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Galloping Response and Graded Early Warning of Ice Covered Transmission Lines under Combined Wind and Rain Excitation

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Abstract: Ice covered transmission lines are prone to large low frequency self excited vibrations under wind, threatening grid safety. To study galloping under wind and rain and to build a graded warning method, this work models a two tower three span 110 kV line using APDL, generates fluctuating wind via linear filtering, and adds a rain load model for combined wind rain excitation. Displacement and spectral responses under various wind speeds and angles identify the critical wind speed for galloping onset and show amplitude saturation. Results show wind speed as the key trigger; beyond a critical range, the system jumps from stable equilibrium to self excited instability with a sharp displacement increase. Wind angle affects galloping intensity through the normal wind load, while transverse and vertical frequencies lock to low order modes with strong coupling and elliptical paths, indicating full span global vibration. Based on displacement jumps, critical wind speeds, and sensitive angles, a three level warning system is proposed, offering a composite criterion for quantitative warning and engineering control of galloping disasters.

Keywords: Transmission lines; wire dancing; wind and rain combined load; early warning indicator

1 Introduction

Transmission lines serve as the main artery of electric power systems, and their

safe and stable operation is directly critical to national economic development and the normal functioning of social production and daily life [1-4]. As the scale of China's power grid continues to expand and extreme weather events become more frequent, galloping of transmission lines has emerged as a major threat to the security and reliability of grid operations. Galloping is a self-excited, low-frequency, large-amplitude vibration of ice-accreted conductors under wind excitation, with oscillation amplitudes that may reach tens to even hundreds of times the conductor diameter and durations ranging from several hours to tens of hours. Consequently, failures such as phase-to-phase flashovers, fatigue fractures of fittings, damage to insulator strings, and instability of tower structures occur repeatedly, resulting in substantial economic losses and significant social consequences [5, 6].

From a mechanical perspective, conductor galloping is a typical nonlinear fluid structure interaction problem, the essence of which lies in the negative damping effect induced by the asymmetric aerodynamic profile of ice accreted conductors [7]. When the wind speed falls within a specific range, the aerodynamic forces exerted on the ice coated conductors become phase coupled with the conductor motion, resulting in sustained energy input that triggers large amplitude self excited vibrations [8]. In addressing this physical process, researchers have conducted extensive investigations from three complementary approaches: theoretical analysis, numerical simulation, and field measurement [9-12]. However, theoretical methods often prove inadequate when dealing with nonuniform wind fields under complex terrain conditions, nonuniform ice accretion, and multi tower multi span configurations, as they struggle to accurately capture the nonlinear characteristics and spatial coupling effects inherent in the galloping process.

With the advancement of computational mechanics and high performance computing technologies, numerical simulation has become an important tool in the study of conductor galloping. The finite element method, owing to its strong adaptability to complex structural systems and loading conditions, has been widely applied in galloping response analysis of transmission tower line systems [13-15].

Conductors are commonly modeled using cable elements, beam elements, or three dimensional cable elements, while tower structures are often represented by mixed beam truss elements to reasonably capture their stiffness and strength characteristics. Studies have shown that tower line coupling effects have a significant influence on galloping amplitude and frequency, and that isolated conductor models neglecting this coupling tend to substantially overestimate the response. Consequently, integrated tower line modeling has become a consensus in the research community. In wind load simulation, the stochastic nature of fluctuating wind is characterized by power spectral density functions, and the harmonic superposition method and the linear filtering method are the two mainstream approaches, both of which can maintain good frequency domain consistency with the target spectrum [16, 17]. In contrast, the influence of rainfall loads on galloping has received relatively little attention in existing studies, with most works treating wind as the sole excitation source. As a result, a systematic understanding of conductor dynamic response characteristics under combined wind and rain actions remains lacking.

In the field of galloping early warning research, existing achievements mainly fall into two categories: statistical early warning models based on meteorological parameters and physical early warning models based on physical processes [18-21]. The former rely on long term accumulated historical galloping records and meteorological observation data to establish empirical relationships between meteorological factors such as wind speed, wind direction, temperature, and humidity and the probability of galloping occurrence. These models offer advantages in computational simplicity and operational feasibility, but their performance is constrained by data quality and regional applicability [22, 23]. The latter attempt to proceed from the underlying galloping mechanism, using real time monitoring of wind speed and conductor state parameters in combination with simplified mechanical models to judge system stability. In theory, these models possess a stronger physical foundation; however, parameter calibration and real time computation still face considerable difficulties [24, 25]. Overall, among the existing early warning indicator

systems, individual indicators such as critical wind speed, vibration amplitude, and vibration frequency each provide useful reference value, yet a systematic early warning framework that comprehensively accounts for the coupling effects of multiple factors remains lacking. In particular, threshold grading standards based on quantitative finite element simulation results have yet to be established [26, 27].

This study models a two tower three span 110 kV transmission line using three dimensional finite elements, with wind and rainfall time histories applied simultaneously under ice accretion. Fluctuating wind is generated via linear filtering to compute equivalent loads, and a rainfall model is incorporated for combined excitation. Multiple wind speeds and incidence angles are considered, and displacement responses and spectra at midspan and quarter span are analyzed to extract amplitude and critical wind speed for graded warning criteria. Inclusion of rainfall reveals nonlinear features such as displacement jumps near critical wind speed and trajectory evolution from transverse to elliptical coupling, leading to a composite criterion combining displacement thresholds and meteorological parameters. Progressive contributions are made in load modeling, mechanism understanding, and warning methods, aiming to offer a physically sound and practical reference for galloping disaster warning.

2 Finite element modeling of transmission tower line structure

2.1 Model parameters

In this study, the finite element model of an actual transmission line is established using APDL, and the wind and rainfall load data are simulated with MATLAB and then imported back into APDL for solution, from which the corresponding displacement time histories are obtained, and recommendations for galloping early warning indicators are proposed. For the three dimensional simulation, this study adopts the specifications of a real engineering project, namely a 110 kV tangent tower with a height of 27 m to the lowest cross arm, a total height of 38.3 m, a base width of 6.6 m, and section types ranging from L123x8 to L40x4, with Q235 steel as the structural material. The relevant material properties of conductors and

ground wires are provided, with a conductor span of 350 m and an insulator length of 1.5 m. A two tower three span model is adopted for analysis, and the nodes at the quarter span, midspan, and three quarter span positions of the middle conductor are examined, from which the displacement time history plots are exported. The modeling in this study mainly covers four components: transmission towers, insulators, conductors, and ground wires. Figure 2.1 presents the overall three dimensional view of the simulation model, and Figure 2.2 shows the detailed tower model.

The main material parameters of the transmission tower, insulators, conductors, and ground wires are presented in Tables 2.1, 2.2, and 2.3, respectively. Specifically, Table 2.1 lists the material parameters of the transmission tower body, Table 2.2 provides the material parameters of the insulators, and Table 2.3 gives the material parameters of the conductors and ground wires. In this study, each conductor and ground wire is divided into 20 equal segments, resulting in a total of 160 loading points that serve as the equivalent nodes for subsequent application of wind and rainfall loads. Figure 2.3 presents a schematic diagram of the conductor and ground wire discretization.

