Research on Aeolian Vibration of a Conductor Based on Finite Particle Method

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***Abstract*—Destruction of transmission lines due to Aeolian vibration is more and more serious recently with wide applications of the Ultra High Voltage Technology, so it is necessary to study the response of Aeolian vibration of conductor. This paper uses the finite particle method which is different from the energy balance method to research the transmission line's response under Aeolian vibration. Base on vector mechanics of structures, the finite particle method divides a structure into particles which are linked by elements. The movement of the particles is followed by the Newton's second law. By establishing the relationship between the Stockbridge-type damper's force and particle's displacement, the responses of Aeolian vibrations of conductors with different type dampers and that with different locations of dampers are calculated. Because the finite particle method can consider the damper's dynamic characteristics, the mass and geometric nonlinearity of a conductor, this method can produce a more accurate analysis result than the energy balance method. At last, the three-dimensional response of Aeolian vibration of conductor is calculated which shows the damping will weaken the lateral movement of a conductor.**

***Index Terms*—Aeolian vibration, finite particle method, description of particle positions, Stockbridge-type damper, transverse wind**

I. Introduction

With the rapid development of China's social and economic, it's particularly urgent that high efficiency, long-distance, large-capacity Ultra High Voltage transmission lines are constructed to ease the growing tension of electricity supply and the transmission network pressure brought by the inconvenience of coal transportation. It also optimizes the layout of China's energy production and consumption and meets the requirements of energy and economic development. All along, problems about fatigue failure of conductors caused by the Aeolian vibration are more concerned by domestic and foreign researchers. With the increase of transmission lines' span and tension, the Aeolian vibration is more likely to happen. As a result, the abrasion of fittings and the conductor breakage caused by fatigue occur frequently [1]-[4]. Therefore, the response calculation of Aeolian vibration of conductor has great practical significance.

Aeolian vibrations on conductors occur when transverse wind with speed between 0.5m/s and 10.0m/s blows the wire**.** The vertical alternating force acting on wire leads to vertical vibration of wire. The frequency of vibration is generally between 3 and 150Hz, the maximum amplitude is often no more than 1 to 2 times of the wire diameter. At present, there is a lot of literature researching on Aeolian vibration of a conductor at home and abroad. J. Vecchiarelli [5] used the finite difference method to study response of Aeolian vibration of the transmission line - damper coupling system. Oumar Barry [6] established finite element dynamic equation about Aeolian vibration of wire-damper coupling system by the Hamilton variational principle and analyzed the conductor vibration modes and the influence that Stockbridge-type dampers have on conductor modes. Li Li, Kong Deyi *et al.* [7], [8] used the improved energy balance method and the finite difference method to calculate responses of Aeolian vibrations of conductors with Stockbridge-type dampers.

The above scholars did more intensive studies on the calculation of response of Aeolian vibration of a conductor with the Stockbridge-type dampers and got more accurate results, but there are still some factors that cannot be considered. The dynamic characteristics of the damper and conductor and the coupling effect of conductor–damper system cannot be considered by energy balance method based on the assumption of a standing wave. Finite difference method usually needs to assume Aeolian vibration modes of a conductor (usually assumed to be sinusoidal). However, the existence of damper would lead to concentrated force on a conductor and the changes of conductor vibration modes. In addition, the above method in the calculation of the wire–damper coupling system was unable to consider geometric nonlinearity of a conductor.

Ying Yu *et al.* [9], [10] of Zhejiang University using the finite particle method for nonlinear dynamic analysis of structures, made more accurate results. On the basis of its proposed method, the author established the coupling relationship between impedance force of damper and displacement of conductor particle and deduced the center differential equations of Aeolian vibration of conductor–damper coupling system by using the finite particle method. In the paper, firstly, the excitation force

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that initiate Aeolian conductor vibration is introduced; secondly, the damping coefficient of a conductor is derived by using the self-damping power and the dynamic characteristics of a Stockbridge-type damper is analyzed by using MATLAB programming; thirdly , the responses of Aeolian vibrations of conductors are calculated by considering different types of dampers and different installation methods of dampers; finally, the three-dimensional response of Aeolian vibration of a conductor are simulated by using three-dimensional rod elements to establish a conductor model.

II. Breeze Excitation Force

Practice shows that the periodic vortex-induced vibration of a conductor would occur at lower wind speeds. Motion of conductor makes interaction between conductor and wind into fluid-structure coupling range (usually called the "lock" effect). The analytical solution is very difficult to obtain, so some semi-empirical models such as harmonic force model, lift oscillator model, empirical linear model, empirical nonlinear models and generalized empirical nonlinear model etc. [11] are usually used. In this paper, the non-empirical vortex-induced vibration model that Scanlan gave based on negative damping is adopted to simulate breeze excitation force.

