

Wind tunnel tests for simulating large-amplitude, low-frequency galloping on overhead transmission lines

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ABSTRACT: In order to carry out a complete investigation of the galloping phenomenon of overhead transmission lines under ice and snow accretion, the authors develop a modeling technique that enables physical simulation of the galloping motion of actual transmission lines in a wind tunnel. The test apparatus proposed here is composed of a transmission wire sector model supported in the wire axis direction by multiple elastic cords. This unique support allows the sector model to vibrate with large amplitudes at low frequencies in the vertical, horizontal, and torsional directions. Dynamic equations were derived for the large-amplitude motions of the model, and the frequency characteristics were examined theoretically and numerically. Free vibration tests in a wind tunnel were performed using a sector model of four-bundled conductors with dimensions identical to ACSR 410 mm² conductors. Observation of large amplitude galloping at low frequencies in these tests verifies the validity of this experimental technique and indicates that it is possible to fully discuss the galloping oscillation characteristics and unsteady aerodynamic forces during the vibration by using this technique.

KEYWORDS: Galloping, Overhead transmission lines, Sector model, Elastic rope

1 INTRODUCTION

The galloping phenomenon of overhead transmission lines is sometimes observed when they are subject to ice and snow accretion, which causes significant vertical oscillation with horizontal and torsional oscillation at low frequency. A considerable amount of research effort has been focused on this phenomenon [1] through studies such as field observation of full-scale transmission lines to investigate the actual characteristics of ice and snow accretion and analysis of the dynamic response of the lines caused by galloping [2-5]. While galloping of full-scale lines can be observed, it is difficult to identify in detail the conditions that induce galloping, e.g., accreted shape distribution and wind speed distribution. Furthermore, systematic clarification of the occurrence conditions and response characteristics is also difficult, because the structural conditions are difficult to alter and climate conditions in the observation period is limited. Thus, numerical analysis methods have been developed to simulate the dynamic response of lines under various conditions (structural characteristics, accreted shape, angle of attack, wind speed, etc.) [6-8]. Generally, aerodynamic forces are taken into account as quasi-steady forces [9] by using steady-state aerodynamic coefficients obtained from a wind tunnel test [10-12] and numerical fluid analysis [13,14]. However, it has been pointed out that the unsteady aerodynamic forces differ from the quasi-steady aerodynamic forces for large-amplitude motion: there is a significant difference in the aerodynamic moment [15,16]. Therefore, it is necessary to clarify the degree to which the simulation results are affected by this discrepancy.

Free vibration tests in a wind tunnel under definite input conditions offer an effective method for clarifying the occurrence conditions and response characteristics of conductor galloping. Furthermore, the influence of each individual condition can be clearly identified in the experiment, and the validity of the quasi-steady theory can be checked against the wind tunnel tests. Although some researchers have previously conducted free vibration tests in a wind tunnel [17-19], the oscillation amplitude has typically been limited to a comparatively small range because of experimental restrictions.

Accordingly, the authors have developed a modeling technique that allows physical simulation of the galloping motion in actual overhead transmission lines. The sector model in the technique can oscillate in the vertical, horizontal, and torsional directions with large amplitude at low frequency, and the frequency of each motion can be selected arbitrarily and individually. This paper presents the details of this technique and the governing equations of motion of the sector model. The results of free vibration tests in a wind tunnel using this technique verify its applicability.

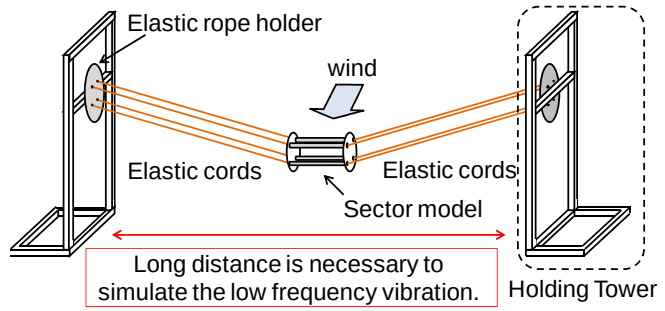


Figure 1 Elastic support technique of the sector model

2 PROPOSED MODEL SUPPORT TECHNIQUE USING ELASTIC CORDS

2.1 Model support technique

The experimental technique proposed here is shown in Figure 1. This system is composed of a transmission wire sector model that is supported by multiple elastic cords extending in the direction of the wire axis. The technique described here is characterized via support from “long” elastic cords with “low” rigidity. This unique support method allows the sector model to vibrate with significant amplitude at low frequencies in the vertical, horizontal, and torsional directions. Furthermore, in this experimental system, the elastic cord holder on the holding tower can be rotated to adjust the angle of attack of the sector model.

