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Numerical Simulation of Galloping Characteristics of Multi-Span Iced Eight-Bundle Conductors

Ding Shunli[1†], Cai Mengqi[2,3†], Tian Bowen[1†], Liang Junhao[1†], Zhou Linshu[4†], Wu Chuan[5†], Huang Hanjie[6†] and Liu Jun[7†]*

[1]School of Mechanical Engineering, Chengdu University, Chengdu, China, [2]School of Architecture and Civil Engineering, Chengdu University, Chengdu, China, [3]Failure Mechanics and Engineering Disaster Prevention Key Laboratory of Sichuan Province, Sichuan University, Chengdu, China, [4]State Grid Sichuan Integrated Energy Service Co., Ltd., Chengdu, China, [5]Henan Electric Power Research Institute, Zhengzhou, China, [6]China Aerodynamics Research and Development Center, Mianyang, China, [7]School of Mechanical and Electrical Engineering, Southwest Petroleum University, Chengdu, China

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****Correspondence:***
Cai Mengqi
mq.cai@foxmail.com

[†]These authors have contributed equally to this work

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In this article, the numerical model of the multi-span iced eight-bundle conductor is established using the nonlinear finite element method, the galloping of the line under different parameters is simulated, and the tension in the galloping process is analyzed. Based on the aerodynamic characteristics and galloping characteristics of conductors, the galloping modes, frequency characteristics, vibration amplitudes, and galloping orbits of multi-span lines under different wind velocities, span lengths, ice shape, and number of spans are analyzed, compared with those of single-span lines. It is demonstrated that there are differences in galloping characteristics between multi-span transmission lines and single-span lines. Each span of the transmission line is different, so it should be fully considered in the research of galloping prevention and control technology.

Keywords: iced eight-bundle conductors, multi-span transmission line, galloping characteristic, numerical simulation, conductor tension

INTRODUCTION

Aiming at solving the problem of unbalanced power supply and demand, the 1,000 kV ultra-high voltage (UHV) bundle conductor transmission line has been launched (Jafari et al., 2020; Cai et al., 2019a). The so-called galloping refers to the phenomenon of self-excited vibration of low frequency and large amplitude generated by the wind load when the conductor forms an asymmetric circular section after freezing in winter (Li et al., 2021a; Min et al., 2021). Conductor galloping usually occurs for an extended period. Therefore, it is harmful for the operation of the power transmission system, and it is liable to cause major accidents such as alternating flashover, power failure, failure of conductors or even conductor disconnection, metal damage, and tower toppling (Liu et al., 2021a). In recent years, serious cases of iced transmission tower lines collapsing under wind load have been reported in Hunan and Anhui provinces, China (Liu et al., 2019). Therefore, anti-galloping is a hot issue in the field of electrical and civil engineering.

In recent years, many experts have studied the problem of galloping transmission lines. Yan et al. (2016) proposed the numerical method to investigate the galloping characteristics of iced-quad bundle conductors. Cai et al. (2015) studied the variation of aerodynamic coefficients varying with angle of wind attack by the finite element method (FEM). The effectiveness of the aerodynamic coefficients determined by numerical simulation in the study of galloping characteristics and anti-galloping technology of overhead transmission lines is verified. By using ABAQUS software, Hu et al.

