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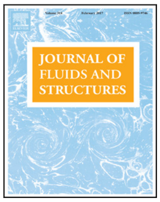

Aerodynamic modeling for large-amplitude galloping of four-bundled conductors

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ABSTRACT

The galloping of overhead transmission lines, which is characterized by large-amplitude, low-frequency oscillations, occasionally occurs when the lines are subjected to ice and snow accretion. To evaluate the applicability of an aerodynamic force model based on the quasi-steady theory for simulating the galloping of overhead transmission lines, aeroelastic tests were performed in a wind tunnel using a rigid-body section model of four-bundled conductors. First, large-amplitude, low-frequency galloping was successfully simulated in a wind tunnel test using a unique support technique proposed in this paper in the vertical, horizontal, and torsional directions. Then, two different formulations of quasi-steady aerodynamic forces affecting four-bundled conductors were presented: one formulation considers all conductors as one group, whereas the other considers each subconductor independently. The two formulations are evidently different in that the aerodynamic forces attributable to torsional velocity can only be derived using the second formulation. Finally, the response amplitudes obtained from the wind tunnel tests and time-history response analyses were compared, and the results suggested that, to simulate large-amplitude, low-frequency galloping, quasi-steady aerodynamic forces should be formulated, not for all conductors together as one group, but for each subconductor independently.

1. Introduction

The phenomenon of galloping occasionally affects overhead transmission lines when they are subjected to ice and snow accretion. Galloping causes considerable vertical oscillation along with horizontal and torsional oscillation at low frequencies. This phenomenon has the potential to cause accidents such as an interphase short circuit, conductor strand burn, and fatigue failure of the crossarm of the tower and insulator. Considerable research efforts have been focused on this phenomenon (CIGRE, 2007) through studies such as field observations, numerical analyses, and wind tunnel tests. Field observations of full-scale transmission lines have been conducted to investigate the dynamic response of the lines caused by galloping and the actual characteristics of ice and snow accretion (Yukino et al., 1995; Morishita et al., 1984; Van Dyke and Laneville, 2008; Matsumiya et al., 2012b). These studies have reported valuable information regarding the actual dynamic response characteristics and meteorological conditions under which galloping occurs: the relationships between the vibration amplitude of the galloping and the vibration mode, wind speed, temperature, etc., have been statistically confirmed in each observation. However, the conditions that induce galloping, such as accreted ice shape distribution and wind speed distribution, are difficult to identify in detail. Furthermore, systematic clarifications of the occurrence conditions

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and response characteristics are also difficult, because the structural conditions are difficult to alter, and climate conditions during the observation period are limited.

To investigate the dynamic response of transmission lines under various conditions, including the structural characteristics, accretion shape, angle of attack, and wind speed, several numerical analysis methods have been developed to analyze galloping conductors (Yu et al., 1993; Desai et al., 1996; Wang and Lilien, 1998; Ohkuma et al., 2000; Matsumiya et al., 2013). In general, aerodynamic forces acting on lines are taken into account as quasi-steady forces (Den Hartog, 1956) using steady-state aerodynamic coefficients obtained from a wind tunnel test (Shimizu et al., 2004; Propplewell, 2005; Matsumiya et al., 2011) and numerical fluid analysis (Oka and Ishihara, 2010; Matsumiya et al., 2012a). However, it has been pointed out that the actual aerodynamic forces may differ from the assumed quasi-steady aerodynamic forces under large-amplitude motion conditions (CIGRE, 2007; Kimura et al., 1999). Research on full-scale overhead transmission lines is important to the study of conductor galloping. Therefore, we have previously reported observations of the galloping phenomenon at full-scale facilities under the ice-accreted condition (Matsumiya et al., 2012b), as well as the results of numerical analyses of galloping on full-scale overhead transmission lines (Matsumiya et al., 2013). Nonetheless, the aerodynamic force model is difficult to validate by comparing the results of the numerical analysis and the data obtained from the field observations of full-scale lines, because there are many uncertain factors in the observation situation that are assumed in the numerical analysis, such as ice and snow accretion shape, wind speed distribution in the span, and structural characteristics.