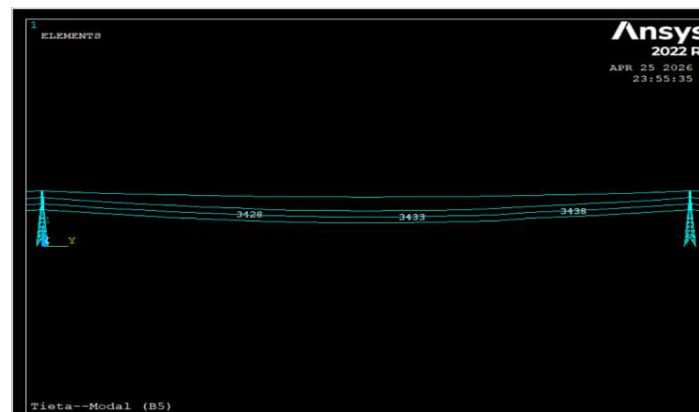
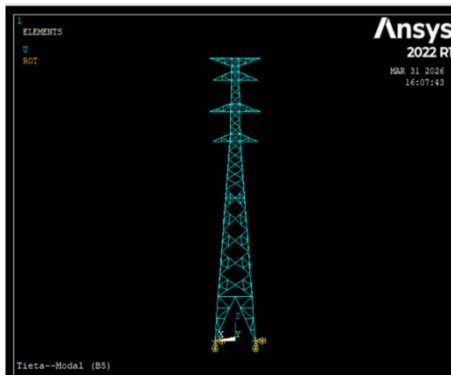
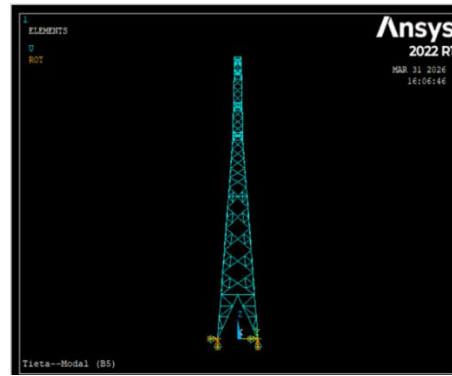


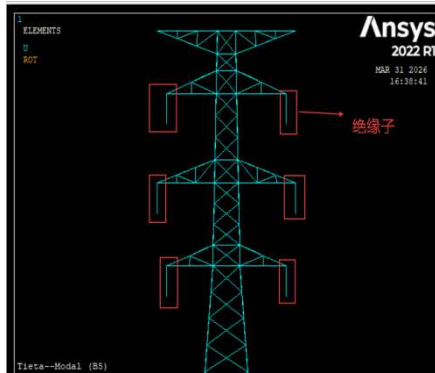
Figure 2.1 Overall transmission tower-line model.



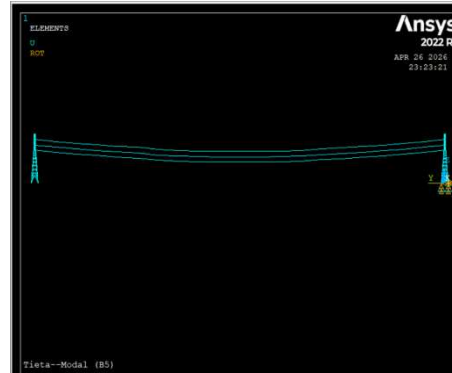
(a) Front view of transmission tower



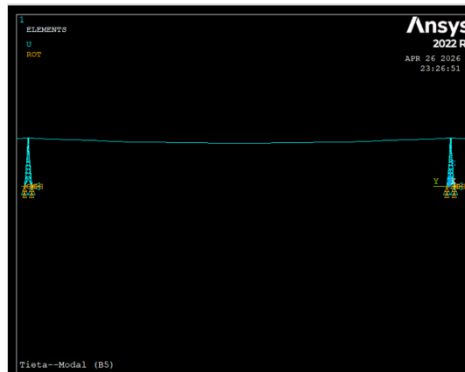
(b) Side view of transmission tower



(c) Schematic diagram of insulator



(d) Schematic diagram of conductor



(e) Schematic diagram of ground wire

Figure 2.2 Schematic diagram of transmission tower structure.

Table 2.1 Material parameters of transmission towers

Name	Material	Elastic Modulus (Pa)	Density (kg/m ³)	Poisson's Ratio
Tower	Q235e	2.1e11	7850	0.3

Table 2.2 Insulator parameters

Name	Length (mm)	Elastic Modulus (Pa)	Weight (kg)	Cross-Section (mm ²)
Insulator	1500	5e9	23	1

Table 2.3 Material parameters of conductors and groundwires

Conductor Type	Diameter (mm)	Cross-Sectional Area (mm ²)	Elastic Modulus (Pa)	Weight per Unit Length (kg/m)
Conductors	22.5	338.99	73e9	922.2
Groundwire	13	100.88	147.2e9	674.1

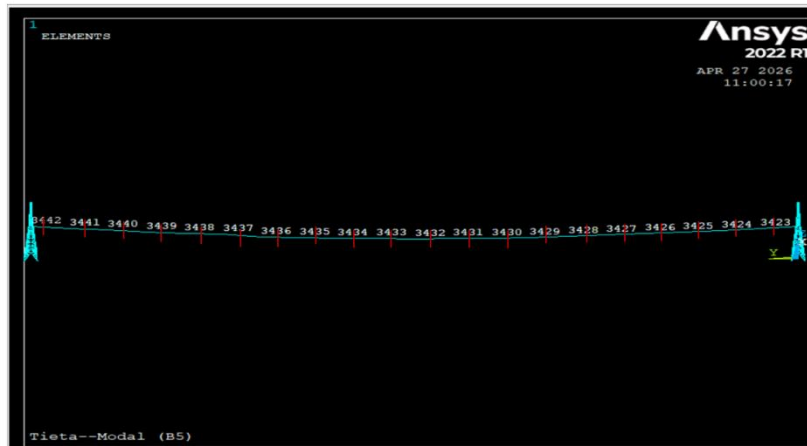


Figure 2.3 Divided diagram of conductor (ground wire).

2.2 Application of ice load

Currently, three commonly adopted methods are available for applying ice accretion loads: the additional force model method, the additional ice element method, and the density modification method. The additional force model method simulates ice accretion conditions by applying concentrated forces at selected points along the conductor. The additional ice element method utilizes finite element software to create additional elements and assign appropriate material properties to these elements, thereby enabling the simulation of ice loads on the conductor. The density modification method achieves the application of ice accretion loads directly by altering the density of the conductor material. In this study, the additional force model method is adopted to apply ice loads directly, as this approach is the simplest and most straightforward. To compare the effects of different ice accretion conditions, varying ice thicknesses are assigned along the conductor according to different spanwise positions. Specifically, for the transmission line conductor with a span length of 350 m, an ice thickness of 2 mm is applied over the first 105 m, an ice thickness of 3 mm is applied over the middle section from 105 m to 245 m, and an ice thickness of 1 mm is applied over the final 105 m. The ice load is implemented by adding concentrated forces at the corresponding elements. Figure 2.4 illustrates the application of the ice loads.

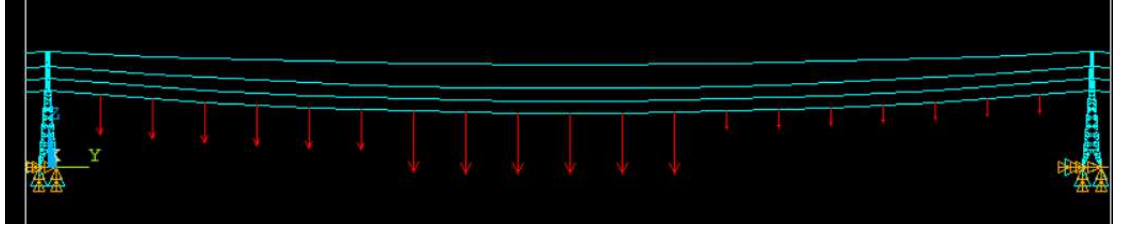


Figure 2.4 Application of ice load on transmission line.

2.3 Application of wind and rain combined load

After the three dimensional model is established and the ice loads are applied, wind and rainfall loads are added as random time varying excitations on the transmission lines to induce galloping characteristics in the simulation and to ensure that the resulting responses more closely resemble actual field observations. To this end, this subsection employs MATLAB as the platform to develop a numerical simulation method for the combined wind and rain action field, aiming to achieve a more realistic reproduction of transmission line galloping responses.

2.3.1 Numerical simulation of random wind field

Wind loads are influenced by multiple factors, including the reference wind speed, ground surface roughness, height above the ground, and the geometric characteristics of the structure itself. In nature, natural wind can be decomposed into two components: mean wind and fluctuating wind. The mean wind refers to the steady component of wind for which both wind speed and direction remain constant over a certain time interval, and it can be treated as a static load. The mean wind speed is affected by ground surface friction and therefore varies with height above the ground. Two commonly used approaches, namely the logarithmic law and the power law, are available to describe the vertical variation of mean wind speed with height.