(2012) defined a new unit by the pneumatic loading unit for ice conductors, the being studied by the numerical method under different wind velocities and line structure parameters of quad-bundle conductor ice galloping. Lu et al. (2019) simulated the galloping of the iced quad-bundle conductor according to the wind tunnel test results. They concluded the impact of wind velocity, ice thickness, conductor type, bundle spacing, and bundle number on the aerodynamic parameters and conductor galloping. Matsumiya et al. (2018) conducted aeroelastic tests in a wind tunnel by using a rigid-body section model of quad-bundle conductors. Liu et al. (2020a) and Liu X. H. et al. (2021) obtained the aerodynamic coefficients of the conductor through a wind tunnel test and studied the stability and galloping characteristics of the iced quad-bundle conductor. Cai et al. (2019b) used nonlinear FEM to analyze the galloping of the sector-shape iced eight-bundle conductor under different wind velocities, span length, and angles of wind attack. Zhou et al. (2018) studied the effects of interphase spacer on the galloping of the iced eight-bundle conductor. Zhou et al. (2016) conducted wind tunnel tests to simulate the galloping of iced eight-bundle conductor segment and studied the galloping behaviors under different parameters. Cai et al. (2020) numerically simulated the galloping behaviors of a D-shape iced six-bundle conductor in the test line under a random wind field. Lou et al. (2021) studied the effects of ice shape and roughness on iced conductors galloping. Liu et al. (2009) studied the nonlinear numerical simulation method of galloping of iced conductors, proved the effectiveness of this method, and found a new possible galloping mode. Liu et al. (2020) compared and analyzed the stability of the iced conductor under the action of uniform and turbulent wind. Kim and Sohn. (2018) simulated the galloping of elliptical and triangular iced sections through wind tunnel tests. Talib et al. (2019) proposed a new dynamic model for the simulation of power-transmission-line galloping. Due to the continual presence of the galloping phenomenon and the great harm which could cause, Oh and Sohn. (2020) analyzed conductor galloping through the study of stability of transmission line. Furthermore, because of the complex aerodynamic characteristics of the eight-bundle conductor and the high cost of the tests required to simulate the galloping, there is no research on the multi-span eight-bundle conductor in the available literature.

In this article, the galloping law of a 1000 kV multi-span iced eight-bundle conductor and the characteristics of the galloping are analyzed. The difference between a multi-span iced eight-bundle conductor and a single-span iced eight-bundle conductor is compared. The research results provide the important basis for the research of transmission line anti-galloping technology.

TYPICAL LINE SECTION AND FINITE ELEMENT MODEL

Wind-driven wet snow may pack onto the windward sides of conductors, forming a hard, tenacious deposit with a fairly sharp leading edge. The resulting ice shape may permit galloping. Combined with actual observation, a crescent shape can be generalized with respect to the great variety of the natural heavy ice shape (Hu et al., 2012; Yan et al., 2016). The aerodynamic forces of bundle conductors are the foundations of the analysis of the galloping of transmission lines (Liu et al., 2009). Herein, the aerodynamic coefficients of crescent-shape iced eight-bundle conductors are experimentally measured by wind tunnel tests.

The three-span and five-span iced eight-bundle lines are the main research objects. The two lines with the span length of 200 and 400 m and the sub-spans of each span are the same. The conductor model is 8 × LGJ-400/50, and the diameter of the sub-conductor is 30 mm. The model of the spacer is FJZ-400, each with a mass of 8.5 kg. The length of the suspension insulator string is set to be 3 m. Assuming that the conductor ice is a 12 mm crescent-shape ice, the initial angle of wind attack is 60°.

The physical parameters of conductors and ice are listed in **Supplementary Table S1**. The cross section of the iced conductor is simplified as a circular section when the galloping of the iced conductor is simulated by ABAQUS software. It is noted that the axial rigidity, torsional rigidity, mass per unit length, moment of inertia of the equivalent cable and those of the original cable should be equal, which can be expressed as follows:

$$\begin{aligned} E'\pi d'^2 \big/ 4 = EA; \quad G'\pi d'^2 \big/ 32 = GI \\ \rho'\pi d'^2 \big/ 4 = \mu; \quad \rho'\pi d'^4 \big/ 32 = J \end{aligned} \tag{1}$$

where E', G', ρ', and d' are, respectively, the elastic modulus, the shear modulus, the density, and the diameter of the equivalent cable, which can be obtained by solving **Eq. 1** whose right hands are the corresponding quantities of the original iced conductor. The physical parameters of the conductors and ice are listed in **Supplementary Table S1**.

