A preliminary analysis on mechanical characteristics of transmission conductors in the vicinity of suspension clamps

Guoliang Zhao, Xiaoming Rui *

School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing, China

*Corresponding author e-mail: rxm@ncepu.edu.cn

Abstract. Overhead transmission conductors are prone to wire strands breaking under the conditions of breeze vibration, and many broken strands occur in the vicinity of suspension clamps. In order to research the stress distribution characteristics of the conductor in the vicinity of suspension clamps, a relatively effective Finite Element (FE) model was proposed. Preliminary verification of model rationality through comparative analysis of theoretical calculation and simulation, and use this model to study the mechanical characteristics of the cross-section of the conductor in the key position of the conductor-clamp system. The research conclusions are as follows: a new concept of equivalent bending stiffness and equivalent diameter is proposed, which is used to calculate the alternating bending stress of conductors under breeze vibration conditions. The alternating bending stress of the wire strands follow the bending amplitude ($Y_b$) increases with increasing. Under the complex load, the Equivalent (Von-Mises) stress of the aluminum wire strands at the Last Point of Contact (LPC) of the conductor and the clamp shows a decreasing trend from the outside to the inside, and the maximum Von-Mises stress occurs at the contact position between the outermost wire strands and the clamp.

1. Introduction

Under breeze vibration conditions, the force of the overhead transmission conductor in the vicinity of the suspension clamp is relatively complicated, except for the large static tension, the squeezing and bending force generated by the conductor's own weight, the holding force of the suspension clamp on the conductor, and the periodic excitation force caused by wind-induced vibration. At the same time, it is also subject to external mechanical damage such as knocks and scratches [1]. If the local stress of the conductor exceeds its ultimate strength and is subjected to this complex load combination for a long time, the conductor will eventually break strands, which may cause greater economic losses. In addition, the conductors in the area are relatively hidden, and the damage of the conductors is generally not easy to be found during inspections. Therefore, it is necessary to study the stress distribution of the conductor in this area.

Researchers at home and abroad have noticed the above-mentioned problems and have conducted some research on the conductor-clamp system. Lalonde et al. [2-4] combined friction theory to establish a FE model of the conductor-clamp system. Frédéric and Cardou et al. [5-9] considered the elastoplastic contact problem and used the FE method, the contact mechanics analysis of the conductor at the clamp.
is carried out, and studied the influence of the geometry of the clamp on the strain of the conductor. Ouaki et al. [10] showed that the strain of the conductor at the suspension clamp is related to its position. Pan and Lu et al. [11-13] through the analysis of the dynamic bending strain of the conductors in the vicinity of the clamp, the influence of related parameters is discussed. However, in view of the importance of conductor breakage in the conductor-clamp system, there are still some issues worthy of further discussion. In previous studies, it is often necessary to assume that there is no contact between the conductor in the vicinity of the clamp. And ignoring the change in stiffness during the vibration of the conductor, and failing to analyze the stress distribution of the conductor in the vicinity of the clamp. Based on the research results provided by the references, the article discusses the influence of bending stiffness on the alternating bending stress of the conductor through theoretical calculation of conductor mechanics and simplified simulation model analysis. Try to verify the validity of the model, and use the model to discuss the stress distribution of the key section of the conductor.

2. Model mechanics calculation of conductor-clamp system

2.1. Analysis of key position of conductor-clamp system
In addition to the contact between the wire strands, there are also contacts between the conductor and the clamp body and between the conductor and the keeper. The stress generated by these contacts easily affects the service life of the conductor. Therefore, this system will focus on the analysis of the two positions of Keeper Edge (KE) and LPC. At the same time, in order to compare with these two key positions, the distance LPC 89mm proposed by the IEEE standard was selected as the third research position. The three key research positions of the conductor-clamp system are shown in Figure 1.

2.2. Mechanical analysis of the conductor in the vicinity of the clamp
In the actual operation of the conductor, most of the wire strand break occur in the vicinity of the suspension clamp, and the alternating bending stress of the wire strand is an important parameter for evaluating the fatigue life of the conductor. Therefore, the alternating bending stress of the wire strand in this area is primary studied. Assuming that the end deflection of the conductor in the vicinity of the suspension clamp is approximately a cantilever beam under the action of a uniform load, the deflection diagram of the conductor in the vicinity of the clamp is shown in Figure 2.

\[
\frac{d^2y_t}{dx^2} = \frac{d^2y_t}{dx^2} = \frac{M}{EI} \tag{1}
\]

Where \( y_t \) is the distance from the sine curve of the conductor centerline in vicinity the clamp; M is the bending moment, \( M = Ty_t \); EI is the bending stiffness of the conductor.

