A Wind Tunnel Study on Aerodynamic Characteristics of Ice Accreted Transmission Lines

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ABSTRACT: To perform realistic transmission line galloping simulations, it is very important to use accurate aerodynamic coefficients of ice accreted transmission lines. The coefficients can be obtained by wind tunnel tests, however, accreted ice profiles were not clearly defined in many of past tests, and the coefficients ever obtained are small in variety, expressly for multi bundled conductors. So in this study, three-component balance tests were conducted to take an accurate measurement of quasi-steady aerodynamic coefficients of 4-conductor bundle as well as single conductor section models with artificial accreted ice whose profiles were clearly defined. The measured coefficients were compared between bundled and single conductor, for the purpose of making conductor bundle effect on aerodynamic characteristics clear. And the relation between accreted ice profiles and aerodynamic characteristics were investigated, using a numerical simulation method together.

1.0 INTRODUCTION

The galloping phenomenon of ice accreted transmission lines in winter may cause incidents such as inter-phase short circuit or damages of insulators or support structures. Hence, authors have developed the finite element analysis code with considering geometrical nonlinear characteristics of transmission lines [1], then analyzed the galloping phenomenon and assessed countermeasures using the code.

Previously, the modeling of aerodynamic force used as the input condition for such the analysis has been quasi-steadily approximated based on the aerodynamic coefficients of ice accreted transmission lines acquired from conventional wind tunnel tests. However, in many of past wind tunnel tests not only accreted ice profiles were not clearly defined but also quasi-steady aerodynamic coefficients were obtained simply on a transmission line namely on single conductor. And the coefficients ever obtained are small in variety, expressly for multi bundled conductors.

So in this study, three-component balance tests were conducted to take an accurate measurement of quasi-steady aerodynamic coefficients of 4-conductor bundle as well as single conductor section models with artificial accreted ice whose profiles were clearly defined.

The measured coefficients were compared between bundled and single conductor, for the purpose of identifying a possibility that conventional wind tunnel test results on single conductor could be applied to the analysis for bundled conductor transmission lines. And the relation between accreted ice profiles and aerodynamic characteristics were investigated, using a numerical simulation method together.

2.0 METHOD OF EXPERIMENT

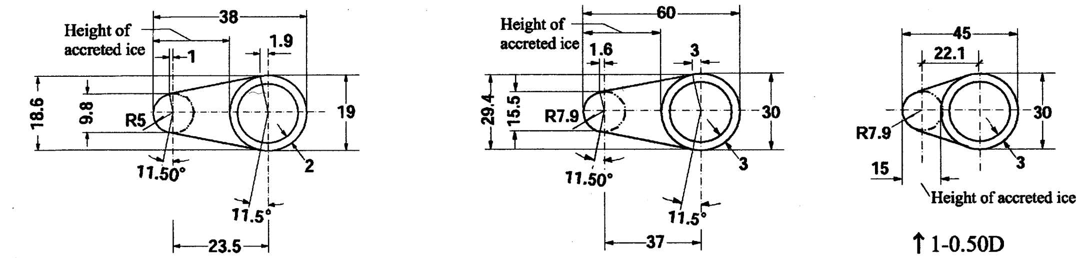
2.1 Wind Tunnel and Specimens

In these experiments, the intense wind simulation tunnel in the wind engineering laboratory building of University of Tokyo was used [2]. Table 1 shows the experimental cases and the specifications of specimens. For specimens, a partial model of 4-conductor bundle with artificial accreted ice (hereafter, simply referred as accreted ice) and 2 partial models of single conductor section with different accreted ice profiles were used as shown in Figure 1. These specimens were installed in the wind tunnel by supporting the center of each end plate with three-component balance as shown in Figure 2.

