Experimental Study on the Effect of a Bifurcated Apex on the Vibration of a Wind Turbine Tower

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Abstract:
Aiming at the vibration problem of wind turbine towers, an improved design method of bifurcated blade tip and end wing is proposed. By testing the vibration characteristics of the tower, the related frequency and acceleration amplitude of the tower before and after the modification design is measured, and the influence of the fork tip with different tip Angles on the vibration characteristics of the tower is studied. It is concluded that the basic amplitude and the second-order amplitude of the axial and radial acceleration corresponding to the vibration of the tower can be reduced by the split tip end wing. Therefore, the split tip end wing can effectively reduce the vibration of this wind turbine tower. Since the effect of vibration reduction is related to the tip Angle of the split tip end wing, this provides a new idea for the study of wind turbine tower vibration reduction.

Keywords: wind turbine, apex, tower vibration characteristics, acceleration amplitude

INTRODUCTION

A wind turbine rotates the wind wheel using wind power and the wind wheel drives the generator to produce electricity. Over the years, wind power has developed rapidly in China, and the design and production of wind turbines have improved [1]. However, the technology in major wind power countries is more advanced compared to China owing to its interest in wind power being relatively new, and this has resulted in shortcomings in the design and production of wind turbines. Researchers have found that some wind turbines suffer from fatigue damage prematurely. Researchers have found that the main reason is the vibration caused by rotation [2]. Therefore, while the economic and social benefits are gradually improved, the study of unit vibration is of great value.

In the exploration of wind turbine vibration, Yulon tried to explore whether the winglets at the blade tip can produce good changes in the mode parameters of the MW class wind turbine [3]. Jianlong studied the influence of the aerodynamic wing structure and bonding position of wind turbines on the natural frequency of wind turbines [4] and the effect of the S-shaped end wing on the vibration of the body is explored [5]. Through experiments, the mechanism of the relationship between wind turbine strain and tower vibration was summarized by Xiangzeng [6]. Liru explores the effect of the actual change of the flow field in the application on the generation of the wind turbine tip end [7]. Yuan Jun discussed the influence law of a V-shaped blade tip and end wing on the vibration of some common models by modifying the blade tip and end wing.[8]. Shuaiheng studied the effects of a composite lay-up angle on wind turbine vibration [9]; Haghdoust suppressed wind turbine vibrations by adding shape memory alloy to wind turbine blade material [10]. JunLing Chen invented a new type of tunable liquid damper to achieve the purpose of vibration reduction [11]; Gangele explored the modal problem of 1.5 MW wind turbines based on the ANSYS platform [12]. Emilio presented a blade crack identification method based on wind turbine blade vibrations [13]. From the literature review, the research on wind turbine vibration characteristics is relatively widespread, but there is less research on blade tip modification to suppress wind turbine tower vibrations.

In this paper, a bifurcated apex with different blade tip angles is proposed and its effects are investigated through a wind turbine tower vibration characteristics test. The research results will provide a new exploration direction for more effective vibration reduction of wind turbines and towers.

EXPERIMENTAL PROTOCOL DESIGN

Subjects Measured

In this study, a 100w type wind turbine with 3 blades was used. the original apex and the three-dimensional blade diagram with a bifurcated apex are shown in Figure 1. The rated values are designed as follows: the incoming flow wind speed is 8m /s, the speed is 600 rpm, and the specific design values are reflected in Table 1.

Table 1. Wind turbine blade design value of 100 watts

Design value	Value	Design value	Value
Total number of leaves	3	Chord length at leaf tip (m)	0.041
Length of single leaf (m)	0.65	Aspect ratio	4.14
Diameter length of wind wheel (m)	1.3	Relative blade thickness	10.26%
Rated tip ratio	5	Airfoil section	S825