Bring the conductor bending moment \( M = Ty_t \) into the above formula (1)

\[
\frac{M}{EI} = \frac{Ty_t}{EI} = p^2 y_t \tag{2}
\]
In the formula, \( p = \sqrt{\frac{T}{EI}} \). T is Tension.

When \( x \) is large enough, \( y_t \) is close to zero, so the solution of the differential equation

\[
y_t = Ce^{-px}
\]

When \( x=0 \), \( \frac{dy_t}{dx} \) is equal to \(-\Delta \beta\), the curvature of the conductor in the vicinity of the clamp is

\[
\left[ \frac{d^2y_t}{dx^2} \right]_{x=0} = p^2 C = p\Delta \beta
\]

Assuming that each wire strand of the conductor is bent along its own neutral axis, the alternating bending stress \( \sigma_a \) of the wire strand in the vicinity of the clamp is expressed as

\[
\sigma_a = \frac{d}{2} E_a \left[ \frac{d^2y_t}{dx^2} \right]_{x=0}
\]

Assuming that the deflection is small, the displacement of the conductor center line relative to the \( x \)-axis is

\[
y(x) = -y_a + \Delta \beta x + y_t
\]

Combine the above formula to find the curvature of the conductor

\[
\left[ \frac{d^2y_t}{dx^2} \right]_{x=0} = p^2 C = \frac{p^2 y(x)}{e^{-px}-1+px}
\]

According to the IEEE standard, \( y(x) \) is obtained by measuring the \( Y_b \) at 89mm from LPC, \( Y_b = 2y(89) \), then the alternating bending stress of the wire strands in the vicinity of the clamp is

\[
\sigma_a = \frac{dE_a(T/4E)}{e^{-px}-1+px} Y_b
\]

Where \( d \) is the diameter of the outermost wire strands of the conductor; \( x \) is the conductor coordinate with LPC as the origin, and \( x = 89 \text{mm} \); \( E_a \) is the elastic modulus of aluminum.

Assuming that the maximum and minimum bending stiffness of the conductor are \( EI_{max}, EI_{min} \)

\[
EI_{max} = \sum_{i=1}^{nb \text{layer}} n_i \left( E_i l_i \sin(a_i) + \frac{A_i R_i^2 \cos^2(a_i)}{2} \right) + E_c I_c
\]

\[
EI_{min} = \sum_{i=1}^{nb \text{layer}} \frac{E_i \pi d_i^4}{64}
\]

Where \( n_i \) is the number of wire strands, \( A_i \) is the cross-sectional area of the wire strands, \( a_i \) is the lay angle of the wire strands, \( R_i \) is the layer \( i \) radius, \( E_c \) and \( I_c \) are the Young modulus and the moment of inertia of the central steel core, respectively. \( E_i \) and \( d_i \) are the Young modulus and the diameter of the wire strand of layer \( i \), respectively.

3. Mechanical simulation model of conductor-clamp system

3.1. The physical model of the conductor-clamp system

3.1.1. Physical model establishment. The research conductor selected JL/G1A-630/45 aluminium conductor steel reinforced (ACSR), which is made up of 7 steel wire strands and 45 aluminium wire strands, which are twisted in 5 layers. Select the lay ratio of the wire of each layer of the conductor, from the inner to the outer pitch diameter ratio \( m_i \) respectively 20, 15.5, 13.2, 11. The structural parameters of each layer of conductor are shown in Table 1.
Table 1. Structural parameters of JL/G1A-630/45 ACSR.

| Layer | 𝑛𝑖 | Material | 𝑑𝑖/mm | 𝐷𝑖/mm | 𝛼𝑖/° | Pitch Distance/mm |
|-------|----|----------|--------|--------|------|------------------|
| Core  | 1  | steel    | 2.81   | 2.81   | -    | -                |
| 1     | 6  | steel    | 2.81   | 8.43   | 5.9  | 168.600          |
| 2     | 9  | aluminum | 4.22   | 16.87  | 8.6  | 261.485          |
| 3     | 15 | aluminum | 4.22   | 25.31  | 11.2 | 334.092          |
| 4     | 21 | aluminum | 4.22   | 33.75  | 14.0 | 371.250          |

Choose the XGU type central rotary suspension clamp that matches the conductor. The clamp is mainly composed of the keeper, body and U-bolt. The length of the suspension clamp is known to be 300mm, and the length of the conductor is 400mm to establish a conductor-clamp system model, as shown in Figure 3.

