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Wind tunnel test of the influence of an interphase spacer on the galloping control of iced eight-bundled conductors

Anqi Zhou[a,b], Xijun Liu[a,b], Suxia Zhang[a,b,*], Fujiang Cui[a,b], Peng Liu[c]

[a] Department of Mechanics, Tianjin University,Tianjin 300354, PR China
[b] Tianjin Key Laboratory of Nonlinear Dynamics and Chaos Control, 300354 Tianjin, China
[c] College of Mechanics, Taiyuan University of Technology, Taiyuan 030024, PR China

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ABSTRACT

To study the anti-galloping effect of interphase spacers with different kinds of arrangements on an iced transmission line, wind tunnel experiments using a full aeroelastic model are carried out in this work. Using similarity theory, the similarity criteria between the aeroelastic model and the prototype have been deduced. A triangular arrangement of three phases is considered, and the arrangements of iced eight-bundled conductors with and without the spacers are divided into six cases. In the experiments, laser sensors at different positions along the span of each phase are used to measure the variation of dynamic displacements with wind speed. Furthermore, galloping characteristics, such as the responses, frequencies, vibration modes, amplitudes and distance between two phases, are obtained for different wind speeds and arrangements. The obtained results show that interphase spacers have a certain inhibitory effect on the first symmetric mode and the first anti-symmetric mode galloping, but not all of the arrangements have a positive effect. The regularity of the variation with wind speed of the anti-galloping effect with interphase spacers is summarized. The galloping amplitude curves indicate that the amplitude is likely to be larger when a modal transformation occurs, in contrast to the results obtained without interphase spacers. The motion of the phase C located close to the diffusion section is different from those of the other two phases. Moreover, due to interphase spacers, the distance between the two phases is increased. The obtained conclusions can be used to predict the positions of interphase spacers and provide a fundamental tool for anti-galloping of eight-bundled conductors.

1. Introduction

Due to the advantage of ultra-high voltage (UHV) transmission in long-distance electricity transmission, an increasing number of UHV transmission systems have been constructed in several countries, i.e., in China, Japan and Canada. Eight bundled is a common arrangement of the conductors in a UHV transmission system. Galloping of iced conductors has been a significant threat to the safety and reliability of common overhead transmission lines since it was first observed and defined in the 1930s, while galloping of UHV transmission systems remains an open issue. Galloping is a self-excited motion with low frequency and large amplitude, the origin of which is related to the instability of the aerodynamic force acting on a non-circular section. Galloping can cause damage to transmission line components, such as conductors, fittings, tower steelworks and insulators. To suppress galloping, several anti-galloping devices, such as the widely used interphase spacer, have been invented for transmission lines (Lu et al. (2007); Nojima et al. (1997); Havard and Pohlman (1984)). An interphase spacer is a spacer with mechanical and insulation properties. It can connect different phases and use their motions to counteract each other in order to reduce the galloping amplitude. Staggered arrangements of interphase spacers are always applied in compact transmission lines because they can effectively enhance the motion synchronization and the distance between two phases.

The two classic theoretical results on galloping are the vertical galloping mechanism proposed by Den Hartog (1932) and the torsional galloping mechanism proposed by Nigol et al. (1977), with several other galloping mechanisms, such as coupled vibration theories and stability criteria, proposed in other published papers Yu et al. (1993); Luongo and Piccardo (2005). On the basis of the above mechanisms, many dynamic models of galloping were constructed. Luongo et al. (2007, 2008) proposed a new model based on curved-beam theory. Yan et al. (2012) formulated a nonlinear galloping model considering bending, rotation and eccentricity of the cross-section and analyzed the

* Corresponding author.
E-mail address: zhangsux@tju.edu.cn (S. Zhang).