In the FEM model, according to the previous research results (Hu et al., 2012), the accuracy requirement can be met when the length of the conductor element is about 0.5 m, and the conductor is selected as the cable element, which is obtained by releasing the bending degrees of freedom of the nodes of the spatial Euler beam element (Yan et al., 2016). The spacer can be simplified into a regular octagonal frame, simulated by spatial beam elements, and the suspension insulator string is also simulated by beam elements.

The upper end of the suspension insulator string in the model is suspended on the tower, and the lower end of the suspension insulator string is connected only to the sub-conductor. The influence of the tower on the suspension insulator string is ignored. Meanwhile, the constraints of three rotational degrees of freedom and sets of three planes are released by the upper end of the suspension insulator string. A fixed constraint with six degrees of freedom is set at both ends of the conductor. The established FEM model of the three-span and five-span iced eight-bundle conductor of 200 m span lines is shown in **Supplementary Figure S1**. For the convenience of comparison and analysis, the galloping characteristics of single-span lines are also simulated and analyzed.

The influence of the initial axial tension in the main and side cables on the element stiffness matrix cannot be ignored. In addition, the cable sags due to its own weight, resulting in a certain decrease or loss of its elastic modulus. In order to consider the influence of cable sag, the concept of equivalent elastic modulus is used to modify the elastic modulus of cable. The equivalent modulus of elasticity generally adopts the E_{Ernst} formula:

$$E_{\mathrm{Ernst}} = \frac{E}{1 + \frac{(ql)^2}{12T^3} AE} \tag{2}$$

where E_{Ernst} is the equivalent elastic modulus of the material; E is the elastic modulus of the material; q is the weight of the unit length of the cable; l is the projection length of the cable element in the horizontal direction; A is the cross-sectional area of the cable, and T is cable tension.

The numerical simulations were carried out on a personal computer Dell Studio Desktop D540, and each job took about 5 hours to arrive at a steady result. To speed up the efficiency, several jobs were submitted simultaneously. The dynamic implicit analysis is used in the numerical method. The dynamic responses of the transmission line with different damping ratios in different directions are analyzed by ABAQUS with the user-defined cable element. The damping ratios ξ_{z1}, ξ_{y1}, and $\xi_{\theta 1}$, in horizontal, vertical, and torsional directions, are set to 0, 0.5, and 2%, respectively, determined and verified by Zhou et al. (2018). Considering the efficiency of the numerical simulation, the time step is set to 0.01.

ANALYSIS OF DYNAMIC CHARACTERISTICS OF ICED CONDUCTORS

For the sake of understanding the galloping characteristics of the iced conductor, the ABAQUS software is used to calculate the dynamic characteristics of each line. The vibration directions are the frequencies corresponding to the low-order modes in the vertical, horizontal, and torsional directions. The typical low-order modes of the three-span iced eight-bundle conductor with a span length of 200 m are shown in **Supplementary Figure S2**. The low-order natural frequency values summarized by the modes and corresponding frequencies are listed in **Supplementary Tables S2, S3**. From **Supplementary Figure S2**, it can be found that the multi-span line has the phenomenon of double frequency, and the wave number of conductors increases with the increasing of frequency.

The galloping characteristics depend on the mode and natural frequency of the transmission line, which can be obtained from the results in **Supplementary Tables S2, S3**. Compared with the single-span line, the natural frequency of the multi-span line is lower, which is less than or equal to the natural frequency of the single-span line, and the phenomenon of repeated frequency appears. In addition, the low-order natural frequencies of the third span and the fifth span multi-span line are very close. In addition, it can be found from **Supplementary Table S3** that the vertical galloping of the 400 m single-span line starts directly from the double half-wave, which is related to the structure of the conductor. Based on the results of the dynamic characteristics of multi-span line, combined with spectrum response analysis, the galloping mode of the multi-span lines can be judged.