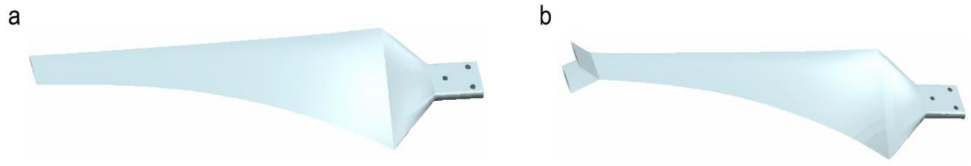

Figure 1. (a)General leaf tip end wing; (b)Bifurcated leaf tip blade

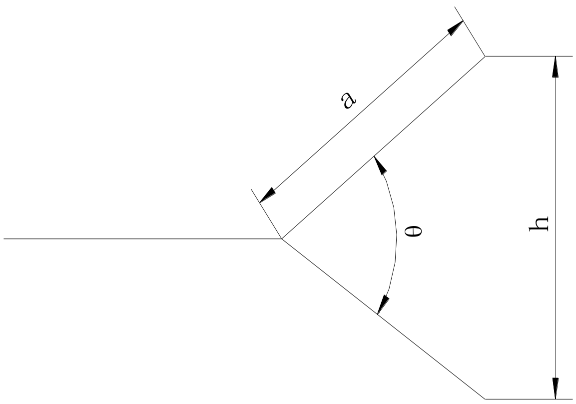

Figure 2. Bifurcated apex

The design of a split-end wing structure is inspired by the split-end wing design of a civil aircraft. The proposed structure can reduce the wingtip vortex strength, enhancing the aerodynamic performance and structural dynamic characteristics of the wing. The structure includes the blade tip angle θ, the blade tip length a, and the blade tip width h. The blade apex and dimensions are shown in Figure 2 and Table 2, respectively.

Table 2. Bifurcated blade apex size chart.

Bifurcation type of leaf tip	The length of the leaf tip (A)	Leaf tip width	The angle of leaf tip bifurcation (θ)
The angle of the leaf tip opening 1	47 mm	24 mm	30°
The angle of the leaf tip opening 2	47 mm	45 mm	60°
The angle of the leaf tip opening 3	47 mm	63.5 mm	90°

The Instruments Used in the Research

The required tests were carried out in a DC low-speed wind tunnel with an opening size of 19.5×3×3 m and a peak wind speed of more than 15m/s. The three-way acceleration sensor was a B&K model 4524-B, and the data acquisition system consisted of a B&K model 3660-C-100 5-module wireless LAN chassis and a model 3053-B-

12/0 The high-density 12-channel data acquisition front-end is assembled. To facilitate later data processing, The speed signal is captured by a B&K 2981 laser speed probe. To meet the working conditions required for the test, The Edex IT8512A+ electronic load meter was used as the load system to control the speed. The instruments used in the study are represented in Figure 3.

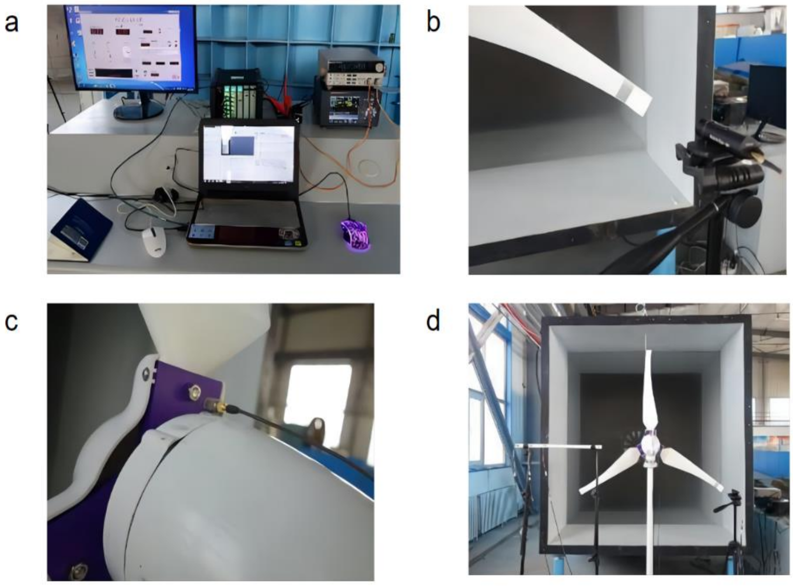

Figure 3. (a) Data acquisition system; (b) Laser speed probe; (c) Three-way acceleration sensor; (d) DC Wind Tunnel

Test Method

The wind turbine vibration characteristics test is performed by GB/T 19068.3-2003 "Off-grid wind turbine part 3: wind tunnel test method" standard. In this paper, a comprehensive study of the effects of fork tips with different tip angles on tower vibration is carried out. The proposed spectrum analysis method was used to adjust the operation of the wind tunnel at a certain wind speed; when the wind wheel is rotated by the pneumatic load, the original vibration data of this tower is collected by the three-way acceleration sensor. The acceleration amplitude and vibration frequency of this tower can be obtained by combining the spectrum analysis method with the data processing.