Model of eddy excitation is divided into three parts: the resonance item of vibration at a Strouhal frequency caused by Vortex shedding, the aerodynamic negative damping term and linear stiffness term, which is expressed as shown in the following equation:

$$F_y = \frac{1}{2}\rho U^2 D[\left(Y_1(K) - Y_2(K)\frac{v^2}{D^2} \right)\frac{\dot{v}}{U} + Y_3(K)\frac{v}{D} + \frac{1}{2}C_L(K)\sin(\omega_{st}t+\phi)] \tag{1}$$

where, ρ is the density of air; U represents the average wind speed; Y_1 is self-excited linear damping term; Y_2 is linear pneumatic stiffness term; ε is self-limited nonlinear damping term; C_L represents a lift coefficient of resonant term; φ is the phase difference; v is displacement perpendicular to wind speed direction; $\omega_{st} = 2\pi S_t U/D$ is the Strouhal circular frequency; S_t is the Strouhal number; $K = \omega D/U$ is the reduced frequency. Generally, Y_3 (K) and C_L (K) are negligible when Aeolian vibration of conductor becomes steady.

III. Conductor Self-Damping

The power dissipation due to conductor self-damping represents the capacity of consuming or absorbing vibration energy during Aeolian vibration process. It is also a major source of energy dissipation during Aeolian vibration. There are many factors affecting the power dissipation due to conductor self-damping, such as Aeolian vibration amplitude and frequency, conductor tension, environment temperature and conductor material etc. Conductor self-damping primarily consists of structural deformation damping and material deformation damping. Because of the difference of production process, dispersion of the power dissipation due to conductor self-damping is large. Currently, the power is generally determined by experiment all around world and it takes the form of expression:

$$P_c = \frac{\pi}{2}H_c {y_0}^2 f^4 T^{-1.5} m^{1.5} \tag{2}$$

where, P_c is the power dissipation due to conductor self-damping; H_c is a constant of proportionality; f is vibration frequency; y_0 is the double vibration amplitude; D is the conductor diameter; T is the conductor tension; m is linear density of conductor.

The energy dissipation of Aeolian vibration of conductor, including sliding friction energy dissipation in the strands and hysteresis damping energy dissipation of material, is different from general viscous damping system. Its damping mechanism is very complex, and it is often equivalent to the classical viscous damping.

By the knowledge of structural dynamics, in a period, the energy dissipation due to damping force of single freedom degree system containing viscous damping under harmonic loads is:

$$W = \int_0^T f_d y dt = cA^2\omega^2 \int_0^T \cos^2(\omega t - \varphi)dt = \pi c A^2 \omega \tag{3}$$

In a period, the energy dissipation due to self-damping of per unit length of the wire is equal to the energy dissipation of single freedom degree system. The equation is given by:

$$W = P_c T \Delta l = P_c \Delta l / f \tag{4}$$

The solution is:

$$c_{eq} = \frac{H_c}{4\pi} f^2 T^{-1.5} m^{1.5} \Delta l \times 10^{-3} \tag{5}$$

The self-damping coefficient in (5) is usually estimated by the energy balance method. In the finite particle method, resistance effect on structure is usually considered by adding virtual damping force on particle, which was expressed as the following equation:

$$f_d = -\xi \cdot m \frac{d}{dt}\begin{bmatrix} x \\ y \end{bmatrix} \tag{6}$$

where, $\xi = c/m$.

IV. Breeze Excitation Force

A Stockbridge-type damper transforms vibration energy it absorbs into thermal energy and acoustic energy and they are dissipated, reducing the steady-state amplitude of Aeolian vibration of a conductor-damper system. The larger value of power dissipation, the stronger inhibitory effect that a Stockbridge-type damper has on Aeolian vibration of conductor is.

Performance of a Stockbridge-type damper is represented by its curve of power characteristics [12]. Since the damper itself is strongly nonlinear, coupled with the impact of manufacturing processes, its dynamic characteristics have a certain degree of dispersion. The power characteristics are generally measured by the experiment. Because of the limited experiment conditions, the theoretical method is adopted to analyze the dynamic characteristics of a Stockbridge-type damper in this paper. Core of the theoretical method is obtaining the dynamic differential equation of a Stockbridge-type damper by establishing its mathematical model. There are several assumptions:

(1) Damper clamp and hammer are rigid.

