

NUMERICAL STUDY ON AERODYNAMIC CHARACTERISTICS OF BUNDLE CONDUCTOR FOR UHV BASED ON ALE METHOD

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Abstract— The bundle conductor is often threatened by the wind-excited or wake-induced vibration generated by vortex shedding. So as to simulate the common fluid–structure nonlinear interaction problems in Ultra-High Voltage (UHV) transmission lines, the N-S equations of incompressible viscous fluid with the ALE description has been adopted to formulate the fluid-solid governing equations in the analogue computation and the 2-bundle and 6-bundle sectional models, as well as the deduced finite element discretization scheme of conductor displacement are introduced in the algorithm. Wind tunnel experimental studies are carried out based on the single stranded model, 6-bundle stranded and 6-bundle circle model for the focus of aerodynamic characteristics and the difference between stranded cable and circle cable. Results show that solution of numerical model agrees favorably with experimental results. The aerodynamic coefficients decrease significantly within the expected critical range of wind speed or Reynolds numbers and the cables roughness is not the principle factor to the aerodynamic coefficient when the Reynolds numbers belong to the critical region. However, the interference effect of the bundle conductor widely influenced the wind load applied on the surface of each cable.

Keywords— fluid-structure nonlinear interaction; ALE method; numerical simulation; bundle conductor; aerodynamic coefficients; wind tunnel experiment; interference effect;

I. INTRODUCTION

Ultra-High Voltage (UHV) transmission lines are often arranged in multi-cables per phase to increase current-carrying capacity. As the interaction among sub-conductors, they are often subjected to wind-induced, such as cable breeze vibration, sub-span oscillation and galloping, etc. The wind-induced displacement can bring the cables close together and cause flashover, in some cases they may even touch together, severely threatening the grids safety. In recent years, the bundle conductor have been widely employed so as to adapt to the rapid construction and development of grids, ensure the efficiency of electricity transmission, inhibit the corona discharge and reduce the linear reactance (Zhang and Chengyong, 2010). Nevertheless, due to the frequent occurrence of disastrous climatic conditions, the accidents resulted from the vibration or galloping in China have been expanding in regions. Since the Overhead transmission lines has great impact on not only the safety of people's life and property but also on the so-

cial stability and development, understanding the sub-cable's behavior under different conditions is of great importance to engineers (Braun and Awruch, 2005).

According to the different oscillation phenomena observed in overhead transmission lines, wind-excited or wake-induced vibration generated by vortex shedding has been considered as a major issue. Although theoretical and experimental methods have been adopted to study these phenomena (Rawlins, 1979), few remedies have been developed to prevent its onset. In this paper, the wind-induced vibration among sub-cables of bundle conductor is simulated by aerodynamic nonlinear fluid-structure interaction model. With regard to the difficulty in nonlinear interaction simulation, it can be well solved by employing the unified coordinate system and by coordinating the interface between two phases. The ALE (Arbitrary Lagrangian Eulerian) method which adapts well to Lagrangian or Eulerian formulations due to its arbitrary moving speed of meshes, can provide an effective unification of the common Lagrange coordinate system for solid mechanics and the common Euler coordinate system for the fluid (Yang, 2005).

In this numerical application, two kinds of bundle conductor are idealized by a two-dimensional cross-sectional model representing the mid span section of the bundle between two towers on considering the deformation of the conductor is much smaller than its actual displacement, and the aerodynamic parameters of the model are finally simulated by programming. In this work, a two dimensional and slightly compressible air flow field is created by using Navier-Stokes equation with the ALE description. So as to combine the nonlinear effect of motion boundary in the calculation, each mesh point continuously renews with the motion of free liquid surface or of the contact surface movement between fluid and solid (Lou, 2008). The influence study of the aerodynamic parameters on 2-bundled conductor is firstly carried out and by comparing the test values of Wardlaw and Cooper (1974), it can conclude that the numerical model agrees favorably with experimental results. Wind-induced vibration of the 6-bundle conductor within the change range of wind speed, as well as the wake influence of windward conductor on leeward conductor is then analyzed. At last, some wind-tunnel test is taken to verify the feasibility of the calculation model.

II. CALCULATION EQUATIONS

A. ALE Method Governing Equation

A cable of the bundle conductor in different arrangements in the cross flow field may vibrate under the unsteady forces acting on the upstream cable. This un-

steady force takes the shape of alternating eddy current, naming Karman vortex stress, which is formed and shed as a result of boundary layer roll-up. In order to discover the wake influence on the downstream conductor, the research is accomplished using the finite element discretization computational algorithm for the calculation of spatial domain and the decoupled system of the Navier-Stokes equation of time domain (Schlichting, 1979).

The governing equations chosen for the analysis are Navier-Stokes equations, assuming that the spatial domain of viscous fluid flow is Ω and the boundary is Γ , the Navier-Stokes equations of viscous flow with the ALE description are given by:

Motion equation

$$\rho \frac{\partial v_i}{\partial t} + \rho(v_j - w_j) \frac{\partial v_i}{\partial x_j} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i, \quad (1)$$

where $i, j=1, 2$.

Mass conservation equation

$$\frac{\partial v_i}{\partial x_i} = 0, \quad (2)$$

Stokes constitutive equation

$$\sigma_{ij} = -p\delta_{ij} + \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right), \quad (3)$$

where v_i is velocity component (m/s); w_j is mesh speed (m/s); ρ is fluid density ($\text{kg}\cdot\text{m}^{-3}$); σ_{ij} is stress tensor ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2}$); f_i is strength vector ($\text{kg}\cdot\text{m}\cdot\text{s}^{-2}$); p is pressure ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2}$); μ is dynamic viscosity coefficient of fluid ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$).