Aeroelastic tests in a wind tunnel offer an effective method of investigating various aerodynamic vibrations of bridges, buildings, and other structures, because each individual condition can be clearly identified in the experiment. In particular, to evaluate the fundamental aerodynamic response characteristics, aeroelastic tests using rigid-body section models (two-dimensional tests), in which the natural frequency of each motion of the model is scaled to have the same ratio as those of the primary or intended modes of the full-scale structures, have been found to compare well with aeroelastic tests using full-scale models (three-dimensional tests) (Simiu and Scanlan, 1986; Holmes, 2001; Fujino et al., 2012). When investigating the galloping response of the transmission lines, the effect of the structural geometric nonlinearity in addition to the aerodynamic nonlinearity should be taken into account, because of its large response. Therefore, the phenomenon is complicated compared to the other aerodynamic vibrations of the other structures that target the small response. However, an experimental approach using a rigid-body section model can also be applied to investigate the aerodynamic force model for conductor galloping, if the oscillation of the section model in a wind tunnel captures the characteristics of the galloping motion in actual overhead transmission lines, which is a large vertical oscillation along with horizontal and torsional oscillations at low frequencies. Furthermore, the two-dimensional tests might be effective to investigate the fundamental characteristics of the galloping response, and the influence of each individual condition (frequency ratio of each motion, ice and snow accretion shape, angle of attack, wind speed) can be clearly identified in the rigid-body aeroelastic tests using the section model. Although some researchers have previously performed section model tests on conductor galloping (Chabart and Lilien, 1998; Kimura et al., 1998; Waris et al., 2008), the oscillation amplitude has typically been limited to a comparatively small range because of equipment limitations.

Therefore, the authors have developed a modeling technique that allows the physical simulation of the large-amplitude, low-frequency galloping motion of overhead transmission lines. The section model used in the proposed technique accounts for all large-amplitude, low-frequency oscillations in the vertical, horizontal, and torsional directions, and it allows the selection of an arbitrary frequency for each motion. To evaluate the applicability of aerodynamic force formulation based on the quasi-steady theory, aeroelastic tests in a wind tunnel were performed using a rigid-body section model of four-bundled conductors with dimensions identical to those of ACSR 410 mm^2 conductors (aluminum conductor steel reinforced, nominal cross-sectional area: 410 mm^2); the response amplitudes of large-amplitude, low-frequency galloping obtained from the tests were compared with the amplitudes obtained from time- history response analyses using the aerodynamic force formulation based on the quasi-steady theory. In addition, two different formulations for four-bundled conductors were presented. The difference between the two aerodynamic force formulations was established: one considers all conductors as one group, whereas the other considers each subconductor independently. This finding is important considering the fact that the two aerodynamic force formulations have typically been confused with each other and used interchangeably, depending on structural modeling.

This paper presents the details of the proposed experimental technique and the governing equations of motion of the section model. The results of aeroelastic tests in a wind tunnel confirm that the large-amplitude, low-frequency galloping observed in actual overhead transmission lines can be reproduced by using the proposed experimental technique. Then, the applicable aerodynamic force formulations for simulating large-amplitude, low-frequency galloping are specified by comparing the response amplitudes obtained from time-history response analyses and those obtained from the tests performed using the proposed technique.

2. Proposed model support technique using elastic cords to simulate large-amplitude, low-frequency galloping

2.1. Model support technique

The proposed experimental technique is shown in Fig. 1. In this system, a rigid-body section model of a transmission wire is supported by multiple elastic cords extending in the direction of the wire axis. The technique is characterized by support from “long” elastic cords with “low” rigidity. This unique support method allows the section model to vibrate with large