(2) Bounded by lamping point, a Stockbridge-type damper is composed of two separate subsystems.

(3) Ignore the quality of strand and consider only its flexibility.

The mathematical model of Damper is shown in Fig. 1.

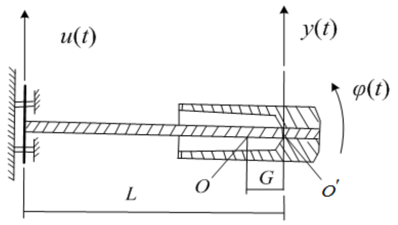

Figure 1. Theoretic calculation model of a Stockbridge-type damper

where, O is the hammer centroid; O' is the inside clamping point of hammer and strand; the L is the distance between damper clamping point and the inside clamping point of hammer and strand; G is the distance between hammer centroid and the inside clamping points of hammer and strand; $y(t)$ is the displacement of the inside clamping point of hammer and strand with damper clamp as a reference system; $\varphi(t)$ is the angle of hammer rotation; $u(t)$ is the displacement of damper clamp.

Based on the above assumptions, the equation of motion about dynamic characteristics of the independent subsystem can be expressed as follows:

$$M\ddot{X} + C\dot{X} + KX = F \tag{7}$$

where, M, C and K are mass matrix, damping matrix and stiffness matrix of Damper independent subsystem, X is displacement array; F is external force array;

here,

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix},\ C = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix},$$

$$K = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix},\ X = \begin{bmatrix} y \\ \varphi \end{bmatrix},\ F = \begin{bmatrix} -m\ddot{u} \\ 0 \end{bmatrix}$$

where,

$M_{11} = m$; $M_{12} = -mG$; $M_{21} = 0$; $M_{22} = J$;

$K_{11} = 12EI/L^3$; $K_{12} = -6EI/L^2$;

$K_{21} = -6EI/L^2 + 12EIG/L^3$;

$K_{21} = 4EI/L\text{-}6EIG/L^2$;

here, m is the hammer mass; J is the rotational inertia of hammer; EI is the strand bending stiffness. The damping matrix C can be derived from the stiffness matrix K as follows:

$$C = \frac{2D}{\omega}K \tag{8}$$

where, D is the damping ratio of system; ω is the circular frequency of vibration.

Considering the steady vibration, X can be solved as follows:

$$X = \left(-M\omega^2 + K + j\omega C\right)^{-1} F \tag{9}$$

here, j is the imaginary unit.

Acceleration of damper clamp vibration $a = \ddot{u}$ in vibration, so the solution can be derived as follows:

$$\begin{Bmatrix} y \\ \varphi \end{Bmatrix} = \left(-M\omega^2 + K + j\omega C\right)^{-1} \begin{Bmatrix} -ma \\ 0 \end{Bmatrix} \tag{10}$$

In the above formula, the acceleration of conductor particle can be obtained by the central difference method. After y and φ solved, the relationship of damper resistance and displacement is $F = K_{11}y + K_{12}\varphi$. In this paper, simulation program using MATLAB language is used to analyze the relationship between damper resistance and particle acceleration.

V. Analysis of Aeolian Vibration of a Conductor with a Stockbridge-Type Damper Attached

The finite particle method is a structure analysis method combining vector structural mechanics with solid mechanics. The method is mainly based on basic concepts which are "description of particle position" and "path element". It models the analyzed domain to be composed by finite particles instead of mathematical functions and continuous bodies in traditional mechanics. The structure mass is assumed to be represented by each particle. Particles in the structure are connected by elements, which are massless. A group of particle positions on discrete time points, which is called "path element", is used to describe the trajectory of particle motion. Newton's second law is adopted to describe the motions of all particles. Pure deformation of an element can be obtained by virtual "reverse movement". Obtaining the pure deformation of an element, it is easy to solve the internal forces of an element.

A. *Description of Conductor Particles Position and Calculation Model*

Vectored mechanics believe that the geometric shape and the spatial position of the structure can be described by the positions of a finite number of particle groups, which is called the description of particle position. The number and configuration of particles can be selected according to the properties of problem and the requirements of accuracy, as shown in Fig. 2.

