Numerical analysis of fluid-structure interaction of iced line galloping

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Abstract: Numerical simulation of transmission lines' movement can reveal the variation of aerodynamic force with conductor vibration. The fluid-structure interaction is considered and, and the software FLUENT is used to numerically analyze the model responses of 0.75D crescent-shaped iced conductor with wind attack Angle of 180° based on the k-ω SST turbulence model. The numerical simulation results of unsteady galloping of the iced conductor are compared with the galloping response of displacement time history analysis. The results show that the results of the fluid-structure interaction analysis are consistent with the quasi-steady analysis.

Keywords: Iced conductor galloping, Fluid-structure interaction, CFD simulation, k-ω SST turbulence model.

1. Introduction

The galloping refers to a kind of self-excited vibration with low frequency and large amplitude generated under the excitation of wind load when the cross-section shape of the conductor changes after icing [1]. In general, the galloping of the iced conductor is numerically simulated based on quasi-steady state theory, and its aerodynamic coefficients are static [2-3]. You [4] used the k-ω SST turbulence model to conduct a numerical simulation of a D-shaped iced conductor and analysis the influence of degrees of freedom and wind attack angle on the galloping. Li [5] established the finite element models with different ice thicknesses and wind speeds, then calculated corresponding aerodynamic characteristics. Talib [6] proposed a simplified dynamic model of transmission conductor galloping and verified the results through experiments. The above research based on quasi-steady theory does not consider the influence of conductor movement on aerodynamic coefficients, so they are not real fluid-structure interaction. Zhang [7] analyzed the dynamic aerodynamic coefficient of the iced conductor. Deng [8] conducted unsteady theoretical research on the wake galloping of suspension bridges. Most of those researches only focus on aerodynamic coefficients, and the numerical simulations of iced conductor movement are less. In this paper, the FLUENT is employed to analyze the model responses of the 0.75D crescent-shaped iced conductor based on the k-ω SST turbulence model, the mesh and time step are determined to calculate and analyze the galloping response results.

2. Numerical model

We take the crescent-shaped iced conductor as the research object and established a two-dimensional wind tunnel model including crescent-shaped iced conductor. The diameter D of the iced conductor is 26.8mm, the thickness of ice is 0.75D, which is 20.1mm, and the initial angle of the iced conductor is 0°. The schematic of the cross section for the crescent-shaped iced conductor is shown in Figure 1.

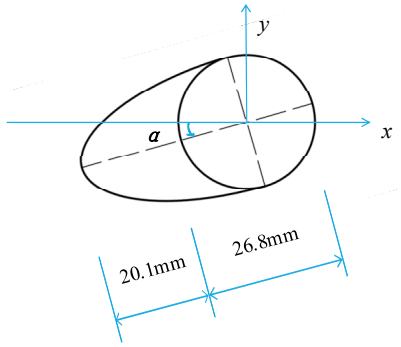


Figure 1. Schematic of the cross-section for the crescent-shaped iced conductor.

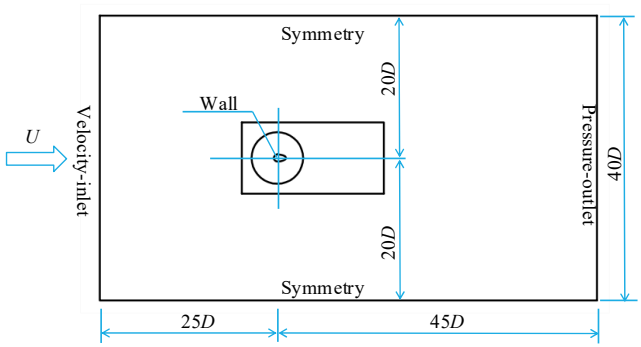
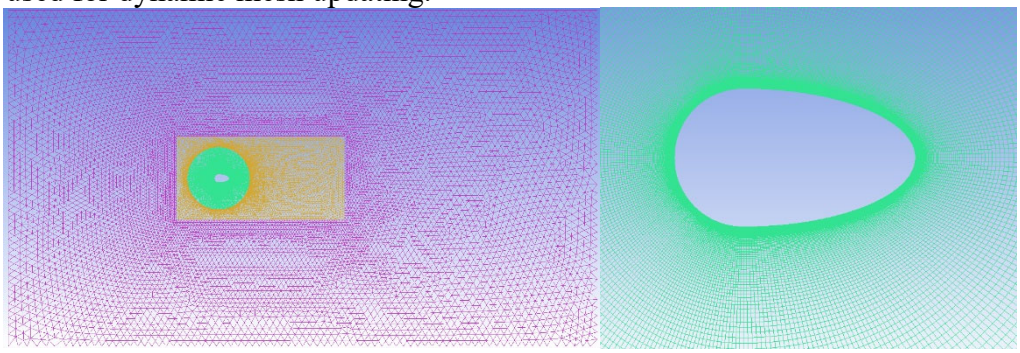


Figure 2. Calculation domain of crescent-shaped iced conductor

In order to weaken the influence of the boundary effect on the conductor, the calculation area is taken as a rectangular area with a size of 1876mm×1072mm, and the center of the iced conductor is the origin of the coordinates. The distance from the center to the upper and lower boundaries is 20*D* (536mm). The distance between the model and the entrance boundary is 25*D* (670mm). In order to ensure the full development of wake flow, the distance between the model and the outlet boundary is set as 45*D* (1206mm). The calculation domain is shown in Figure 2.

