the absolute value of negative aerodynamic damping which was identified by test increased exponentially with wind speed increasing, it was not increasing linearly according to Den Hartog galloping mechanism.

Combining with the Tab.9、Fig.13(b) and Fig.14(b) could discover, under the specific wind attack angle when both Den Hartog coefficient and Nigol coefficient were negative, the vertical aerodynamic damping which was identified by test increased first and then inclined to stable value or firstly increased then decreased with wind speed increasing when $f_y / f_\theta < 1.0$. It also indicated that there was only one wind speed range existed while the absolute value of negative aerodynamic damping was greater than structure damping. It was important to note that when $f_y / f_\theta = 0.89$, probably due to the range of galloping wind speed was too small or it was more sensitive to changes in the vicinity of this ratio of vertical to rotational natural frequency, so galloping motion was failed to be simulated and calculated, but the change rule between identified vertical aerodynamic damping and wind speed also supported those above conclusions. When $f_y / f_\theta \geq 1.0$, the absolute value of negative aerodynamic damping which was identified by test increased exponentially with wind speed increasing, and it was significantly greater than Den Hartog theoretical value, and galloping phenomenon could also be observed actually under a specific wind speed when $\xi_y + \xi_{y,Den气动} > 0$, which further illustrated the disadvantages of Den Hartog galloping mechanism with single degree of freedom.

5.2.1 Study on torsional aerodynamic damping of galloping

The tested value, calculated value and Nigol theoretical value of torsional aerodynamic damping ratio for those which happened when conductor model produced galloping under typical working condition were given in Fig.15. The tested values of torsional aerodynamic damping ratio of conductor under different ratios of vertical to rotational natural frequency were given in Fig.16. It could be found, for torsional aerodynamic damping ratio, the one which was identified by test tended to be approximate to the one which was identified by calculation of galloping response, moreover, the one which was identified by test tended to be larger than the theoretical value which was calculated by Nigol galloping mechanism. Took a further comparison between the aerodynamic damping which was calculated by Nigol galloping mechanism and model structure damping, it could be found that when $\xi_\theta + \xi_{\theta,Nigol气动} > 0$, torsional galloping of conductor model could still be observed in the test, this showed that there were some deviations existed when the torsional aerodynamic damping ratio of conductor was calculated by Nigol galloping mechanism. The abuse of Nigol galloping mechanism with single degree of freedom was also revealed.

Combining with Tab.10, Fig.15 and Fig.6 may discover, under the specific wind attack angle when Den Hartog coefficient was positive and Nigol coefficient was negative, the absolute value of negative aerodynamic damping of conductor model increased with the ratio of vertical to rotational natural frequency increasing, and increased exponentially with wind speed increasing.

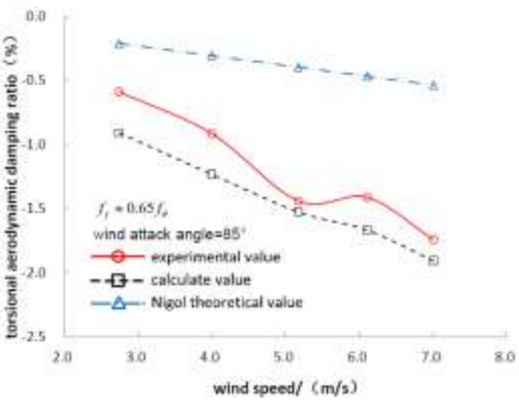

Fig. 15 Torsional aerodynamic damping of iced 6-bundled conductors

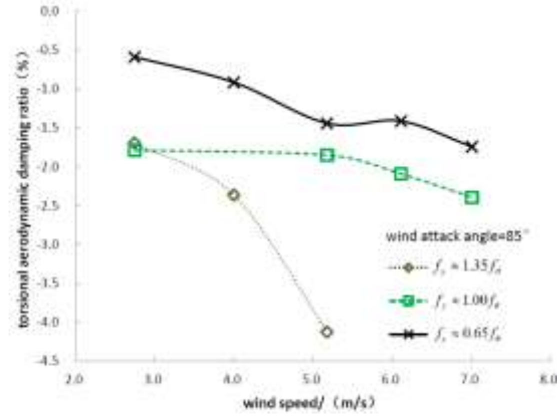

Fig. 16 Tested torsional aerodynamic damping at different ratios of vertical to rotational mode frequency

6 CONCLUSIONS

Wind tunnel test and nonlinear numerical calculation of galloping were carried out for 3-DOF sectional aeroelastic model of D-shape iced 6-bundled conductors. For aerodynamic characteristic, natural vibration characteristic and wind speed, the influence of galloping characteristic and aerodynamic damping on it has been studied respectively. The main conclusions were as follows:

(1) Conductor mainly showed vertical galloping under specific wind attack angle that Den Hartog coefficient was negative and Nigol coefficient was positive. When $f_y / f_\theta \geq 1$, wind speed which could cause galloping was in an interval, no galloping would exist when wind speed got too high or too low. When $f_y / f_\theta < 1$, displacement amplitude of vertical galloping increased with wind speed increasing.