Measurement Point Arrangement

In the tower vibration characteristics test, the eight acceleration sensors of the tower are uniformly distributed on the leeward side of the tower. Therefore, the dynamic vibration spectrum can be obtained by a fast Fourier transform, and the corresponding frequency and acceleration amplitude of the tower vibration can be obtained by combining the spectrum analysis method. Figure 4 shows the measurement point arrangement of the tower. The X-axis of the three-way acceleration sensor is set opposite to the direction of the incoming wind speed, the Y-axis is parallel to the ground to the left, and the z-axis is perpendicular to the ground upward.

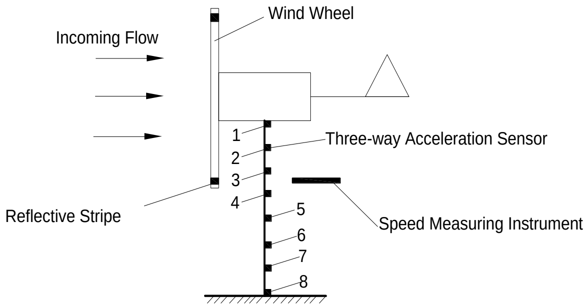

Figure 4. Wind turbine tower vibration characteristics test point layout

ANALYSIS OF EXPERIMENTAL DATA

BK Connect software was used to process the test data of the vibration characteristics of the tower of the unit. The data processing module of BK Connect performs a fast Fourier transform on the original vibration signal, and the frequency and acceleration amplitude corresponding to the tower vibration are finally obtained by using the fast Fourier transform method.

Effect Of Split Blade Tip on Tower Vibration under Rated Operating Conditions

Taking the incoming flow wind speed of 8 m/s and the speed of 600 rpm as an example, as shown in Figure 5, the vibration is the fundamental frequency of the universal tip wing tower top and bifurcating tip wing wind turbine. When the tower has the original tower top and the forked tower top blade, the difference in the base vibration frequency is less than 1 Hz, and the tower top has the same frequency at the eight measurement points. Therefore, in the standard state, the bifurcation vertex does not affect this tower vibration approximation.

Figure 6 shows the basic amplitudes of the tower of a general wind turbine and a bifurcated tip airfoil wind turbine. In the standard state, the acceleration amplitude corresponding to the base vibration of the tower of the bifurcated tip-wing wind turbine is lower than that of the general tip-wing wind turbine. The acceleration amplitude corresponding to the base vibration of the eight measuring points of the tower decreases gradually, and the peak appears at the top of the tower, and the rules of the eight measuring points are consistent. The comprehensive analysis shows that the split tip wing can effectively reduce the acceleration amplitude corresponding to the vibration of the unit tower under the designed standard operating conditions. Figure 6 shows that the bifurcation blade tip and end-wing 3 have the lowest overall acceleration amplitude, and the tower has the best vibration reduction effect.

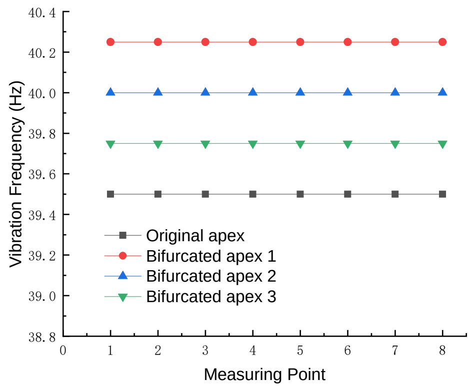

Figure 5. The fundamental vibration frequency of this tower under rated conditions

