Measures for Fatigue Damage Reduction in Electrical OCL Connections

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Electrical connections between the contact wire and the messenger wire are always subject to fatigue damage due to vibration caused by the passage of pantographs. Therefore, it is necessary to clarify the fatigue mechanisms affecting electrical connections to propose measures to mitigate damage. In this paper, the authors focus on the resonance of the electrical connection with catenary system and relative vibration displacement between the contact wire and the messenger wire considering them as major fatigue factors. As a result of OCL-pantograph simulation, the authors clarified the conditions under which fatigue damage of the electrical connection can occur. In addition, the authors proposed a new electrical connection which has a fatigue life exceeding 10 million vibration cycles.

Keywords: connector, fatigue life, installation position, relative displacement, resonance, natural frequency

1. Introduction

Electrical Connections (hereinafter referred to as ‘connector(s)’) for Overhead Contact Line (hereinafter referred to as ‘OCL’) are the metal fittings forming the electrical connection between lines such as the contact wire and messenger wire of an OCL, and they generally consist of lead wires using soft-drawn copper wire strands, ears, and clamps. Among these, lead wires suffer fatigue due to OCL vibration which can result in the rupture of wires. Effective measures therefore need to be found to prevent connector fatigue.

Previous studies by the authors included a proposed method to estimate bending strain of lead wires, by vibration analysis using a virtual solid wire having the same dynamic characteristics as the lead wires (which are stranded wires), and a method to estimate fatigue life of connectors from the fatigue life curves obtained from lead wires fatigue tests and estimated bending strain [1].

This paper focuses on the vibration displacement of contact wires and messenger wires as well as the resonance of connectors with catenary system, as the main factors causing connector fatigue, and proposes a set of design guidelines for connectors based on these main factors. A prototype connector was then produced with improved fatigue resistance using these design guidelines. The improvement in fatigue resistance was subsequently confirmed through field tests. The results are reported below.

2. Main factors contributing to connector fatigue and fatigue prevention measures

2.1 Main factors contributing to connector fatigue

The connector used in this study was a “MT type connector” which is used to connect contact and messenger wires on conventional lines (Fig. 1).

Past research [1, 2] has already clarified that one of the main factors contributing to connector fatigue is the difference in vibration displacement (hereinafter referred to as ‘relative displacement’) between the contact wire and the messenger wire that occurs with the passage of a pantograph. Figure 2 shows actual OCL vibration displacement and the resulting estimated lead wire bending strain, measured on a commercial line. It was found that the relative peak displacement and peak strain of the lead wire occurred simultaneously, and that the magnitude of the relative displacement significantly affected lead wire fatigue.

Another factor other than relative displacement, contributing to fatigue is “resonance” where the natural frequency of the connector accords with an OCL frequency. When the connector resonance is excited by residual vibration after the passage of a pantograph, significant bending deformation occurs multiple times in the connector, generating a risk of wire rupture over a very short period of time, due to fatigue.

The following measures were found to be effective in preventing the two key fatigue-causing factors, “relative displacement” and “resonance”:

![Fig. 1 Example of MT type connector [2]](image-url)
2.2 Generation mechanism and measures against relative displacement

In order to study measures (1) and (2) in detail, insight into relative displacement between the contact wire and the messenger wire at the passage of a pantograph was gained through simulation. In order to conduct the simulation, a two-dimensional numerical analysis program of the OCL-pantograph system using a finite element method was used, which can calculate the displacement waveforms of the contact wire and the messenger wire at the passage of a pantograph. The line was divided using an Euler beam element while the OCL was modeled. The rigidity of the line considering the bending rigidity of the line itself, besides the tension applied to the line, and proportional viscous damping was assumed for damping of the line. The simulation was performed on the assumption that significant relative displacement can be suppressed by maintaining the appropriate tension in the contact and messenger wire.

Table 1 Simulating conditions [2]

| OCL            | Simple catenary |
|----------------|-----------------|
| Span length (m)| 50              |
| Passing speed of pantograph (km/h) | 50, 75, 100, 125 |
| Contact wire   | Wire type       |
| Tension (kN)   | GT110 GT170     |
| Messenger wire | Wire type       |
| Tension (kN)   | St90 St135      |
| Pantograph     | Static uplift force (N) | 59 |
| Number         | 5               |

Figure 4 shows the maximum relative displacement within the span for all the calculation conditions shown in Table 1. The stiffness in the messenger wire close to the supporting point made it hard for the messenger wire to follow the uplift of the contact wire, increasing relative displacement at this point. The relative displacement before the supporting point in the running direction of the train was also large. This is because the pantograph contact force before a supporting point is large.