The logarithmic law description is presented below, and all subsequent plots in this study are based on a reference wind speed of 15 m/s.

$$V(z) = V_{10} \frac{\ln(z / z_0)}{\ln(10 / z_0)} \quad (2.1)$$

In the equation, $V(z)$ denotes the mean wind speed at the target height, V_{10} represents the wind speed at a reference height of 10 m, which is also

termed the reference wind speed, and Z_0 is the ground surface roughness length.

The power law description is presented below.

$$V(z) = V_{10} \left(\frac{z}{10} \right)^\alpha \quad (2.2)$$

In the equation, α denotes the ground surface roughness exponent.

In this study, the power law is adopted to describe the mean wind profile, and the value of α varies according to the ground surface roughness. In China, the ground surface roughness is classified into four categories, as presented in Table 2.4.

Table 2.4 Ground roughness of various types

Category	Terrain Type	Roughness exponent value
A	Desert areas, coastlines, offshore sea surfaces	0.12
B	Open countryside, hilly terrain, and other flat areas	0.16
C	Urban areas	0.22
D	Dense urban areas with high building density	0.30

The ground surface roughness category B is adopted, with a roughness exponent of $\alpha=0.16$. In contrast to the steady characteristics of the mean wind, the fluctuating wind exhibits randomness and high frequency content, manifesting in the time history as irregular fluctuations around the mean wind speed. Since the fluctuating wind cannot be precisely determined, the principle of random vibration is commonly employed, treating the fluctuating wind as a stationary Gaussian random process. The power spectral density function is used to quantitatively analyze the frequency characteristics of the fluctuating wind, and the wind induced vibration coefficient is introduced to convert the fluctuating wind into an equivalent static load through a magnification factor. Several commonly used wind spectra are available, as outlined below.

The Davenport power spectrum is based on the Gaussian distribution characteristics of wind speed and is capable of describing both the mean and variance of wind speed. It can be expressed as follows.

$$S_V(n) = \frac{4\alpha_1 V_{10}^2 x^2}{n(1+x^2)^{\frac{4}{3}}} \quad (2.3)$$

$$x = 1200 \frac{n}{V_{10}} \quad (2.4)$$

In the equation, n denotes the frequency, and α_1 represents the ground surface roughness coefficient.

The Kaimal spectrum can be expressed as follows.

$$s(z, n) = 200u^2 \frac{x}{n(1+50x)^{\frac{5}{3}}} \quad (2.5)$$

$$x = \frac{nz}{V_z} \quad (2.6)$$

$$u^2 = \alpha_1 V_{10}^2 \quad (2.7)$$

In the equation, $s(z, n)$ denotes the instantaneous wind speed, α_1 is the ground surface roughness coefficient, z represents the height, n is the frequency, and V_z is the mean wind speed at height z , with the spectrum accounting for the effect of height variation.

The Simiu Scan spectrum describes both the mean and variance of wind speed and can be expressed as follows.

$$S_V(n) = 0.26\alpha_1 V_{10}^2 \frac{x}{nx^{2/3}} \quad (2.8)$$

In the equation, α_1 represents the ground surface roughness condition.

In this study, the Kaimal spectrum, which accounts for height variation, is adopted to generate the target wind spectrum, and the linear filtering method with a fourth order autoregressive model (**AR-4**) is employed to produce the simulated spectrum suitable for long span structures. The fluctuating wind data are generated through MATLAB, from which the wind speed time histories at each conductor node are obtained, and the wind loads and rainfall loads are then generated by combining these data with the wind speed. All plots in this subsection are obtained with a wind incidence angle of 90° , a reference wind speed of 15 m/s, a roughness exponent α_1

=0.16, and a frequency range from 0.01 to 10 Hz.

The p th order univariate autoregressive **AR** model is presented below .

$$y(n) = -\sum_{k=1}^p a_k y(n-k) + \beta_0 w(n) \quad (2.9)$$

In this study, a fourth order multivariate autoregressive **AR** model is adopted, which can be expressed as follows.

$$y(n) = -a_4 \cdot (n-4) - a_3 \cdot (n-3) - a_2 \cdot (n-2) - a_1 \cdot (n-1) + La(t) \quad (2.10)$$

In the equation, $y(n)$ denotes the fluctuating wind speed at point n , a_k represents the autoregressive **AR** model coefficients that indicate the influence of the wind speed at the k step on the current wind speed, $y(n-k)$ denotes the fluctuating wind speed of order $k-1$ serving as historical data, β_0 is the driving noise intensity coefficient, and $a(t)$ is the random sequence.

$$\mathbf{X} = \text{inv}(\mathbf{A}) \times \mathbf{B} \quad (2.11)$$

$$\mathbf{A} = \begin{bmatrix} -R_0 & -R_1 & -R_2 & -R_3 \\ -R_1 & -R_0 & -R_1 & -R_2 \\ -R_2 & -R_1 & -R_0 & -R_1 \\ -R_3 & -R_2 & -R_1 & -R_0 \end{bmatrix} \quad (2.12)$$

$$\mathbf{B} = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix} \quad (2.13)$$

To determine the value of R , the reference value R_0 is solved based on the parameters adopted in this study, a ground surface roughness coefficient of $\alpha = 0.16$, and n varying from 0.01 to 10 Hz with an increment of 0.01 Hz.

$$s(z, n) = 200u^2 \frac{x}{n(1+50x)^{\frac{5}{3}}} \quad (2.14)$$

$$x = \frac{nz}{V_z} \quad (2.15)$$

$$u^2 = \alpha_1 V_{10}^2 \quad (2.16)$$

Using the Kaimal wind spectrum computation method described above, the

values of $S_i(n)$ and $S_j(n)$ are calculated, and then the empirical formula for the spatial correlation of fluctuating wind is applied.

$$\text{Coh}(n) = \exp \left[-2n \frac{\sqrt{C_x^2(x_j - x_i)^2 + C_y^2(y_j - y_i)^2 + C_z^2(z_j - z_i)^2}}{[\tilde{v}(z_i) + \tilde{v}(z_j)]} \right] \quad (2.17)$$

In the equation, C_x, C_y, C_z denotes the spatial correlation decay coefficient ($C_x = 6, C_y = 16, C_z = 10$). Finally, the obtained values are substituted into the following formula for computing the matrix $\mathbf{R}$.

$$R_0(i, j) = \int_{0.01}^{10} \sqrt{S_i(n)S_j(n)} \cdot \text{coh}_{ij}(n) dn \quad (2.18)$$

$\mathbf{R}_0$ is a lower triangular matrix and needs to be completed into a symmetric matrix. The other matrices $\mathbf{R}_1, \mathbf{R}_2, \mathbf{R}_3, \mathbf{R}_4$ are treated in a similar manner, and all are then substituted into Equation (4.11).

$$\mathbf{X} = \begin{bmatrix} \mathbf{q}_1 \\ \mathbf{q}_2 \\ \mathbf{q}_3 \\ \mathbf{q}_4 \end{bmatrix} \quad (2.19)$$

Because the $\mathbf{AR}$ model requires historical data, it is necessary to define the initial conditions at the starting time. To this end, the covariance matrix $\mathbf{R}_N$ of the driving noise is solved and used as the initial intensity.

