods with lengths of 1.0 m, 1.1 m, 1.2 m, and 1.3 m are selected in this study. By changing different tail rod lengths, the effect of gravity speed governing mechanism on the vibration characteristics of wind turbine and tower is investigated.

4.1. Impact Of Tail Rod Length On The Vibrational Properties Of Wind Turbines Within Gravity Speed Regulation Systems

Figure 6 (a) illustrates the first-order vibration frequency plot produced by the disc effect of the wind turbine at yaw angles between 0° and 60°, with variations in the length of the tail bar. The findings indicate that the vibration frequency is minimal when the tail bar length is established at 1.1 m. At a yaw angle of 60°, the vibration frequency of the 1.1 m tail rod (with a 95'% confidence interval of 38.39 ± 0.95 Hz) was reduced by 4.05 %, 12.05 %, and 15.83 % relative to that of the 1.0 m, 1.2 m, and 1.3 m tail rods, respectively. During the yawing process of the wind turbine from 0° to 60°, the vibration-damping effect of the 1.1 m tail rod is significant. Figure 6 (b) illustrates the first-order vibration acceleration amplitude of the wind turbine disc effect during the yawing process, contingent upon variations in the tail bar length. As the length of the tail bar increases, the amplitude of the first-order vibration acceleration of the gravity return type wind turbine disk exhibits a pattern of initially falling followed by increasing. The most significant difference is observed at a wind turbine yaw angle of 30°, yielding a difference of 0.17 m/s^2. In comparison, the most minor difference occurs at a yaw angle of 60°, resulting in a difference of 0.13 m/s^2. The magnitude of vibration acceleration diminishes as the yaw angle of the wind turbine increases. Of all the investigated tail boom lengths, the 1.1-meter tail boom exhibits the lowest amplitude of vibration acceleration and demonstrates relatively effective vibration damping.

4.2. Impact Of Tail Rod Length On The Vibrational Properties Of Towers In Gravity Speed Mechanisms

The gravity return wind turbine requires many modifications to achieve balance during yawing, resulting in notable differences in the tower's vibration characteristics compared to conventional horizontal axis wind turbines. Subsequent experiments are performed to examine the impact of varying the tail bar length on the tower's vibration characteristics inside the gravity speed regulation mechanism.

Figure 7 (a) illustrates the tower's first-order axial vibration frequency diagram when the tail rod length is altered during wind turbine yaw. A comparison investigation reveals that changes in tail bar length significantly influence the tower's first-order axial vibration frequency during the wind turbine's yawing process. As the yaw angle increases, the first-order axial vibration frequency of the tower progressively diminishes. The maximum frequency difference of 5.4 Hz occurs at a tail boom length of 1.3 m. In contrast, the minimum frequency difference of 3.7 Hz is observed at a tail boom length of 1.1 m, indicating that the tower exhibits the lowest first-order axial vibration frequency during wind turbine yawing at a tail boom length of 1.1 m. The trends regarding the impact of the four tail bar lengths on the first-order axial vibration frequency of the tower are usually uniform.

Figure 7 (b) illustrates the amplitude of the tower's first-order axial vibration acceleration during the wind turbine's yawing process as the length of the tail bar is modified. The findings indicate that the amplitude of the first-order axial vibration acceleration of the tower diminishes as the yaw angle increases, given a constant tail bar length and the operation of the gravity speed controlling mechanism. The maximum phase difference during the yawing process of the wind turbine at angles of 0°, 15°, 30°, 45°, and 60° is observed with a tail bar length of 1.2 m, yielding a value of 0.26 m/s^2. Conversely, the minimum phase difference occurs with tail bar lengths of 1.0 m and 1.3 m, resulting in a value of 0.23 m/s^2. The minimal impact of the four tail rod lengths on the amplitude of the first-order axial vibration acceleration of the tower occurs at a tail rod length of 1.1 m. In contrast, the maximal amplitude is observed at a tail rod length of 1.3 m. When comparing the 1.3 m tail boom length, the vibration acceleration amplitude of the 1.1 m tail boom decreases by 10.87 %, 14.63 %, 23.68 %, 20 %, and 26.09 % at each corresponding yaw angle. The amplitude of first-order axial vibration acceleration

