Finite element analysis on ice-shedding of GFRP-steel composite transmission tower-line coupling system

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ABSTRACT

Ice-shedding phenomenon usually triggers severe disaster in power transmission project. This paper adopted numerical method to investigate the ice-shedding response of a new-type GFRP-steel composite transmission tower-line coupling system. Various numerical models were established to examine the effects of span numbers, ice-shedding ratios and span distances. The results indicated that: compared to the slight difference of span numbers, the ice-shedding response of coupling system increased significantly as the ice-shedding ratio and span distances were enhanced; the maximum jump height respectively increased 78.17\% and 135.23\% from ice-shedding ratio 50\% to 80\% and 100\%; increasing the span distance from 400 m to 500 m, the maximum value of wire jump height enhanced by 53.71\% and the maximum deflection and compressive force of cross arm respectively increased by 125.00\% and 48.88\%.

1. INTRODUCTION

The ice disaster in transmission line is a natural phenomenon where the water in air or the rain freezes into frost (Jamaleddine et al. 1993). Under the certain temperature and wind, the covered ice would fall off, resulting in the up-and-down vibration and lateral oscillation of the wires. After the ice-shedding, the potential energy accumulated in the wire can be released to make the wires jump up, leading to an unbalanced tension between the adjacent spans, which will reduce the safe distance and cause the flashover or circuit short (Fu et al. 2006). On the other hand, the severe ice-shedding tends to induce dynamic instability of structural components and collapse of pylons (Fig. 1) (Kalman et al. 2007).

Moreover, the GFRP-steel composite transmission tower as a new-type pylon gradually attracts attention of the power supply department due to the characteristics of the reduced electricity corridor and construction land as well as the excellent insulation performance (Fig. 2). In practical power project, adopting composite materials in the
whole tower usually is difficult for the heavy-load carrying pylons due to the high cost, however, it can be accepted when the main structures still employ the steel but the cross arms adopt GFRP (Saboori and Khalili 2011). During the structural design in GFRP-steel composite pylons, the ice-resistant capacity induced by adopting GFRP cross arms (e.g., the jump height distance of wires and internal force of cross arm) should be attached great importance (Jones and Peabody 2006, Kollár et al. 2012).

Fig. 1 Ice disaster in transmission towers

Fig. 2 GFRP-steel composite transmission towers

Many researchers have carried out numerical modeling on ice-shedding response of traditional steel transmission tower-line coupling system. Fekr and McClure (1998) studied the dynamic response of a two-span transmission tower-line system under 21 ice-shedding conditions. McClure and Lapointe (2003) analyzed the transient response of electric wires under the impact loading (e.g., component damage and break line), and conducted a comparative study of the two-dimensional and three-dimensional tower-line coupling system. Kalman et al. (2007) simulated the dynamic response of single ground wire in the impulsive load caused by the mechanical de-icing; subsequently, the effects of different span distance and impulsive loads on ice-shedding were investigated for the establishment of failure criterion based on stress-
strain relationship. Yang et al. (2010, 2014) studied the ice-shedding response by varying the spacing bar diameter, ice thickness, span distance and elevation difference, etc. Ji et al. (2015, 2016) calculated the adhesive and cohesive force of ice for suggesting a criterion of ice-shedding. Moreover, some scholars also performed relevant experimental research on the ice-shedding response of the traditional steel transmission tower-line coupling system (Kollár et al. 2010, Meng et al. 2011 and 2012). However, it should be noted that aforementioned numerical studies mainly aimed at the traditional steel tower-line system; besides, the relevant experimental research usually be limited to the scaled test model and can hardly to simulate the actual dynamic response caused by ice-shedding. Therefore, this paper performed numerical modeling on ice-shedding response of the new-type GFRP-steel composite transmission tower-line coupling system for providing the basic design references.

2. GFRP-STEEL COMPOSITE TRANSMISSION TOWER-LINE COUPLING SYSTEM

This section introduced the establishment and validation of the finite element model of the coupling system, including the GFRP-steel composite transmission tower, wires and insulator, different tower-line coupling system and the model validation.

