Investigation of effect of galloping countermeasure for four-bundled conductor through field observation

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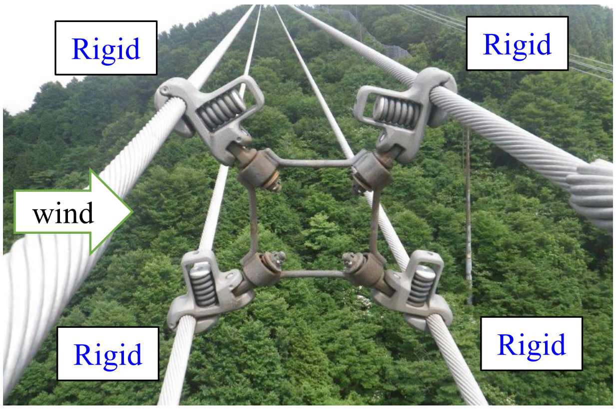
Abstract— **To prevent galloping of four-bundled conductors, loose spacers, which are a galloping countermeasure, are normally installed in Japan. Loose spacers have two rigid clamps and two rotatable clamps, in contrast to normal line spacers, which have four rigid clamps. There are two types of loose spacers: diagonal and one-sided loose spacers. The former has two rotatable clamps facing each other diagonally. In the latter case, the two rotatable clamps were installed in the upwind side. The galloping-suppressing effect of the diagonal loose spacers has already been proven through field observations. In contrast, the effect of the one-sided loose spacers and the difference of their effects from those of the diagonal loose spacers have not been investigated in real environments. However, one-sided loose spacers were found superior to the diagonal loose spacers through experiments using a model conductor. In this study, the effectiveness of one-sided loose spacers and their difference from the diagonal loose spacers were investigated through field observations of four-bundled conductors over eight winter periods. The results showed that the one-sided loose spacer was superior to the diagonal loose spacer because the maximum tension fluctuation of the conductor with the one-sided loose spacers was smaller than that with the diagonal loose spacers. However, galloping of conductors with one-sided loose spacers may occur when the rotational angle of the rotatable clamps is smaller than the limit angle of the equipment, and the rotational angle of the conductor is relatively large.**

Keywords— ***Galloping, Ice accretion, Field observation, Four-bundled conductor, Loose spacer***

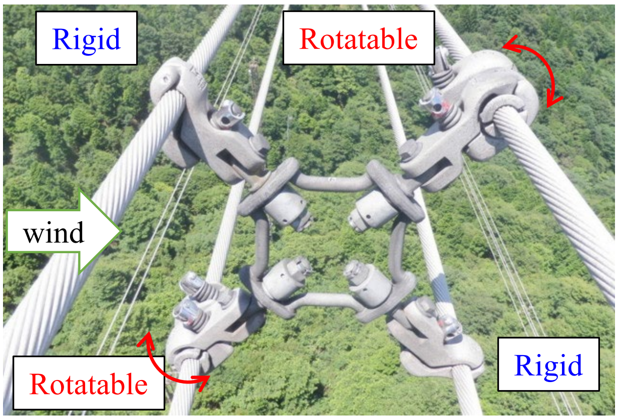
I. Introduction

Galloping of transmission lines under ice and snow accretion may lead to electrical faults and equipment fatigue. Galloping should be prevented to maintain a stable electricity supply. In four-bundled conductors, line spacers are normally installed on the conductors to keep distances between them. To prevent galloping of four-bundled conductors, galloping countermeasures, such as loose spacers, are normally installed instead of conventional "normal spacers".

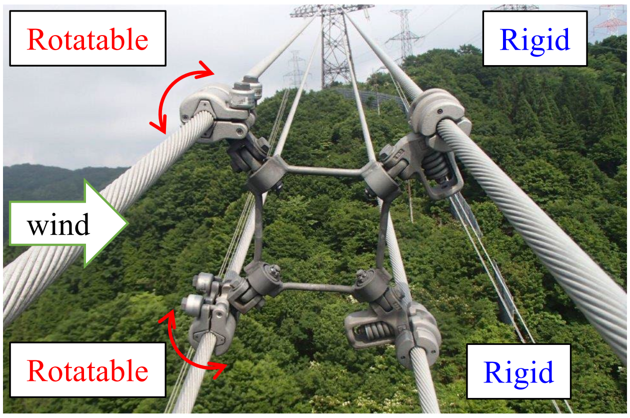
Figure 1 shows the different types of line spacers. Loose spacers have two rigid and two rotatable clamps, whereas normal spacers have four rigid clamps. There are two types of loose spacers. Diagonal loose spacers have two rotatable clamps facing each other diagonally. However, they are set on the upwind side in the case of a one-sided loose spacers. When all conductors are clamped by a rigid clamp, ice and snow accretions tend to grow in the same direction. However, a rotatable clamp can change the direction of ice and snow accretions because the conductor clamped by the rotatable clamp can rotate in the range of ±80°. Consequently, the aerodynamic characteristics of the four-bundled conductor change, which helps to prevent galloping.