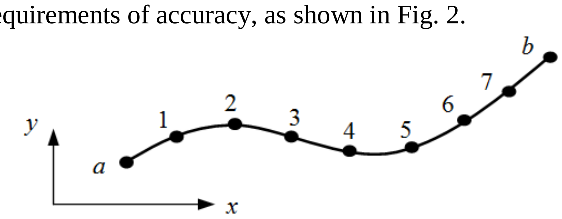

Figure 2. Description of particle position

The properties of a particle consist of particle mass, coordinates, forces, generalized movement and motion constraints. These properties are used to indicate the position of structure, quality, forces, shape, deformation and boundary conditions, the specific concept is given as follows:

(1) There is only concentrated force acting on a particle. All internal forces (forces acting on the particle which is provided by the elements connected to the particle) and external forces are equivalent to the concentration force acting on the particle, and the particle is in dynamic equilibrium state at any moment.

(2) Particles in the structure are connected by elements and the elements have no mass. The mutual restraint relationship between two particles is represented by the internal forces of an element. Elements under the external force remain static equilibrium.

(3) Nodal displacements of an element are determined by the motion of particles. Particles in the structure are connected by elements. The deformation of the element is associated with the motion of particles. Thus, the forces due to deformation of elements work on the particles connected to it in opponent direction.

Based on the above analysis, when using the finite particle method to calculate the response of Aeolian vibration of conductor, the first step is to divide the conductor into a finite number of particles. Since the amplitude of a conductor is quite to conductor diameter, it is necessary to consider the impact of conductor geometry nonlinearity. The calculation model is shown in Fig. 3.

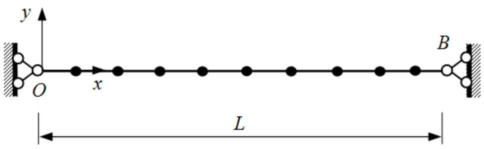

Figure 3. Calculation model of a conducor

B. Description of Path Element

In finite particle method, the track of particle is described by a group of particle positions on discrete time points. When the external force acts on structure, the position vector of particle is a time-related function called path. Assume that the starting and ending position vectors of a particle are x_a and x_b and the two time point are t_0 and t_f, a set of time points t_0, t_1, t_2, …, t_a, t_b, …, t_f are used to disperse the time course of whole analysis. The period t_a-t_b represents a path element, as shown in Fig. 4.

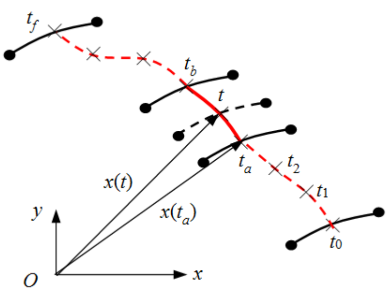

Figure 4. Path element

The internal forces and deformation in a path element meet the following assumptions:

(1) Calculating the displacement, deformation and stress of the structure are based on its original form

(2) The deformation of component is small and the rotation can be regarded as moderately large rotation;

(3) The effect that geometric transformation has on the calculation of the deformation and internal forces of component can be ignored;

(4) Composition and constraints of structure and the properties of component do not change. The element is independent of each other and its internal forces and deformation can be calculated independently instead of integrating all elements.

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After setting the path elements, it is access to analyze the time histories of particle position and velocity during Aeolian vibration of conductor. For large deformation and large rotation structure, a set of path elements that continue to increase can be used to handle it. The assumptions of a path element can ensure the internal forces and deformation of structure to meet the requirements of the material mechanics.

C. Description of the Deformation of an Element

Mutual restraint in particles is determined by the pure deformation of an element. Beam and bar elements are common connecting elements. Beam elements can provide axial, bending and torsional deformation, and bar elements can only provide axial deformation. In this paper, the bar elements are used to model a conductor.

In the process of particle motion, the relative positions among particles are changed. It will cause the deformation of an element, resulting in the change of internal forces. In return, internal force change of an element will restraint the next movement of particles. Therefore, it is very important to solve the internal forces. In the finite particle method, the pure deformation of an element is obtained by “reverse movement” of an element, and then the knowledge of material mechanics is used to solve the internal forces.

D. Differential Equation of Particle Motion

A conductor is described by a set of discrete particles and elements. The external loads and internal forces of an element act directly on the particle. The motion of the arbitrary particle α follows Newton’s second law:

$$M_\alpha \ddot{d}_\alpha = F_\alpha^{\text{ext}} + F_\alpha^{\text{int}} \tag{11}$$

where M_α is the mass value, d_α is the displacement vector, $\ddot{d}_\alpha$ is the acceleration vector, F_α^{ext} and F_α^{int} are the external force and internal force of particle α, respectively.

If the damping force is taken into consideration, the motion equation can be expressed as:

$$M_\alpha \ddot{d}_\alpha = F_\alpha^{\text{ext}} + F_\alpha^{\text{int}} - F_\alpha^{dmp} \tag{12}$$

where the damping force $F_\alpha^{dmp} = \mu M_\alpha \dot{d}_\alpha$, μ is the damping factor, which is the same as the definition in the dynamic relaxation method.