3.1.2. Simplification of the physical model. Due to the focus on the stress distribution of the conductor in the conductor-clamp system, in order to facilitate the FE calculation, the conductor-clamp system model is appropriately simplified, and the simplified model basically meets the contact conditions and main characteristics. Considering that the structure of the suspension clamp is relatively complex and symmetrical, only the contact force of half of the suspension clamp with the conductor is studied to reduce the calculation time. The simplified model of conductor-clamp system is shown in Figure 4.

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Figure 3. Model of conductor-clamp system. Figure 4. Simplified model.

3.2. Establishment of FE model
Use the ABAQUS software to analyze the mechanical characteristics of the simplified model of the conductor-clamp system, considering the contact, elastoplastic and other issues of the model.

3.2.1. FE model preprocessing. The main materials of JL/G1A-630/45 ACSR are steel and aluminum, and the main material of XGU type suspension clamp is KTH330-08 malleable cast iron. The main material parameters of this model are shown in Table 2. Due to the focus on the conductor, the plastic problem of the suspension clamp is no longer considered.

Table 2. Material parameters of conductor-clamp system.

| Property                  | Steel | Aluminum | KTH330-08 |
|---------------------------|-------|----------|-----------|
| Density / (kg/dm³)        | 7.780 | 2.703    | 7.300     |
| Poisson ratio             | 0.28  | 0.30     | 0.27      |
| Elastic Modulus / Pa      | 190   | 55       | 190       |
| Yield stress / MPa        | 620   | 120      | -         |
| Ultimate strength / MPa   | 1290  | 160      | -         |

Since there are more interactions between the various parts of the model, the interaction between the parts is automatically generated by General contact of Explicit. The normal behavior of the contact attribute is selected by default, and the tangential behavior sets the penalty function and friction coefficient. Combining the ACSR structural characteristics, the Medial axis algorithm and Minimize the
mesh transition, and the Sweep Technique is used to divide the mesh. The element type is C3D8R, and considering the geometry of the suspension clamps, directly use the Tet element shape for meshing, as shown in Figure 5. Shown.

![Figure 5. Meshing of conductor-clamp system model.](image)

3.2.2. Boundary conditions and loads. All nodes of the cross section of the conductor end are coupled to the center point of the section to act as a rigid surface, and constraints and external loads are applied at the coupling point. The boundary condition of the conductor takes the form of one end fixed and one end applied with load. All the degrees of freedom are constrained on the coupling node of the fixed end. The body is completely fixed, and the keeper restricts all the degrees of freedom except the movement of the Y axis.

The creation of boundary conditions and interactions is completed in the initial step. The loading process is stepwise, and the loading process is shown in Table 3. Among them, the clamping effect is introduced by the holding force $F_w$ applied to the keeper

$$F_w = n \frac{T_c}{K \cdot d_b} \quad (11)$$

In the formula, $n$ is the number of torque bolts, where $n=2$; $T_c$ is the bolt torque, taking $T_c = 47.5 \text{Nm}$ [4]; $d_b$ is the nominal diameter of the bolt, $d_b=16 \text{mm}$; $K$ is the thread friction, and $K=0.2$.

Considering that there will be a certain deviation in the direct application of force, the "displacement control" method will be adopted. Tension and holding force are applied by displacement instead of force to ensure component displacement compatibility [4].

| Load Step | $F_w$/kN | $T$/kN  | $Y_b$/mm |
|-----------|---------|---------|----------|
| Step 1    | 30      | -       | -        |
| Step 2    | 30      | 25%RTS  | -        |
| Step 3    | 30      | 25%RTS  | 1.3      |
| Step 4    | 30      | 25%RTS  | 1.3      |

4. Preliminary verification of FE model of conductor-clamp system

4.1. Theoretical calculation results of wire strands in the vicinity of the clamp

According to the above equations (9) and (10), the minimum and maximum bending stiffness of JL/G1A-630/45 ACSR are $E_{l_{min}} = 42.60 \text{Nm}^2$, $E_{l_{max}} = 2384.45 \text{Nm}^2$, respectively. Under actual working conditions, the conductor may appear slightly loose strands due to vibration, and its stiffness will also change accordingly. Therefore, it is assumed that the outermost aluminum wire strands appear slightly loose during vibration. Only the outermost aluminum wire strands are rotated around their own central axis alone, and other wire strands as a whole. At this time, combining the above equations (9) and (10), the hypothetical equivalent bending stiffness is $E_{l_{eq}} = 789.50 \text{Nm}^2$. Considering the occurrence of loose strands in the outermost wire strands, it is assumed that the equivalent diameter is the diameter of the conductor except the outermost strands and used for alternating bending stress calculation.
It is known that the rated tensile strength (RTS) of the conductor is 150.45 kN. In order to determine the influence of the bending stiffness on the alternating bending stress of the conductor in the vicinity of the clamp, the analysis is carried out considering different tensions and bending amplitudes. The results are shown in the table below.