In addition, the $\mathbf{AR}$ model must satisfy a further condition. Since $\mathbf{a}(t)$ is a random sequence in the form of a 160×1000 matrix, a normally distributed random matrix is generated using MATLAB, and therefore the following relation holds.

$$E(\mathbf{a}(t)) = 0 \quad (2.20)$$

$$D(\mathbf{a}(t)) = E(\mathbf{a}(t)^2) = 1 \quad (2.21)$$

For the multivariate $\mathbf{AR}$ model, it is assumed that the following relations hold.

$$\mathbf{L}\mathbf{a}(t) = \boldsymbol{\varepsilon}(t) \quad (2.22)$$

$$D(\boldsymbol{\varepsilon}) = E(\boldsymbol{\varepsilon}^2) = \mathbf{R}_N = \mathbf{L} \times \mathbf{I} \times \mathbf{L}^T \quad (2.23)$$

In the equation, $\mathbf{R}_N = \mathbf{R}_0 + \mathbf{Q}_1\mathbf{R}_1 + \mathbf{Q}_2\mathbf{R}_2 + \mathbf{Q}_3\mathbf{R}_3 + \mathbf{Q}_4\mathbf{R}_4$, $\mathbf{Q}_i$ denotes the transpose of the matrix $\mathbf{q}_i$, and $\mathbf{R}_N$ is the covariance matrix of the driving noise.

The covariance matrix R_N is then subjected to Cholesky decomposition, yielding L , L as a lower triangular matrix. This result is subsequently substituted into the equation for the case when $n = 1$.

$$V_r(1:160,1) = L \times a(:,1) \quad (2.24)$$

The same procedure applies to the remaining three cases.

$$V_r(1:160,2) = L \times a(:,2) - Q_1 \times V_r(1:160,1) \quad (2.25)$$

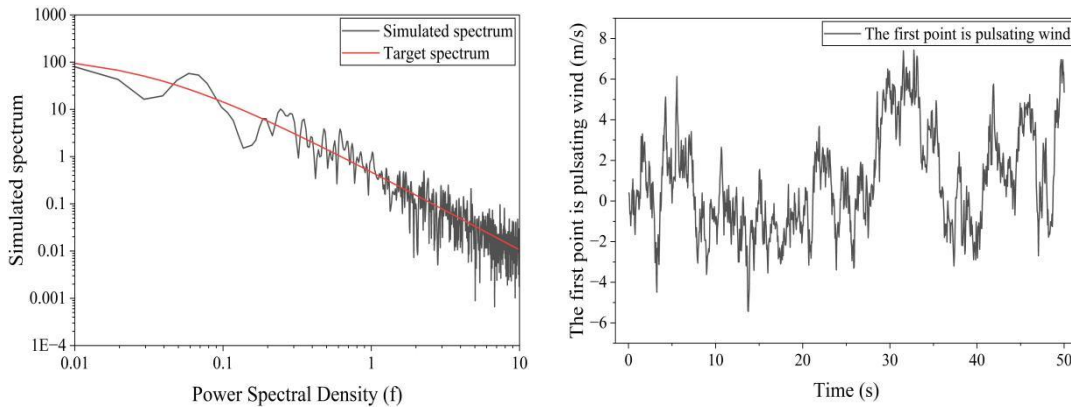
$$V_r(1:160,3) = L \times a(:,3) - Q_1 \times V_r(1:160,2) - Q_2 \times V_r(1:160,1) \quad (2.26)$$

$$V_r(1:160,4) = L \times a(:,4) - Q_1 \times V_r(1:160,3) - Q_2 \times V_r(1:160,2) - Q_3 \times V_r(1:160,1) \quad (2.27)$$

In this study, a fourth order AR model is adopted; therefore, when $t > 5$, the fluctuating wind speed is given by the following expression.

$$V_r(1:h,t) = - \begin{pmatrix} Q_1 \times V_r(1:h,t-1) + Q_2 \times V_r(1:h,t-2) + \\ Q_3 \times V_r(1:h,t-3) + Q_4 \times V_r(1:h,t-4) \end{pmatrix} + L \times a(:,t) \quad (2.28)$$

At this point, the generation of fluctuating wind is completed. In addition, it is necessary to compare the simulated spectrum with the target spectrum in terms of the power spectral density function of the wind speed time history. Figure 2.5 presents the power spectrum comparison and the fluctuating wind speed time history at Node 1.



(a) Comparison curve of power spectrum

(b) Fluctuating wind speed

Figure 2.5 Power spectrum and fluctuating wind of the first node.

2.3.2 Simulation of wind load on conductors

To simplify the experimental procedure, this study reduces the actual complex time varying wind load to an equivalent static wind load W_x . This treatment substantially reduces the complexity of the simulation while remaining within the

acceptable margin of error. The expression for the equivalent static wind load is given as follows.

$$W_x = \alpha \cdot W_0 \cdot \mu_z \cdot \mu_{sc} \cdot \beta_c \cdot d \cdot L_p \cdot B_1 \cdot \sin^2 \theta \quad (2.29)$$

$$W_0 = V^2 / 1600 \quad (2.30)$$

In the equation, W_x denotes the standard value of the horizontal wind load acting perpendicular to the conductors and ground wires, α is the nonuniformity coefficient of wind pressure, taken as 1.0 in this study, μ_z is the wind pressure height variation coefficient, with the reference height of 10 m, also taken as 1.0, μ_{sc} is the shape coefficient of the conductor or ground wire, taken as 1.1, β_c is the wind load adjustment coefficient for conductors and ground wires of 500 kV and 750 kV transmission lines, applicable only to the wind loads on conductors and ground wires acting on towers, and taken as 1.0 in this study, d is the outer diameter of the conductor or ground wire, L_p is the horizontal span of the tower, B_1 is the ice load amplification factor for conductors, ground wires, and insulator strings, θ is the angle between the wind direction and the conductor or ground wire alignment, W_0 is the standard reference wind pressure, and V is the wind speed, taken as the sum of the mean wind and the fluctuating wind in this study.

Table 2.5 presents the corresponding values of α, β_c . In this study, α is taken as 1, and β_c is taken as 1.

Table 2.5 Wind pressure nonuniformity coefficient and wind load adjustment coefficient

Wind Speed (m/s)	<20	20≤V<27	27≤V<31.5	≥31.5
α (Calculate tower load)	1.00	0.85	0.75	0.70
α (Design tower)	1.00	0.75	0.61	0.61
β_c	1.00	1.10	1.20	1.30

The load distribution on the conductors and ground wires corresponding to different wind incidence angles is presented in Table 2.6, where x and y denote the wind load components perpendicular and parallel to the conductor alignment, respectively.

Table 2.6 Corresponding coefficients for each wind direction angle

Wind Direction Angle θ (°)	Line wind load	
	x	y
0	0	$0.25 W_x$

45	$0.5 W_x$	$0.15 W_x$
60	$0.75 W_x$	0
90	W_x	0

Figure 2.6 presents a schematic diagram of the wind load. In this study, the wind load acts in the horizontal plane of the transmission line, and therefore it primarily affects the cross wind displacement. Figure 2.7 shows the wind load time history at the first node.

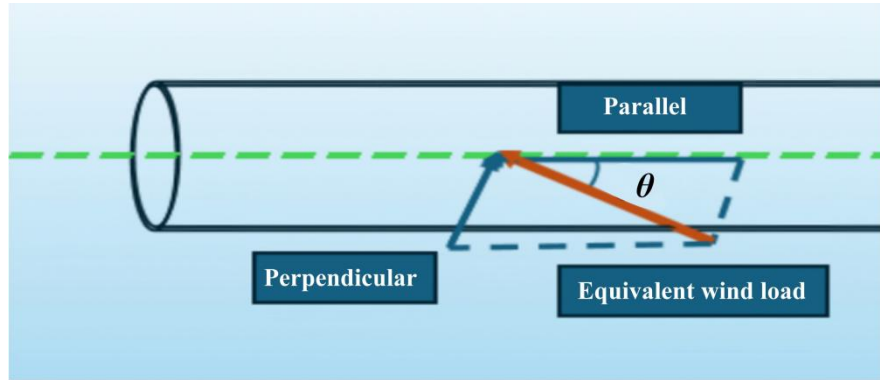


Figure 2.6 Schematic diagram of wind load.