The accreted ice profiles in Figure 1 are ones that

Table 1: Case No. of Experiment and Specifications of Specimens

No.	Specimen Name	Number of conductors	Conductor Length L (mm)	Conductor diameter D (m)	Height of Accreted Ice (mm)	Projected Area A (mm^2)	Typical Diameter B (mm)	Remarks
1	4-1.00D	4	1270	19	19(=1.00D)	48260	247	A is calculated by $2D \times L$ and B is assumed as the interval between conductor centers.
2	1-1.00D	1	1270	30	30(=1.00D)	38100	45	A is calculated by $D \times L$ and B is assumed as the distance from conductor center to the tip of accreted ice.
3	1-0.50D	1	1270	30	15(=0.50D)	38100	30	
4	1-0.25D	1	1270	30	7.5(=0.25D)	38100	22.5	

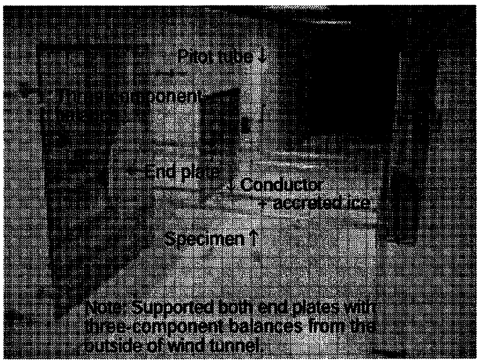


↑ 4-1.00D: Used 4 lines, interval distance of lines = 0.4m.

↑ 1-1.00D

↑ 1-0.50D

Figure 1: Cross sectional dimensions of conductors and accreted ice (mm)



Note: Supported both end plates with three-component balances from the outside of wind tunnel.

Figure 2: Specimens in measurement section

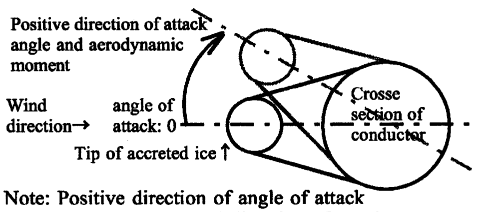
geometrically imitate naturally accreted ice profiles regarded as easily causing galloping. The materials of the specimens were plywood with aluminum plate reinforcements on the portions attaching jigs and conductors for end plates, aluminum pipe for conductor section, and Japanese cypress for accreted ice.

2.2 Conditions of Measurement

The aerodynamic coefficients are obtained as the quotient of quasi-steady aerodynamic force divided by velocity pressure at the wind velocity of 10 m/s. Figure 3 shows the definitions of angle of attack of zero and its positive direction.

3.0 RESULTS AND CONSIDERATIONS

As the experimental results, Figure 4 and 5 show the measured drag coefficient C_D, lift coefficient C_L and aerodynamic moment coefficient C_M.



Note: Positive direction of angle of attack agrees with the rotational direction of specimen.

Figure 3: Definition of positive direction

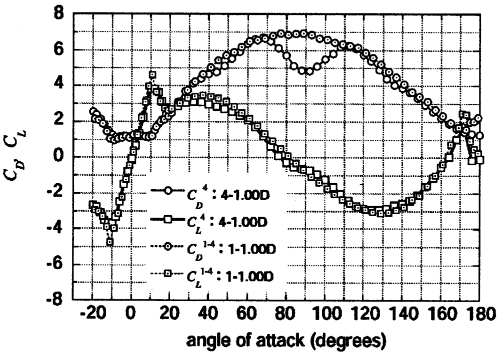
3.1 Comparison between The Results of 4-conductor Bundle and Single Conductor Section

3.1.1 Drag Coefficient and Lift Coefficient

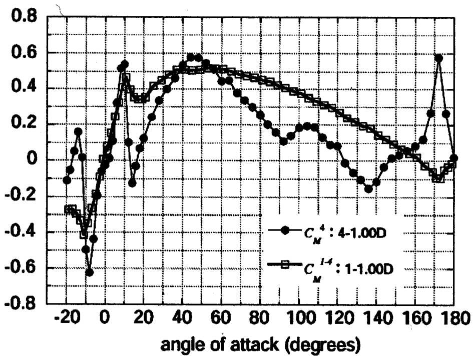
In this investigation, for the projected area of 4-1.00D the projected area of only 2 conductors in upstream side are took into account as shown in Table 1. Thus, the drag coefficient and lift coefficient for a single conductors (hereafter, written as C_D^1 and C_L^1, respectively) can be converted to the values for 4 conductors (hereafter, written as C_D^{1-4} and C_L^{1-4}, respectively) as follows.