(a) Normal spacer



(b) Diagonal loose spacer



(c) One-sided loose spacer

Fig. 1. Types of line spacers

Matsumiya et. al. [1] conducted field observations for four winter periods to compare the galloping phenomena of four-bundled conductors with normal and diagonal loose spacers. The results showed that the diagonal loose spacer effectively reduced the amplitude caused by galloping. Matsumiya et.

al. [2] also investigated the difference in the galloping-suppressing effect between a diagonal loose spacer and a one-sided loose spacer through wind tunnel tests. The experimental results showed that the one-sided loose spacer was superior to the diagonal loose spacer in an environment where the wind direction was almost constant. However, this difference has not yet been proven in real environments.

In this study, the effectiveness of one-sided loose spacer and its difference from the diagonal loose spacer was investigated through field experiments. A field study was conducted in the "Tsuruga test line" in Japan, which was the same field used in [1].

II. Observation Method

Figure 2 shows the location and an overview of the Tsuruga test line. It is located in central Japan, approximately 10 km from the Sea of Japan. The towers are built on a mountain ridge, approximately 700–800 m above sea level. The wind direction around the Tsuruga test line was generally north because of this terrain condition. The observation targets were Phases A and C in Figure 2. They consisted of four-bundled aluminum steel-reinforced ACSR410 conductors with a nominal cross-sectional area of 410 mm^2; these conductors are normally used in Japan. The span length, sag, and height difference between two support points were 345, 10.8, and 95 m, respectively. The support points and heights depended on the phase. Phase A was supported at the center of the tower, 50 m from the ground, whereas Phase C was supported at the arm of the tower, 40 m from the ground.

Observations were conducted from 2012 to 2019 (fiscal years). The observation cases for each year are listed in Table 1. Note that the data obtained in 2012 and 2013 were the same as the data obtained by [1]. From 2014 to 2016, one-sided loose spacers were installed at Phase C to compare the results obtained from 2012 to 2013. From 2017 to 2019, spacers at phases A and C were swapped to investigate the impacts of support point position and height from the ground. Approximately 50 ice accretion events were recorded during each observation period.

Figure 3 shows the layout of the measurement equipment. The data presented in Table 2 were obtained from this equipment. The motions of the Light Emitting Diode (LED) targets at the 1/4 and 1/2 spans were captured using a camera installed on tower no.2. The displacements were calculated via image analysis of the videos captured by the camera. Note that the displacements were unavailable when the LED targets were not visible owing to poor weather conditions. During each ice accretion event, 10-min or 1-min statistical values of the displacements at the 1/4 and 1/2 positions in the span, tensions, and wind speeds orthogonal to the direction of the span (orthogonal wind speed) were calculated. Here, tension was calculated as a quarter of the total tension, which represents the tension per conductor. Orthogonal wind speeds were calculated from the average wind speeds and directions. The difference in the galloping suppression effect between observation cases and the main factors are discussed in Section III using the calculated values.

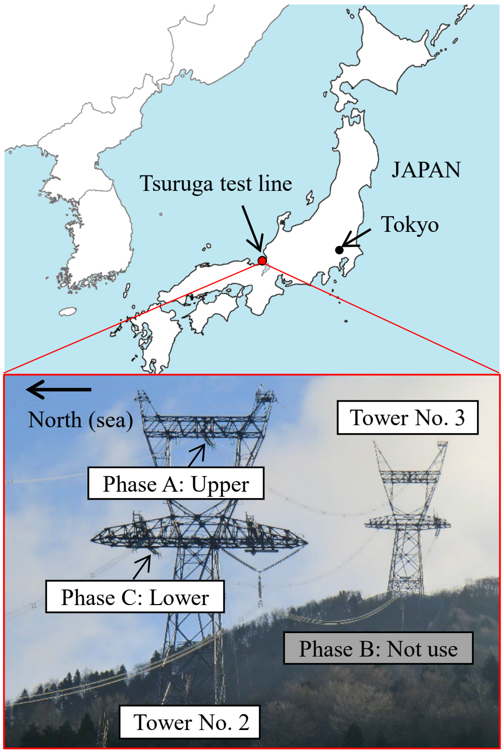


Fig. 2. Location and overview of Tsuruga test line

Table 1. Observation cases SP: spacer

Year	Phase A (Upper)	Phase C (Lower)	Number of Ice accretion event
2012–2013	Normal SP	Diagonal loose SP	53
2014–2016	Normal SP	One-sided loose SP	47
2017–2019	One-side loose SP	Normal SP	65