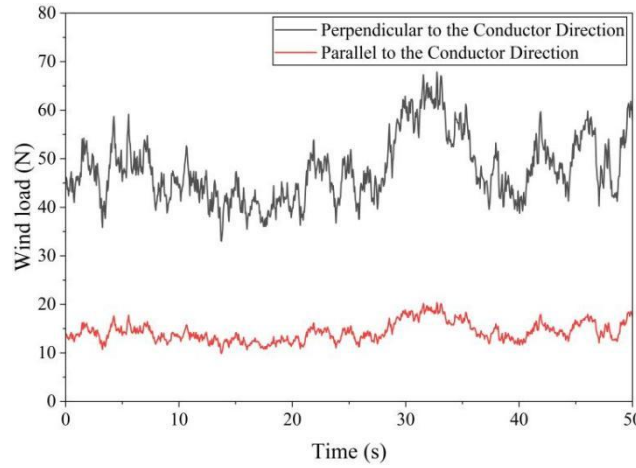


Figure 2.7 Time-history diagram of wind load at the first point.

2.3.3 Simulation of rainload on wires

In the study of transmission line galloping, in addition to wind loads, other environmental factors that affect transmission lines also need to be considered. This study further investigates the influence of rainfall loads on transmission line galloping. For a raindrop with diameter D , the horizontal rainfall pressure P_{rh} and the vertical rainfall pressure P_{rv} are given by the following equations.

$$P_{rh} = 102 \rho_r S_r n_r V_{rh}^3 D^3 \quad (2.31)$$

$$P_{rv} = 102 \rho_r S_r n_r V_{rv}^3 D^3 \quad (2.32)$$

$$V_{rh} = \gamma V_w \quad (2.33)$$

$$V_{rv} = 9.4 \left(1 - \exp(-0.557 D^{1.15}) \right) \quad (2.34)$$

$$\gamma = \begin{cases} C \left(\frac{D}{3} \right)^{0.8} \frac{\alpha}{0.12} + 1 & H \leq 150\text{m} \\ 1 & H > 150\text{m} \end{cases} \quad (2.35)$$

$$\Delta t = \frac{\sqrt{2}}{\sqrt[3]{N_r V_{rh}}} \quad (2.36)$$

$$N_r = \int_0^7 n_r dD \quad (2.37)$$

$$n_r = 8000 \exp(-\Lambda D) \quad (2.38)$$

In the equations, ρ_r is the density of raindrops, taken as 1000 kg/m^3 , V_{rh} and V_{rv} are the horizontal and vertical components of the instantaneous velocity of the raindrop when it strikes the conductor or tower, respectively, V_w is the wind speed at any position in the wind field, taken as the sum of the mean wind and the fluctuating wind, γ is the velocity ratio, $C = 0.2372H^{-0.5008} - 0.0167$, S_r represents the integral of the normalized regularization curve from 0 to Δt , N_r is the total number of raindrops per unit volume, n_r is the raindrop size distribution refers to the distribution of the number of raindrops per unit volume as a function of raindrop diameter, and it is treated in exponential form, Λ is the slope factor, given by $\Lambda = 4.1I^{-0.21}$, where I is the rainfall intensity.

Figure 2.8 presents a schematic diagram of the rainfall load, which can be decomposed into a vertical component and a horizontal component. Figure 2.9 shows the rainfall load time history at the first node.

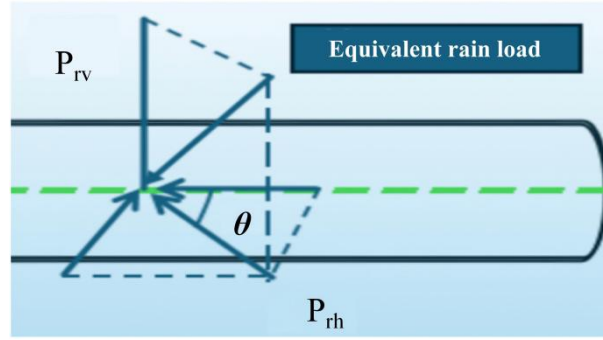


Figure 2.8 Schematic diagram of rain load.

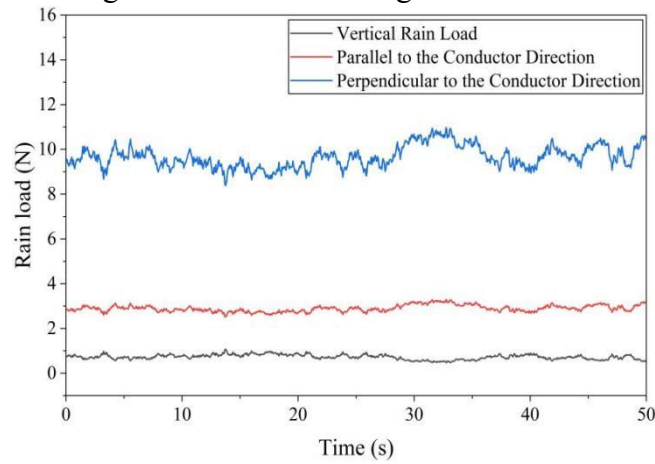


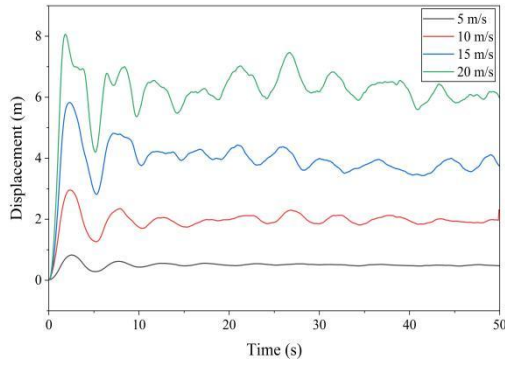
Figure 2.9 Time-history diagram of rain load at the first point.

3 Results and discussion

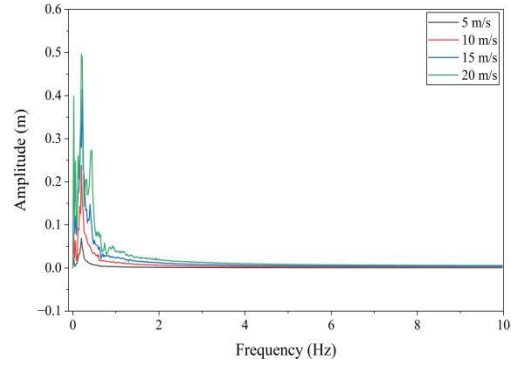
3.1 Study on the influence of different wind speeds and wind direction angles on the dance response of transmission lines

To better investigate the effects of wind speed and wind incidence angle on transmission line galloping, this study performs comparative simulations under different wind speeds and different wind incidence angles.

The first group is configured with a fixed wind incidence angle of 90° , while the wind speed is varied among four values, namely 5, 10, 15, and 20 m/s, for comparison. The corresponding results are presented in Figures 3.1, 3.2, and 3.3. In these figures, the X direction denotes the direction perpendicular to the conductor alignment, the Y direction denotes the direction along the conductor alignment, and the Z direction denotes the direction perpendicular to the plane formed by the conductors.

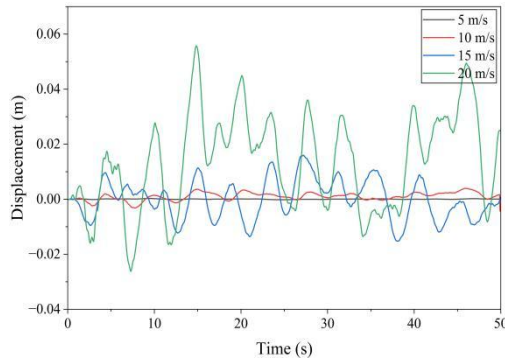


(a) Displacement-time diagram

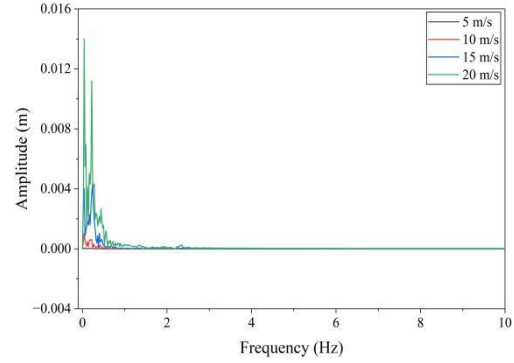


(b) Frequency-amplitude diagram

Figure 3.1 Frequency comparison diagram of x-direction displacement at a wind angle of 90° .