The N-S equations of incompressible viscous fluid with the ALE description may be written as follows.

Motion equation:

$$\frac{\partial v_i}{\partial t} + c_j \frac{\partial v_i}{\partial x_j} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i, \quad (4)$$

where $i, j=1, 2$.

Mass conservation equation

$$\frac{\partial v_i}{\partial x_i} = 0, \quad (5)$$

Stokes constitutive equation

$$\sigma_{ij} = -\frac{p}{\rho} \delta_{ij} + \nu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right), \quad (6)$$

where v_i is velocity component (m/s); w_j is mesh speed (m/s); ρ is fluid density ($\text{kg}\cdot\text{m}^{-3}$); σ_{ij} is stress tensor ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2}$); f_i is strength vector ($\text{kg}\cdot\text{m}\cdot\text{s}^{-2}$); p is pressure ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2}$); μ is dynamic viscosity coefficient of fluid ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$).

By substitution of eq. (6), eq. (4) and eq. (5) can be presented respectively as follows.

$$\frac{\partial v_i}{\partial t} = -c_j \frac{\partial v_i}{\partial x_j} - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 v_i}{\partial x_i \partial x_j} + f_i, \quad (7)$$

$$\frac{\partial v_i}{\partial x_i} = 0, \quad (8)$$

Discrete time factorization of eq. (7) and eq. (8), eq. (9) and eq. (10) are obtained.

$$v_i^{n+1} = v_i^n - \Delta t \left(c_j^n \frac{\partial v_i^n}{\partial x_j} + \frac{1}{\rho} \frac{\partial p^{n+1}}{\partial x_i} - \nu \frac{\partial^2 v_i^n}{\partial x_i \partial x_j} - f_i^{n+1} \right), \quad (9)$$

$$\frac{\partial v_i^{n+1}}{\partial x_i} = 0, \quad (10)$$

By removing the gain of pressure and introducing the intermediate speed, Eq. (9) can be presented as follows.

$$\bar{v}_i^{n+1} = v_i^n - \Delta t \left(c_j^n \frac{\partial v_i^n}{\partial x_j} + \frac{1}{\rho} \frac{\partial p^n}{\partial x_i} - \nu \frac{\partial^2 v_i^n}{\partial x_i \partial x_j} - f_i^{n+1} \right) \quad (11)$$

Thus, the calculation formulas of pressure and speed can be written respectively as follows.

$$\frac{\partial^2 p^{n+1}}{\partial x_i^2} = \frac{\rho}{\Delta t} \frac{\partial \bar{v}_i^{n+1}}{\partial x_i} + \frac{\partial^2 p^n}{\partial x_i^2}, \quad (12)$$

$$v_i^{n+1} = \bar{v}_i^{n+1} - \frac{\Delta t}{\rho} \left(\frac{\partial p^{n+1}}{\partial x_i} - \frac{\partial p^n}{\partial x_i} \right). \quad (13)$$

Speed and pressure formulas can be calculated in the independent equations with the finite element decoupled method, so assuming that

$$v_i = \phi_\alpha v_{\alpha i}, \quad (14)$$

$$p = \phi_\alpha p_\alpha, \quad (15)$$

where ϕ_α is interpolation function, while $v_{\alpha i}$ and p_α represent the i^{th} speed component and pressure component at the α^{th} node of finite element.

On considering the Galerkin weighted residual method, the finite element numerical discretization equation is the deduced as follows.

For the calculation of intermediate speed $\bar{u}_i^{n+1}$, p^{n+1} and u_i^{n+1} , the equations are

$$M_{\alpha\beta}^{n+1} \bar{u}_{\beta i}^{n+1} = M_{\alpha\beta}^n u_{\beta i}^n - \Delta t K, \quad (16)$$

where,

$$K = B_{\alpha\beta}^n u_{\beta i}^n + \frac{1}{\rho} C_{\alpha\beta i}^n p_\beta^n + D_{\alpha i \beta j}^n u_{\beta j}^n - F_{\alpha i}^{n+1} - E_{\alpha i}^{n+1}$$

$$A_{\alpha\beta}^{n+1} p_\beta^{n+1} = -\frac{\rho}{\Delta t} C_{\alpha\beta i}^{n+1} \bar{u}_{\beta i}^{n+1} + A_{\alpha\beta}^n p_\beta^n + Q_\alpha^{n+1} - Q_\alpha^n, \quad (17)$$

$$M_{\alpha\beta}^{n+1} u_{\beta i}^{n+1} = M_{\alpha\beta}^{n+1} \bar{u}_{\beta i}^{n+1} - \frac{\Delta t}{\rho} (C_{\alpha\beta i}^{n+1} p_\beta^{n+1} - C_{\alpha\beta i}^n p_\beta^n), \quad (18)$$

In which,

$$\begin{aligned}
M_{\alpha\beta}^{(e)} &= \int_V \phi_\alpha \phi_\beta dV & B_{\alpha\beta}^{(e)} &= \int_V \phi_\alpha \phi_{\beta,j} c_j^n dV \\
C_{\alpha\beta j}^{(e)} &= \int_V \phi_\alpha \phi_{\beta,i} dV & D_{\alpha\beta j}^{(e)} &= \int_V \phi_{\alpha,j} v(\phi_{\beta,j} \delta_j + \phi_{\beta,i}) dV \\
F_{\alpha i}^{(e)} &= \int_V \phi_\alpha f_i dV & E_{\alpha i}^{(e)} &= \int_S \phi_\alpha \bar{t}_i dS \\
A_{\alpha\beta}^{(e)} &= \int_V \phi_{\alpha,i} \phi_{\beta,j} dV & Q^{(e)} &= \int_S \phi_\alpha \rho v_i n_i dS
\end{aligned}$$

In these equations: α and β are the number of unit nodes; i, j (1, 2, 3) is the number of spatial dimensions; v_i is the structural speed on the interaction interface; $\bar{t}_i$ is the given pressure on the boundary.