The external force includes breeze excitation force and damper force acting on the conductor, and the internal forces are obtained by the pure deformation of element. Therefore, the external force can be written as:

$$F_\alpha^{\text{ext}} = f_\alpha^{\text{ext}} + \sum_{i=1}^{n} f_i^{\text{ext}} \tag{13}$$

where, f_α^{ext} is the external force vector acting on particle α, f_i^{ext} is the internal force vector exerted by element *i* connecting with the particle α, *n* represents the number of elements connected to the particle. Because this study involves only two kinds of load which are concentrated load acting on the conductor and uniform load in the direction perpendicular to axial direction of element, only the equivalent forces of the two loads are elaborated in this section. The concentrated external load acting on the conductor is divided into two equivalent forces which are related to distances between the acting point and the two particles, as shown in Fig. 5. Where, f_C is the concentrated external load acting on point *C*; l_{AC} is the distance between point *C* and particle *A*; l_{BC} is the distance between point *C* and particle *A*; the equivalent force f_A^{ext} acting on particle *A* and the equivalent force f_B^{ext} acting on particle *B* are:

$$f_A^{\text{ext}} = \frac{l_{BC}}{l_{AC} + l_{BC}} f_C^{\text{ext}} \tag{14}$$

$$f_B^{\text{ext}} = \frac{l_{AC}}{l_{AC} + l_{BC}} f_C^{\text{ext}} \tag{15}$$

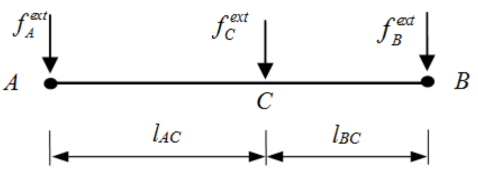

Figure 5. Equivalent force of concentrated load

The breeze excitation force acting on a conductor is uniform. The equivalent force is solved by using integral method. The uniform force is dispensed onto the two particles at both ends of the element according to range and distribution of the uniform force, as shown in Fig. 6:

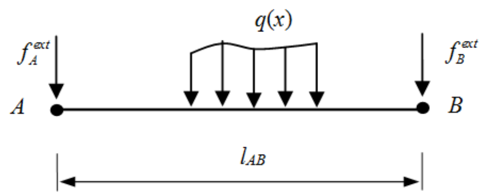

Figure 6. Equivalent force of uniform load

The two equivalent forces of the uniform force are calculated by using static balance principle, as follows:

$$f_A^{\text{ext}} = \frac{1}{l_{AB}} \int_0^{l_{AB}} q(x) \cdot x dx \tag{16}$$

$$f_B^{\text{ext}} = \frac{1}{l_{AB}} \int_0^{l_{AB}} q(x) \cdot (l_{AB} - x) dx \tag{17}$$

The description in Section 4.3 indicates that the internal forces are only related the pure deformation of an element, and the pure deformation is regardless of rigid displacement and rigid body rotation of an element. In order to obtain the pure deformation, the rigid displacement and rigid body rotation must be removed from the relative displacement. There are three steps to obtain real internal forces of an element in the finite particle method. Firstly, making the element go through a virtual reverse movement, the pure deformation and internal forces of the element are obtained in the initial position as reference. Secondly, making the element go through a virtual forward movement, the element returns to its true position after deformation. Finally, the real internal forces are calculated by transformation of coordinates. The above processes are shown in Fig. 7 and Fig. 8.

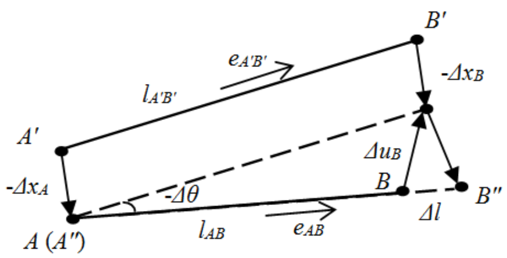

Figure 7. Reverse movement of an element

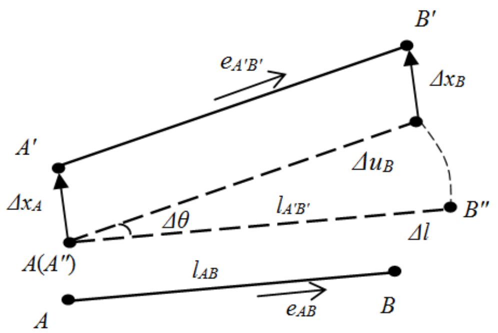

Figure 8. Forward movement of an element

When the state of element changes from state *AB* into state *A'B'*, the internal forces are given by:

$$f_{B'}^{\text{int}} = -f_{A'}^{\text{int}} = \left[\sigma_a A_a + \frac{EA_a}{l_{AB}}\left(l_{A'B'} - l_{AB}\right)\right]\vec{e}_{A'B'} \quad (18)$$