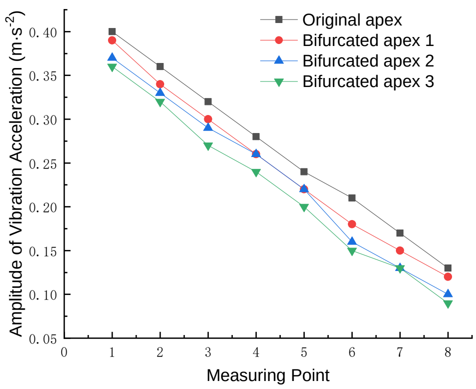

Figure 6. The fundamental vibration acceleration amplitude of this tower under rated conditions

On the other hand, the second-order data corresponding to the tower vibration of conventional airfoil and split-tip wing wind turbines are processed, and the results are similar to the basic theory. From the above processing of tower second-order vibration data, it can be seen that the effect is not obvious, but it can effectively reduce the amplitude. In summary, the eight main points of the tower are consistent. In the next section, we will explore the vibration of the tower under different operating conditions, please consider selecting one of the points for treatment.

Effect on Tower Vibration Characteristics When Pneumatic Load Law Increases

The X-axis direction of the three-way acceleration sensor is axial, and the Y-axis direction is specified radially. The test conditions of the vibration characteristics of the tower are set to be the same as the fan vibration characteristics test. Taking the analysis of tower vibration data at four measurement points of the tower as an example, the axial data of the tower are reflected in Table 3. In the process of the incoming wind speed change, the frequency of the tower vibration base axis corresponding to the general tip wing fan and the fork tip wing fan shows a regular increase trend. The results show that the vibration of the tower is greatly affected by aerodynamic load, especially the axial frequency, and the impact of the split blade tip on the axial frequency of tower vibration is more obvious.

Table 3. As the aerodynamic load law increases, the basic axial vibration frequency of the tower (Hz).

Incoming wind speed (m/s)	6(m/s)	7(m/s)	8(m/s)	9(m/s)
General leaf tip end wing	38.25	39.00	39.75	40.50
The angle of the leaf tip opening 1	38.00	38.75	40.25	41.00
The angle of the leaf tip opening 2	37.75	38.25	40.25	41.25
The angle of the leaf tip opening 3	37.50	38.75	40.00	41.25

Figure 7 shows that the amplitude of the axial acceleration corresponding to the tower vibration increases regularly with the increase of the incoming wind speed. Whether the top of the tower is the original structure or the top of the tower is a bifurcated structure, it can be seen that the basic vibration of the tower is greatly affected by the incoming wind speed, especially the axial amplitude. The comparative analysis shows that the axial amplitude corresponding to the steepening tower vibration is lower than the amplitude of the original steepening wind turbine tower. Under the four incoming wind speeds, the corresponding axial amplitude of the tower vibration with spire 1 bifurcation blade is higher than that with spire 1 original blade. The axial amplitude corresponding to the vibration of the second tower with bifurcation tip is reduced by 5.26%, 4.55%, 11.54% and 10.71%, respectively, and the axial amplitude corresponding to the vibration of the second tower with bifurcation tip is reduced by 15.79%, 13.64%, 15.38% and 19.71%, respectively. The tower and end wing of the Type 3 fan are reduced by 19.71% respectively. The axial acceleration amplitude corresponding to the foundation vibration of the fork tip wing 3 fan tower is reduced by 15.79%, 18.18%, 19.23% and 14.29%, respectively. It is concluded that the foundation vibration of the wind tower corresponding to the fork tip wing design can be effectively reduced, and the axial acceleration amplitude has an obvious effect. The results show that the tip wing of the third bifurcation blade has the best damping effect.

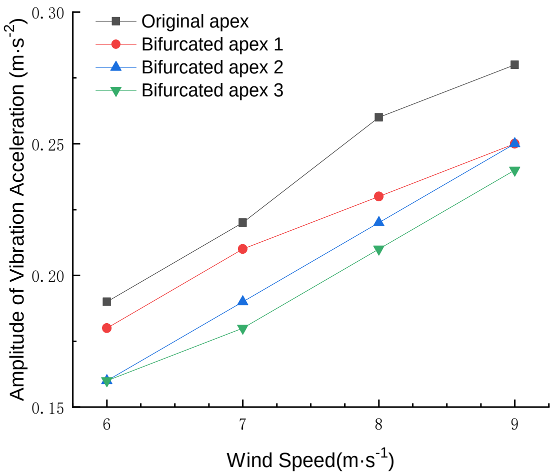

Figure 7. The incoming wind speed changes and the basic corresponding axial acceleration amplitude of the tower's first-order vibration