Connectors are conventionally installed close to the supporting points where relative displacement is large. Therefore, connector fatigue could be mitigated if the connector...
was installed closer to the second or the third dropper where relative displacement is smaller.

2.3 Method to reduce bending strain of lead wire due to large relative displacement

When large relative displacement occurs at the connector, resulting lead wire deformation differs depending on the shape of the connector. Figure 5 shows the analysis results of bending strain generated when vibration of the OCL, as shown in Fig. 2, was applied to the commonly used connectors shown in Fig. 6. Since the lead wire on a C-type connector is generally more flexible than other types, bending deformation is not very concentrated, and bending strain is small.

Another possible mitigation measure is to use highly flexible lead wires, because the more flexible the lead wire the smaller the bending deformation near the fixed part.

2.4 Method for suppressing connector-OCL resonance

In order to suppress connector-OCL resonance, it is important to avoid generating an OCL vibration frequency that matches the natural frequency of the connector. The vibration on the contact and messenger wires is generally about 3 to 6 Hz before the passage of a pantograph, while a residual vibration of about 1 to 2 Hz is generated following its passage.

Figure 7 shows the analysis results of the natural frequency relative to the connector height (distance between the contact wire and messenger wire) for each of the connectors shown in Fig. 6. Figure 7 clearly shows that the natural frequency does not depend much on the shape of connector, but rather on the connector height, especially when the connector height approaches 1,500 mm where the possibility of resonance with the residual OCL vibration becomes clear.

In practice, if connector-OCL resonance occurs with the passage of a pantograph, one possible countermeasure would be to reduce the connector height and shorten the length of the lead wire, by changing the installation position of the connector. However, a shorter lead wire, tends to increase the bending strain due to relative displacement.

Taking the results of the study found so far, measures to prevent connector fatigue can be summed up as follows:

1. Suppression of significant relative displacement by maintaining suitable OCL tension;
2. Installation of connectors closer to the 2nd or 3rd droppers along a span, to reduce relative displacement;
3. Mitigation of lead wire strain due to relative displacement, by using highly flexible lead wires;
4. If connector-OCL resonance occurs, increase the natu-
ral frequency of the connector by shortening the length of the lead wire, to prevent accordance of the natural frequency of the connector with OCL vibration, to prevent resonance.

3. Development of fatigue-resistant connector

3.1 Design guidelines for fatigue-resistant connector

First, a fatigue life in excess of $10^7$ (which in industrial terms is deemed to be infinity) was fixed as an objective, in order to achieve a fatigue resistance that would bear even the toughest operating conditions of a relative displacement of 40 mm, as shown in the relative displacement analysis results shown in Fig. 4. Then, in order to prevent connector resonance with OCL vibration, the primary natural frequency of the connector was set to 8 Hz or above.

Figure 8 shows the fatigue characteristics in relation to modified connector height for each of the connectors shown in Fig. 6. The horizontal axis of Fig. 8 shows the primary natural frequency of the connector, while the vertical axis shows the fatigue life of the lead wire estimated using the method described in [1], for strain against a relative displacement of 40 mm.

Figure 8 shows that it is not possible to achieve the design target with the existing connector. Therefore, a new type of connector, based on the 2 design guidelines described previously, was proposed with a shorter lead wire length and greater flexibility.

3.2 Configuration of fatigue-resistant connector

Figure 9 shows configuration of the fatigue-resistant connector; it fixes the lead wire to the dropper by means of a metal fitting (hereinafter referred to as a ‘clip’). Using this configuration, the length of the lead wire that can vibrate freely is reduced, and a higher natural frequency can be obtained.