ANALYSIS OF GALLOPING CHARACTERISTICS OF MULTI-SPAN ICED CONDUCTORS

This section studies the characteristic analysis of multi-span iced conductors-galloping. Firstly, a theoretical analysis of the galloping of the line is carried out. Because the iced conductors are mostly of irregular shapes, not only resistance but also lift and moment are generated by the wind load. The force F_D, lift F_L, and moment M acting on a unit length of the non-circular cross section iced conductor can be determined by the following formula (Cai et al., 2020b):

$$F_D = \frac{1}{2} C_D(\alpha)\rho U^2 d;\ \ F_L = \frac{1}{2} C_L(\alpha)\rho U^2 d;\ \ M = \frac{1}{2} C_M(\alpha)\rho U^2 d^2 \tag{3}$$

where ρ is the air density, U is the wind velocity, and d is the diameter of the conductor. $C_D(\alpha)$ is the drag coefficient, $C_L(\alpha)$ is lift coefficient, and $C_M(\alpha)$ is moment coefficient of the iced conductor, which are related to the angle of wind attack α. The change of angle of wind attack during the movement of the iced conductor can be determined by the following formula:

$$\alpha \approx \theta - \left(\frac{R\dot{\theta} + \dot{V}}{U} \right) \tag{4}$$

where θ, R, $\dot{\theta}$, and $\dot{V}$ are, respectively, the torsion angle, characteristic radius, torsion angular velocity, and vertical velocity of the iced conductor. In the numerical simulation of this article, the aerodynamic coefficients of each sub-conductor of the iced eight-bundle conductor measured by the wind tunnel test varies with the angle of wind attack.

Galloping Characteristics of the Conductor

The wind velocity of 8 m/s, the thickness of crescent-shaped ice is 12 mm, the initial angle of wind attack is 60°, and each span length is 200 m. The corresponding numerical simulation of the galloping process of the three-span iced eight-bundle conductor is carried out. The motion state of the three-span multi-span iced eight-bundle conductor at different times is shown in **Supplementary Figure S3**. According to **Supplementary Figure S3**, the three-span iced eight-bundle conductor with a span of 200 m has a single-half-wave galloping model for each sub-span, and galloping occurs in each sub-span.

The displacement time and galloping trace of the midpoint of sub-conductor 1 in each span are shown in **Supplementary Figures S4, S5**. The galloping amplitude is listed in **Supplementary Table S4**. It can be seen from **Supplementary Figure S4** that the galloping displacement of each span is different and slight fluctuations. Referring to **Supplementary Figure S5**, the traces of the midpoints of each span are close to an elliptical limit cycle. In the 200 m multi-span line, the vibration of the conductors of each span under the wind velocity of 8 m/s is all vertical galloping. It can be seen intuitively from **Supplementary Table S4** that there are also significant differences in the galloping amplitudes of the conductors in each span in the 200 m span multi-span line. The third span of vertical displacement is the largest, but the middle span of the torsional angle is the largest (Hung et al., 2014).

Galloping Mode and Frequency Characteristics

The galloping mode and frequency characteristics of the conductor in the galloping process are important parameters for the research of galloping prevention and control technology. Through the displacement response spectrum of the conductor, combined with the mode and natural frequency of the line (**Supplementary Tables S2, S3**), the vibration mode and frequency characteristics of galloping are analyzed. The displacement spectrum analysis is carried out according to the displacement time history response of **Supplementary Figure S4**, and the data results are shown in **Supplementary Figure S6**. It can be seen that the spectra of vertical displacement, horizontal displacement, and torsional angle of each conductor all have peaks at the first-order natural frequency of 0.286 Hz, in which the vibration frequency of torsion angle has four peaks, which are close to 0.286, 0.411, 0.697, 0.858 Hz, which correspond to the low-order natural frequencies of (**Supplementary Table S2**) the 200 m multi-span and single-span iced eight-bundle conductors.