The basic radial frequency of tower vibration is shown in Table 4. When the incoming wind speed increases regularly, the frequency of the tower of a general wind turbine has no specific change compared with that of a forked blade tip airfoil wind turbine, and the change in amplitude is less than 1 Hz, so the influence of pneumatic load on the radial frequency corresponding to the vibration of the tower is small, and the influence of bifurcated apex on the fundamental radial vibration frequency is also small.

Table 4. The fundamental radial vibration frequency of this tower when the aerodynamic load law increases (Hz)

The incoming wind speed (m/s)	6(m/s)	7(m/s)	8(m/s)	9(m/s)
General leaf tip end wingGeneral leaf tip end wing	40.25	39.25	39.75	40.25
The angle of the leaf tip opening 1	40.25	39.75	40.25	40.25
The angle of the leaf tip opening 2	39.75	39.50	39.75	40.00
The angle of the leaf tip opening 3	40.00	39.75	39.50	40.25

According to Figure 8, the fundamental radial vibration acceleration amplitude of this tower changes insignificantly with the increase of pneumatic load, the fundamental radial vibration acceleration amplitude of this tower with an original apex wind turbine and this tower with a bifurcated apex wind turbine, the fluctuation of the data is the error is within the allowable range of wind speed on this tower fundamental radial The effect of the aerodynamic load on the fundamental radial acceleration amplitude of this tower is insignificant. Compared to the wind turbine tower with original apex, the fundamental radial vibration acceleration amplitudes of this wind turbine tower with bifurcated apex 1 were reduced by 7.41%, 14.81%, 7.69%, and 14.29% at the four incoming wind speeds, and the fundamental radial vibration acceleration amplitudes of this wind turbine tower with bifurcated apex 2 were reduced by 7.41%, 14.81%, 7.69%, and 14.29%, respectively. The fundamental radial vibration acceleration amplitudes of wind turbine towers with bifurcated apex 2 were reduced by 11.11%, 14.81%, 11.54% and 21.43%, respectively, and the fundamental radial vibration acceleration amplitudes of wind turbine towers with bifurcated apex 3 were reduced by 14.81%, 18.52%, 15.38% and 25.00% respectively. The bifurcated tip wing can effectively reduce the radial amplitude of the tower vibration, and the results show that the bifurcated tip wing 3 has the best reduction effect.

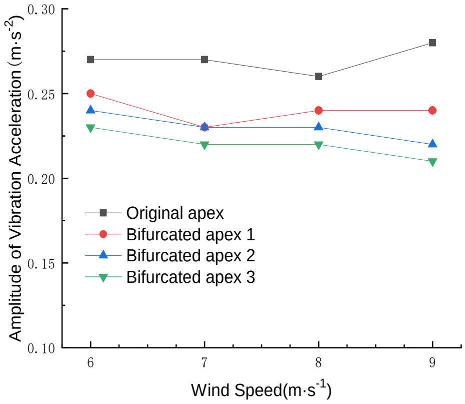

Figure 8. The acceleration amplitude of the fundamental radial vibration of this tower when the aerodynamic load law increases

In addition, data processing shows that the second-order frequency and amplitude corresponding to tower vibration satisfy the variation law. Through the above data processing of the second-order axis, radial frequency and amplitude corresponding to the tower vibration, it can be seen that the axis frequency and amplitude corresponding to the tower vibration are greatly affected when the wind speed is fixed and the incoming wind speed is changed. The influence of the radial frequency and amplitude corresponding to the vibration is small. It is obtained that the change of the outflow wind speed is the main excitation component that affects the frequency and amplitude corresponding to the axial vibration of the tower. The relative influence of the fork blade tip on the radial direction is small, but it will affect the axial vibration frequency of the tower. Compared with the original spire wind turbine tower, the axial and radial acceleration amplitudes corresponding to the vibration of the wind turbine tower after the addition of the fork tip wing are significantly reduced, which proves that the fork tip wing has an improved effect on the tower. The results show that fork-tip wing 3 achieves the best improvement.