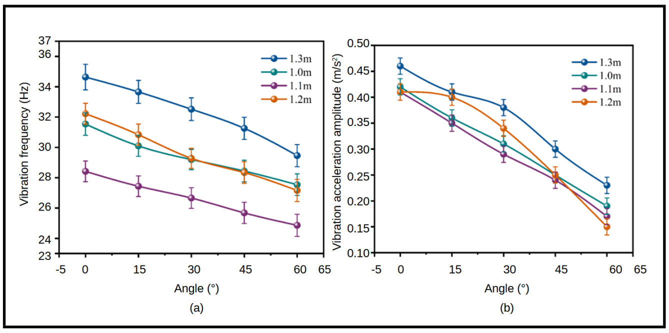

Figure 7. The parameters for the first-order axial vibration test of the tower as the length of the tail rod varies. (a) Frequency diagram of Rank 1 axial vibration of the tower as the tail rod length varies. (b) The amplitude diagram shows the first-order axial vibration acceleration of the tower as the length of the tail rod varies.

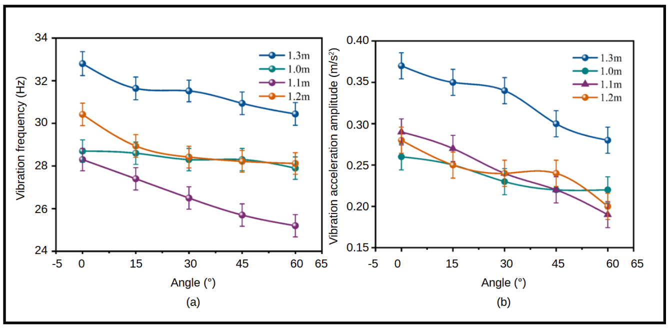

Figure 8. Parameters for first-order radial vibration testing of the tower as the tail rod length varies. (a) First rank radial vibration frequency of the tower as a function of tail rod length variation. (b) Amplitude of radial vibration acceleration at Rank 1 of the tower as a function of tail rod length variation.

in gravity return type wind turbine towers can be significantly diminished by modifying the tail boom length, with a 1.1 m tail boom demonstrating superior vibration attenuation efficacy. Figure 8 (a) illustrates the tower's first-order radial vibration frequency diagram as the tail rod length varies. As the yaw angle of the wind turbine increases, the first-order radial vibration frequency of the tower exhibits a general decline due to the influence of the gravity speed regulation mechanism. In the yawing process of the wind turbine at angles of 0°, 15°, 30°, 45°, and 60°, the reduction in vibration frequency is 2.44 %, 10.95 %, 7.57 %, and 7.32 % for tail bar lengths of 1.0 m, 1.1 m, 1.2 m, and 1.3 m, respectively. The most significant reduction in vibration frequency occurs at a tail boom length of 1.1 m, signifying that the tower's vibration properties are optimally enhanced at this measurement. The decreasing trend is consistent with a tail boom length of 1.0 m, whereas the vibration frequency stabilizes after yaw angles of 15° and 30° with a tail boom length of 1.2 m. Consequently, the gravity speed control mechanism is more effective in diminishing the first-order radial vibration frequency of the tower when the tail boom length is 1.1 m, with a smoother decline observed at lengths of 1.0 m and 1.2 m.