2.2 Governing equations of motion

The equations of motion of the sector model can be derived using Lagrange's equation. The relevant parameters in this experiment are listed here and shown in Figure 2.

m	mass of the sector model [kg]
I	mass moment of inertia of the sector model [kgm^2]
B_r	radius of the elastic cord support on the sector model side [m]
D_r	radius of the elastic cord support on the holding tower side [m]
α_B	inclined angle of the elastic cord support on the sector model side [rad]
α_D	inclined angle of the elastic cord support on the holding tower side [rad]
L	horizontal length of the elastic cords [m]
H	sag (depth) of the sector model from the support point [m]
T	tension in the elastic cords [N]
EA	axial rigidity of the elastic cords [N]

The sector model is supported by eight elastic cords from the right and left sides, i.e., four elastic cords on each side. The distance between each elastic cord is B ($B = \sqrt{2}B_r$) on the sector

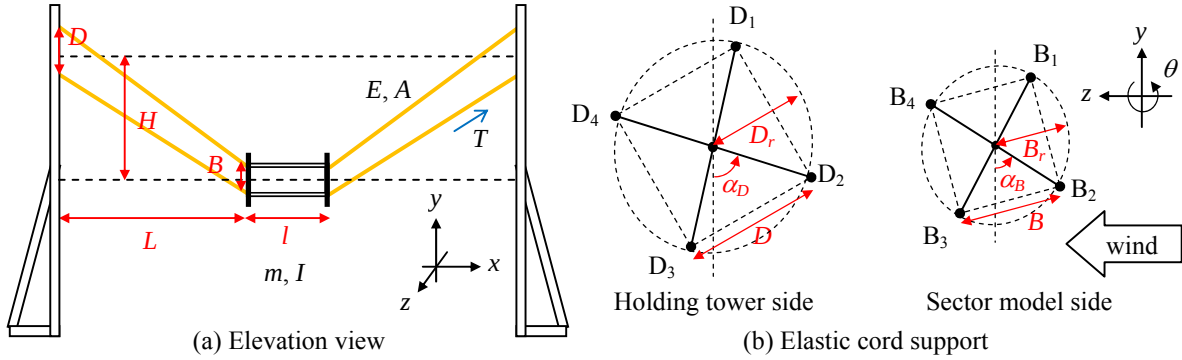


Figure 2 Definition of each parameter

model side and D ($D = \sqrt{2}D_r$) on the holding tower side. It is assumed that all elastic cords are uniform and are set with same tension, and the weight of the elastic cords is ignored.

As shown in Figure 2 (b), the elastic cord support points on the holding tower side are defined as D_1 to D_4 , and those on sector model side are defined as B_1 to B_4 . When the sector model is in the stationary condition, the cord lengths L_{i0} ($i = 1, 2, 3, 4$) (i.e., the distance from D_i to B_i) are described as follows.

$$L_{10}^* = \left\{ L^2 + (-H + B_r \sin \alpha_B - D_r \sin \alpha_D)^2 + (-B_r \cos \alpha_B + D_r \cos \alpha_D)^2 \right\}^{1/2} \quad (1)$$

$$L_{20}^* = \left\{ L^2 + (-H - B_r \cos \alpha_B + D_r \cos \alpha_D)^2 + (-B_r \sin \alpha_B + D_r \sin \alpha_D)^2 \right\}^{1/2} \quad (2)$$

$$L_{30}^* = \left\{ L^2 + (-H - B_r \sin \alpha_B + D_r \sin \alpha_D)^2 + (+B_r \cos \alpha_B - D_r \cos \alpha_D)^2 \right\}^{1/2} \quad (3)$$

$$L_{40}^* = \left\{ L^2 + (-H + B_r \cos \alpha_B - D_r \cos \alpha_D)^2 + (+B_r \sin \alpha_B - D_r \sin \alpha_D)^2 \right\}^{1/2}. \quad (4)$$

When the axial rigidity of the elastic cords is constant regardless of the rate of elongation, the initial lengths are

$$L_{i0} = \frac{EA}{T + EA} L_{i0}^*. \quad (5)$$

The vertical, horizontal, and torsional displacements from the stationary position during vibration of the sector model are y , z , and θ , respectively, and thus the lengths " L_i^* " at this time are described as follows:

$$L_1 = \left\{ L^2 + (-H + y + B_r \sin(\alpha_B + \theta) - D_r \sin \alpha_D)^2 + (z - B_r \cos(\alpha_B + \theta) + D_r \cos \alpha_D)^2 \right\}^{1/2} \quad (6)$$

$$L_2 = \left\{ L^2 + (-H + y - B_r \cos(\alpha_B + \theta) + D_r \cos \alpha_D)^2 + (z - B_r \sin(\alpha_B + \theta) + D_r \sin \alpha_D)^2 \right\}^{1/2} \quad (7)$$

$$L_3 = \left\{ L^2 + (-H + y - B_r \sin(\alpha_B + \theta) + D_r \sin \alpha_D)^2 + (z + B_r \cos(\alpha_B + \theta) - D_r \cos \alpha_D)^2 \right\}^{1/2} \quad (8)$$

$$L_4 = \left\{ L^2 + (-H + y + B_r \cos(\alpha_B + \theta) - D_r \cos \alpha_D)^2 + (z + B_r \sin(\alpha_B + \theta) - D_r \sin \alpha_D)^2 \right\}^{1/2}. \quad (9)$$