### Table 4. 18% RTS alternating bending stress theoretical calculation.

| $\sigma_a$/MPa | $Y_b=0.3$mm | $Y_b=0.5$mm | $Y_b=0.9$mm | $Y_b=1.3$mm |
|---------------|-------------|-------------|-------------|-------------|
| $EI_{\text{min}}$ | 8.20 | 13.66 | 24.59 | 35.52 |
| $EI_{\text{max}}$ | 38.75 | 64.59 | 116.26 | 167.93 |
| $EI_{\text{eq}}$ | 31.13 | 51.89 | 93.40 | 134.91 |

### Table 5. 22% RTS alternating bending stress theoretical calculation.

| $\sigma_a$/MPa | $Y_b=0.3$mm | $Y_b=0.5$mm | $Y_b=0.9$mm | $Y_b=1.3$mm |
|---------------|-------------|-------------|-------------|-------------|
| $EI_{\text{min}}$ | 8.65 | 14.41 | 25.94 | 37.46 |
| $EI_{\text{max}}$ | 39.14 | 65.24 | 117.43 | 169.62 |
| $EI_{\text{eq}}$ | 31.66 | 52.76 | 94.98 | 137.19 |

### Table 6. 25% RTS alternating bending stress theoretical calculation.

| $\sigma_a$/MPa | $Y_b=0.3$mm | $Y_b=0.5$mm | $Y_b=0.9$mm | $Y_b=1.3$mm |
|---------------|-------------|-------------|-------------|-------------|
| $EI_{\text{min}}$ | 8.96 | 14.93 | 26.88 | 38.82 |
| $EI_{\text{max}}$ | 39.41 | 65.69 | 118.24 | 170.79 |
| $EI_{\text{eq}}$ | 32.02 | 53.37 | 96.07 | 138.77 |

4.2. Comparative analysis of simulation results

In the FE, the alternating bending stress of the outermost aluminum wire strands at a distance of LPC 89mm is extracted and compared with the theoretical calculation, as shown in the following figure.

![Figure 6. Alternating bending stress diagram of aluminum wire strands.](image)

(a) 18% RTS  
(b) 22% RTS  
(c) 25% RTS
higher degree of fit with the simulation results. Therefore, it is recommended to use the assumed equivalent bending stiffness for alternating bending stress calculation under vibration.

In addition, the study found that the simulation results of the simplified model under breeze vibration conditions are relatively consistent with the theoretical calculation results. Which preliminarily verified the rationality and accuracy of the model.

5. Stress Analysis of aluminum wire strands

The aluminum wire strands in ACSR mainly play a conductive role, and the stress value should not be too large. And the ultimate strength of the aluminum wire strands is smaller than that of the steel core, so the stress distribution of the aluminum wire strands of the conductor-clamp system is mainly analyzed.

5.1. Preliminary study on the effect of tensile on the stress of aluminum wire strands.

When studying the influence of breeze vibration on the conductor of the conductor-clamp system, the first consideration is that the loading end of the model is only subjected to the tensile load. There is no influence of the bending amplitude. Take the tensile as 25%RTS, the friction coefficient as 0.5, the holding force as 30kN, and the bending amplitude as 0. Extract the axial stress and Von-Mises stress cloud diagrams of three sections at KE, LPC, and 89mm from LPC.

It can be seen from the figure that under the working condition of zero bending amplitude, the cross-sectional stress distribution of aluminum wire strands gradually increases from the outer layer to the inner layer, and the maximum axial stress and Von-Mises stress appears at the contact position. This is due to the combined effects of contact stress and bearing stress when the conductor is only subjected to tensile load. In addition, the stress distribution of the KE and LPC sections is not uniform compared to the 89mm section, which is due to the effect of the clamp.

5.2. Analysis of stress characteristics of aluminum wire strands in the vicinity of the clamp

In order to study the stress distribution characteristics of the aluminum wire strand in the vicinity of the suspension clamp affected by the breeze vibration, three sections of KE, LPC, and 89mm away from LPC were also selected for research. The bending amplitude was 1.3mm, the tensile, the holding force and the friction coefficient remains unchanged, the Von-Mises stress cloud diagram is shown in the figure below.
According to the comparative analysis of the above simulation results, the maximum cross-sectional stress is generally located at the contact position. This is caused by the lay angle of the wire strands and the squeezing force between the wire strands of adjacent layers.