If a simple central difference is adopted, the velocity and acceleration can be approximated as:

$$\begin{aligned} \dot{d}_n &= \frac{1}{2\Delta t}\left(d_{n+1} - d_{n-1}\right) \\ \ddot{d}_n &= \frac{1}{\Delta t^2}\left(d_{n+1} - 2d_n + d_{n-1}\right) \\ d_{n+1} &= \Delta t^2\left(F_\alpha^{\text{ext}} + F_\alpha^{\text{int}}\right)/M_\alpha + 2d_n - d_{n-1} \end{aligned} \quad (19)$$

where, d_{n+1}, d_n and d_{n-1} are the displacements of an arbitrary particle at steps n+1, n and n-1, respectively; Δt is the constant time increment. Substituting (19) into (12) yields.

$$\begin{aligned} d_{n+1} = &\left(\frac{2}{2+\mu\Delta t}\right)\frac{\Delta t^2}{M_\alpha}\left(F_\alpha^{\text{ext}} + F_\alpha^{\text{int}}\right) + \\ &\left(\frac{4}{2+\mu\Delta t}\right)d_n - \left(\frac{2-\mu\Delta t}{2+\mu\Delta t}\right)d_{n-1} \end{aligned} \quad (20)$$

VI. Numerical Examples

Three examples are presented in this section. The first one is dealt with a conductor without a Stockbridge-type damper. The second one refers to a conductor with Stockbridge-type dampers. The other one is about three-dimensional response of Aeolian vibration. The research object in the three examples is the LGJ-500/450 conductor. The tension T is the force acting on ends of the conductor, the span L is 300m, the main physical parameters of the LGJ-500/450 conductor are shown in Table I.

A. Example 1: The Response of Aeolian Vibration of a Conductor without a Stockbridge-Type Damper

The finite particle method is used to calculate the response of Aeolian vibration of conductor without a Stockbridge-type damper in this section. The tension is 18% of the rated tensile strength. Calculation diagram is shown in Fig. 9.

Using MATLAB programming, the responses of Aeolian vibrations are obtained under six conditions in Table II. Taking 1m conductor as an element and the time step h as 0.0001s, the calculation time for each condition is 100s. Before exerting the breeze excitation, initial disturbance need acting on a conductor. An initial load 100N is applied on each particle in order to make an initial velocity and displacement of the conductor.

Under the breeze excitation, there may be a stable vibration of the conductor. Responses of Aeolian conductor vibration for each condition are listed in Table III.

Fig. 10 to Fig. 12 are displacement-time curves of the mid-span particle at the wind speed v=2m/s, 3 m/s and 4 m/s.

According to the displacement-time curves of the mid-span particle, after the initial load is exerted, the conductor will experience a transition period while vibration of the conductor is unstable. Ultimately, the vibration reaches a steady state in about 60s.

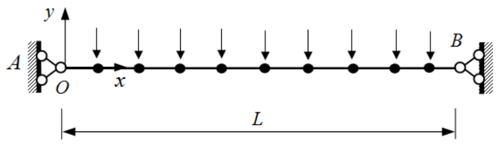

Figure 9. Calculation diagram of a conductor

TABLE I. Conductor Parameters

Parameters	Value
conductor type	LGJ-500/45
diameter (mm)	25
Elastic Modulus (N/ m^2)	6.3×10^{10}
Sectional area (mm^2)	531.68
Mass per unit length (kg/m)	1.688
Rated Tensile Strength (N)	128100

TABLE II. Conditions of Aeolian Vibration of Conductor

Condition Number	Wind Speed (m/s)	Frequency(Hz)
Condition 1	2	16
Condition 2	2.5	20
Condition 3	3	24
Condition 4	3.5	28
Condition 5	4	32
Condition 6	4.5	36

TABLE III. Amplitude of Aeolian Vibration of Conductor

Condition Number	Wind Speed (m/s)	Amplitude (mm)
Condition 1	2	8.5
Condition 2	2.5	9.3
Condition 3	3	10.8
Condition 4	3.5	13.5
Condition 5	4	18.5
Condition 6	4.5	22.6