Equation (16), Eq. (17) and Eq. (18) can be sorted out into matrixes as follows.

$$M^{n+1} \bar{u}_i^n = M^n u_i^n - \Delta t K', \quad (19)$$

In which $K' = (B^n \delta_{ij} + D_{ij}) u_j^n - \frac{1}{\rho} C_i p^n - E_i$

$$M^{n+1} p^{n+1} = -\frac{\rho}{\Delta t} C_i^{n+1} \bar{u}_i^{n+1} + A^n p^n + Q^{n+1} - Q^n, \quad (20)$$

$$M^{n+1} \bar{u}_i^{n+1} = M^{n+1} \bar{u}_i^n - \frac{\Delta t}{\rho} (C_i^{n+1} p^{n+1} - C_i^n p^n), \quad (21)$$

On the interaction boundary, the condition of speed interaction is considered:

$$u = T^T v, \quad (22)$$

where v is the structural motion speed on the interaction boundary; and T^T is the matrix of geometrical relationship (Schlichting, 1979; Zhang and Huang, 2002).

So as to solve the unsteady Navier-Stokes equations, i.e. solving the averaged Reynolds equations, the low-order correlation function and the average flow characteristics are employed in the algorithm to simulate the high-order correlation function for closing the relevant equations. Due to the simulated rules of conductor model, the turbulent kinetic energy-dissipation rate ($k-\varepsilon$) model is adopted.

B. Interaction Vibration Equations

The motion equation of the structure is shown as follows.

$$M_s \ddot{x} + C_s \dot{x} + K_s x = L_s, \quad (23)$$

where M_s is the mass matrix of the structure; C_s is the damping matrix of the structure; K_s is the rigidity matrix of the structure; $\ddot{x}$, $\dot{x}$ and x are respectively the vectors of acceleration, speed and displacement of the structure; L_s is the load vector.

$$L_s = L_{flow} + L_g, \quad (24)$$

$$L_{flow} = -TF = -\int_S n \cdot [\phi] ds \cdot p, \quad (25)$$

in which, L_{flow} is the fluid load on conductor; L_g is the gravity of conductor.

Equation (25) is deduced from the interaction interface, of which T^T is the geometrical matrix, F is equivalent

node load, $n=[n_1, n_2, n_3]^T$ is wall surface normal vector, and $[\phi]$ is the matrix of interpolation function.

$$p^{n+1} = (M^{n+1})^{-1} \left(-\frac{\rho}{\Delta t} C_i^{n+1} \bar{u}_i^{n+1} + A^n p^n + Q^{n+1} - Q^n \right), \quad (26)$$

$$Q^{n+1} = \int_S \rho [\phi]^T n ds \cdot \dot{v} = \rho T^T \cdot \dot{v}, \quad (27)$$

Therefore, the discrete time factorization of conductor speed can be deduced as follows.

$$[m + \rho T (M^{n+1})^{-1} T^T] \ddot{x} + C_s \dot{x} + K_s x = L_s, \quad (28)$$

$$L_s = -[(M^{n+1})^{-1} \left(-\frac{\rho}{\Delta t} C_i^{n+1} \bar{u}_i^{n+1} + M^n p^n - Q^n \right)] + L_g, \quad (29)$$

Also,

$$\frac{\partial x^n}{\partial t} = \frac{x^n - x^{n-1}}{t_{Step}}, \quad (30)$$

$$\frac{\partial \dot{x}^n}{\partial t} = \frac{\dot{x}^n - \dot{x}^{n-1}}{t_{Step}}, \quad (31)$$

In which, t_{Step} is the step of nonlinear calculation.

Finally, the finite element discretization scheme of the conductor displacement can be deduced as follows and by means of numerical algorithm, the structural motion component of every time step can be calculated.

$$x^n = \frac{L_s + \frac{\dot{x}^{n-1}}{t_{Step}} + \left(\frac{1}{t_{Step}^2} + \frac{C_s}{t_{Step}} \right) x^{n-1}}{\frac{1}{t_{Step}^2} + \frac{C_s}{t_{Step}} + K_s}, \quad (32)$$

III. CONDUCTOR WAKE ANALYSIS

In this paper, the trend analysis of wake influences that arises from bundle layouts of windward conductor and leeward conductor was carried out. Therefore, numerical results focused on the changes in key parameters of cables' position. The example considered first of all is 2-bundle conductor and the conductor distribution is shown in Fig. 1. A smooth circular cross sectional cylinder whose position is assumed fixing represented the windward cable; meanwhile the right identical leeward circular cross section with the smooth wall surface at a fixed horizontal distance ($X/D = 10$) is considered as the leeward conductor. The lift coefficient and drag coefficient will be calculated as a function of the different intersections (Y/D) of two cables in fluid field. The boundary conditions of simulation are assumed as follows: the speed entrance boundary conditions for entrance boundary, i.e. $u=U$, $v=0$ (u and v represent the speed vectors in the directions X and Y respectively); the outlet boundary conditions for exit boundary, assuming that the downstream is long enough, the outlet surface has no impact on upstream flow, i.e. $\partial u/\partial x=0$, $\partial v/\partial x=0$; the symmetrical boundary condition for upper and lower boundaries, i.e. $\partial u/\partial y=0$, $v=0$; the calculation time is set as 5s with an interval of 0.002s.