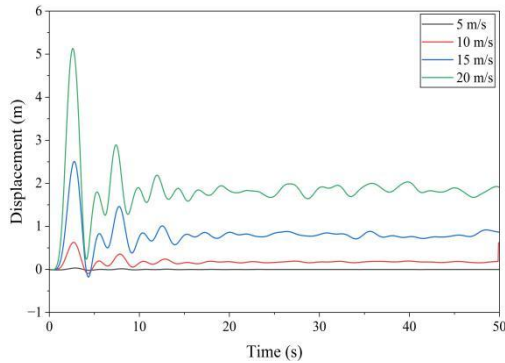


(a) Displacement-time diagram

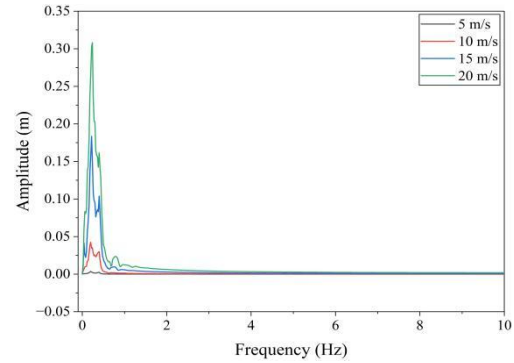


(b) Frequency-amplitude diagram

Figure 3.2 Frequency comparison diagram of y-direction displacement at a wind angle of 90° .



(a) Displacement-time diagram



(b) Frequency-amplitude diagram

Figure 3.3 Frequency comparison diagram of z-direction displacement at a wind angle of 90° .

From the first set of simulation results, it is evident that the vibration response of the transmission line exhibits significant nonlinear characteristics with varying wind speed. At a wind speed of 5 m/s, the maximum displacement of the conductor in the X direction is only 0.82 m, with a corresponding dominant frequency amplitude of approximately 0.06, while the Z direction displacement and amplitude are about 0.03

m and 0.003, respectively, indicating that the system remains in a state of slight disturbance without developing effective vibration. When the wind speed increases to 10 m/s, the X direction displacement jumps to 2.95 m, representing an increase of nearly three times, and the amplitude simultaneously rises to 0.233, suggesting the existence of a critical onset wind speed within the range of 5 to 10 m/s. Once this threshold is exceeded, aerodynamic energy is continuously injected into the vibrating system, and the system transitions from a stable equilibrium to self excited instability, triggering large amplitude galloping. As the wind speed further increases to 15 m/s and 20 m/s, the X direction displacements reach 5.81 m and 8.06 m, with corresponding amplitudes rising to 0.414 and 0.496, yet the growth rates slow down considerably. Between 10 and 15 m/s, the displacement and amplitude increase by about 1.9 times and 1.7 times, respectively, whereas between 15 and 20 m/s, the increases are only 1.3 times and 1.19 times. This indicates that beyond the critical wind speed, nonlinear effects, such as geometric large deformation, material damping, and aerodynamic damping, exert a saturation suppression on the vibration amplitude, causing the displacement and amplitude to approach limiting values rather than growing without bound. The Z direction displacement exhibits a similar evolutionary trend, increasing from 0.03 m to 5.12 m, with the amplitude rising from 0.003 to 0.308, and a clear jump occurs at 10 m/s, further confirming the existence of the critical wind speed. These results collectively demonstrate the threshold triggered mechanism dominated by wind speed and the nonlinear amplitude saturation characteristics inherent in the transmission line galloping system.

Moreover, the ratio of X direction displacement to Z direction displacement varies continuously with wind speed. At a wind speed of 5 m/s, the ratio X/Z is approximately 27, indicating that the displacement in the X direction is significantly larger than that in the Z direction, and thus the X direction motion dominates. When the wind speed increases to 10 m/s, this ratio reduces to 4.91, with the X direction displacement still being dominant. At 20 m/s, the ratio approaches 1.57. It is also observed that the spectral amplitude in the X direction is greater than that in the Z

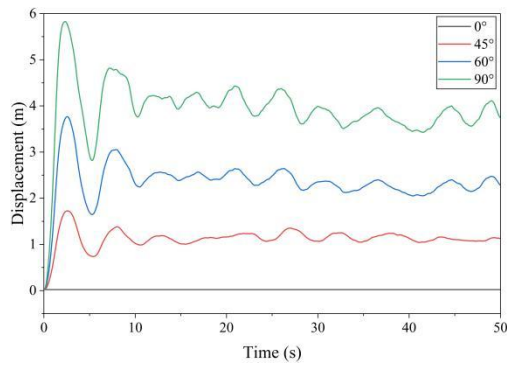
direction under all simulated conditions, which is consistent with the fact that the transverse oscillation component is inherently larger than the vertical oscillation component during transmission line galloping. However, in terms of growth rates, as the wind speed increases from 10 m/s to 20 m/s, the amplitude in the Z direction increases by approximately 100 times, whereas that in the X direction increases by only about 8 times. This indicates that the Z direction response is gradually excited only after galloping is initiated. This explains why the ratio of displacements in the X and Z directions gradually approaches unity as wind speed increases, implying that the conductor trajectory evolves from an initial swaying pattern to an elliptical or even circular shape. This evolution reflects the progressively intensified coupling between the transverse and vertical motions during the galloping process of transmission lines.

As for the Y direction, which is along the conductor alignment, the displacement remains at a very small magnitude regardless of wind speed variations, with a maximum value of only about 0.06 m, which is one to two orders of magnitude smaller than those in the X and Z directions. This further demonstrates that transmission line galloping is essentially a cross wind self excited vibration rather than an along wind forced vibration. No matter how much the along wind load is increased, galloping of the transmission line will not be induced.

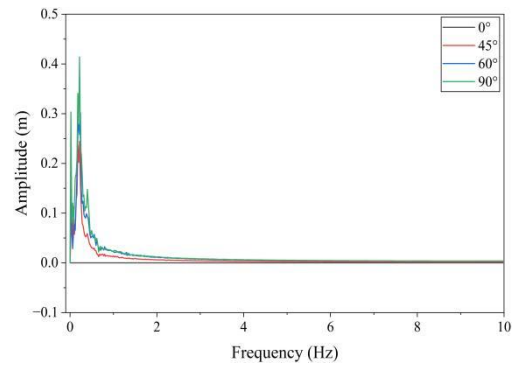
The second group of simulations is configured with a fixed wind speed of 15 m/s but varying wind incidence angles, providing an alternative perspective on the modulating effect of wind incidence angle on galloping responses (as shown in Figures 3.4, 3.5, and 3.6). When the wind incidence angle is 0° , the displacements in the X, Y, and Z directions are all very small, and the corresponding spectra show almost no discernible dominant peaks. In particular, the dominant frequency in the X direction is 0.199, while the vibration frequency in the Y direction is zero, indicating no vibration in the along wind direction. This wind incidence case further confirms that cross wind loading is the primary factor inducing transmission line galloping.

When the wind incidence angle increases to 45° , the displacement in the X

direction rises to 1.92 m, and the dominant frequency returns to 0.219 Hz. In comparison with the case of 0° , where the X direction displacement is only 0.02 m, the displacement at 45° undergoes a substantial change, with the amplitude also increasing to 0.146 m. The same trend is observed in the Z direction. Moreover, the dominant frequencies in both the X and Z directions are highly consistent, indicating that frequency locking has occurred and that the conductor has developed a stable self excited vibration.