Effect on Tower Vibration Characteristics When the Centrifugal Force Changes Regularly

The axial frequency values corresponding to the base vibration of the tower are shown in Table 5. The centrifugal load increases regularly, and the axial frequency of the tower of the general wind turbine and the tower of the wind turbine with the split blade tip and end wing is small, less than 1 Hz. It can be seen that the centrifugal load will not cause a change in the tower's axial fundamental vibration frequency. It is concluded that the effect of the split blade tip and end wing on the axial fundamental frequency of the tower vibration is low.

Table 5. The fundamental axial vibration frequency of this tower is when the centrifugal force changes regularly (Hz)

Leaf tip speed ratio	4.5	5.0	5.5	6.0
General leaf tip end wing	39.50	40.25	40.00	39.75
The angle of the leaf tip opening 1	39.75	40.50	40.25	39.75
The angle of the leaf tip opening 2	40.00	40.50	40.00	39.75
The angle of the leaf tip opening 3	39.50	40.25	39.75	40.50

The data in Figure. 9 shows that the rotational speed increases regularly, and the variation of the axial amplitude corresponding to the tower vibration is smaller than that of the fan tower with general tip wings and bifurcation blades. This result verifies that the axial amplitude corresponding to the vibration of the tower with the tip and end wing opening Angle is lower than that of the wind turbine tower with the tip and end wing co-opening Angle. The corresponding axial amplitude of the tower vibration of the bifurcated tip wing is lower than that of the ordinary tip wing wind turbine tower. Under four different working conditions, compared with the fan tower at the initial cusp, the axial amplitude corresponding to the fan tower vibration at the cusp 1 bifurcation is reduced by 3.70%, 7.14%, 7.41% and 10.71% compared with the fan tower vibration at the cusp 2 bifurcation. The axial acceleration amplitude corresponding to the base vibration of the tower belonging to the third type of fan with blade tip and end wing open Angle increased by 7.41%, 14.29%, 14.81% and 14.29% respectively, and the axial acceleration amplitude corresponding to the base vibration of the tower belonging to the fan increased by 14.81%, 17.86%, 22.22% and 17.86% respectively. Therefore, the forked tip wing can effectively optimize the acceleration amplitude corresponding to the base vibration of the tower to which the fan belongs, and the third tip wing opening Angle has the best vibration reduction effect.

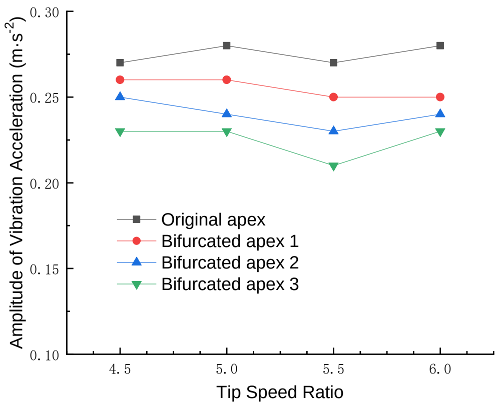

Figure 9. The acceleration amplitude of the axial vibration of this tower when the centrifugal load law increases

The radial fundamental frequency of the vibration of this tower is specifically reflected in Table 6. With the increase of the wind wheel speed, the radial frequency corresponding to the base vibration of the general tip wing and the fork tip wing increases, so the wind wheel speed is the main factor causing the variation of the radial frequency corresponding to the base vibration. Through comparative study, it is concluded that the radial fundamental vibration data of tower vibration is affected by the tip and wing of the open-angle blade.