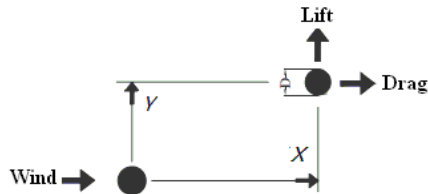


Fig. 1. Configuration of the cable in downstream position in a wake interference study

Table 1 Calculation parameters of the fluid

ρ [kg·m ⁻³]	1.2
ν [m ² ·s ⁻¹]	3.85×10^{-4}
R_e	2.6×10^4
v_0 [m·s ⁻¹]	10
L_0 [m]	1

The calculation parameters of the fluid are shown in Table 1.

The wake interference calculation results in terms of drag and lift forces which compared with the test results of Wardlaw and Cooper (1974), shows that there was no significant differences between the case studied and the experiment, shown in Fig. 2, proving that the algorithm is in accord with the actual working conditions. The drag coefficient of the bundle conductor has its smallest value when $Y/D = 0$. Affected by the constantly increasing wake turbulence, the drag coefficient increases constantly and converges to the value of the single cable as

the separation between two cables (Braun and Awruch, 2005). The lift coefficient increased until $Y/D = 1$ where wake effects become more intensive, representing the single cable situation. Then the lift coefficient begins to decrease as the Y/D increased.

The dynamic responses of lift and drag coefficient at mid span of the downstream cable is shown in Fig. 3. It is obvious that the lift and drag coefficient time-history curves of leeward conductor under the wake interference when the time ranges from 1s to 2s, clearly reflect the vortex shedding of near-wall boundary layer, justifying the method presented in this paper.

IV. SIMULATION ANALYSIS of the 6-BUNDLE CONDUCTOR

Taking the 6-bundle conductor of UHV transmission line as an example, the wind-induced vibration and the wake influence of the bundle were simulated and analyzed. The bundle conductor distribution is shown in Fig. 4, where $X/D = 14$, $Y/D = 0$ and $\theta = 0^\circ$. Fluid properties as well as the geometrical characteristics are shown in Table 2. The flow is imposed prescribing the velocity components in the global coordinate directions on the cable surface with its conditions described in conductor wake analysis and the Reynolds numbers ranges from $10^4 \sim 6 \times 10^4$. The time-intervals adopt for the time marching process is 0.002s.

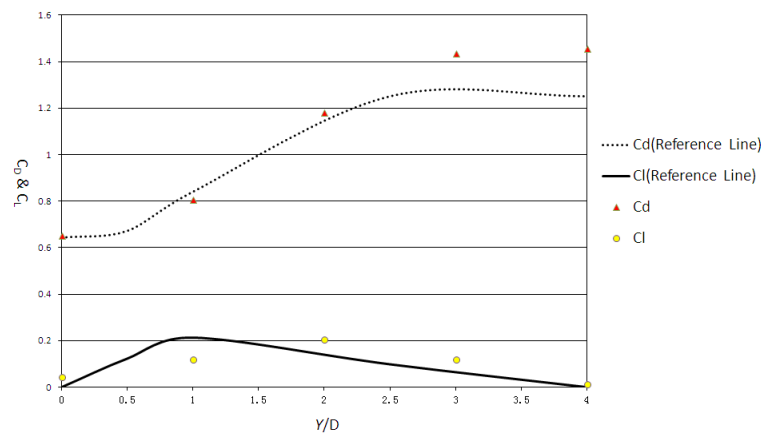


Fig. 2. Aerodynamic coefficients obtained in the wake interference analysis

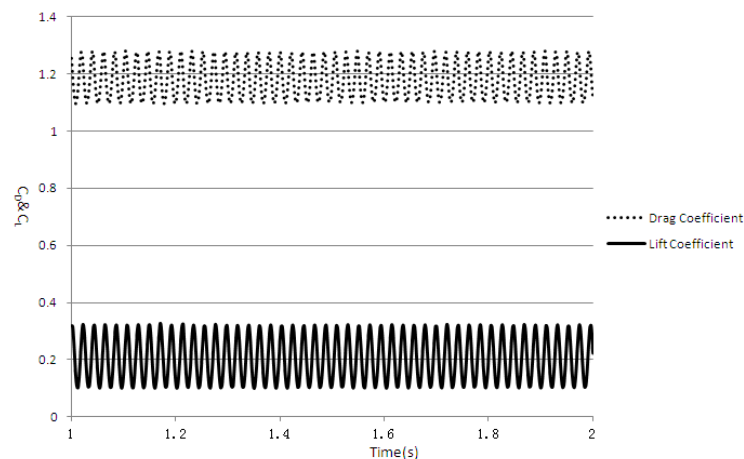


Fig. 3. Time-history curve of the downstream cylinder from $t=1 \sim 2$ s

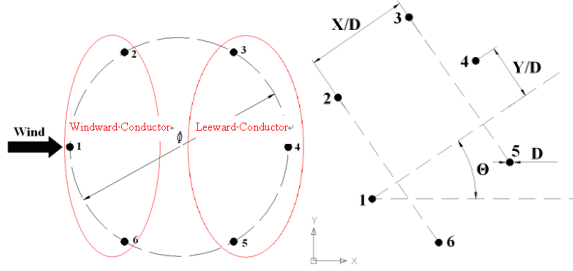


Fig. 4. Configuration of the bundle in the aerodynamic study of Reynolds numbers influence.