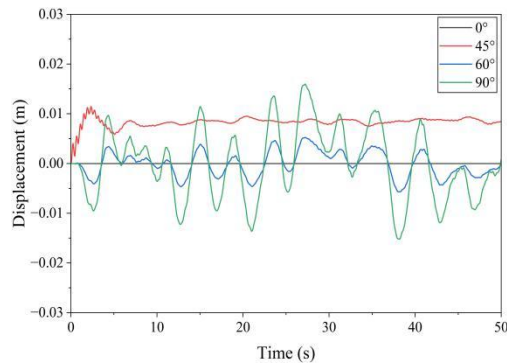


(a) Displacement-time diagram

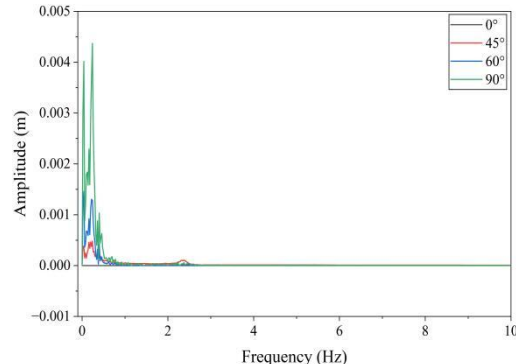


(b) Frequency-amplitude diagram

Figure 3.4 Frequency comparison diagram of x-direction displacement at a wind speed of 15 m/s.

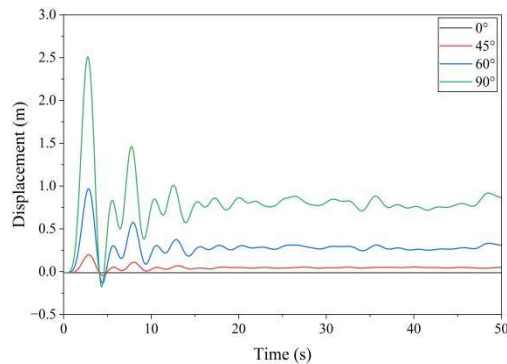


(a) Displacement-time diagram

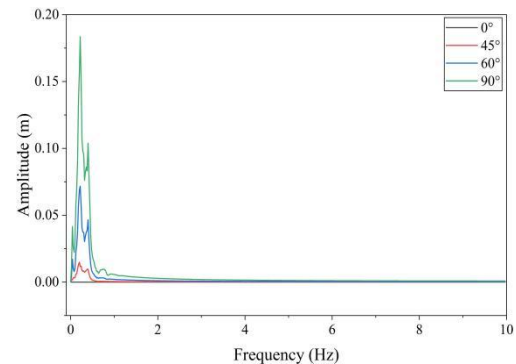


(b) Frequency-amplitude diagram

Figure 3.5 Frequency comparison diagram of y-direction displacement at a wind speed of 15 m/s.



(a) Displacement-time diagram

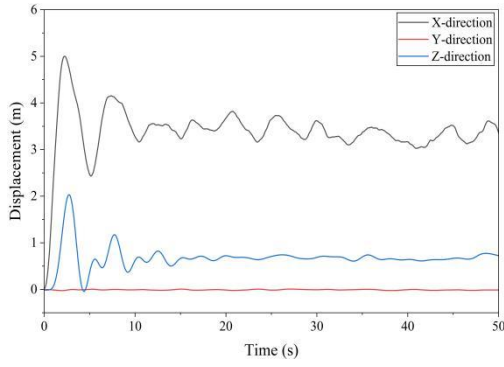


(b) Frequency-amplitude diagram

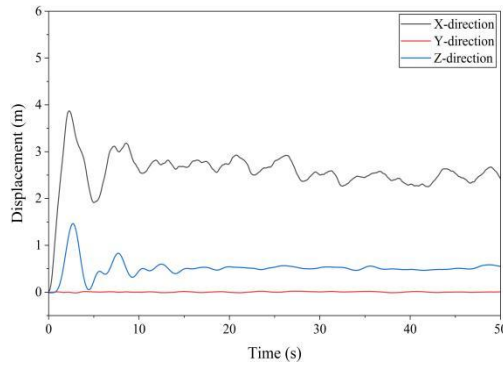
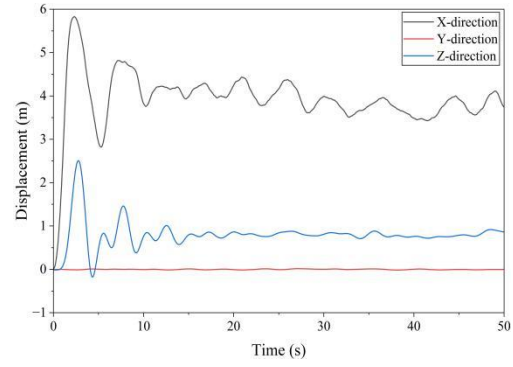
Figure 3.6 Frequency comparison diagram of z-direction displacement at a wind speed of 15 m/s.

Further increasing the wind incidence angle to 60° yields an X direction displacement of 3.76 m, with an amplitude of 0.264 m and a dominant frequency of 0.219 Hz, while the Z direction displacement is 0.96 m with an amplitude of 0.07 m and the same dominant frequency of 0.219 Hz. As the wind incidence angle reaches 90° , corresponding to pure cross wind loading, the X direction displacement attains 5.81 m with an amplitude of 0.414 m and a dominant frequency of 0.219 Hz, and the Z direction displacement reaches 2.49 m with an amplitude of 0.183 m, also at a dominant frequency of 0.219 Hz.

For the three cases with wind incidence angles of 45° , 60° , and 90° , the dominant frequencies in both the X and Z directions remain consistently within the range of 0.18 to 0.24 Hz, indicating that the cross wind component exerts a certain influence on the dominant frequency, and that as the wind incidence angle increases, the frequency approaches the lower order natural frequency of the structure. In terms of displacement evolution, the displacements in both the X and Z directions increase with increasing wind incidence angle. Specifically, as the wind incidence angle rises from 45° to 90° , the X direction displacement increases from 1.92 m to 5.81 m, representing a 3.02 fold increase, while the Z direction displacement also increases by a comparable multiple. This demonstrates that during the increase of wind incidence angle, transmission line galloping is accomplished through the coupling of both the X and Z directions.



(a) Displacement of the quarter-span node



(c) Displacement of the three-quarter-span node

Figure 3.7 Displacement of three nodes at a wind speed of 15 m/s and a wind angle of 90° .

The third group of simulations is configured with a fixed wind speed of 15 m/s and a fixed wind incidence angle of 90° . In this group, the quarter span, midspan, and three quarter span positions are selected to examine the displacement time histories at different points along the same transmission line under identical conditions. From the Figure 3.7 , it is evident that at all three positions, the displacements in both the X and Z directions are far greater than those in the Y direction. This indicates that at every point, the response is governed by the coupling of the X and Z direction displacements, reflecting the overall nature of transmission line galloping, and no isolated independent vibration occurs at any single node.

Synthesizing the three groups of simulation data, it can be concluded that wind speed is the decisive factor in determining whether transmission line galloping occurs, and a critical wind speed exists within the range of 5 to 10 m/s. Once the wind speed exceeds this threshold, both displacement and frequency amplitude undergo substantial changes. The role of wind incidence angle is to indirectly influence the

galloping intensity by modifying the normal wind load component. Therefore, transmission line galloping is a low frequency, large amplitude vibration that occurs under the coupled action of these two factors, with wind speed playing the dominant role and wind incidence angle exerting a secondary modulating effect.

3.2 Establishment of dance warning indicators

Based on the computational results for different wind speeds, different wind incidence angles, and displacements at multiple nodes, this study summarizes several distinctive characteristics of transmission line galloping. The first characteristic is the existence of a critical wind speed. When the wind speed is below this threshold, the conductor displacement remains relatively small, indicating that the conductor is in a stable state or undergoing low amplitude vibration. However, once the wind speed exceeds the critical value, a sudden jump in displacement occurs, with the displacement potentially increasing to two or three times its original value. The second characteristic is that transmission line galloping is not a unidirectional phenomenon but rather results from multi directional coupling. The simulations in this study reveal that during galloping, the conductor does not exhibit large amplitude vibration solely in the X direction; substantial vibration in the Z direction also occurs and cannot be ignored. Consequently, the conductor trajectory tends to be elliptical, and if the maximum amplitude ratio between the X and Z directions approaches unity, the trajectory becomes circular. The third characteristic is that during the initial stage of galloping, the amplitude grows rapidly with a pronounced increase, typically reaching its maximum value within the first 5 seconds of the total time history. The fourth characteristic is that the galloping frequency is relatively low, as evidenced by Figures 3.1 to 3.6, where all galloping states exhibit very low frequencies, indicating that transmission line galloping is a low frequency vibration phenomenon. In summary, these characteristics demonstrate that conductor galloping is essentially a low frequency, large amplitude, self excited vibration. Based on these features, this study establishes a practical set of early warning indicators for galloping, including displacement amplitude, wind speed level, wind incidence angle, and rainfall intensity.