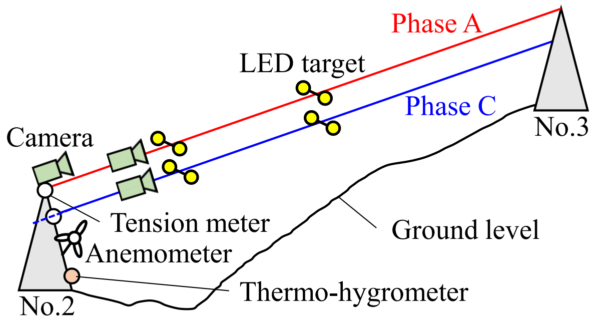


Fig. 3. Layout of the measurement equipment

Table 2. List of observation data

	Equipment	Sampling frequency
Displacement	LED targets and camera	10 Hz (when it is visible)
Tension	Tension meters	20 Hz
Wind direction and speed	Anemometer	20 Hz
Temperature and humidity	Thermo-hygrometer	Every hour (-2017) Every 10 min (2018-)
Image of ice accretion	Cameras	Every 10 min (daytime only)

III. Observation Results

A. Observation results for appropriate evaluation of galloping suppressing effect

1) Relationship between galloping amplitude and tension fluctuation: Mitigation of galloping amplitudes is important in the prevention of galloping through installation of loose spacers. However, it is difficult to obtain sufficient amplitude data because displacements are unavailable during bad weather conditions. To statistically investigate galloping phenomena, an analysis using tension, which can be measured almost every time, is appropriate. This section presents the investigation of the relationship between the galloping amplitude and tension fluctuation for the estimation of amplitudes using tension fluctuations.

Many galloping events were obtained from the ice accretion events, as shown in Table 2. Based on the displacements and video data, second loop galloping occurred in all cases of Phase C and in Phase A with line spacers. However, the first loop galloping occurred in phase A with one-sided loose spacers. Note that the word "loop" indicates the number of antinodes of vibration, as shown in Figure 4. In a previous study [1], tension fluctuations with a band-pass filter and cutoff frequencies of 0.6 and 0.8 Hz were used as galloping strengths because the tension fluctuation caused by the second loop galloping occurred twice its natural frequency (approximately 0.7 Hz). It was necessary to confirm whether this value was appropriate for evaluating the first-loop galloping.

Figure 5 shows the relationship between the tension fluctuation and amplitude. The peak-to-peak amplitude was approximately proportional to the square root of the peak-to-peak tension fluctuations in both cases of the first and second loop galloping. Therefore, the peak-to-peak tension fluctuation, which was applied a band-pass filter (0.6–0.8 Hz), was used as an indicator of the galloping amplitudes.

2) Influence of phase (span height and position): To appropriately compare each observation case, the difference in the observation results depending on the phase was confirmed. Figure 6 shows the relationship between the average orthogonal wind speed and tension fluctuation using the normal spacer. The maximum tension fluctuations were approximately 24 kN in Phase A and 10 kN in Phase C. Although the observation years were different, this result was reliable because the tension fluctuation data obtained was for a wind speed of up to 20 m/s, and large tension fluctuations were mainly observed at approximately 15 m/s in all observation cases. This indicates that the comparison should be made for results from the same phase because Phase A tended to experience larger galloping events than Phase C.