The grid is set up and generated by ICEM CFD software. In the area close to the wall of the iced conductor, a locally encrypted structured grid is used to improve the calculation accuracy. This area is the follow-up area, which changes synchronously with the vibration of the iced conductor, and the wake area is also encrypted to improve the calculation accuracy. In the area far from the conductor, the triangular unstructured mesh is used to improve the calculation speed. This region is the deformation region, update the grid and adjust with the change of the follower region. The total number of grids is 62914, as shown in Figure 3. Spring smoothing and local mesh reconstruction models are used for dynamic mesh updating.



(a) Whole model mesh. (b) Local mesh around the iced conductor

Figure 3. Mesh of crescent-shaped iced conductor

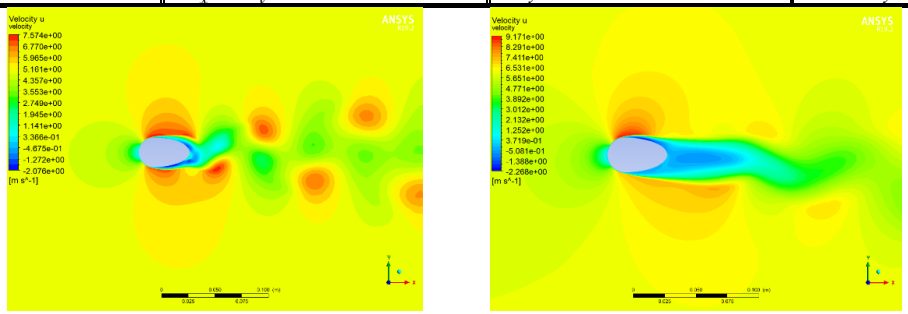
The SIMPLEC algorithm is used to solve the coupled equation of pressure and velocity. The fluid is incompressible uniform flow with a certain velocity, and the boundary conditions are set as follows: When the wind attack Angle is 0°, the left boundary of the calculation domain is set as the velocity inlet, the right boundary is set as the pressure outlet, the surface of the iced conductor is set as the smooth wall without slip, and the upper and lower boundaries are defined as the symmetric boundary. The second-order implicit scheme is used in numerical simulation to discretization the time term, and the second-order upwind scheme is used to discretization the momentum term. The pressure term is also a second-order scheme, and the convergence residuals of the continuity equation and momentum equation are set as 10^{-6}. The turbulence model adopts Reynolds average method based on the *k*-*ω* SST model, and the turbulent kinetic energy and dissipation rate are set as a second-order upwind scheme in the calculation.

3. Results and analysis of fluid-structure interaction simulation

The fluid-structure interaction of the crescent-shaped iced conductor was simulated. The physical parameters shown in Table.1 were selected to simulate the galloping of the 0.75*D* crescent-shaped iced conductor with the wind attack Angle of 180° at the wind speed of 5m/s and 6m/s. The lift force and drag force of the flow field acting on the conductor are solved at the end of each time by the self-designed UDF, and the vibration response variable of the conductor is calculated by combining the Newmark-β method and stored in the file. Then the information is transferred to FLUENT, and the conductor is rotated to the corresponding position. This method is an unsteady numerical simulation, and the aerodynamic forces applied on the conductors are obtained by solving the governing equations in the fluid domain.

Table.1 Physical parameters

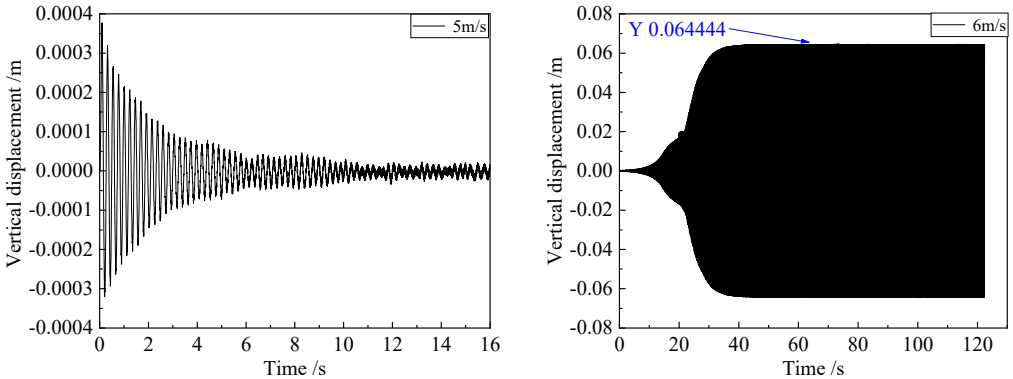
Parameters	Data	Parameters	Data	Parameters	Data	Parameters	Data
M / (kg·m^{-1})	0.7345	D / m	0.0268	ω_x / Hz	23.6248	ω_z / Hz	25.1327
I / (kg·m^{-2})	0.1035	S_x、S_y	0	ω_y / Hz	34.0549	ξ_x、ξ_y、ξ_z	0.002