These lengths can then be used to derive the equations of motion. Lagrange's equation without a damping term is given by

$$\frac{d}{dt} \left(\frac{\partial T_v}{\partial \dot{q}} \right) - \frac{\partial T_v}{\partial q} + \frac{\partial (U_k + U_g)}{\partial q} = 0. \quad (10)$$

Here, T_v is the kinetic energy of the sector model, U_k is the gravitational potential energy of the sector model, U_k is the elastic potential energy of the cords, and q is the displacement (y , z , and θ). Each energy term is described as follows:

$$T_v = \frac{1}{2} m (\dot{y}^2 + \dot{z}^2) + \frac{1}{2} I \dot{\theta}^2, U_k = 2 \sum_{i=1}^4 \frac{1}{2} \frac{EA}{L_0} \{L_i - L_0\}^2, U_g = mgy. \quad (11)$$

Here, g is gravitational acceleration. By substituting these equations into Equation (10), the differential equations for the vertical, horizontal, and torsional motion are

$$\begin{aligned}
m\ddot{y} + 2EA\{-H + y + B_r \sin(\alpha_B + \theta) - D_r \sin \alpha_D\} & \{L_{10}^{-1} - L_1^{-1}\} \\
+ 2EA\{-H + y - B_r \cos(\alpha_B + \theta) + D_r \cos \alpha_D\} & \{L_{20}^{-1} - L_2^{-1}\} \\
+ 2EA\{-H + y - B_r \sin(\alpha_B + \theta) + D_r \sin \alpha_D\} & \{L_{30}^{-1} - L_3^{-1}\} \\
+ 2EA\{-H + y + B_r \cos(\alpha_B + \theta) - D_r \cos \alpha_D\} & \{L_{40}^{-1} - L_4^{-1}\} + mg = 0,
\end{aligned} \tag{12}$$

$$\begin{aligned}
m\ddot{z} + 2EA\{z - B_r \cos(\alpha_B + \theta) + D_r \cos \alpha_D\} & \{L_{10}^{-1} - L_1^{-1}\} \\
+ 2EA\{z - B_r \sin(\alpha_B + \theta) + D_r \sin \alpha_D\} & \{L_{20}^{-1} - L_2^{-1}\} \\
+ 2EA\{z + B_r \cos(\alpha_B + \theta) - D_r \cos \alpha_D\} & \{L_{30}^{-1} - L_3^{-1}\} \\
+ 2EA\{z + B_r \sin(\alpha_B + \theta) - D_r \sin \alpha_D\} & \{L_{40}^{-1} - L_4^{-1}\} = 0,
\end{aligned} \tag{13}$$

$$\begin{aligned}
I\ddot{\theta} + 2EAB_r\{+(-H + y) \cos(\alpha_B + \theta) + z \sin(\alpha_B + \theta) + D_r \sin(\alpha_B - \alpha_D + \theta)\} & \{L_{10}^{-1} - L_1^{-1}\} \\
+ 2EAB_r\{+(-H + y) \sin(\alpha_B + \theta) - z \cos(\alpha_B + \theta) + D_r \sin(\alpha_B - \alpha_D + \theta)\} & \{L_{20}^{-1} - L_2^{-1}\} \\
+ 2EAB_r\{-(-H + y) \cos(\alpha_B + \theta) - z \sin(\alpha_B + \theta) + D_r \sin(\alpha_B - \alpha_D + \theta)\} & \{L_{30}^{-1} - L_3^{-1}\} \\
+ 2EAB_r\{-(-H + y) \sin(\alpha_B + \theta) + z \cos(\alpha_B + \theta) + D_r \sin(\alpha_B - \alpha_D + \theta)\} & \{L_{40}^{-1} - L_4^{-1}\} = 0.
\end{aligned} \tag{14}$$

2.3 Adjustment technique of each frequency

If $B_r = D_r$, $\alpha_B = \alpha_D$, and the motion is assumed to be infinitesimal, the frequencies are given by

$$f_z = \frac{1}{2\pi} \sqrt{\frac{g}{H}}, \quad f_y = \frac{1}{2\pi} \sqrt{\frac{g}{H} \sqrt{1 + \frac{EAH^2}{TL_g^2}}}, \quad f_\theta = \frac{1}{2\pi} \sqrt{\frac{g}{H} \frac{B_r}{R} \sqrt{1 + \frac{EAH^2}{2TL_g^2}}}. \tag{15}$$

Here, f_z , f_y , and f_θ are the frequencies of the horizontal, vertical, and torsional motion, respectively, L_g is the cord length ($=\sqrt{L^2 + H^2}$), and R is the radius of gyration of the sector model around the x axis ($=\sqrt{I/m}$). Then, the tension in the elastic cords T is

$$T = \frac{mg}{8} \frac{L_0^*}{H}. \tag{16}$$

The relationship between the frequencies and the parameters in Equations (15) and (16) show that each frequency, f_z , f_y , and f_θ , can be arbitrarily chosen by calibrating T , EA , and B_r , respectively. This adjustment technique is also applicable when $B_r \neq D_r$, $\alpha_B \neq \alpha_D$, and the motion is large. In that case, the torsional frequency can be adjusted through the choice of B_r or D_r . However, when $B_r \neq D_r$, the torsional motion is coupled structurally to the horizontal motion.