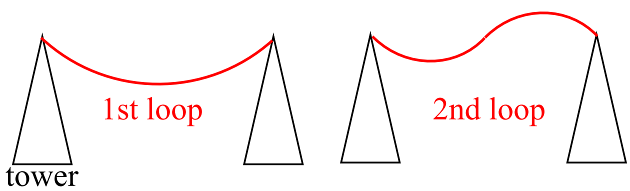


Fig. 4. Schematic of the loop of vibrations

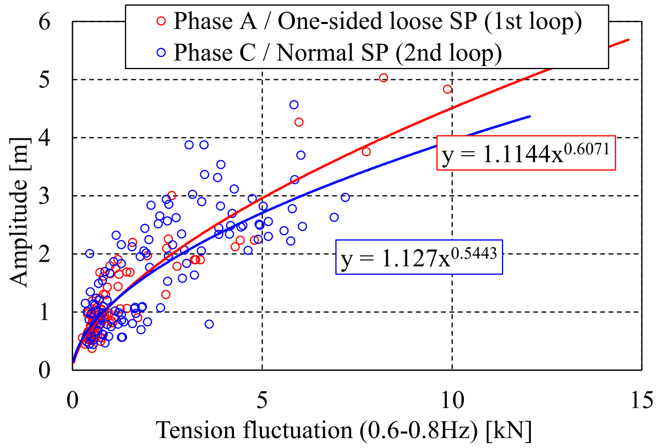


Fig. 5. Relationship between tension fluctuation and amplitude (peak-to-peak value in 10-min data)

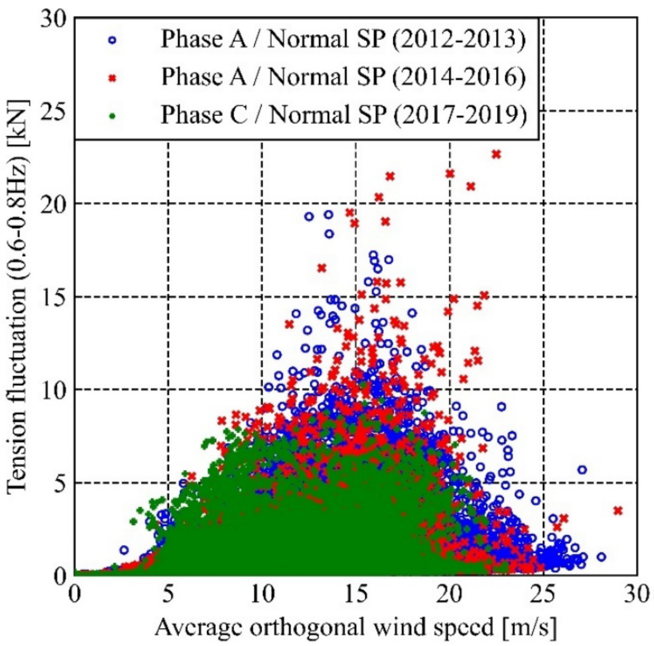


Fig. 6. Relationship between average orthogonal wind speed and tension fluctuation using normal spacer (1-min statistical value)

B. Comparing between the diagonal and one-side loose spacer

In this section, the galloping suppressing effects of the diagonal and one-sided loose spacers are compared using the observation data obtained from Phase C.

Figure 7 shows the relationship between the average orthogonal wind speed and tension fluctuation in Phase C. The maximum tension fluctuation was approximately 10 kN at a wind speed of 15 m/s for the normal spacer. This value was reduced to approximately 6 and 3 kN by installing diagonal and one-sided loose spacers, respectively. Figure 8 shows the proportions of the tension fluctuations in Phase C. Compared with the normal spacer, the proportions of the large tension fluctuations were substantially smaller using the one-sided loose spacer. In terms of the maximum value and frequency of tension fluctuations, the one-sided loose spacer was superior to the diagonal loose spacer.

To confirm the difference in the phases, the data obtained in Phase A were also compared to each other. Figures 9 and 10 show the relationship between the average orthogonal wind speed and tension fluctuation, and the proportions of tension fluctuations in Phase A. The maximum tension fluctuation was approximately 24 kN at a wind speed of 19 m/s for the normal spacer. This value was reduced to approximately 14 kN by installing one-sided loose spacers. The frequency of tension fluctuation using the one-sided loose spacer was lower than that with normal spacer. Thus, the one-sided loose spacer was also effective in phase A.

However, the maximum tension fluctuation in Phase A with one-sided loose spacers was relatively larger than that in Phase C with normal spacers. Although Phase A tended to experience larger galloping than Phase C, the maximum tension fluctuation observed in Phase A with one-sided loose