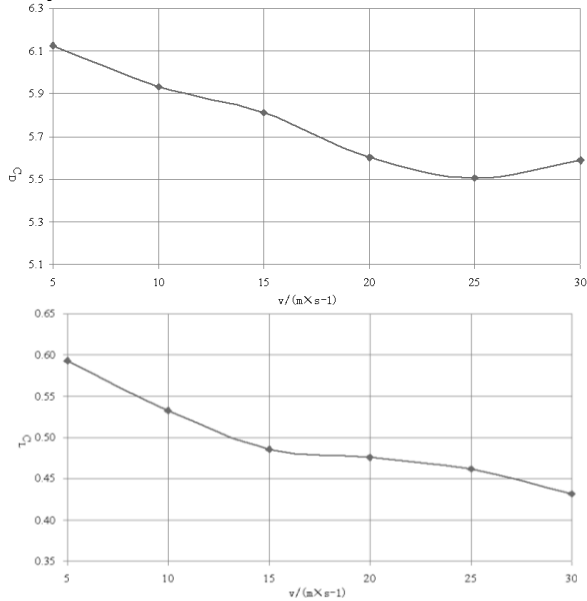


Fig. 5. Aerodynamic coefficient obtained in the bundle conductor analysis

Table2. Calculation parameters of the fluid

ρ [$\text{kg}\cdot\text{m}^{-3}$]	1.2
ν [$\text{m}^2\cdot\text{s}^{-1}$]	3.85×10^{-4}
Re	$10^4\sim 6\times 10^4$
L_0 [m]	0.03

Figure 5 shows respectively the variation of the global lift and drag coefficient as a function of wind speed or Reynolds number. It is obvious that the Reynolds number decreases the magnitude of aerodynamic coefficients. In the regions of the negative slope of the drag coefficient, the average coefficient of the bundle conductor shows the trend of rapid decrease when the wind speed ranges from 5m/s to 15m/s, then it decreases slowly within the section of 15m/s~30m/s. As the wind speed is between 5m/s and 30m/s, the average lift coefficient also decreases, moreover, there exists a section of rapid decrease for the coefficient when the wind speed is between 5m/s and 15m/s, while the decreased trend begins to turn slow down within the section of 15m/s~30m/s (Xie *et al.*, 2011).

The aerodynamic coefficients on a bundle conductor are generated by the location of flow separation on the fluid-solid interface and the wake influence of windward conductor on leeward conductor. As a result, it is clear that the turbulence on the lift and drag coefficient must be due to the changes in the pressure distribution around the model (Chadha and Jaster, 1975). When the Reynolds number changes in the critical range, the flow

separation points and the distribution of the pressure become so sensitive to wind velocity, turbulence level, etc. (Chadha, 1974). In the algorithm, the range of critical wind speed was simulated from 5m/s to 30m/s, so the aerodynamic coefficients were performed when the Reynolds number was in the critical range. In order to investigate the role of turbulence in affecting the aerodynamic coefficients of the bundle conductor, the Fast Fourier Transform (FFT) was carried out to gain the spectrum lines for the time-history curves of lift coefficient and drag coefficient at the wind speed of 20m/s, shown in Fig. 6 and Fig. 7. The drag coefficient spectrum lines of windward conductors show the characteristics of multi-frequency while the lift coefficient spectrum lines of windward conductors are much simpler, which is obviously caused by Karman Vortex Street. The beat vibration occurs to the leeward cables whose frequencies consist of two approximate waveforms caused by both the wake of Karman Vortex Street of windward cables and the Karman Vortex Street of leeward cables (Sarrate *et al.*, 2001; Oliveira, 2002; Aetal *et al.*, 2004). The double influences which result in a double asymmetry of flow, shift the location of the separation points at the top and the bottom surfaces of the cables and affect the separation and reattachment of flow in the model.

V. WIND TUNNEL TEST OF AERODYNAMIC PARAMETERS FOR CONDUCTORS

In order to give a further understanding of the subject, the aerodynamic tests were carried out to assess the variation law of aerodynamic parameters for different conductor structures at different wind speeds and incidence angles. The wind tunnel adopted which is equipped with the simulation device of atmospheric boundary layer and a high-precision and high-frequency balance, is an open-circuit closed system. This return-flow device has a $1.4\text{m}\times 1.4\text{m}$ wind section where the test wind speed ranges from 10m/s to 65m/s and is measured and controlled by a flow master and by a pilot tube jointed to a manometer. The test section in the shape of corner rectangular is 1.8632m^2 and 2.8m long, shown in Fig. 8.

All the data measured during the whole test period were processed by six-component force balance which is used to measure the drag force, lift force and torque of the model, shown in Fig.9. The collecting instrument was controlled by the PXI (PCI eXtensions for Instrumentation) system, while the angle and speed-pressure governing were realized by the corresponding IPC (Inter Process Communication) system. The network communication was provided to deliver the commands between equipments and transferred the data for further calculation.

Data concerning the test set up are summarized in the following list.

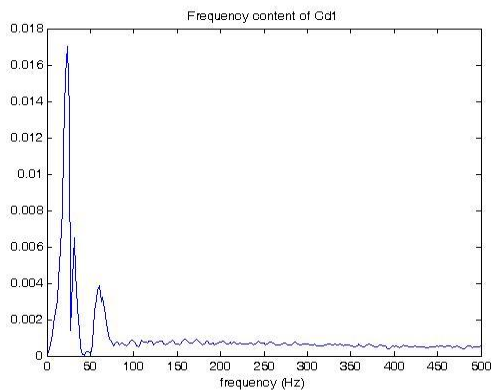
- Dimension of test section: $1.4\text{m}\times 1.4\text{m}\times 2.8\text{m}$;
- Turntable diameter of test section: 0.92m;
- Maximum wind speed: 65m/s
- Minimum stable wind speed: 10m/s;
- Common wind speed: 20~25m/s;

- Wind tunnel input energy ratio: 1.2;
- Range of turntable up and down: $\pm 180^\circ$;
- Axial static pressure gradient: 0.009/m;
- Flow field of model region: $\Delta\alpha \leq 0.26^\circ$, $\Delta\beta \leq 0.46^\circ$;
- Dynamic pressure field coefficient of model region: $\mu \leq 1.0\%$;
- Turbulence: $\leq 0.14\%$.