THE INFLUENCE OF DIFFERENT PARAMETERS ON THE GALLOPING OF MULTI-SPAN ICED CONDUCTOR

Effect of Span on Galloping

In this section, the effect of galloping of the iced eight-bundle conductor under different span lengths is studied. The span condition of conductors in *Galloping Characteristics of the Conductor* is changed to 400 m. The remaining parameters are in accordance with those of the previous conductors. The galloping of the three-span iced eight-bundle conductor is numerically simulated. The galloping shape of an iced eight-bundle conductor of three-span at different times with a span length of 400 m is shown in **Supplementary Figure S7**. Compared with the motion state of Section 4.1 200 m three-span iced eight-bundle conductor, the conductor galloping mode has changed, and the whole span galloping and sub-span vibration have taken place on the line. The three-span iced eight-bundle galloping with a span of 400 m has a double half-wave, which is no longer a single half-wave galloping mode.

The time history of midpoint displacement of each sub-conductor 1 is shown in **Supplementary Figure S8**, and the galloping amplitude is listed in **Supplementary Table S5**. As can be seen from **Supplementary Figure S8**, the horizontal displacement of the midpoint of each sub-conductor 1 remains basically unchanged, and the vertical displacement of the middle span is larger than that of both sides, indicating that the galloping of the middle span is more intense. Compared with **Supplementary Figure S4**, the galloping of the conductor with span length of 400 m is not as stable as that of 200 m. As can be seen from the results in **Supplementary Table S5**, the vertical amplitude, horizontal amplitude, and torsional angle are all large in the middle span, and the galloping amplitudes of the first span and the third span are similar.

It shows the mid-point displacement spectrum of the wind velocity of 8 m/s span 400 m three-span iced eight-bundle conductor 1 in **Supplementary Figure S9**. Combined with the results of **Supplementary Table S3** and **Supplementary Figure S9**, it can be found that the in-plane vibration frequency and out-of-plane vibration frequency of each span have a peak near the natural frequency 0.153 Hz of one half-wave, it is indicated that the vibration mode is one half-wave. The torsional vibration frequency of each span has the maximum peak near the natural frequency 0.269 Hz of the single half-wave; that is, the vibration mode is dominated by the one half-wave. Moreover, there is also a small peak value in the plane of the two spans, which is close to the natural frequency of 0.285 Hz, and its corresponding mode is double half-wave. According to the motion form of conductor galloping, the galloping mode on both sides of the three 400 m multi-span transmission line is mainly double half-wave, and there is an obvious single half-wave, while the middle span is mainly one half-wave. It is galloping mode has changed compared with the 200 m three-span line, which indicates that the larger the span, the more complex the conductor galloping mode. As can be seen from **Supplementary Figure S9C**, the horizontal angle spectrum is more complex, and the galloping will excite multiple frequencies.

Effect of Wind Velocity on Galloping

Wind excitation is the direct cause of conductor galloping, which will cause galloping under the stable action of wind velocity of 4 m/s~20 m/s. In this section, the influence of wind velocity on galloping is studied, and the galloping response of the 200 m three-span iced eight-bundle conductor at wind velocity 12 m/s is simulated and compared with the galloping response at 8 m/s wind velocity given in *Galloping Characteristics of the Conductor*.

The galloping pattern of the three-span iced eight-bundle conductor with a wind velocity of 12 m/s and a span of 200 m at different times is given in **Supplementary Figure S10**. Compared with **Supplementary Figure S3** in *Galloping Characteristics of the Conductor*, the galloping mode of the conductor has changed. The galloping mode on both sides of the 200 m multi-span changes from a single half-wave to one half-wave or double half-wave, while the middle span is still one half-wave.

Supplementary Figure S11 shows the time history of midpoint displacement of each sub-conductor of the three-span iced eight-bundle conductor with span length of 200 m in 12 m/s. Compared to the lower wind velocity length of 8 m/s, it is obvious that the galloping is unstable, and there are wave in the upper and lower limits of vertical amplitude, horizontal amplitude, and torsion angle of each span, which demonstrates that the galloping of the conductor is more unstable with the increasing of wind velocity. In addition, it can be seen that the greater the wind velocity, the greater the vertical amplitude, horizontal amplitude, and torsion angle of the conductor, which shows that the effect of wind velocity on galloping is very significant and intense.