3 FREE VIBRATION TESTS IN A WIND TUNNEL

To verify the applicability of this experimental technique, free vibration tests in a wind tunnel were performed using a sector model of four-bundled conductors. The test conditions and free vibration test results are presented in this section.

3.1 Test conditions

3.1.1 Wind tunnel facilities

The tests were performed in an Eiffel-type wind tunnel with an axial fan at the Central Research Institute of Electric Power Industry (Figure 3). The outlet area of the wind tunnel is 1.6 m $\times$ 2.5 m (width $\times$ height), and the maximum wind speed is 17 m/s. The sector model was set up in the center of the wide open test space, 1.0 m in front of the outlet as shown in Figure 4. The variation of the wind speed was $\pm 1.0\%$, and the turbulence intensity was less than 0.5% in a 1.2 m $\times$

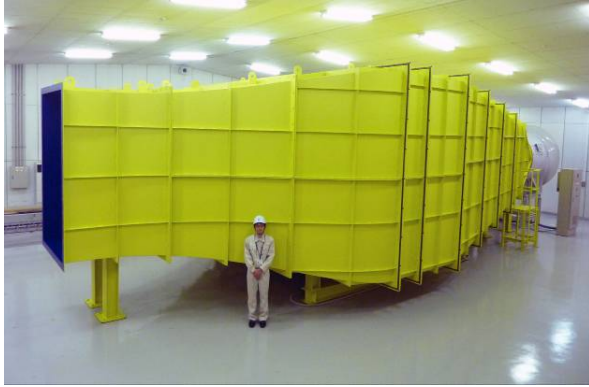


Figure 3 Overall view of wind tunnel

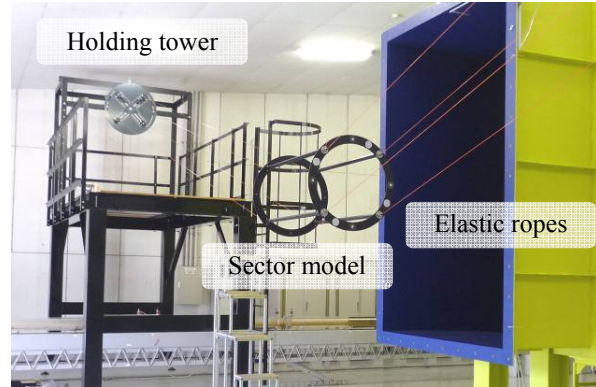


Figure 4 Experiment system

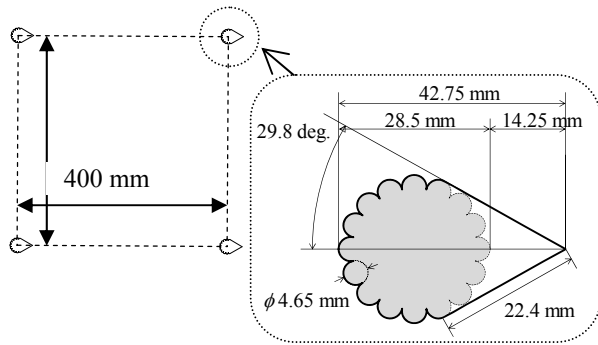


Figure 5 Cross-section of the sector model

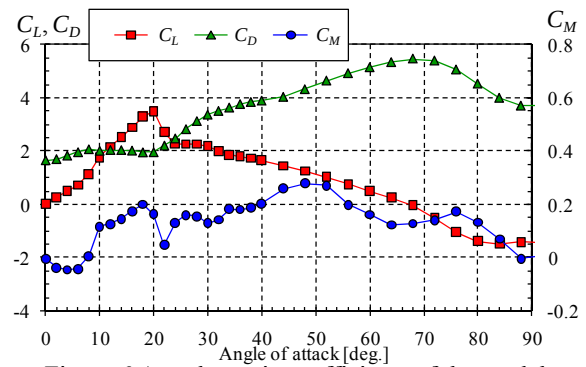


Figure 6 Aerodynamic coefficients of the model

2.0 m (width × height) area 0.5 m downstream of the outlet. The variation of the wind speed was $\pm 1.0\%$ in a 1.0 m × 1.5 m (width × height) area 2.5 m downstream of the outlet.

3.1.2 Sector model shape and aerodynamic characteristics

The four-bundled-conductor sector model had imitated snow accretion with a sharp triangular tip, the height of which was half the conductor diameter, as shown in Figure 5. The dimensions and weights of the model are identical to ACSR 410 mm² conductors with a span length l of 1.0 m. The angle of attack α was the same as α_B . The end plate was not installed this sector model because aerodynamic instability in the yaw rotation or spanwise directions may occur through the aerodynamic force on the end plate. The effect of the absence of the end plate should be discussed in future work.