In the KE sections, the stress distribution law of aluminum wire strands is the same as when only tensile load is applied. This is because the rigidity of aluminum wire strands is the largest in this area, and the impact of vibration is small. It is obvious from the figure that the stress of the upper aluminum wire strands is relatively large. This is due to the influence of bending amplitude.

In the LPC sections, the stress of aluminum wire strands shows a decreasing trend from the outermost layer to the inner layer, and the maximum Von-Mises stress is located in the contact area with the clamp. This is because the keeper gives the conductor a vertical holding force and the body gives the conductor an upward supporting force produces a squeezing effect, and at the same time it is affected by the combined effects of bending amplitude and tension. Therefore, the wire strands in this area are more prone to stress concentration, resulting in damage to the aluminum wire strands. This is also consistent with the first strand breakage of the outermost aluminum wire strand of the conductor in the vicinity of the suspension clamp under actual working conditions.

When the conductor is only subjected to a tensile, the stress of the aluminum wire strands shows an increasing trend from the outside to the inside. In the 89mm sections, the reason for the maximum stress in the layer 3 in Figure 11 is that the conductor is also affected by the bending amplitude. In addition, the stress distribution of aluminum wire strands is related to the lay angle of the wire strands. Obviously, from Fig.9 to Fig.11 to Fig.10, the stress change law of the aluminum wire strands subjected to vibration. The stress distribution of the aluminum wire strands may gradually increase to the outer layer.

Figure 9. Stress distribution of aluminum wire strands in KE section.

Figure 10. Stress distribution of aluminum wire strands in LPC section.

Figure 11. Stress distribution of aluminum wire strands in 89mm section.
5.3. Influence of bending amplitude on stress characteristics of aluminum wire strands

Under certain conditions of tensile, the influence of bending amplitude on the stress characteristics of aluminum wire strands can be studied. Take the tensile load as 25% RTS, keep the friction coefficient and holding force unchanged. Change the different bending amplitudes, and analyze the Von-Mises stress of the aluminum strands of the KE, LPC and 89mm sections, as shown in Figure 12.

![Figure 12. The curve of the stress of the aluminum wire strands with the bending amplitude.](image)

It can be seen from the figure that as the bending amplitude increases, the overall Von-Mises stress of the aluminum wire strands shows a gradual increase trend. The stress of the outermost layer of the aluminum wire strands of the LPC section is smaller at low amplitude. As the bending amplitude increases, stress concentration occurs at the LPC point, making the outermost layer of the aluminum wire strands of the cross-section the maximum stress.

A comprehensive comparison of the stresses of the layered aluminum wire strands of KE, LPC and 89mm sections shows that the overall stresses of aluminum wire strands of each layer of the LPC section are larger than those of the KE and 89mm section under higher bending amplitude. This is because the bending stiffness of the LPC section conductor is smaller than that of the KE section, and the LPC section is affected by the clamp relative to the 89mm section. Which leads to greater stress on the aluminum wire strands at the LPC section, and more prone to injury. Therefore, under actual working conditions, it is necessary to add corresponding protective measures to the aluminum wire strands in the KE and LPC areas.

6. Conclusion

This paper proposes a FE modeling and simulation method for the conductor-clamp system. Through the comparative analysis of theory and simulation, the reasonable accuracy of the simplified model is initially verified, and the model is used to analyze the stress distribution of the conductor in vicinity the suspension clamp under breeze vibration conditions. Concluded as follow:

1. As the bending amplitude increases, the alternating bending stress of the aluminum wire strands shows an increasing trend; at lower bending amplitudes, the alternating bending stress approaches the maximum bending stiffness assumption, and as the bending amplitude increases, the alternating bending stress begins to tend to the minimum bending stiffness assumption. Therefore, in order to make the theoretical calculation results fit the numerical simulation, it is recommended to choose equivalent bending stiffness and equivalent diameter are used for the alternating bending stress calculation.

2. Studying the position of the conductor cross section found that the Von-Mises stress of the aluminum wire strands gradually increases with the increase of the bending amplitude. The Von-Mises stress of the aluminum wire strands of LPC cross-sections shows a decreasing trend from the outside to the inside, and the maximum Von-Mises stress occurs at the contact position of the outermost wire strand and the clamp. This is due to the complex load received at this position. Therefore, this area needs to increase protection measures and regular inspection and maintenance.
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