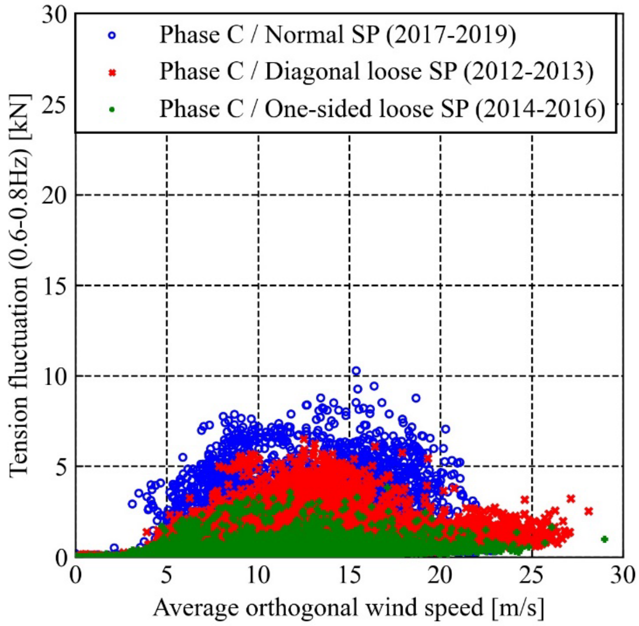


Fig. 7. Relationship between average orthogonal wind speed and tension fluctuation for Phase C (1-min statistical value)

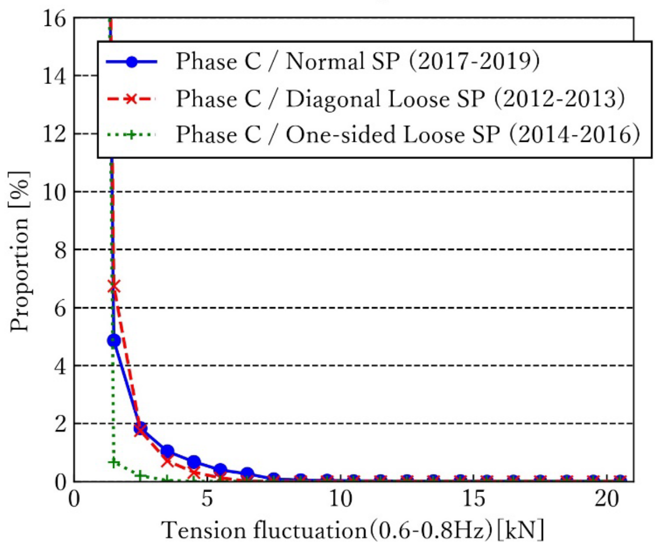


Fig. 8. Proportions of tension fluctuations in the case of Phase C

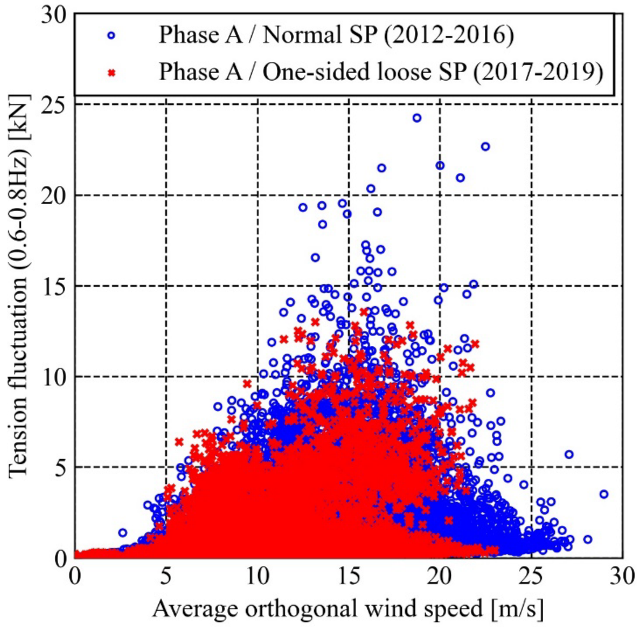


Fig. 9. Relationship between average orthogonal wind speed and tension fluctuation for Phase A (1-min statistical value)