2.1 GFRP-steel Composite Transmission Tower

A practical cat-head transmission tower (height=68.2 m) in China was taken as an example for ice-shedding analysis in ANSYS program. The origin in overall coordinate system of GFRP-steel composite tower was set at the center of the tower head; the z-axis orientation toward gravity was positive and the x-axis was perpendicular to the wires. The composite transmission tower was established in beam element method. The tower model was shown in Fig. 3 and the material properties were listed in Table 1.
### Table 1 Basic material property

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Density ( /\text{kg/m}^3 )</th>
<th>Poisson’s ratio</th>
<th>Elastic modulus/( \text{GPa} )</th>
<th>Shear modulus/( \text{GPa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross arm</td>
<td>GFRP</td>
<td>2000</td>
<td>PRXY 0.287</td>
<td>EX 43.15</td>
<td>GXY 16.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PRYZ 0.091</td>
<td>EY 14.32</td>
<td>GYZ 2.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PRXZ 0.287</td>
<td>EZ 14.32</td>
<td>GXZ 16.5</td>
</tr>
<tr>
<td>Main steel</td>
<td>Q235 ~</td>
<td>7850</td>
<td>0.3</td>
<td>206</td>
<td>/</td>
</tr>
<tr>
<td>body</td>
<td>Q420</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The constitutive model of steel adopted elastic-perfectly plastic relationship.

#### 2.2 Coupling System

In the GFRP-steel composite transmission tower-line coupling system, the wires could be simulated by the cable element based on the catenary equations (Yang et al. 2010). Therefore, the wires in coupling system can be modeled based on the actual parameters in Table 2, especially for the tension force and sag.

### Table 2 Parameters of wires

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conductor wire</th>
<th>Ground wire</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Span: 400m</td>
<td>Span: 500m</td>
</tr>
<tr>
<td>Type</td>
<td>4×JL/LB1A-500/45</td>
<td>JLB20A-120</td>
</tr>
<tr>
<td>Area/mm(^2)</td>
<td>531.68</td>
<td>531.68</td>
</tr>
<tr>
<td>Elastic Modulus/MPa</td>
<td>66000</td>
<td>66000</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Unit weight/( \text{kg/m} )</td>
<td>1.6353</td>
<td>1.6353</td>
</tr>
<tr>
<td>Tension force / N</td>
<td>17651</td>
<td>17325</td>
</tr>
<tr>
<td>Sag/m</td>
<td>18.21</td>
<td>29.03</td>
</tr>
</tbody>
</table>

Based on the aforementioned finite element model of composite tower, the coupling system could be developed by assembling the wire model. In this paper, three different coupling systems were respectively established (Fig. 4, Fig. 5 and Fig. 6), moreover, the fixed constraints were applied at the ends of the wires and tower foots (Fig. 7). Moreover, the joint part between the tower and wires could be modeled by the simplified insulator link (Fig. 8), and the detailed parameters were shown in Table 3.
To verify the established coupling system model, the calculated tension forces in wires were extracted to compare with the design force, e.g., the calculated tension force in conductor wire and ground wire of the second span of the model in Fig. 4 were 17312.3 N and 6946.5 N respectively compared with the target values of 17325 N and 6959 N, reflecting a minor error of 0.07% and 1.8% to be allowed.

### Table 3 Parameters of insulator link

<table>
<thead>
<tr>
<th>Component</th>
<th>Element type</th>
<th>Elastic modulus/Pa</th>
<th>Density/kg/m³</th>
<th>Poisson’s ratio</th>
<th>Area/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link bar</td>
<td>LINK10</td>
<td>1e11</td>
<td>2000</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Link beam</td>
<td>BEAM189</td>
<td>4e10</td>
<td>2000</td>
<td>0.3</td>
<td>0.00785</td>
</tr>
</tbody>
</table>

**3. Ice-shedding dynamic analysis**
This section clarified the ice-shedding dynamic analysis, including the ice-shedding modeling method and effects of span numbers, ice-shedding ratios and span distances.