$$C_D^{1-4} = 2C_D^1, \quad C_L^{1-4} = 2C_L^1 \qquad (1)$$

Figure 4 (a) compares C_D^{1-4} and C_L^{1-4} with the corresponding values for 4-1.00D (hereafter, written as C_D^4 and C_L^4, respectively). As shown in the Figure, although the absolute values of extremes of C_L^4 are slightly lower than the corresponding values of C_L^{1-4} in the angle of attack range from -20 to 60 degrees, other extremes and their corresponding angles of

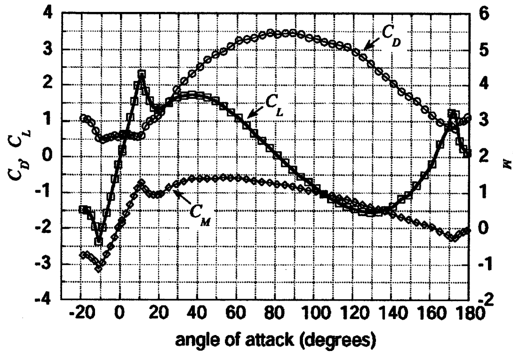


(a) Conversion to C_D, C_L of 4 Conductor Bundle

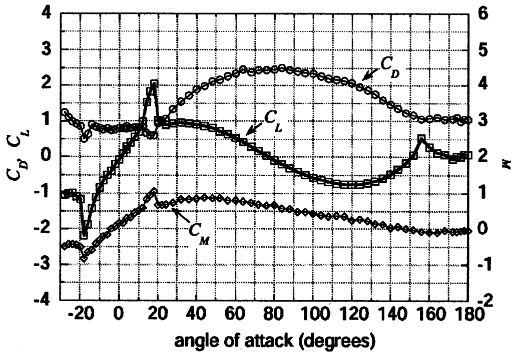


(b) Conversion to C_M of 4 Conductor Bundle

Figure 4: Experimental Results: No. 1 and No. 2



(a) Experiment No.2: Specimen 1-1.00D



(b) Experiment No.3: Specimen 1-0.50D

Figure 5: Experimental Results: No. 2 and No. 3

attack almost agree with between both specimens.

In the angle of attack range from 60 to 180 degrees shown in Figure 4 (a), C_D^4 has 3 extremes at angles of attack of about 70, 90 and 110 degrees as differing from the case of C_D^{1-4}, and C_L^{1-4} tend to decrease more smoothly as compared with C_L^4. Especially, C_D^4 is far less than C_D^{1-4} at the angle of attack of 90 degrees. The reason may be that the wind receiving area of 4-1.00D varies depending on the angle of attack and thereby the conductors in downstream are affected by wake of the conductors in upstream.

3.1.2 Aerodynamic Moment Coefficient

Because in this investigation the definition of typical diameter is different among specimens as shown in Table 1, a correction should be required on the typical diameter in the comparison between aerodynamic moment coefficients of 4-conductor bundle and single conductor (hereafter, written as C_M^4 and C_M^1, respectively). Hence, by assuming that 4 specimens of 1-1.00D are arranged with an interval between conductors similar to a case of 4-1.00D, the aerodynamic moment coefficient of a single conductor is converted to the coefficient of 4 conductors (hereafter, the converted value is written as C_M^{1-4}) as follows.

$$C_M^{1-4} = 2C_M^1 \cdot B_1 / B_4 \qquad (2)$$

Here, B_1 and B_4 are typical diameter of 1-1.00D and 4-1.00D (Refer to Table 1), respectively. And then C_M^{1-4} is compared with C_M^4 in Figure 4 (b).