The spectrum at the midpoint displacement of each span at 12 m/s wind velocity is illustrated in **Supplementary Figure S12**. The peak value of the displacement spectrum of each span appears near 0.358 Hz, and there are multiple peaks. According to the results of **Supplementary Table S2**, the wind velocity is changed, and the galloping is still dominated by a single half-wave. However, the increasing of wind velocity will increase the galloping amplitude and make the circuit more unstable.

Effect of Initial Angle of Wind Attack on Galloping

Wind excitation is another necessary condition for transmission line galloping. Different wind velocities will affect the aerodynamic state, thus affecting the conductor galloping. Meanwhile, the size and shape of the galloping of a section of the line are also determined by the angle between the wind and the conductor axis, that is, the initial angle of wind attack. The galloping amplitudes of a 200 m three-span iced eight-bundle conductor under several typical angles of wind attack are depicted in **Supplementary Table S6**. It can be seen from the table that, with the increasing of angle of wind attack, the greater the galloping amplitude, the greater the vertical displacement, horizontal displacement, and torsional angle. When the included angle is 0°, that is, when the wind direction is parallel to the axis of the conductor, the possibility of galloping is the least, and there is basically no vibration. When the initial angle of wind attack is 90°, the lift coefficient of the conductor decreases and tends to 0, so it is difficult to cause galloping. The difference between the amplitudes of 30°and 60°is obvious. Therefore, the initial angle of wind attack has a great influence on the galloping of the conductor. Referring to the aerodynamic curve of an iced eight-bundle conductor obtained in reference (Hartog, 1932; Nigol et al., 1977), it is known that galloping may occur in the range of 60° using Den Hartog theory.

Effect of the Number of Spans on Galloping

This section studies the effect of the number of spans on galloping, simulates the galloping of the five-span iced eight-bundle conductor with 200 m at the wind velocity of 8 m/s, and compares it with the galloping of the three-span iced conductor with the span length of 200 m in *Galloping Characteristics of the Conductor*.

Supplementary Figure S13 shows the galloping pattern of the five-span iced eight-bundle conductor under wind velocity of 8 m/s at different times. Compared with the results of the three consecutive spans in *Galloping Characteristics of the Conductor*, the galloping pattern of the conductor is the same, and each span is a single half-wave.

Supplementary Figure S14 shows the time history of the mid-point displacement of each sub-conductor 1 of the five-span iced eight-bundle conductor with a wind velocity of 8 m/s and a span of 200 m, and the displacement spectrum of the middle point of each sub-conductor 1 is shown in **Supplementary Figure S15**. From this, we can know that the vibration amplitude of the five-span transmission line is slightly smaller than that of the third span transmission line. Compared with the displacement time history of the third span, it can be seen clearly that the vibration amplitude of the fifth span is more unstable, the upper and lower limits are unstable, and there are slight fluctuations. Meanwhile, the vertical displacement of the middle span is larger than that of the two sides. It can be seen clearly from the displacement spectrum that the vertical displacement of each span has many peaks, which are concentrated near 0.286 Hz. Compared with the third span, the fifth span is still dominated by a one half-wave, but the galloping is more chaotic.

Supplementary Figure S16 shows the galloping trace of the midpoint of each sub-conductor 1. It can be seen that the motion trace is still close to the oval limit cycle, and the ellipse trace on both sides is fuller, indicating that the horizontal galloping on both sides is larger, and the galloping trace in the middle span is slender, indicating that the galloping in the middle span is more complex. The vertical displacement of the middle span is also larger.

Effect of Ice Shape on Galloping

Different ice types will cause aerodynamic differences. When the temperature is low (−8°C ~ −11°C) and the rainfall is low (Liu et al., 2020b), the typical crescent-shape ice is easy to form because the small water droplets coagulate upon contact with the conductor surface. When the temperature is high and the rainfall is high, the water droplets cannot reach the contact point when they reach the surface of the conductor. In this case, if the wind velocity is low, it is easy to form typical sector-shape ice.