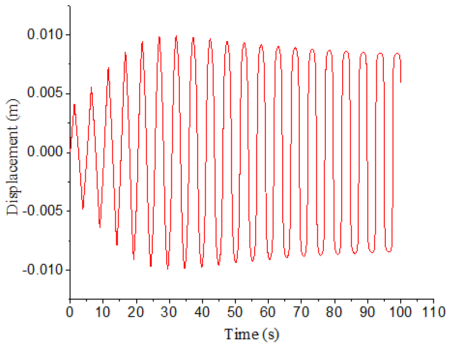

Figure 10. Displacement-time curve at the wind speed v=2m/s

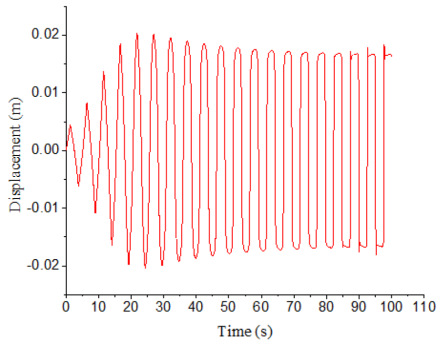

Figure 11. Displacement-time curve at the wind speed v=3m/s

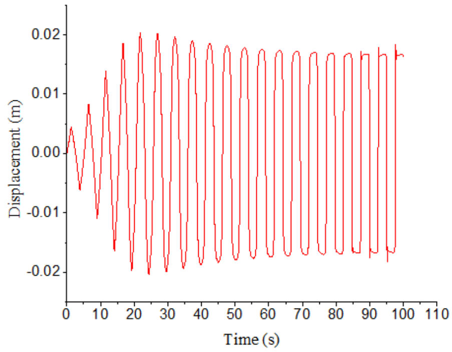

Figure 12. Displacement-time curve at the wind speed v=4m/s

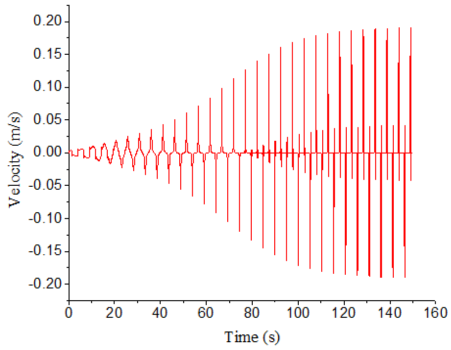

Figure 13. Velocity-time curve at the wind speed v=4m/s

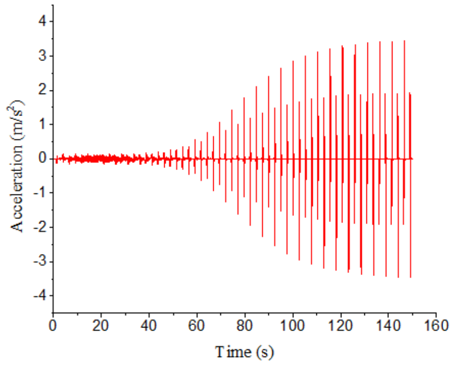

Figure 14. Acceleration-time curve at the wind speed v=4m/s

Fig. 13 to Fig. 14 are velocity-time curve and acceleration-time curve of the mid-span particle at the wind speed v= 4 m/s.

The calculation speed of the finite particle method is much faster than the finite element method, because there is no a complex nonlinear stiffness matrix which need to be solved by repeated iteration.

B. *Example 2: The Response of Aeolian Vibration of a Conductor with Stockbridge-Type Dampers*

This section is based on example 1. Take different types and different locations of Stockbridge-type dampers into consideration, the response of Aeolian vibration of conductor is calculated at wind speed v=2 m/s. The Stockbridge-type dampers are symmetrically arranged with midpoint as a symmetry center. Specific conditions and appropriate results are shown in Table IV.

The results in the above table show that the type and position of dampers have a greater impact on the response of Aeolian vibration of conductor. The vibration damping effect of FR3 type damper is better than FR4 type damper. The damper installed at x_d = 2.0m has a better damping effect than that installed at x_d = 1.0m, because it is closer to the antinode. Reasonable installation Damper and the best installation location of dampers have yet to be studied. The displacement-time curve of the mid-span particle corresponding to the 4th condition in Table IV is shown in Fig. 15.