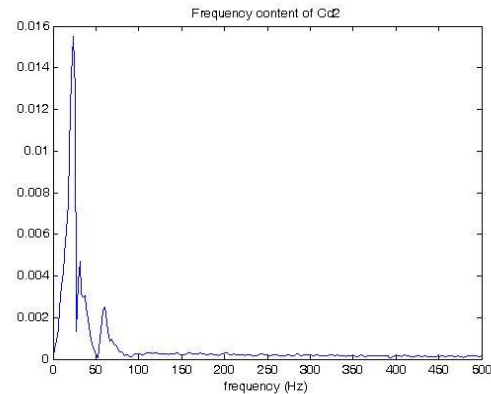
A. Test Results of Aerodynamic Coefficients for Single Stranded Conductor

The aerodynamic coefficient study on the single stranded conductor at different wind speeds and different angles of attack were firstly tested. Taking the conductor LGJ500/45 ($\varphi=30\text{mm}$) as an example, the curves of lift

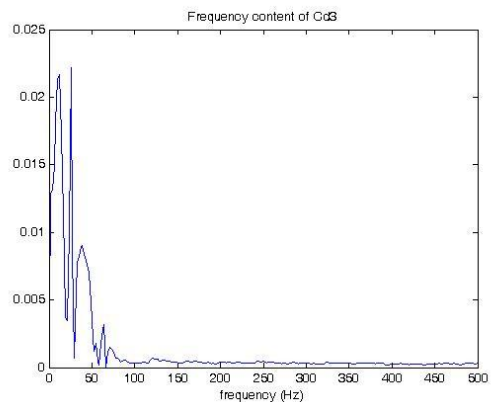
and drag coefficients under different working conditions are shown in Fig. 10. According to the figure, the lift coefficient curves are antisymmetric with respect to $\alpha=180^\circ$, while the drag coefficient curves are symmetric with respect to $\alpha=180^\circ$. The test results indicate that the aerodynamic coefficients flat curves when the wind incidence angle ranging $0^\circ \sim 120^\circ$ and $240^\circ \sim 360^\circ$ for four wind speed due to the cable symmetry when it was referenced to the stream direction, three zones where the lift curves are antisymmetric and the drag curves are symmetric with respect to $\alpha=135^\circ$, $\alpha=180^\circ$, $\alpha=225^\circ$. As the wind speed increases, both the drag coefficient and the lift coefficient decrease, but the lift coefficient changes slightly.



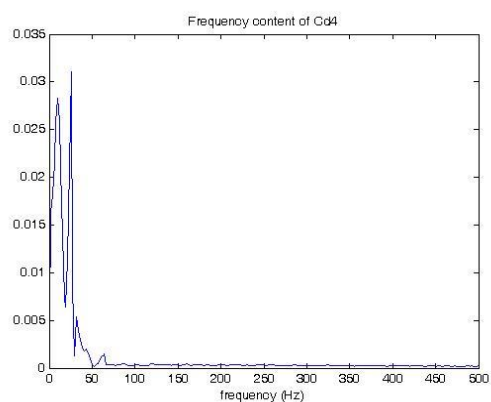
a) Spectrum lines of drag force of cable 1



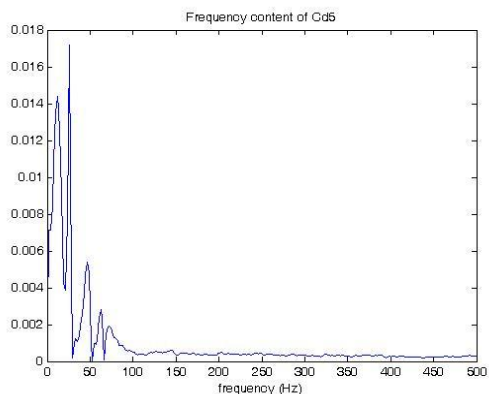
b) Spectrum lines of drag force of cable 2



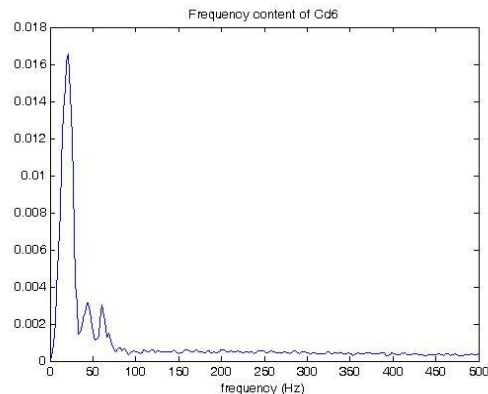
c) Spectrum lines of drag force of cable 3



d) Spectrum lines of drag force of cable 4



e) Spectrum lines of drag force of cable 5



f) Spectrum lines of drag force of cable 6

Fig. 6. Spectrum lines of drag force.