3.2.1 Displacement amplitude warning indicators

From the simulation results, as the wind speed increases from 5 m/s to 20 m/s, the X direction displacements are 0.82 m, 2.95 m, 5.81 m, and 8.06 m, respectively, with clear changes at each wind speed increment. Therefore, using displacement magnitude to assess transmission line galloping is the most intuitive and easily implementable monitoring approach. Accordingly, the maximum displacement at the midspan node is adopted to classify the early warning into three levels (Figure 3.8).

The first level is defined as the condition when the maximum galloping displacement of the transmission line is less than 1 m. Under this condition, although conductor vibration does exist, the amplitude is relatively small and may represent only normal wind induced oscillation, which is unlikely to cause damage to the conductors, tower body, insulators, or other structural components.

The second level is defined as the condition when the maximum galloping displacement of the transmission line falls between 1 m and 5 m. Under this condition, the vibration amplitude is considerably large, and it can generally be determined that the conductor has entered a galloping state. However, this may correspond to low or moderate intensity galloping, and therefore the monitoring frequency should be increased and the galloping condition should be closely tracked.

The third level is defined as the condition when the maximum galloping displacement of the transmission line exceeds 5 m. Under this condition, the conductor amplitude is extremely large, and the system has entered a state of intense galloping, with the conductor undergoing large amplitude periodic motion that may cause fatigue damage or even direct failure of the transmission tower structure. At this stage, protective measures should be considered to safeguard the transmission line.

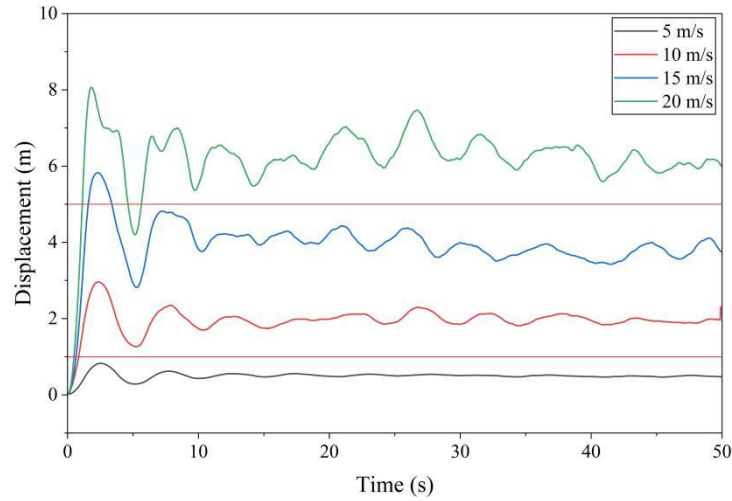


Figure 3.8 X-direction displacement under different wind speeds.

3.2.2 Critical wind speed warning indicators

In the simulation results of this study, a critical wind speed exists within the range of 5 to 10 m/s. Once the wind speed exceeds this critical value, the conductor amplitude increases substantially, and the probability of galloping occurrence becomes very high. The critical wind speed is not a fixed value; it depends on factors such as the ice accretion condition of the conductor and the material parameters of the transmission tower itself. In the present model, the critical wind speed should be taken into account, and therefore the wind incidence angle is fixed at 90° . When the wind speed is increased from 5 m/s to 10 m/s, the conductor displacement increases by a factor of 3.59; however, as the wind speed continues to rise, the growth factor diminishes. Accordingly, a wind speed of 10 m/s is designated as the critical wind speed. Nevertheless, when the wind speed exceeds 5 m/s, the maximum displacement in the X direction can reach 0.82 m, which is close to 1 m and enters the warning zone, as shown in Figure 3.9, although galloping may not yet occur. Therefore, a wind speed of 5 m/s is defined as the warning threshold. When the wind speed exceeds 10 m/s, the conductor displacement increases dramatically, and this region is defined as the danger zone.

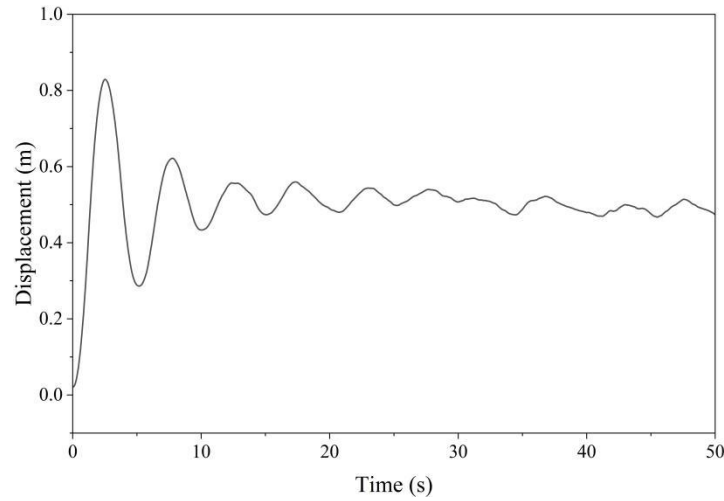


Figure 3.9 X-direction displacement at a wind speed of 5 m/s and a wind angle of 90° .

3.2.3 Wind direction angle warning indicators

The simulation results also show that the wind incidence angle has a notable effect on transmission line galloping. When the wind incidence angle is 0° , meaning the wind blows along the conductor alignment, virtually no significant galloping is observed, and even at a wind speed of 15 m/s, large displacements in the X and Z directions are not generated. As the wind incidence angle increases to 45° , 60° , and 90° , the displacements gradually grow, with the most severe galloping occurring at 90° , where the amplitude can become very large. For instance, at a wind speed of 15 m/s, the X direction displacements at wind incidence angles of 45° and 90° are 1.92 m and 5.82 m, respectively, representing a difference of 3.02 times. Therefore, 45° can be set as the warning threshold; when the wind incidence angle exceeds 45° , the system enters the warning zone. When the wind incidence angle exceeds 60° , the conductor displacement increases further, and this region is defined as the danger zone.

4 Conclusion

This study focuses on the galloping response of transmission lines by establishing three dimensional models, analyzing the characteristics of galloping responses, and developing early warning indicators for galloping. The three dimensional model of the transmission line is built using APDL, and the galloping behavior under various operating conditions is examined, from which the early

warning indicators are derived. The main conclusions are summarized as follows.

(1) Through three dimensional modeling, the critical wind speed for galloping onset is identified. Once the wind speed reaches this critical value, the conductor amplitude increases substantially, reaching up to several meters. It is also verified that the wind incidence angle exerts an influence on the galloping response. Even under galloping conditions, different wind incidence angles give rise to stronger multi directional coupling characteristics, indicating that the wind incidence angle is also an important factor affecting the galloping response.

(2) During galloping, transverse and vertical vibrations are strongly coupled, with dominant frequencies locked to low order structural modes and showing little variation with wind speed or angle, indicating a stable self excited state. Displacement responses are consistent across spanwise nodes, confirming galloping as a global vibration mode rather than a local one, which supports the use of single point displacement monitoring for full span galloping detection.

(3) Based on numerical simulations and further combined with the displacement response characteristics of the conductor and the variation patterns of the wind field, a set of early warning indicators for transmission line galloping is established from three aspects, namely displacement, wind speed, and wind incidence angle. Through coordinated monitoring and comprehensive analysis of these three dimensional indicators, the galloping risk characteristics of transmission towers under complex environmental conditions can be more fully reflected, thereby improving the accuracy of galloping risk identification.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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