TABLE IV. CONDITIONS AND ANALYSIS RESULTS OF AEOLIAN VIBRATION OF A CONDUCTOR WITH DAMPERS

Condition Number	**Stockbridge-type Damper Type**	**Damper Location**	**Maximum Amplitude (mm)**
Condition 1	FR3	x_d=1.0m	3.9
Condition 2	FR3	x_d=2.0m	3.2
Condition 3	FR4	x_d=1.0m	6.5
Condition 4	FR4	x_d=2.0m	4.8

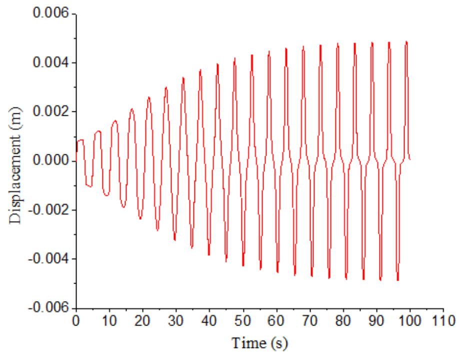

Figure 15. Displace-time curve for 4th condition in Table IV

C. *Example 3: The Three-Dimensional Desponse of Aeolian Vibration of a Conductor*

The Aeolian vibrations of the conductor in section A and section B are regarded as a plane problem. Actually, there is transverse displacement of the conductor due to transverse uniform wind.

In this section, considering transverse displacement of the conductor, three-dimensional rod elements are used to model the conductor in order to research the three-dimensional response of Aeolian vibration. Still with the example of conductor as research object, the displacement of the mid-span particle with damping and that without damping are calculated at wind speed *v*=4m/s. The force acting on the conductor due to the transverse uniform wind is given as follows:

$$F_z = \frac{1}{2}\rho U^2 D C_D \qquad (21)$$

where C_D represents resistance coefficient. At wind speed *v*=4m/s, the three-dimensional vibration curve of the mid-span particle with damping and that without damping are shown in Fig. 16 and Fig. 17, respectively.

Fig. 16 and Fig. 17 can indicate that the lateral motion of conductor due to lateral wind does exist. Without considering damping, the stable vibration locus of conductor particle is a closed curve. Considering damping, amplitude of the lateral motion decreases rapidly, so the process can be considered as an unstable stage of Aeolian vibration of a conductor. As a result of the relatively short duration, the process can be ignored and the Aeolian vibration of a conductor is considered as a two-dimensional vibration.

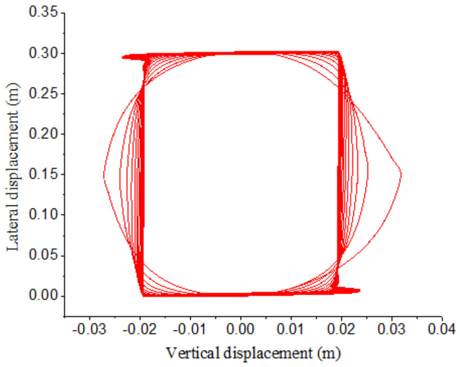

Figure 16. Three-dimensional vibration curve with damping

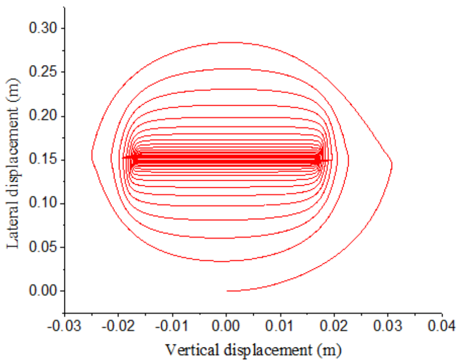

Figure 17. Three-dimensional vibration curve without damping

VII. CONCLUSIONS

1. By using the finite particle method to calculate the response of Aeolian vibration of conductor, the conductor nonlinearity is taken into consideration. This method can produce a more accurate analysis result than the energy balance method.

2. The mathematical model of a Stockbridge-type damper is established and used to calculate the response of Aeolian vibration of conductor with Stockbridge-type dampers. The results show that the type and installation location of Stockbridge-type dampers have a significant impact on the response. Reasonable arrangement of Stockbridge-type damper has yet to be studied

3. The three-dimensional response of Aeolian vibration of conductor is obtained by using three-dimensional rod elements to model the conductor. The results show that the amplitude of the lateral motion with damping decreases rapidly and the Aeolian vibration of conductor can be considered as a two-dimensional vibration.

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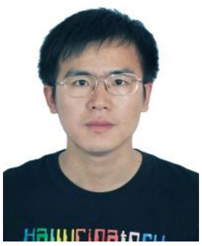

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