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bifurcation and stability of two cases. To describe the nonlinear interactions between the in-plane, out-of-plane and torsional vibrations, Liu and Huo (2015) proposed the partial differential governing equations of an iced transmission line that take into account the geometrical and aerodynamic nonlinearities. Kollár and Farzaneh (2009) studied the effects of an ice-shedding-induced cable vibration on spacer dampers by applying a dynamic model that simulated cable vibration and bundle rotation at the mid-span where the spacer was attached to the cables and took into account the spacer deformation and forces acting on the spacer during the vibration of twin, triple and quad conductor bundles. However, the effect of interphase spacers as important anti-galloping devices was rarely taken into account in dynamic models. With the development of the CAE software, many researchers built finite element models of conductors with interphase spacers and conducted simulations to explore the efficacy of interphase spacers. Considering three phases of iced-single/two-bundled conductors with/without spacers, Kim and Nguyen (2004) applied ANSYS/LS-DYNA to calculate the behaviors of interphase spacers in five different cases in order to predict the optimal interphase spacer positions. Yan et al. (2016) performed finite element analysis (FEA) on the anti-galloping design of interphase spacers in three-phase conductor lines with a triangular arrangement and verified the anti-galloping efficiencies of interphase spacers with 300-m spans, 400-m spans and 500-m spans. Fan et al. (2011) established five nonlinear FEA models of three-phase iced quad-bundled conductors and simulated the effect of interphase spacers, finding that the staggered arrangement is a good choice for anti-galloping. Hou et al. (2007) used a lumped mass for constructing a model and studied the effect of the spacer rod diameter, mass and bending stiffness on galloping. Observation and measurement of operational conditions are also useful for investigating the influence of the interphase spacers. Van Dyke et al. (2008) reported galloping measurements conducted on a high-voltage overhead test line equipped with a single conductor as well as a second configuration of three conductors with interphase spacers, highlighting that the wind azimuth may strongly influence the galloping amplitude. Due to the difficulties in controlling the environment and other conditions in an overhead test line, wind tunnel tests of full aeroelastic models satisfying the similarity principle are a widely-used and reliable method for evaluating the actual mechanical behaviors of the iced transmission line under wind loads. Using aeroelastic wind tunnel testing of cable models, Loredo-Souza and Davenport (2001), Loredo-Souza and Davenport, 2002) examined the behavior of two parallel transmission cables under high winds. Cables with different characteristics and different spacings between the cables were simulated and tested at transverse wind incidence. Lébatto et al. (2015)] sought to compare the results of a three-dimensional numerical morphogenetic model of glaze ice accretion on a non-rotating unheated cylinder with experimental data and found that the model was able to predict arrays of icicles, even for icicles that are very long and thin. Zhou et al. (2016) carried out a wind tunnel test to model the galloping of an iced eight-bundle conductor segment, and the validity of the numerical simulation method was demonstrated by the agreement of the galloping orbit of the bundle conductor segment model with the numerical results recorded during the wind tunnel test. Liang et al. (2015) established a full aeroelastic model with one tower and two lines to simulate an electrical transmission tower-line system. The results indicated that the effects of the coupling between the transmission tower and the line on the wind-induced responses of the tower and the across-wind vibration of the tower must be considered in the wind-resistant design of electrical transmission towers. However, due to the structural particularities of transmission lines, further wind tunnel tests of multi-phases conductors with interphase spacers are necessary.

Overall, after an extensive literature review, we find that most studies of the anti-galloping effect used truncated models, whereas studies using the full aeroelastic model are rare. Based on our previous research, a full aeroelastic model in the wind tunnel test is clearly superior for analyzing the global vibration profile and galloping control. Hence, the objective of the present paper is to investigate the anti-galloping effect of the arrangement and number of interphase spacers on iced transmission lines via wind tunnel experiments on a full aeroelastic model. The rest of the paper is organized as follows. Experimental setup and procedures and the similarity criterion between the aeroelastic model and the prototype are introduced in Section 2. In Section 1, diagrams and tables are given to show the results and illustrate the phenomena discovered in the test. Finally, some discussion and conclusions are given in Section 2.

2. Experimental setup

2.1. Similarity criteria

A scale model should be used due to the limitations of experimental conditions. The model in the experiment needs to be geometrically similar to the prototype. Dimensional analysis and the formula analysis method are applied to obtain the similarity between the model and the prototype. For this model, the parameters are simplified from the large number of high-order coupling items in the dynamic formulas into three items, which are the initial conditions, aerodynamic force and energy.

- Initial condition similarity

The catenary equation of an iced conductor can be written in two forms, as shown in the following equation:

$$\begin{aligned} y_0 &= -\frac{2T_0}{g\rho_m}\sinh\frac{g\rho_m x}{2T}\sinh\frac{g\rho_m(1-x)}{2T}, \\ y_0 &= -\frac{2\sigma}{h}\sinh\frac{hx}{2\sigma}\sinh\frac{h(1-x)}{2\sigma}, \end{aligned} \tag{1}$$

where T_0 is the initial tension of the transmission line, h is the combined load of the conductor, σ is the axial stress, l is the span length, ρ_m is the mass per unit length, and g is the gravitational acceleration. Since σ and h have the same dimensions,σ is chosen. g can be ignored because it is invariant. Based on the initial conditions, the key parameters are T_0, l, ρ_m, and σ.

- Aerodynamic force similarity

The unbalanced aerodynamic force is the main origin of the galloping of iced conductors. The aerodynamic force in the vertical equation is given by

$$F_y = \frac{1}{2}\rho U_r^2 D C_y, \tag{2}$$

where ρ is the air density, D is the characteristic length of the iced conductors' section, C_y is the aerodynamic coefficient in the vertical direction, and U_r is the wind velocity. The air density in the experiment is the same as that in actual operational conditions, and C_y is coupled to other variables. Thus, the key parameters are D and U_r.

- Energy similarity

The strain energy of the system is given by

$$V = \int_0^l \left(T_0 + \frac{1}{2}EA\varepsilon\right)(\mathrm{d}s - \mathrm{d}s_0), \tag{3}$$

where E is the elasticity modulus, and A is the area of the cross-section. As A is coupled to the radius, E is chosen as the key parameter.

Based on the three similarities, seven key parameters that primarily influence the system are found. The characteristic length of the iced conductors' section D and the wind velocity U_r are derived from the aerodynamic force similarity. The elasticity modulus E is derived from the energy equation similarity. The initial tension of the transmission line T_0, the span length l, the mass per unit length ρ_m and the axial stress