Figure 8 (b) illustrates the effect of variations in tail bar length on the first-order radial amplitude of the tower while the gravity speed-controlling mechanism is operational. As the yaw angle of the wind turbine increases, the first-order radial amplitude of the tower progressively diminishes, with reductions of 15.38 %, 34.48 %, 28.57 %, and 24.32 % seen for tail bar lengths of 1.0 m, 1.1 m, 1.2 m, and 1.3 m, respectively, for yaw angles of 0°, 15°, 30°, 45°, and 60°. The most significant decrease occurs in the 1.1 m tail rod, which is diminished by 0.1 m/s^2, resulting in a lesser impact of the wind turbine yaw on the tower's first-order radial vibration acceleration amplitude. In the yawing process, the peak relative amplitude of 1.1 m was diminished by 21.62 %, 22.86 %, 29.41 %, 26.67 %, and 32.14 %, respectively. The lengths of the tail boom at 1.0 m and 1.2 m had minimal impact on the tower's first-order radial vibration acceleration amplitude during the wind turbine's yawing process. In contrast, the 1.1 m tail boom length demonstrated superior efficacy. The above analysis shows that the results of the present study are consistent with the prediction of the Lagrangian model of Audierne et al.[7] that an increase in the length of the tail rod enhances the gravitational return moment through leverage. In addition, Zhang et al.[14] suggested that the optimized roller damper can reduce the vibration amplitude by 20 %∼ 30 % under typical working conditions, while in this study, a certain amplitude reduction (e.g., the first-order radial amplitude of the 1.1 m-long tail rod at a yaw of 60° decreased by 32.14 % relative to the amplitude maximum) was achieved through the structural optimization (length adjustment of the tail rod) with a better vibration damping effect. This indicates that both the optimization of mechanical parameters and the additional damping device have a certain vibration reduction effect. By independent samples t-test, the P-value of all comparison groups (1.1 m compared with other tail rod lengths) is less than 0.05, indicating that the vibration damping effect of 1.1 m tail rod is statistically significant.

4.3. Comparison Of First-Order Axial And Radial Vibration Frequencies And Acceleration Amplitudes Of The Tower As The Length Of The Tail Rod Varies

When the gravity speed governing mechanism is activated, the wind turbine undergoes yaw adjustments of 0°, 15°, 30°, 45°, and 60°, while the tower remains stationary. After rotating to an intermediate angle of 45°, the wind turbine's position relative to 0° allows for interchangeability along the three-dimensional X-axis and Y-axis. Consequently, it is essential to investigate and analyze the tower's comparative first-order axial and radial vibration frequencies influenced by the gravity speed governing mechanism as the tailstock length varies. As illustrated in Fig. 9 (a), the data analysis for axial and radial directions corroborates the preceding findings. At yaw angles of 0° to 30°, the axial vibration frequency associated with each tailstock length exceeds the radial vibration frequency; at a yaw angle of 45°, the axial and radial vibration frequencies for each tailstock length are nearly equivalent, with a maximum difference of 0.3 Hz. At a yaw angle of 60° for the wind turbine, the first-order axial vibration frequency for each tail bar length is lower than the radial vibration frequency, exhibiting a maximum discrepancy of 0.9 Hz, under 1 Hz. In the scenario when the tail rod measures 1.1 m, the minimal difference seen is 0.3 Hz. Consequently, when the tail boom length fluctuates, the gravitational speed regulating mechanism increasingly diminishes the tower's first-order axial and radial vibration frequencies with a 1.1 m tail boom length. When the yaw angle of the wind turbine is between 0° and 45°, the axial vibration frequency for each tail rod length exceeds the radial vibration frequency. Conversely, when the yaw angle is between 45°

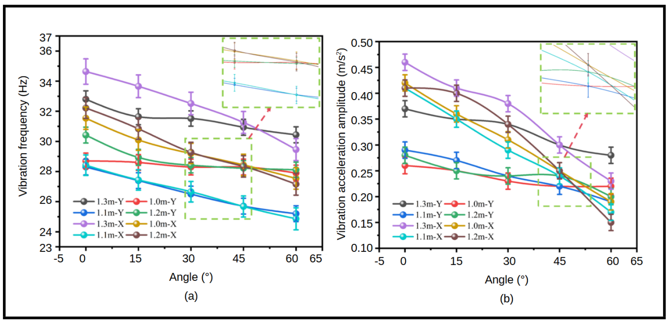

Figure 9. Comparison of the first-order axial and radial vibration test parameters of the tower when the length of the tail rod changes. (a) Comparison of Rank 1 axial and radial vibration frequencies of the tower when the length of the tail rod changes. (b) Comparison of the Rank 1 axial and radial vibration acceleration amplitude of the tower when the length of the tail rod changes.

and 60°, the axial vibration frequency for each tail rod length is lower than the radial vibration frequency.