(a) Velocity cloud under wind speed 5m/s (b) Velocity cloud under wind speed 6m/s

Figure 4. Velocity cloud at different wind speeds in unsteady analysis

Figure 4 shows the velocity cloud diagram obtained at different times after the iced conductor galloped and stabilized under 5m/s and 6m/s wind speed. It can be seen from the figure that there is a static wind zone at the stagnation point on the top of the iced conductor, and the wind speed on the upper side of the conductor reaches the maximum. The flow field at the wind speed of 5m/s is more symmetric, and the wind speed of the lower side near the wall surface of the ice-covered end is the smallest under this wind speed. When the wind speed is 6m/s, the wind speed on the upper side near the wall surface of the ice-covered end is the minimum.



(a) unsteady response results at wind speed 5m/s (b) unsteady response results at wind speed 6m/s

Figure 5. Time history of vertical displacement by FLUENT

The response results of iced conductor dancing under unsteady conditions at wind speeds of 5m/s and 6m/s are shown in Figure 5. When the wind speed is 5m/s, the vertical displacement of the iced conductor is very small and tends to converge. When the wind speed is 6m/s, the vertical displacements first increase and then gradually stabilize. Then, the galloping characteristics of the 0.75D crescent-shaped iced conductor were further analyzed through the displacement spectrum. It can be concluded

that the first mode is the main mode of crescent-shaped iced conductor galloping, and the conductor galloping has the maximum spectrum peak around 4.37Hz and 4.33Hz at 5m/s and 6m/s wind speed, respectively. The peak value of this frequency is close to the natural frequency value of the vertical half-wave 4.36Hz.

Meanwhile, the quasi-steady assumption was used to analyze the time history of the above 0.75D crescent-shaped iced conductor. The incoming flow velocity is also set as 5m/s and 6m/s, and the static average three-component coefficient under these two wind speeds is taken. The relative wind attack angle α was obtained, and the lift coefficient CL, drag coefficient CD and torque coefficient CM under the relative wind attack Angle were obtained by interpolation. The actual aerodynamic force is calculated, and the displacement responses result are iterated by the Newmark-β method. The vertical displacement results calculated by MATLAB at 6m/s is 0.06569m. It can be seen that the displacement response results of the two simulation methods have little difference. The discrepancy of the calculated results is 1.9%, which is small and almost negligible.

4. Conclusions

In this paper, for 0.75*D* two-dimensional crescent-shaped iced conductor with a wind attack Angle of 180°, the fluid-structure interaction numerical simulation of the iced conductor's movement was carried out by FLUENT after geometric modeling, mesh division, boundary condition setting, turbulence model selection, solution parameter setting, etc. The results show that the galloping condition of the iced conductor is greatly affected by the wind speed, the vibration amplitude calculated by unsteady and quasi-steady analysis at different wind speeds is similar, and the response time history is also consistent. In the vertical displacement spectrum at different wind speeds, there is an obvious peak at the natural frequency of one-half wave close to the vertical direction.

Acknowledgements

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References

[1] Chen, B., Wu, J.B., Ouyang, Y . and Deng, Y . Response evaluation and vibration control of a transmission tower-line system in mountain areas subjected to cable rupture. Struct. Monitor. Maintenance,2018, 5(1), 151-171.

[2] Gani, F. and Legeron, F. Dynamic response of transmission lines guyed towers under wind loading. Can J. Civil Eng. 2010, 37(3), 450-465.

[3] Jia, X.L, Fu, X., and Li, H.N. Experimental study on aerodynamic characteristics of conductors covered with crescent-shaped ice, Wind Struct. 2019, 29(4), 225-234.

[4] Y You, ZT Yan, XC Nie, Numerical Simulation of Fluid-Structure Interaction of D-shape Iced Conductor. Eur J. Comput Mech,2019;147-190.

[5] Xinmin, L., Kuanjun, Z., Liu, B., 2013. Numerical and experimental simulation anerodynamic character of crescent-shaped iced conductor. Appl. Mech. Mater.275–277, 622–627.

[6] Talib, E., Shin, J., Kwak, M. K. and Koo, J.R. Dynamic modeling and simulation for transmission line galloping, J. Mech Sci Technol, 2019,33(9), 4173-4181.

[7] Zhang, Z., Yang, X.P . and Hao, S.Y . Numerical simulation and analysis of dynamic aerodynamic characteristics of iced conductor. J. Vib. Shock, 2015,34(7), 209-214 (in Chinese).

[8] Deng, Y .C.,Li,S.Y. and Chen, Z.Q. Unsteady theoretical analysis on the wake-induced vibration of suspension bridge hangers, J. Bridge Eng. 2019, 24(2), 04018113.