Table 6. The radial frequency corresponds to the base vibration of the wind wheel when the centrifugal force changes regularly (Hz)

Leaf tip speed ratio	4.5	5.0	5.5	6.0
General leaf tip end wing	37.25	39.50	41.75	42.25
The angle of the leaf tip opening 1	37.00	39.25	42.00	43.00
The angle of the leaf tip opening 2	36.75	39.00	42.50	42.75
The angle of the leaf tip opening 3	36.75	39.25	42.00	43.25

According to the data law in Figure 10, as the tip speed ratio increases, the radial amplitude corresponding to the tower foundation vibration of the general tip wing wind turbine and the fork end wing wind turbine increases. It can be seen that this variation of the working condition has a great influence on the radial amplitude corresponding to the foundation vibration. According to the data processing, the radial acceleration amplitude corresponding to the base vibration of the tower with end-bifurcation type 1 is smaller than that with end-bifurcation type 2. Under the four working conditions, the radial acceleration amplitude corresponding to the foundation vibration of the tower of the bifurcating tip wing type 1 wind turbine is 10.00%, 8.33%, 7.41% and 12.90% lower than that of the bifurcating tip wing type 2 wind turbine, respectively. Forked blade tip wing type 2 decreased by 25.00%, 20.83%, 14.81% and 16.13% respectively, and forked blade tip wing type 3 decreased by 30.00%, 25.00%, 18.52% and 16.13% respectively. The results show that the split tip wing can effectively reduce the amplitude of the tower radial basis, and the split tip wing 3 has the best vibration reduction effect.

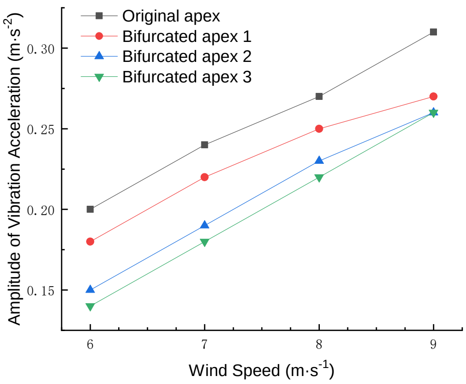

Figure 10. The acceleration amplitude of the fundamental radial vibration of this tower when the centrifugal load law increases

In addition, the axial and radial frequency and acceleration amplitude of the second-order vibration of the tower are studied, and the analysis results are similar to the basic change law of vibration. Under constant aerodynamic load and increasing centrifugal load, the axial frequency and acceleration amplitude of the fan tower vibration are analyzed. It can be seen that the centrifugal load changes regularly, the axial frequency and acceleration amplitude of the fan tower vibration have no specific change, and the radial vibration frequency and acceleration amplitude increase regularly. Therefore, the aerodynamic load is an important consideration in causing the variation of the radial frequency and acceleration amplitude corresponding to the tower vibration. The effect of the split blade tip on the axial frequency corresponding to tower vibration is not obvious, but there is an effect of term pair on the radial frequency corresponding to tower vibration. Compared with the general tip wing wind turbine tower, the axial and radial acceleration amplitudes corresponding to the vibration of the split tip wing wind turbine tower are significantly reduced. This proves that the bifurcation tip wing has a good optimization effect on vibration reduction of the tower, and the third type of blade tip wing opening Angle has the best improvement effect.

CONCLUSION

To investigate whether the split tip end wing can improve the vibration characteristics of the wind turbine tower, the vibration characteristics of the wind turbine tower were tested and the obtained data were sorted out:

1) The test results of the vibration characteristics of wind turbine towers show that the bifurcated apex can reduce this tower's fundamental, second-order axial and radial vibration acceleration amplitude. Under the rated operating conditions, the axial vibration acceleration amplitude of the tower base can be reduced by 11.54% ~ 19.23%, and this tower's fundamental radial vibration acceleration amplitude by 7.69% -15.38%. The bifurcated apex 3 blade has the best effect in reducing the vibration acceleration amplitude.

2) It is found that the aerodynamic load is an important consideration in changing the axial frequency and acceleration amplitude corresponding to the tower vibration, and the centrifugal force change is an important consideration in changing the radial frequency and acceleration amplitude corresponding to the tower vibration.

3) The opening Angle of the split tip and end wing is an important consideration in improving the vibration characteristics of the wind turbine. In the range of 0°-90° opening Angle, the larger the opening Angle is, the better the improvement effect on the vibration of the split tip end wing wind turbine is.

4) Bifurcating blade tip and end wing can improve the vibration of wind turbine tower, and it is found that the vibration reduction effect of bifurcating blade tip and end wing 3 is the best. The relevant research results provide a new idea for the research of wind turbine vibration reduction.

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