The aerodynamic coefficients of the model in a wind speed of 10 m/s are shown in Figure 6 [12], and the aerodynamic coefficients fulfill the conditions of the Den Hartog criterion [10] in that the angle range is 20 to 24 degrees, which is just larger than the stalling angle. The definitions of the aerodynamic coefficients in this study are expressed as follows:

$$D_F = \frac{1}{2} \rho U^2 2D_l C_D, L_F = \frac{1}{2} \rho U^2 2D_l C_L, M_F = \frac{1}{2} \rho U^2 2D_l B_l C_M. \quad (17)$$

Here, ρ and U are the air density [kg/m³] and wind velocity [m/s], respectively. The mean value of the drag D_F [N], lift L_F [N], and pitching M_F [Nm] moments depend on the coefficients of the drag C_D , lift C_L , and moment C_M , respectively. The diameter of the conductor D_l is 0.0285 m, and the conductor center interval B_l is 0.40 m.

3.1.3 Experimental set up and test cases

Each of the eight elastic cords supporting the sector model was a two-bundled urethane rubber rope with a diameter of 3 mm. To discuss the vibration characteristics of a certain structural con-

dition (frequency and damping), free vibration tests should be performed by changing both the angle of attack and wind speed simultaneously. However, in this study, the purpose of the tests is mainly to verify the applicability of this experimental technique, free vibration tests were performed by changing the angle of attack and wind speed individually. In case 1, the angle of attack was set to about 20 degrees to fulfill the conditions of the Den Hartog criterion [9], and free vibration tests were conducted at various wind speeds. In case 2, the wind speed remained constant at $U = 11.9$ m/s, and tests were conducted at varying angles of attack. The other conditions for each case are shown in Table 1, along with the frequencies calculated by Equation (15).

Since the oscillation amplitude caused by galloping might have hysteresis characteristics, the dynamic response was measured in two ways for each wind speed (or angle of attack): after disengaging from the stationary position and after applying a large initial vibration. The vertical, horizontal, and torsional oscillating displacements were measured by a video tracking system with a frame rate of 60 Hz.

3.2 Shift of natural frequency and structural damping with an increase in oscillation amplitude

To investigate the natural frequency characteristics and structural damping, free vibration tests were conducted in a wind speed of 0 m/s. In these tests, the response was measured after applying an initial displacement in one direction only; a total of three measurement test were performed, one for each direction. The amplitude of the vertical, horizontal, and torsional displacements are defined as A_y , A_z , and A_θ respectively. Figure 7 shows the natural frequency characteristics as a function of the total (peak-to-peak) oscillation amplitude of each degree of freedom. The results show a shift in the natural frequency with an increase in oscillation amplitude, and the torsional displacement frequency, in particular, decreases with an increase in the oscillation amplitude.

The relationship between the frequency and amplitude was also calculated analytically, and the results are plotted in Figure 7. Here, by using the Runge-Kutta method, the time-series behavior after the initial vibration, which has a specific amplitude for each degree of freedom, is calculated by Equations (12) to (14), which are non-damping equations of motion. A power spectrum analysis of the displacement data then shows the predominant frequency of each vibration for each amplitude. The analytically calculated frequency is in good agreement with the test results and therefore verifies the validity of the governing equations of motion in Section 2.2.

Table 1 Test conditions

Parameters	Case 1	Case 2
m	6.692 kg	6.692 kg
I	0.535 kg m ²	0.535 kg m ²
$B = D$	0.400 m	0.400 m
$\alpha_B = \alpha_D$	19.2 deg.	-0.8 to 29.4 deg.
L	6.293 m	6.255 m
H	1.696 m	1.657 m
T	31.5 N	32.0 N
EA	176.4 N	176.4 N
U	1.6–14.6 m/s	11.9 m/s
f_{y0}	0.449 Hz	0.452 Hz
f_{z0}	0.383 Hz	0.387 Hz
$f_{\theta 0}$	0.417 Hz	0.421 Hz