Figure 9 (b) illustrates the outcomes of the comparison analysis regarding the influence of tail rod length variation on the amplitude of the tower's first-order axial and radial vibration acceleration induced by the gravity speed-controlling mechanism. The findings from the distinct examination of axial and radial vibration acceleration amplitudes align with the preceding section. For yaw angles ranging from 0° to 45°, the amplitude of axial vibration acceleration for each tailstock length exceeds that of radial vibration acceleration, with a maximum difference of 0.16 m/s^2 and a minimum difference of 0.01 m/s^2, which is insignificant relative to the data error. At a yaw angle of 60°, the first-order axial vibration acceleration amplitude for each tail bar length is somewhat less than the radial vibration acceleration amplitude, with a maximum discrepancy of 0.05 m/s^2 and remaining below 0.1 m/s^2. The slightest change occurs when the tail bar length is 1.1 m, measuring 0.02 m/s^2.In the gravity return wind turbine, the tower's first-order axial and radial amplitude exhibits optimal changes with a tailboard length of 1.1 meters. For yaw angles ranging from 0° to 45°, the amplitude of axial vibration acceleration for each tail rod length exceeds that of radial vibration acceleration; however, at a yaw angle of 60°, the amplitude of axial vibration acceleration for each tail rod length is less than that of radial vibration acceleration. The second-order law is roughly equivalent to the first-order law.

5. CONCLUSIONS

Compared to traditional wind turbines, gravity-return wind turbines experience more severe fatigue damage due to vibration. To assess the effect of tail rod length on the vibration characteristics of the wind turbine during the action of the gravity speed controlling mechanism, an examination of the vibration characteristics of the gravity return type wind turbine was conducted, leading to the following conclusions:

1. The vibration frequency of the 1.1 m tail rod shows a more regular and smooth decreasing trend during the yawing process of the wind turbine from 0° to 60°. At a yaw angle of 60°, the first-order vibration frequency of the disk effect decreases by 4.05 %, 12.05 %, and 15.83 % for the 1.1 m tail rod compared to the 1.0 m, 1.2 m, and 1.3 m tail rods, respectively. The vibration acceleration amplitude of the 1.1 m tail rod is always kept at the lowest level among all of the tail rod lengths tested, which shows a better vibration damping effect.
2. In the yaw angle range from 0° to 30°, the axial vibration frequency is generally higher than the radial. At 45°, the axial and radial frequencies are similar. At 60°, the situation is reversed. During the wind turbine yawing process, the first-order axial vibration frequency of the tower is the lowest when the length of the tail rod is 1.1 m. The frequency difference is 3.7 Hz. The first-order radial vibration frequency decreases the most, which is 10.95 %, and the first-order radial amplitude decreases the most, which is 34.48 %.
3. This work elucidates the influence mechanism of tail rod length on vibration characteristics through theoretical assumptions and verification by experiment. The proposed optimization mechanism of the leverage effect and moment balance is thoroughly validated by the experiments: the 1.1 m tail rod significantly diminishes the tower's vibration frequency and amplitude by adjusting the force arm ratio, thereby confirming its crucial function in dynamic moment balance. Moreover, most of the existing studies focus on parameters such as blade geometry and damper design, while the effect of tail rod length on vibration characteristics has not been systematically explored. This study experimentally reveals the significant suppression effect of the tail rod length (1.1 m) on the axial and radial vibration of the tower, and its vibration reduction effect is more relative to the adjustment of similar structural parameters. This discovery provides a clear optimization direction for the design of the gravity speed mechanism, which will provide technical support for the designers of the small gravity return-type wind turbines, and the developers of the renewable energy sources in the urban and windy mountainous areas, and will improve the efficiency of the operation and maintenance of the equipment.

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