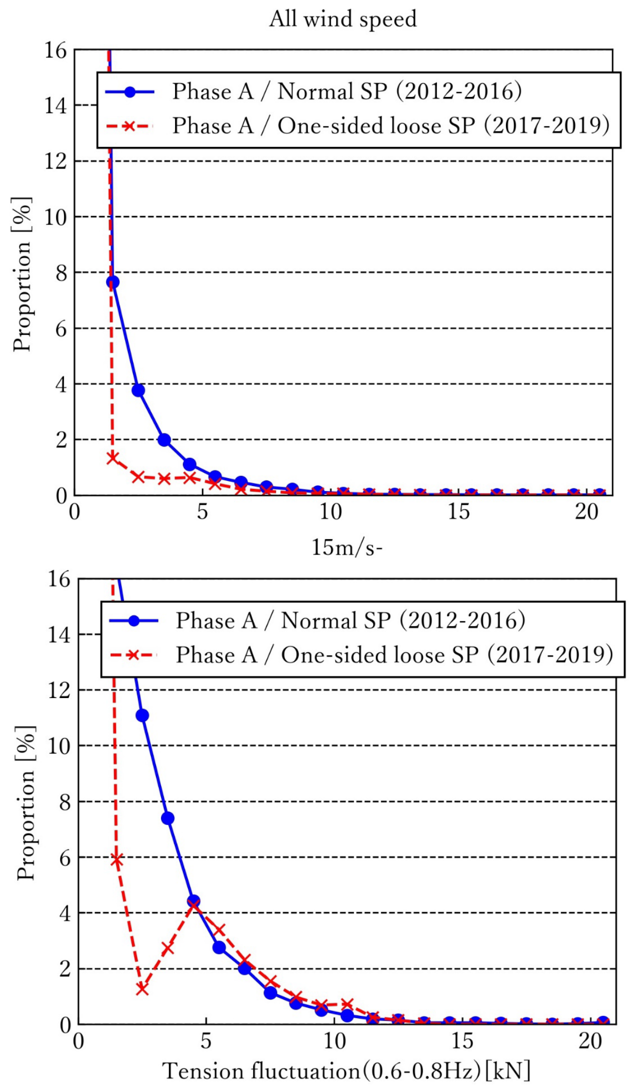


Fig. 10. Proportions of tension fluctuations in Phase A

spacers (14 kN) was equivalent to an amplitude of greater than 5 m, based on the approximate equation shown in Figure 5. The galloping events in Phase A with one-sided loose spacers should be investigated to understand the condition and mechanism in which the galloping suppression effect was relatively small compared to other situations.

Based on a comparison between Figures 8 and 10, the reduction in the proportion of tension fluctuations by installing one-sided loose spacers in Phase A was smaller than that in Phase C, particularly in the range higher than 5 kN. Focusing on the data with a wind speed ≥ 15 m/s, the proportions of tension fluctuations were almost the same for both types of spacers. This indicates that the galloping-suppressing effect of the one-side loose spacer may be reduced under high wind speed conditions.

C. Galloping phenomena in the phase with one-sided loose spacers

This section presents the investigation of a typical galloping event observed in Phase A with one-sided loose spacers using the data on tension fluctuations, displacements, wind speeds, rotational angles of rotatable clamps and entire four-bundled conductor, and images of ice accretion. This event occurred on January 9, 2019. Ice accretion lasted for approximately 24 h, and the total time that galloping was observed was approximately 7 h. The maximum tension fluctuation during the displacements was measured to be 11 kN.

Figures 11, 12, and 13 show the time history of the observation data, rotational angles of rotatable clamps, and examples of ice accretion, respectively. The rotational angles of the rotatable clamps were calculated as the rotational angles of the cross sticks (Figure 13) from horizon. Note that these data were available only from clear images. During this event, galloping occurred from 8:00 to 16:00. The galloping amplitude gradually decreased as the wind speed decreased from 15 m/s to 10 m/s. Although the amount of ice accretion seemed to be less than that of other events, it tended to increase gradually. Based on these data, the event was divided into three periods, as presented in Table 3. The characteristics of each period are as follows:

During Period 1, the maximum tension fluctuation was 9 kN. The average horizontal displacement and rotational angle of the conductor were 1.5 m and 40° downward, respectively. The upper rotatable clamp rotated upward, whereas the lower one rotated downward. The rotational angles of both clamps were less than the 80° limit. As shown in Figure 13, the direction of the ice accretion in the upper rotatable clamp appeared to be diagonally upward because the ice was not visible, whereas that of the lower clamp was diagonally downward.

At the beginning of Period B (8:54), the rotation directions of the two rotatable clamps were the same. It is assumed that phenomena such as torsional vibration of rotatable clamps or wind turbulence change the rotation direction of the upper rotatable clamp. This change seemed to cause an increase in the average horizontal displacement and the rotational angle of the conductor (2.0 m and 50°downward, respectively). Consequently, the maximum tension fluctuation increased to 11 kN.