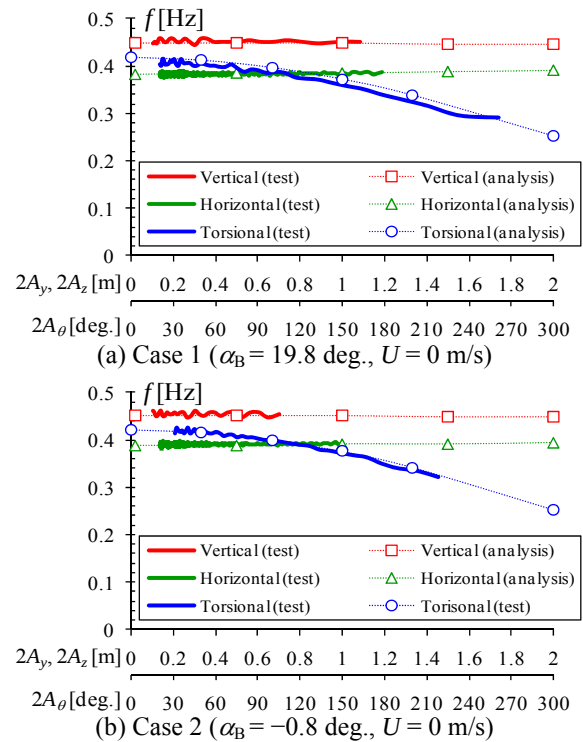


Figure 7 Natural frequency characteristics

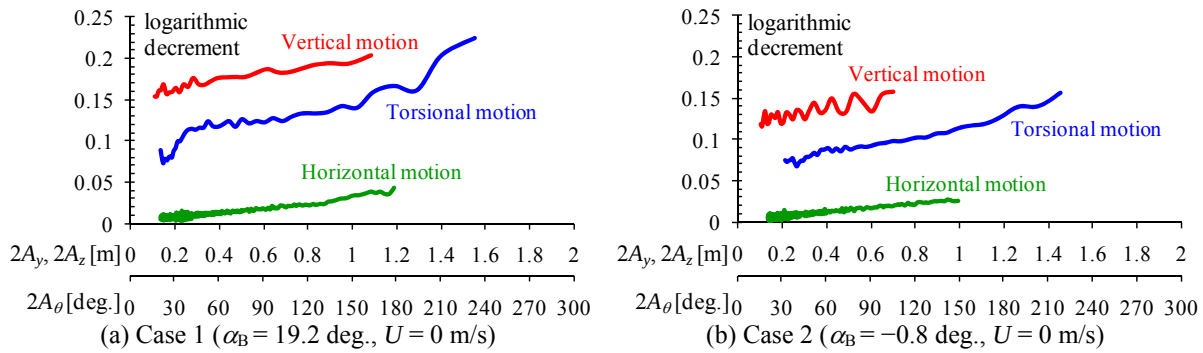


Figure 8 Structural damping characteristics

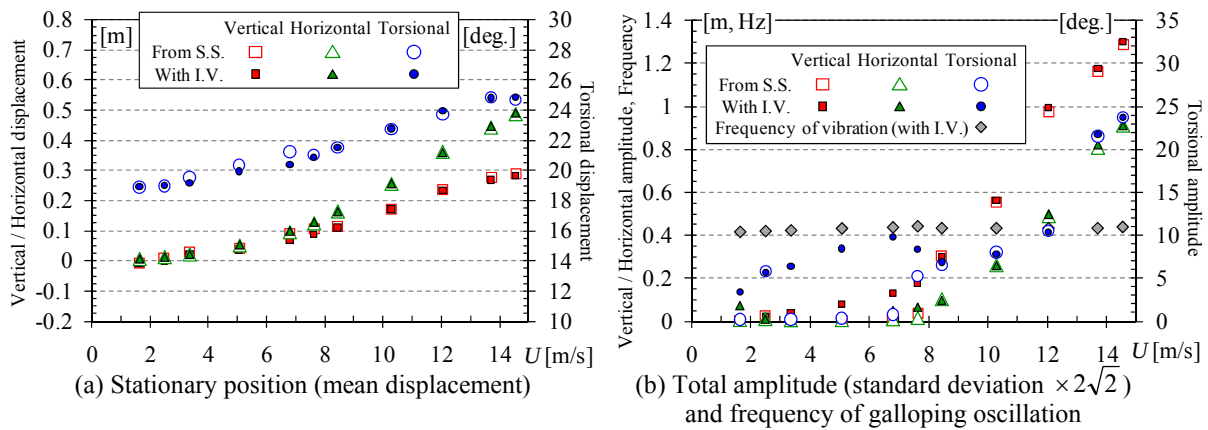


Figure 9 Test results at each wind speed in Case 1 ($\alpha = 19.2$ deg.)

Figure 8 shows the structural damping characteristics, which also display a change with increasing oscillation amplitude. The structural damping of the vertical motion is the largest of the three directions because the elongation of the elastic cords is the longest. It was not possible to adjust the structural damping in the currently system, and thus, an adjustment technique will be developed in future work.

3.3 Results of free vibration tests

The results of the free vibration tests at each wind speed in Case 1 are shown in Figure 9. In these tests, “from S.S.” indicates measurements of the response disengaged from the stationary state, and “with I.V.” indicates measurements of the response after applying a large initial vibration. Figure 9(a) shows the stationary position at each wind speed that corresponds to the mean displacement from the stationary position in a wind speed of 0 m/s. The galloping oscillation observed in this tests had a steady amplitude and only one predominant frequency. Figure 9(b) shows the $2\sqrt{2}$ standard deviation, which corresponds to the total (peak-to-peak) amplitude, and also shows the frequency of the galloping oscillation. For some wind speeds in the range 1.6–7.6 m/s, galloping occurred when applying an initial vibration, although it did not occur from the stationary state. At wind speeds exceeding 7.6 m/s, the oscillation amplitude increased with increasing wind speed, with the vertical amplitude peaking at about 1.3 m and accompanied by horizontal and torsional oscillation. The vibration frequency was about 0.40–0.45 Hz. These results validate that the large-amplitude, low-frequency galloping observed in actual overhead transmission lines can be reproduced by using this experimental technique.