3.1 Ice-shedding Modeling Method

The loads considered in the simulation procedure included dead weight of wires, icing load, de-icing load and wind load. Currently, it is usually assumed that the ice is evenly covered on the surface of the wires (Ji et al. 2016), therefore, this paper applied the ice load uniformly along the wires. Moreover, the ice thickness covered about 20 mm, and the design force on the conductor wires and ground wires were respectively 25.49 N/m and 17.96 N/m. As for the wind load on the wires, the load in unit length specified in DL/T 515402012 could be modeled as follows:

\[ p_u = \frac{1}{1600} \alpha \mu_c \beta_c d B_1 V_0^2 \]  

(1)

where \( \alpha \), \( \mu_c \), \( \mu_c \) and \( \beta_c \) are the uneven factor of wind pressure, height variation factor of wind pressure, size factor of wire and load adjustment coefficient, respectively; \( d \), \( B_1 \) and \( V_0 \) are the wire diameter after covering ice, adjustment factor of wind load in ice (1.5 ~ 2.0 under ice thickness=20 mm) and basic wind speed at the height of 10 m. In this paper, the basic wind speed was 15 m/s and the adjustment factor \( B_1 \) was 1.75. Then, the ice-shedding process could be modeled as follows:

(1) The equilibrium state under the self-weight was firstly calculated;
(2) The equilibrium state under the covered ice thickness 20 mm was calculated;
(3) The dynamic analysis was conducted in the basic wind speed 15 m/s and ice load;
(4) The ice load of certain span was suddenly deleted at a short time \( t=0.01 \) s;
(5) The ice-shedding dynamic response was performed \( 0 \sim 21s \).

During the dynamic process, the structural damping ratio adopted 0.02. The calculated conditions of the GFRP-steel tower-line coupling system were listed in Table 4.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Span number</th>
<th>Span distance</th>
<th>Ice-shedding ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>400</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>400</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>400</td>
<td>100%</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>400</td>
<td>50%</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>400</td>
<td>80%</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>500</td>
<td>100%</td>
</tr>
</tbody>
</table>

3.2 Effects of Span Numbers

The effects of span numbers on ice-shedding response could be observed as follows. Fig. 9 demonstrated the effect of span number on jump height at the wire center of the middle span, in which the Model 1, Model 2 and Model 3 respectively
denoted the coupling system with two spans, five spans and seven spans. A slight difference in the history response of jump height existed in the three models, where the maximum value (MV) respectively decreased 3.13% and 3.68% from Model 1 (three spans) to Model 2 (five spans) and Model 3 (seven spans). Besides, the corresponding average stable value (SV) between three models was 9.72 m.

![Jump height response history](image1.png)  ![Jump height values](image2.png)

(a) Jump height response history  
(b) Jump height values

Fig. 9 Effects of the span numbers on jump height

Fig. 10 and Fig. 11 demonstrated the effects of span number on deflection (parallel to wire direction) of hanging line end in cross arm and compressive load in cross arm. Similarly to aforementioned effect on the jump height, the various span numbers resulted in slight differences in deflection and compressive load of cross arm, where the average MVs and SVs of deflection and compressive load respectively were 0.017 m, 0.013 m, 49.08 kN and 43.01 kN. Moreover, the compressive load in cross arm decreased gradually with the increased span numbers, reflecting that the more spans in coupling system served as a damper after ice-shedding to reduce the dynamic response. Therefore, the compressive load in the Model 1 (three spans) usually had the maximum value due to the few spans in the fixed boundary constraints. On the whole, the established different models had slight discrepancy in the ice-shedding analysis, thus, the model with three spans could be served as a simplified analytical model due to the computational efficiency.