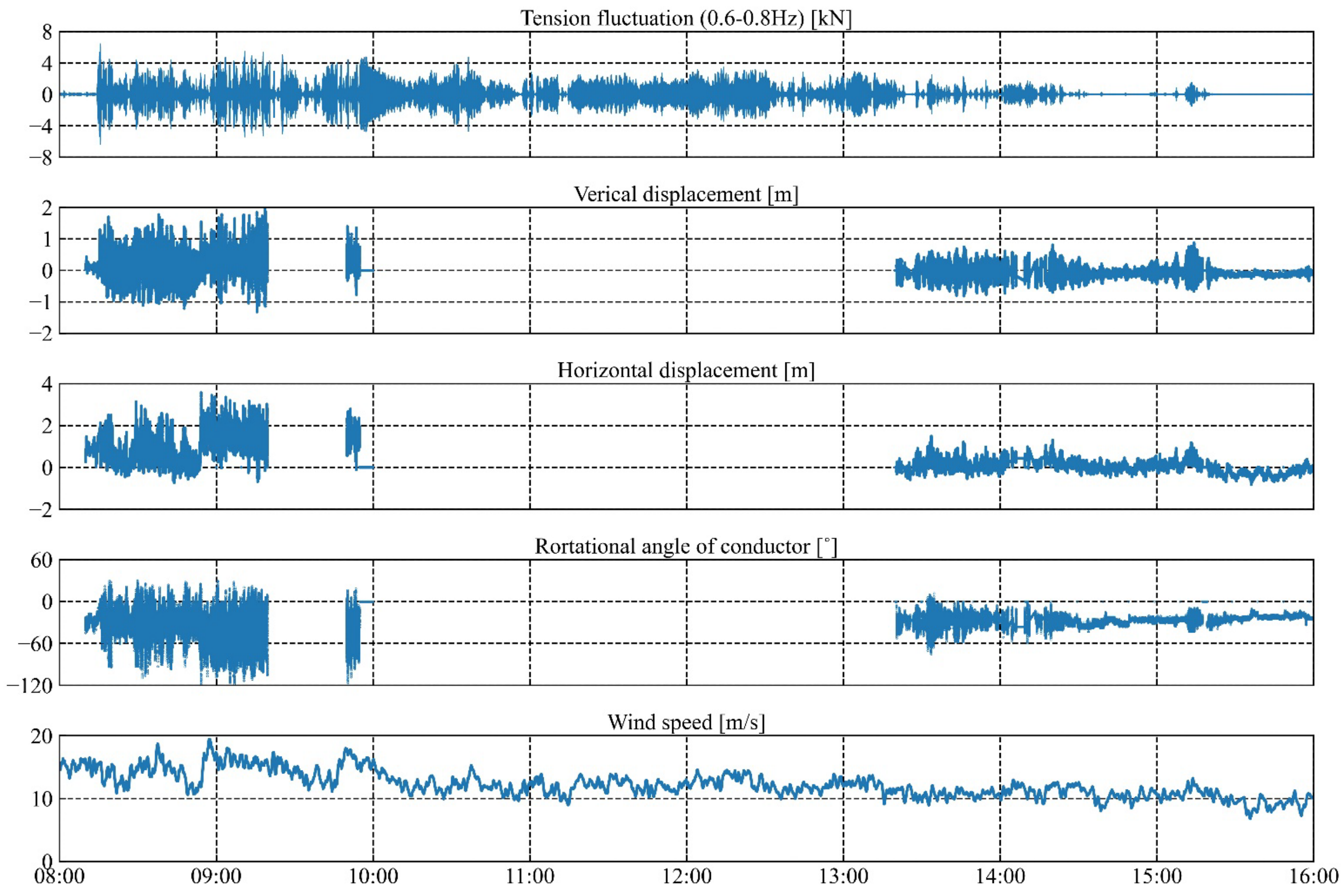


Fig. 11. Time history of observation data

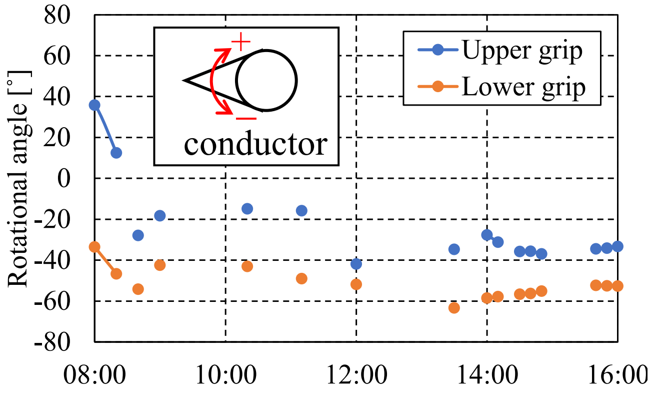


Fig. 12. Time history of the rotational angle of rotatable clamps

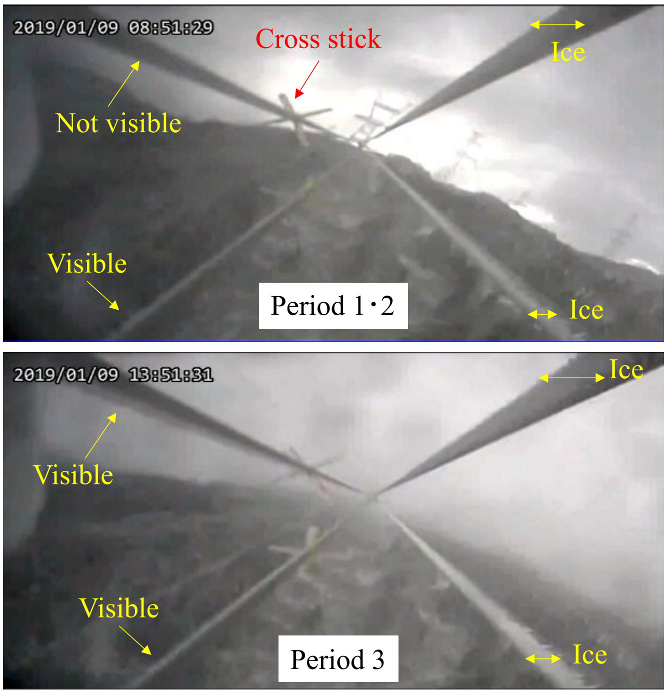


Fig. 13. Example of ice accretion in Periods 1 to 3

Table 3. Characteristics of Period 1 to 3

	Period 1	Period 2	Period 3
Time	8:17–8:54	8:54–9:19	13:30–16:00
Max. tension fluctuation	9 kN	11 kN	5 kN
Average wind speed	15 m/s	16 m/s	11 m/s
Rotational angle of rotatable clamps	Upper: 20° Lower: -40°	Upper: -20° Lower: -40°	Upper: -40° Lower: -60°
Horizontal displacement	1.5 m	2.0 m	0.5 m
Average rotational angle of conductor	-40°	-50°	-25°

Period 3 started at 13:30 because displacements from 9:20 to 13:30 were unavailable. The wind speed decreased to 10 m/s at 13:30. Consequently, the wind load decreased, and the average horizontal displacement and rotational angle of the conductor dropped to 0.5 m and 25° downward, respectively. The rotational angle of the rotatable clamps was larger than that in Period 2 by 20° because the amount of ice accretion in Period 3 was larger than that in Period 2. Consequently, the maximum tension decreased to 5 kN.

From these characteristics of each period, it is concluded that one-sided loose spacers become less effective when the rotational angle of rotatable clamps is insufficient compared to the limit angle of 80°, and the rotational angle of four-bundled conductor becomes relatively large. In Period 3, galloping was probably weakened because of the decrease in wind speed. However, the rotational angles of the rotatable clamps and the four-bundled conductor were more important factors because of a galloping event which had a tension fluctuation of approximately 10 kN at a wind speed of approximately 10 m/s, as shown in Figure 9.