(2) Conductor mainly showed vertical galloping under specific wind attack angle that both Den Hartog coefficient and Nigol coefficient were negative. When $f_y / f_\theta \geq 1$, displacement amplitude of vertical galloping increased with wind speed increasing. When $f_y / f_\theta < 1$, wind speed which could cause galloping was in an interval, no galloping would exist when wind speed got too high or too low.

(3) Conductor mainly showed vertical galloping under specific wind attack angle that Den Hartog coefficient was positive and Nigol coefficient was negative, and torsional angle amplitude increased with wind speed increasing, When $f_y / f_\theta > 1$, conductor showed torsional and horizontal coupled galloping.

(4) Under specific wind attack angle that Den Hartog coefficient was negative, because of the difference of positive and negative of Nigol coefficient, the absolute value of conductor's negative aerodynamic damping would increase exponentially with wind speed increasing, or that the one will first increase and then decrease to less than structural damping. Under specific wind attack angle that Nigol coefficient was negative, the absolute value of conductor's negative aerodynamic damping would increase with f_y / f_θ increasing, and it would increase exponentially with wind speed increasing.

(5) For aerodynamic damping ratio, the one which was identified by test tended to

be approximate to the one which was identified by calculation of galloping response, moreover, the one which was identified by test tended to be larger than the theoretical value which was calculated by Den Hartog or Nigol galloping mechanism. Using galloping mechanism of single degree of freedom to predict three freedom coupled galloping had great defects, and it was not safe.

REFERENCES

[1] Den Hartog J P. Transmission line vibration due to sleet[J]. American Institute of Electrical Engineers, Transactions of the, 1932,51(4):1074-1076.
[2] Nigol O, Buchan P G. Conductor Galloping Part I Den Hartog Mechanism[J]. Power Apparatus and Systems, IEEE Transactions on, 1981, (2):699-707.
[3] Nigol O, Buchan P G. Conductor Galloping-Part II Torsional Mechanism[J]. Power Apparatus and Systems, IEEE Transactions on, 1981, (2):708-720.
[4] Shimizu M, Ishihara T, Pham Van P. A wind tunnel study on quasi-steady and unsteady forces of ice accreted four bundled and single conductor transmission lines [R]. Japan: Abiko Research Laboratory, 2004(in Japanese)
[5] Keutgen R, Lilien J L. Benchmark cases for galloping with results obtained from wind tunnel facilities validation of a finite element model[J]. Power Delivery, IEEE Transactions on, 2000,15(1):367-374.
[6] Muhammad B W, Takashi I, Muhammad W S. Galloping response prediction of ice-accreted transmission lines[C]. 4th Advances in Wind and Structures (AWAS'08), 2008, 876-885.
[7] Lou Wenjuan, Wang Xin, Xu Fuyou. A wind tunnel study on galloping of an aeroelastic iced conductor model[J]. China Civil Engineering Journal, 2011, 44(11): 18-23.
[8] Liu Xiaohui. Nonlinear Numerical Simulation Method and Wind Tunnel Test for Galloping of Iced Conductor[D]. Chongqing University, 2011.
[9] SUN Zhenmao. Analysis of Transmission Line Galloping and Research on Anti-galloping Technology[D]. Zhejiang University, 2010.
[10] Wang Xin, Lou Wenjuan, Shen Guohui, Aerodynamic damping identification for iced transmission line galloping[J]. Journal of Vibration and Shock, 2011,30(10):160-164.
[11] LIN Wei. Wind Tunnel and Numerical Study on Aerodynamic Characteristics of Ice Accreted Transmission Lines[D]. Zhejiang University, 2012.
[12] Wang Xin, Lou Wenjuan. Numerical Approach to the Galloping of Iced Conductor[J]. Engineering Mechanics, 2010, 27(1): 290-310