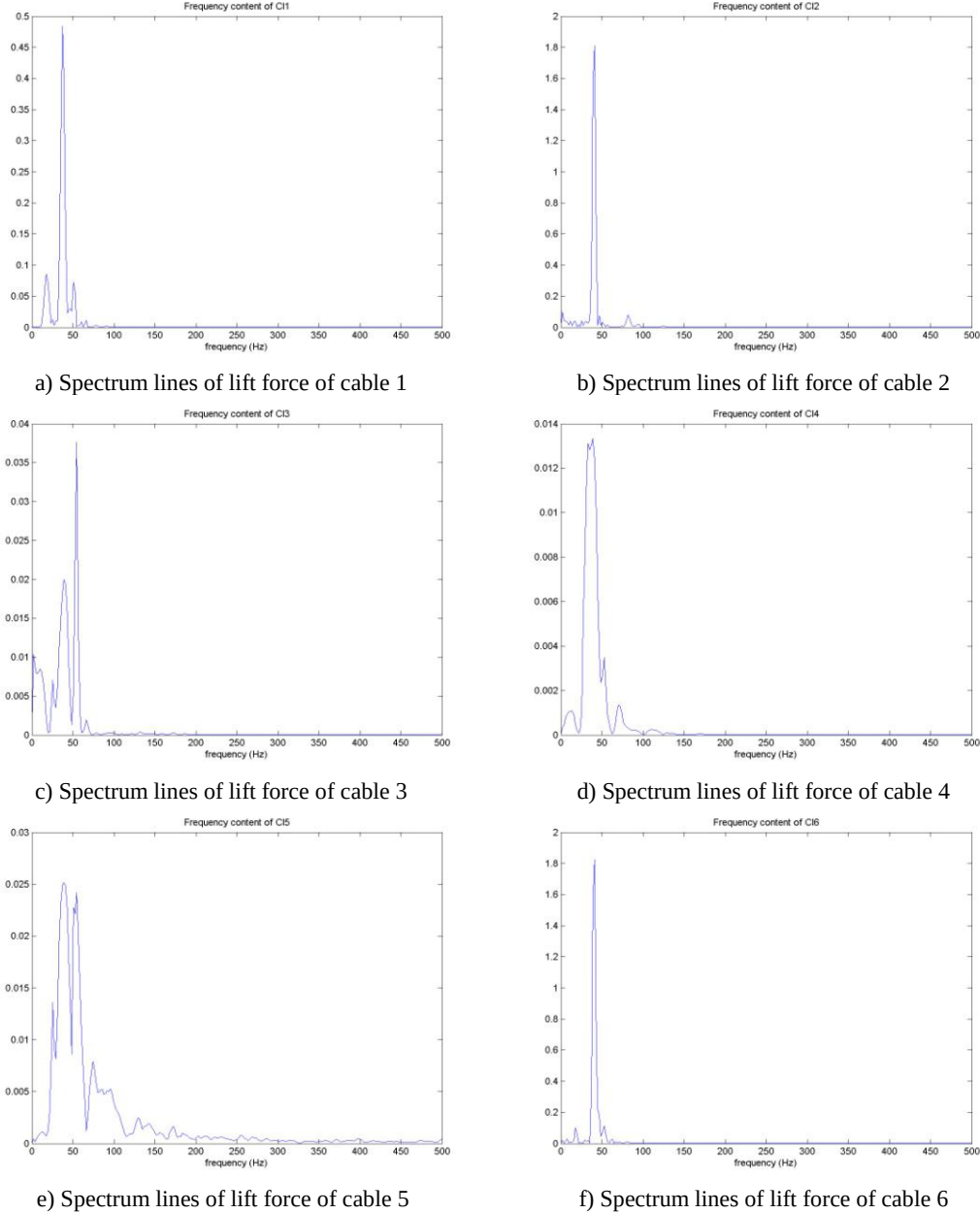


Fig. 7. Spectrum lines of lift force.



Fig. 8. Wind tunnel of aerodynamic experiments for the conductor

B. Test Results of Aerodynamic Parameters for 6-Bundle Conductor

An important factor cause the differences between the experiments and numerical studies is the cable roughness for the numerical algorithm didn't take cables' surface into account (Pan *et al.*, 2001). Hence, the difference between the 6-bundle stranded cables and 6-bundle with cables were tested in this paper. Two bundles were

fixed to the force balance through a round base and the aerodynamic loads were obtained through subtraction of the test results and the force applied to the base. The experiment as a function of the wind velocity was carried out only when the angle of attack was 0° and the test results are shown in Fig. 11. Despite the cable roughness,