In this section, a typical galloping event with sufficient data for evaluation is analyzed. To obtain a more reliable mechanism, the characteristics of other galloping events must be determined. However, information related to the displacements and angles was only available from clear videos and images. For statistical analysis of the galloping mechanism and occurrence conditions when one-sided loose spacers were installed, calculation methods for those parameters from other parameters that are easily available should be built in the future. Additionally, analytical or theoretical investigations of the weather conditions that lead to the rotational angles of rotatable clamps and four-bundled conductors that cause galloping are needed.

IV. Conclusion

In this study, the effectiveness of one-sided loose spacers and their difference from diagonal loose spacers were investigated through field observations. Investigations of four-bundled conductors were conducted over eight winter periods. The results showed that the maximum tension fluctuation of the conductors with one-sided loose spacers was smaller than that with diagonal loose spacers. Although both types of loose spacer have a galloping suppressing effect, the one-sided loose spacer was found superior to the diagonal loose spacer. However, some high amplitude galloping of the conductor with one-sided loose spacers occurred under certain weather and equipment conditions. Through an analysis of a typical galloping event, it is concluded that the galloping of conductors with one-sided loose spacers could occur when the rotational angles of rotatable clamps are smaller than the limit angle of 80°, and the rotational angles of the conductors are relatively large. More galloping events should be analyzed to obtain more reliable knowledge about the galloping mechanism and occurrence conditions in conductors with one-sided loose spacers.

Acknowledgment

Investigations were performed with the cooperation of Kansai Transmission and Distribution, Inc., and Sumitomo Electric Industries, Ltd. The authors are grateful for their support.

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