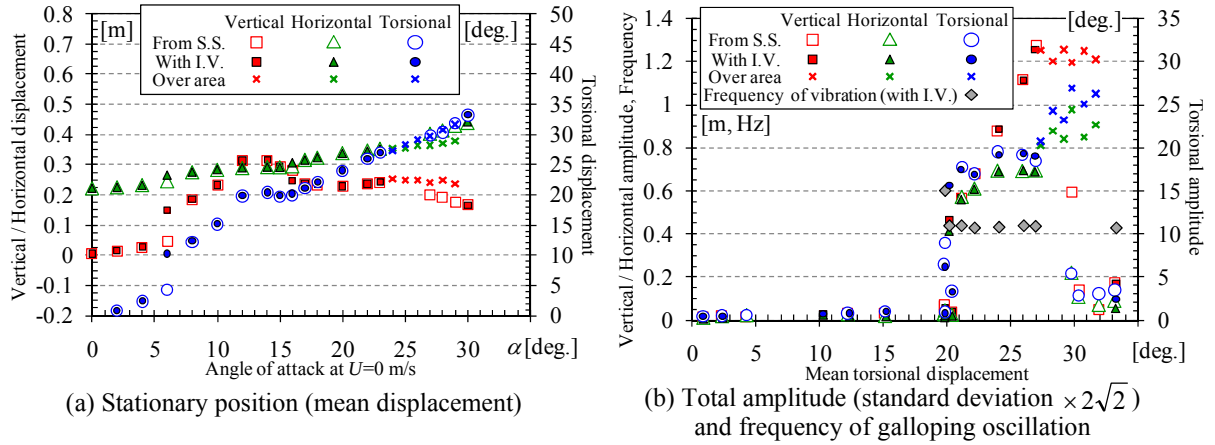


Figure 10 Test results at each angle of attack in Case 2 ($U = 11.9$ m/s)

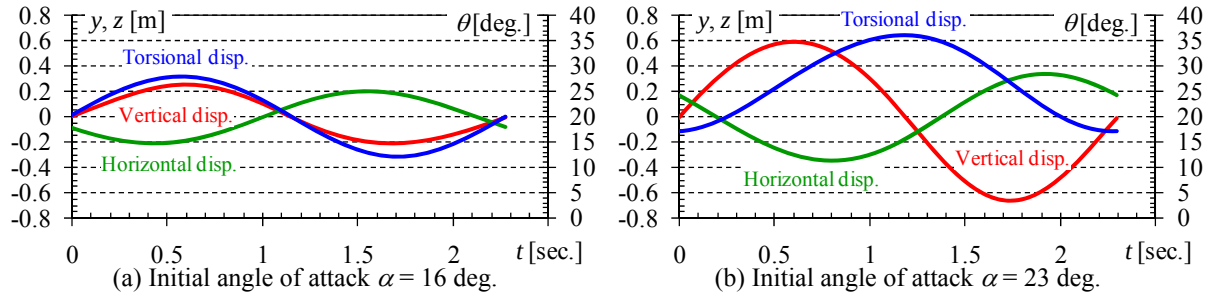


Figure 11 Time series of phase averaged displacement in Case 2

The results of the free vibration tests at each angle of attack in Case 2 are shown in Figure 10. The horizontal axis of Figure 10(a) represents the initial angle of attack at $U = 0$ m/s, which is the same value as the elastic cord support angle, and the horizontal axis of Figure 10(b) represents the mean torsional displacement. In some cases, the oscillation amplitude was larger than the area in which the wind speed distribution is approximately uniform. These cases are indicated as “over area” in Figure 10, and the actual value may differ from the represented value. As shown in Figure 10(a), the stationary angle to the wind is different from the initial angle of attack, especially in the case when the initial angle of attack is slightly less than the stalling angle (20 degrees). In contrast, as shown in Figure 10(b), when the stationary angle is larger than the stalling angle, galloping occurs. Figure 11 shows the phase averaged data of the galloping displacement in one period when the initial angle of attack α is 16 and 23 degrees in Case 2. The phase difference of each displacement varies with the initial angle of attack. In both cases, the torsional displacement range fulfills the Den Hartog criterion, and the mechanism of oscillation onset is thought to be essentially the same as “Den Hartog galloping” [1], which is the aeroelastic instability in a one-degree-of-freedom (vertical motion) only system. As above, a detailed discussion of the oscillation characteristics and onset conditions of galloping can be conducted by this experimental technique.