In order to investigate the galloping of iced eight-bundle conductors under different ice shapes, the wind velocity is 8 m/s, the sector-shape ice thickness is 18 mm, the initial angle of attack of ice is 140° (Cai et al., 2020b), the 200 m three-span conductor is discussed, and the galloping characteristics are numerically simulated. The galloping state of a 200 m three-span iced eight-bundle conductor at different times is shown in **Supplementary Figure S17**. Compared with the motion state of a 200 m three-span crescent-shape ice eight-bundle conductor in *Galloping Characteristics of the Conductor*, the galloping mode of the conductor is mainly single half-wave, and there are double half-waves. There are galloping among each span of sub-conductors, and the galloping form is also different, which demonstrates that the sector-shape ice galloping under the same conditions is more disordered.

The time history of displacement and the response spectrum of the midpoint of each span of sub-conductor 1 are shown in **Supplementary Figures S18, S19**. Compared with the crescent crescent-shape, the galloping tends to be stable. However, the upper and lower limits of the vertical amplitude, horizontal amplitude, and torsional angle of each span fluctuate slightly, which is not as regular as the galloping amplitude of the crescent-shape shape. Compared with the crescent-shape ice eight-bundle conductors, it can be found that the vertical amplitude, horizontal amplitude, and torsional angle of the sector-shape ice conductor are larger than those of crescent-shape ice, and the torsional angle changes violently. It can also be seen from the spectrum that the frequency of torsional angle excites multiple peaks, which shows that sector-shape ice is more prone to galloping than crescent-shape ice, and the destructive force of galloping is stronger.

The galloping trace of the midpoint of each span sub-conductor 1 is presented in **Supplementary Figure S20**. It can be seen that the galloping trace is still close to the elliptical limit cycle. The change of the three-span galloping trace is the same as that of the crescent-shape, but it can be clearly compared that the sector-shape trace is rougher, and there is no smoothness of the crescent-shape, which also shows that the sector-shape ice galloping is more intense and irregular. In addition, the difference in galloping amplitude between sub-conductors of each span is small, which is due to the whole span oscillation of the line due to the reinforcement of spacers during conductor galloping.

The existing research on iced conductor galloping shows that the wind velocity has an obvious influence on conductor galloping. In this section, the FEM is used to compare the influence of wind velocity on the galloping of the sector-shape ice eight-bundle conductor. **Supplementary Table S7** compares in detail the galloping amplitude at the midpoint of the span line under the different wind velocities (4 m/s and 8 m/s) of the sector-shape ice eight-bundle conductor with angle of wind attack 140° under the 200 m span (Cai et al., 2020a). It can be seen from the table that, with the increasing of wind velocity, the galloping mode of the conductor changes significantly, and the vertical amplitude and horizontal vibration amplitude increase gradually. This is consistent with the conclusion of crescent-shape under the influence of wind velocity. The greater the wind velocity, the greater the galloping amplitude and the more complex the galloping mode.

ANALYSIS OF CONDUCTOR TENSION

Tension Change in the Process of Conductor Galloping

Conductor galloping seriously threatens the safe and stable operation of transmission lines. The main threats of galloping to the transmission lines are mechanical damage and electrical faults of the line, which are closely related to the mechanical strength and electrical performance of the line itself (Zhang et al., 2000). In terms of mechanical strength, the additional tension caused by galloping on the conductor must be tested. Therefore, the study of dynamic tension important to include in the study of galloping.