![Deflection response history](image3.png)  ![Deflection values](image4.png)

(a) Deflection response history  
(b) Deflection values

Fig. 10 Effects of the span numbers on deflection
3.3 Effects of Ice-shedding Ratios

This part aimed to discuss the effects of the ice-shedding ratios. In the dynamic analysis process, the unit weight after the ice-shedding ratio of $\beta$ could be determined by $W_2(1 - \beta)$, where $W_2$ was the ice weight. Taking the model of two towers and three spans as an example, the ice-shedding analysis was carried out when the middle span appeared ice-shedding, subsequently, the jump height of wires, deflection of hanging line end in cross arm and compressive load in cross arm were investigated. Fig. 12 demonstrated the effects of ice-shedding ratios on jump height of wires. In Fig. 12, it can be observed that the jump height increased as the ice-shedding ratio increased; the MV increased 78.17% and 135.23% from ratio 50% to 80% and 100%, respectively; the corresponding SV increased 75.59% and 133.18%, respectively.

Fig. 13 and Fig. 14 demonstrated the effects of ice-shedding ratios on deflection of hanging line end in cross arm and compressive load in cross arm. It indicated that increasing the ice-shedding ratio from 50% to 80% and 100%, the MV and SV of deflection hanging line end in cross arm increased 30.83% and 46.67%, respectively; the MV of compressive load respectively increased by 4.77% and 6.51% in the ice-shedding ratio of 80% and 100%, however, the SV in 100% ice-shedding ratio decreased by 3.66% compared to that value in 50% ice-shedding ratio, which was due to the fact that the higher ice-shedding ratio tended to significantly induce the up-and-
down deflection amplitude, resulting an obvious dynamic compressive response in GFRP cross arms, but the stable compressive force decreased by increasing the ice-shedding ratio, revealing the apparently decreased ice weight.

![Deflection response history](image1)
![Deflection values](image2)

**Fig. 13** Effects of the ice-shedding ratio on deflection

![Compressive load response history](image3)
![Load values](image4)

**Fig. 14** Effects of the ice-shedding ratio on compressive load

### 3.4 Effects of Span Distances

The effects of span distances on ice-shedding response were displayed as follows. In Fig. 15, it can be observed that an obvious difference appeared in the various span distances, in which increasing the span distance from 400 m to 500 m, the MV and SV enhanced by 53.71% and 47.05%, respectively. It was due to the fact the jump height was proportional to the flexibility characteristic of wires, therefore, the jump height in larger span distance tended to perform apparent dynamic response in the same loading condition.

**Fig. 16** and **Fig. 17** demonstrated the effects of span distances on deflection of hanging line end in cross arm and compressive load in cross arm. Obviously, increasing the span distance could enhance the ice-shedding response of GFRP cross arm, where increasing span distance from 400 m to 500 m the deflection respectively enhanced by 125.00% and 134.15% in MV and SV. Moreover, the compressive load in GFRP cross arm increased by 48.88%, 53.76% and 21.40% in MV, SV and no ice-shedding, respectively, owing to the fact that the increased span distance enlarged the gravity component of wires. Therefore, during design process of the long span power
transmission project in ice-frozen region, the great attention should be attached for new-type GFRP-steel tower-line structural system.

3. CONCLUSIONS

This paper adopted numerical method to investigate the ice-shedding response of GFRP-steel transmission tower-line coupling system. The conclusions within the study scope are as follows.
(1) The various numerical models with different span numbers show slight difference on the ice-shedding response of the coupling system; the compressive load in GFRP cross arm increases slightly as the span number exceeds five spans due to the decreasing boundary constraints.

(2) The ice-shedding response of coupling system increases significantly as the ice-shedding ratio is enhanced gradually. The maximum value of jump height of wires in the ratios of 50%, 80% and 100% are 8.43 m, 15.02 m and 19.83 m, respectively; the corresponding deflections of cross arm are 0.012 m, 0.0157 m and 0.0176 m, respectively.

(3) The span distance significantly affects the ice-shedding response of coupling system. Increasing the span distance from 400 m to 500 m, the maximum value of wire jump height enhances by 53.71%; the maximum deflection and compressive force of cross arm respectively increase by 125.00% and 48.88%. During design process of the long span power transmission project in ice-frozen region, the great attention should be attached for new-type GFRP-steel tower-line structural system.

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