4 DISCUSSION ON UNSTEADY AERODYNAMIC FORCES

The quasi-steady aerodynamic forces can be calculated using the relative wind speed V_r and the relative angle of attack α_r as

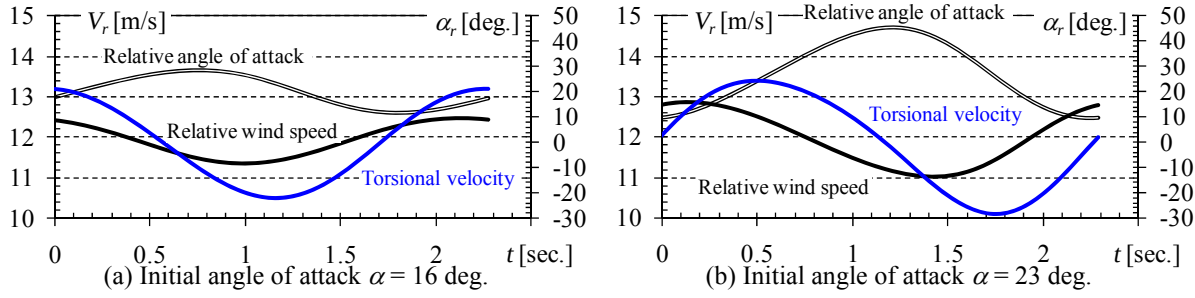


Figure 12 Time series of relative wind speed, relative angle of attack, and torsional velocity in Case 2

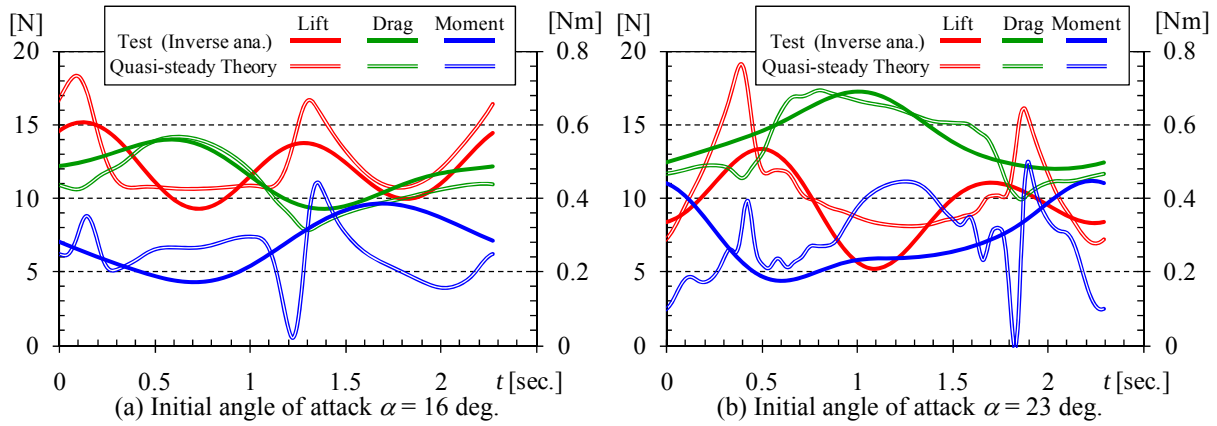


Figure 13 Comparison of the aerodynamic forces obtained by inverse analysis of the free vibration tests and those calculated by quasi-steady theory in Case 2

$$V_r = \sqrt{(V - \dot{z})^2 + \dot{y}^2}, \alpha_r = \theta + \tan^{-1} \left(\frac{-\dot{y}}{V - \dot{z}} \right). \quad (18)$$

Furthermore, when the four-bundled conductor has a torsional velocity, each sub-conductor has a velocity in a circumferential direction. Thus, by using the aerodynamic coefficients [12], relative wind speed, and relative angle of attack of each sub-conductor, the quasi-steady aerodynamic force theory can calculate some effects of torsional velocity. Figure 12 shows a time series of the relative wind speed, relative angle of attack, and torsional velocity for Case 2.

In contrast, the unsteady aerodynamic forces acting on the sector model can be derived from an inverse analysis of the time-series displacements shown in Figure 11. In the inverse analysis, the structural characteristics are assumed to be expressed by Equations (12) to (14). Furthermore, the structural damping force is taken into account as an internal force. The total oscillation amplitude of each case is calculated by time-series displacements, and the value of the logarithmic decrement corresponding to the amplitude is derived from Figure 8. Figure 13 shows a comparison of the aerodynamic forces obtained by an inverse analysis of the free vibration tests and the quasi-steady aerodynamic forces that take into consideration the quasi-steady aerodynamic forces of each sub-conductor.

As shown in Figure 13, the drag data for both methods is in good agreement. The trend in the lift data is similar but the drastic changes seen in the quasi-steady forces are not present in the unsteady force calculation. Furthermore, there is a large discrepancy in the moment data. Although the reason for this discrepancy will be clarified in future work, the characteristics of the unsteady aerodynamic forces during large amplitude vibrations caused by galloping can be identified by the developed experimental technique.

5 CONCLUSION

The authors have developed and successfully implemented a modeling technique to physically simulate the galloping motion of actual overhead transmission lines in a wind tunnel at low frequency with a large amplitude. Furthermore, the technique allows the possibility of an in-detail discussion of the galloping oscillation characteristics and unsteady aerodynamic forces during the vibration. Future work will involve systematically determining the occurrence conditions and response characteristic of conductor galloping under definite input conditions: accretion shape, angle of attack, frequencies ratios, and wind speed. The results will then permit discussion of a model of the unsteady aerodynamic forces.

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