As shown in Figure 4 (b), the agreement of the extremes and the angles of attack corresponding to the extremes is insufficient between C_M^{1-4} and C_M^4. The reason may be an effect of wake from the conductors in upstream and a variation of wind receiving area by the rotation of 4 conductors. Hence, currently it may be difficult to predict the aerodynamic moment coefficient of 4 conductors from corresponding coefficient of a single conductor.

3.2 Relation between Height of Accreted Ice and Aerodynamic Coefficients

As the relation between the height of accreted ice and aerodynamic coefficients recognized from Figure 5 (a) and (b), when the height of accreted ice reduces, ① the variation of aerodynamic coefficients associated with the change of angle of attack become smaller and ② the angle of attack corresponding to the extremes increases at extremes near 0 degree and decreases at extremes near 180 degrees.

4.0 RELATION BETWEEN HEIGHT OF ACCRETED ICE AND GALLOPING

In this chapter, we will pay attention to the relation between the aerodynamic characteristics shown in Figure 5 (a), (b) and the galloping amplitude and describe the results of time history response simulation. For calculations, we used three dimensional geometrical nonlinear finite element analysis code "CAFSS" [1].

4.1 Conditions for Simulation

An objective transmission line model to be analyzed was a span of a single conductor transmission line having the specifications in Table 2 installed in a typical stringing scheme and a uniform horizontal flow with velocity of 10 m/s was applied from the direction perpendicular to the span with considering the aerodynamic characteristics in the Figure 5 (a), (b). Calculation was implemented in 6000 steps by an time increment of 0.05 second, Newmark-β method was used for direct integration, and Rayleigh damping of 0.1% and 0.3% at 0.1 Hz and 0.3 Hz, respectively, was assumed for structural damping.

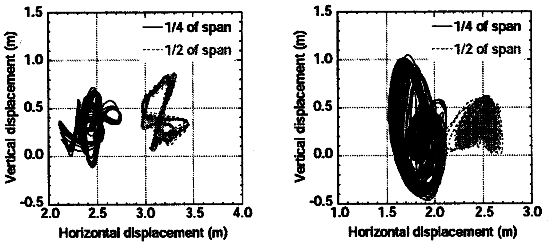
4.2 Results of Simulation

As the results of simulation, the displacement Lissajou's patterns were obtained at 1/4 and 1/2 of the span as shown in Figure 6.

From this Figure, it could be demonstrated that a galloping occurred because a steady loop oscillation was identified under a constant wind velocity in every case taking account of any aerodynamic coefficients. And a correlation between the height itself of accreted ice and the amplitude of galloping seems to be weak. Further, because the size relations of fluctuation widths at 1/4 and 1/2 of the span are different depending on the aerodynamic coefficients, it is recognized that galloping motions with different oscillation mode are stimulated by the difference in the height of accreted ice.

Table 2: Specifications of Simulation Model

Span (m)	350
Sag (m)	10.5
Initial tension (N)	1.049×10^4
Cross sectional area (m^2)	1.965×10^{-4}
Typical diameter (m)	1.820×10^{-2}
Polar inertia moment (m^4)	6.143×10^{-9}
Young's modulus (N/m^2)	8.898×10^{10}
Poisson ratio	0.3
Density (kg/m^3)	3.73×10^3
Element	Truss taking account of twist
Division number of elements	80 elements



(a) Taking Account of 1-1.00D

(b) Taking Account of 1-0.50D

Figure 6: Simulated Displacement Lissajou

5.0 SUMMARY

The findings obtained in this investigation are as follows:

① If a conversion is carried out by taking account of the differences in typical diameter and number of conductors, the drag coefficient and lift coefficient of a single conductor almost agrees with that of 4-conductor bundle. However, because the effect of wake from upstream conductors in 4 conductors can not be taken into account, the aerodynamic moment coefficient does not agree with between 4-conductor bundle and single conductor.

② When the height of accreted ice reduces, the variation of aerodynamic coefficients associated with the change of angle of attack become smaller. And, if the accreted ice profile is different, the oscillation mode of stimulated galloping may differ.

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