The tension analysis of the two terminals of the three-span iced eight-bundle conductor under the 8 m/s wind velocity is shown in **Supplementary Table S8**. Because the position of each sub-conductor has a certain offset, there is a slight difference in the tension of the eight sub-conductors. Meanwhile, the tension of each conductor at the left and right ends is not the same but also has a certain deviation. The longitudinal comparison shows little difference in the average value of the eight sub-conductors between the left and right ends, indicating that the tension between the two ends is balanced. **Supplementary Figure S21** shows the tension analysis of each sub-conductor at the left end in different periods. It can also be seen from the figure that the tension of the eight sub-conductors in different periods is very similar, with slight changes, but the overall difference is small. This shows that the damage of line galloping to the tower comes from long-term fatigue damage.

Adaptability Analysis of Simplified Formula for Galloping Amplitude Traverse

This section contains a comparative analysis and analyzes the existing theoretical simplification and formula correction for calculating the galloping amplitude of conductors based on the results of numerical simulation (Liu et al., 2021c). The comparison between the calculated values of the vertical amplitude of the improved formula and the results of numerical simulation are illustrated in **Supplementary Table S9**.

Based on the energy balance method, Hunt and Richards gave a simplified formula for calculating the amplitude (peak-peak) of conductor galloping (Hunt and Richards, 1969):

$$A_{max} = \frac{0.26V}{f} \tag{5}$$

where V is the wind velocity and f is the natural frequency of the conductor.

Equation 5 shows that the galloping amplitude of the conductor is directly proportional to the wind velocity. However, it is inversely proportional to the natural frequency of the conductor. The natural frequency of the conductor decreases with the increasing of the number and length of the span, so the result shows that, in **Supplementary Table S8**, the vertical amplitude of the conductor with the span length of 400 m is larger than that of the conductor with the span length of 200 m. The modified formula of reference is defined as (Zhao, 2014)

$$A_{max} = \frac{0.18V}{f} + 0.34 \tag{6}$$

As can be seen from the table below (**Supplementary Table S9**), the modified formula greatly improves the calculated value of the vertical amplitude of the conductor galloping (Rossi et al., 2020). However, from the relative error, it can be seen that there is still a big gap between the amplitude calculated by the individually modified formula and the numerical simulation. As the galloping of transmission lines is very complex and there are many factors affecting galloping (Liu et al., 2021d; Liu et al., 2021e), it is very difficult to obtain a formula to accurately calculate the vertical amplitude of galloping in order to be consistent with the actual numerical simulation (Li et al., 2021b).

CONCLUSION

In this article, the galloping process of the conductor is simulated and analyzed under different span lengths, span numbers, wind velocities, and initial angle of wind attacks using FEM. Finally, the tension at both ends of the conductor is numerically simulated. Based on the dynamic analysis and dynamic response results of the line, the galloping mode, frequency characteristic, vibration amplitude, galloping trace, and tension analysis of the line are studied, and the following conclusions are obtained. Those conclusions are as follows:

1) Compared with single-span transmission lines, the natural frequency of multi-span transmission lines is lower, and the number of span has less effects on the natural frequency. The initial angle of wind attack has a significant influence on the conductor galloping, and the large amplitude galloping is most likely to occur under the angle of wind attack of 60°.
2) As span length increasing the galloping half-wave number of the multi-span line increases, the galloping becomes more complex. The galloping mode of the two sides of the multi-span line changes, with the wind velocity increasing, in which the galloping amplitude also increases.
3) With the increasing of the number of spans, the difference of the galloping mode between each span decreases, the vertical displacement has multiple peaks, and the galloping is more disordered. The vertical vibration amplitude of the middle span of the multi-span transmission line is larger than that of the two sides, and the horizontal displacement and torsion angle of each span has little difference.
4) Under the same conditions, sector-shape ice conductors are more prone to galloping than crescent-shape ice conductors. Because the tension at both ends of the conductor is similar, the galloping modes on both sides of the multi-span line are similar.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. Among them, DS is mainly responsible for numerical simulation and article writing; CM is responsible for providing ideas for project implementation; TB and LJ participate in processing some data; ZL and HH provide technical consulting services, and WC and LJ provide article modification opinions.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.812367/full#supplementary-material

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