Fig. 9. Test devices

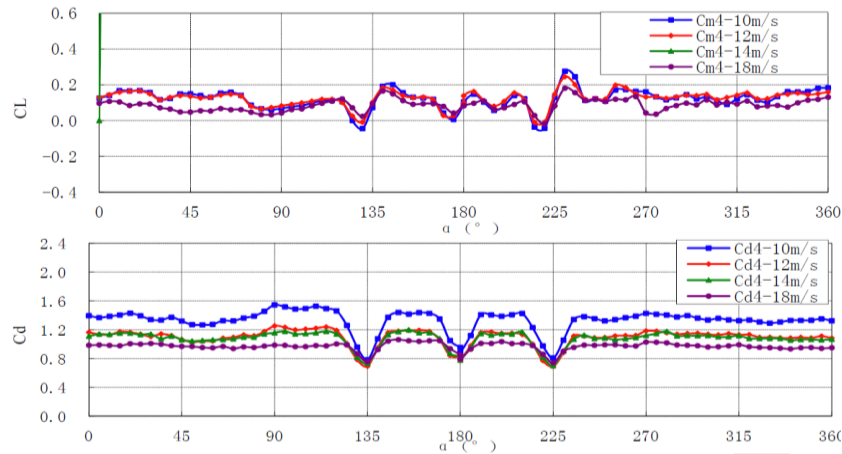


Fig. 10. Aerodynamic curve of the single conductor

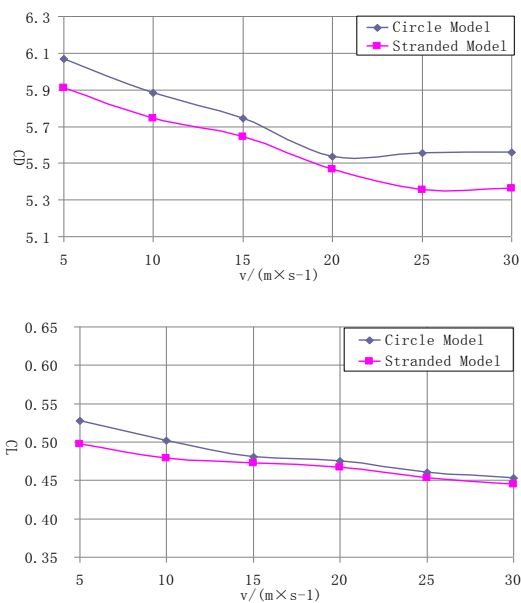


Fig.11 Relation between drag and lift coefficients and wind speed of the 6-bundle conductor

good agreements of the change trends were obtained between stranded model and circle model while the lift and drag coefficients of the stranded model obtained are smaller than that of the circle model.

As shown in Fig. 11 and Fig. 5, the experimental results are approximate to the values and the trend of the numerical model in Section 4, which means that the numerical algorithm and the wind tunnel experiment are in accord with each other to some extent. The drag force values are related to the area of the cables and the Reynolds numbers of the flow. With regard to the circle model, the average values of the bundle intend to decrease rapidly in the wind speed section between 5m/s and 20m/s and the curves become smooth when the wind speed ranges from 20m/s to 30m/s. Meanwhile, due to the difference of six coefficients, the lift forces have inexpressive values as the wind velocity increases in the critical region (Jacob, 2006; Zhu *et al.*, 2010).

According to the curves of stranded model, when the wind speed and the Reynolds number reach respectively to 10m/s and 2×10^4 , the drag coefficient starts decreasing significantly. Then it experiences a rapid decrease until the speed reaches 20m/s, after that the curve becomes smooth when the wind speed is between 20m/s and 30m/s. The lift coefficient also decreases when the wind speed is between 5m/s and 30m/s as that of the circle model. Hence, the aerodynamic coefficients of the stranded model decrease along with the increase of Reynolds number and the surface of stranded model can effectively reduce the aerodynamic parameters. Moreover, on considering the little difference between two curves, the conclusion that cables roughness is not the principle factor to the aerodynamic coefficient when the Reynolds numbers belong to the critical region can be drawn.

VI. CONCLUSIONS

In this paper, a numerical model to simulate the wind-induced or wake-induced vibration generated by vortex shedding on the bundle conductor of Ultra-High Voltage transmission lines was presented. Based on the decoupled finite element numeric method with the ALE description, the discretization formula of the conductor displacement was firstly deduced and the fluid-solid nonlinear interaction algorithm was then created to analyze the idealized middle-span cross-sectional model. After the calculation study on change trends for aerodynamic coefficients of 2-bundle conductor and 6-bundle conductor, the results showed that the algorithm was able to obtain the correct values when compared with the wake interference test results of Wardlaw and Cooper. The aerodynamic aspects related to the analysis have been briefly summarized as below:

- 1) The calculation results of 2-bundle conductor showed that there were no significant differences between the case studied and the tests, meanwhile the time-history curves of aerodynamics clearly revealed the phenomenon of vortex shedding. Hence, the numerical model agrees favorably with the actual situation to some extent.
- 2) The aerodynamic coefficient curves of the 6-bundle conductor obtained describe the variation with respect to wind speed. Within the velocity range of interest, both drag and lift coefficients decrease more significantly in the critical range of 5m/s~20m/s. The drag coefficient drops 10% from 6.10 to 5.60, while the lift coefficient

cient drops 24% from 0.60 to 0.46, demonstrating that the aerodynamic coefficients decrease significantly within the expected critical range of wind speed or Reynolds numbers.

3) By performing the Fast Fourier Transform for the time-history curves of aerodynamic coefficients, it is concluded that the drag coefficient spectrum lines of windward conductors have the feature of multi-frequency and the lift coefficient is obviously caused by Karman Vortex Street. With regard to the leeward cables, the beat vibration can be observed that the frequencies consist of two approximate waveforms. The spectral analysis on the leeward cables reveal that when unstable behavior occurs, the motion is formed by divergent type and the limited-amplitude type of motion, caused by both the wake of Karman Vortex Street of windward cables and the Karman Vortex Street to the leeward cables (Sarrate *et al.*, 2001; Oliveira, 2002; Aetal *et al.*, 2004; Cheng *et al.*, 2008).

Wind tunnel experiments were carried out to study the aerodynamic coefficients of the single stranded conductor and the 6-bundle of stranded model and circle model, as well as to verify the simulation results of the algorithm. The curves of single stranded model tested at different wind speeds and different angles of attack presented that the lift values were antisymmetric, while the drag values were symmetric with respect to $\alpha=180^\circ$. With the increases of wind speed, both the drag and the lift coefficient decreased. With regard to the bundle model, cables roughness is not the principle factor to the aerodynamic coefficient when the Reynolds numbers belong to the critical region. However, the interference effect of the bundle conductor widely influenced the wind load applied on the surface of each cable. Taking the 6-bundle conductor in the average fluid field of 10m/s as an example, the drag and lift coefficients of the bundle were respectively 29.6% and 33.5% lower than 6 times of that for the single stranded conductor.

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