Table 2 Radius of virtual solid wire for each lead wire type [2]

| Wire type | Strand diameter (mm) | Number of strands per bundle | Number of bundles | Radius of virtual solid wire (mm) |
|-----------|----------------------|------------------------------|------------------|----------------------------------|
| 37/1.2    | 1.2                  | 37                           | 1                | 1.55                             |
| 61/0.9    | 0.9                  | 61                           | 1                | 1.2                              |
| 19/4/0.8  | 0.8                  | 4                            | 19               | 1.1                              |
| 19/6/0.67 | 0.67                 | 6                            | 19               | 1.0                              |

Fig. 10 Rotary bending fatigue testing machine for lead wire [1]

3.3 Selection of lead-wire type

It was possible to improve the fatigue resistance of the lead wire against relative displacement by increasing the flexibility of the lead wire. Four kinds of stranded wire with different strand diameters and twisting methods were used, as shown in Table 2. The radius of the lead wire for when it is replaced with a virtual solid wire, was obtained using the method in [1]. The wires were all 37/1.2 soft-drawn copper, which is the standard for lead wires on existing connectors. The results shown in Table 2 indicate that the thinner the radius of the virtual solid wire, the higher the flexibility of the lead wire, and the thinner the strand diameter is, the higher the flexibility.

The fatigue life of each lead wire was investigated using a Rotary bending fatigue testing machine, shown in Fig. 10. The fatigue life was determined when a broken strand touched the shock sensor. Figure 11 shows the fatigue life characteristics relative to the half amplitude of...
bending strain given to the virtual solid wire. The figure also shows that the thinner the strand diameter, the longer the fatigue life against the bending strain.

However, as the strand diameter becomes thinner, concerns arise, such as strand disconnection due to wear, [4], and lowering of corrosion resistance due to increase in surface area of the stranded wire. Consequently, 61/0.9 wire was selected for the lead wire in the fatigue-resistant connector.

3.4 Shape design of fatigue-resistant connector

As described above, lead wire flexibility varies depending on its shape. A finite element analysis was therefore carried out of the upper part of the lead wire as shown in Fig. 9, to obtain the bending strain against a relative displacement of 40 mm, and natural frequency of the connector by changing the upper vertical and horizontal distance of the lead wire.

Figure 12 shows the relationship between the maximum bending strain generated on the upper part of the lead wire with a relative displacement of 40 mm and the upper vertical and horizontal distance of the lead wire. The dash-dotted line in Fig. 12 shows the total amplitude of strain when fatigue life of the lead wire 61/0.9 reached 10⁷, in Fig. 11.

Figure 13 shows the relationship between the primary natural frequency of the upper part of the lead wire and the upper vertical and horizontal distance of the lead wire. The dashed line in Fig. 13, shows the natural frequency of 8 Hz corresponding to the design target, while the dash-dotted line shows the fatigue limit condition obtained in Fig. 12. Accordingly, the shaded range in the Figure shows the dimensional range that fulfils the design target.

4. Performance confirmation by field test

Dimensions of the prototype connector were set at 200 mm for the vertical distance and 250 mm for the horizontal distance, based on analysis results in Fig. 13. The fatigue-resistant performance expected of the prototype connector, was: a fatigue life against relative displacement of 40 mm in excess of 10⁷, and a natural frequency of 8.6 Hz.

Another performance requirement for connectors is not to increase contact wire wear at connector installation points. One major concern was whether the prototype connector might become a hard spot, due to its weight because of the clips fitted to the dropper.

Accordingly, prototype connectors were installed on a commercial line for 190 days, and the wear rate of the contact wire was examined. They were installed in two positions in two stations with conventional lines, where connector lead wire rupture had already occurred in the past due to fatigue (hereinafter referred to as the station A and station B).

![Fig. 12 Maximum strain in upper part of lead wire against a relative displacement of 40 mm](image1)

![Fig. 13 Natural frequency](image2)

![Fig. 14 Measurement result of residual diameter of the contact wire](image3)
Figure 14 shows the measured residual diameters of the contact wires where each of the prototype connectors were installed, and where existing C-type connectors were installed next to the prototype connectors. Figure 14 also shows the approximation formulas used. The gradient of the respective approximation formulas confirms that wear where prototype connectors were installed did not progress, and that the prototype connector did not significantly influence contact wire wear, even compared with wear found where existing connectors were installed.

Furthermore, when the prototype connectors were removed, no cases of strand disconnection were found in any of the prototype connectors.

5. Conclusion

In order to improve the fatigue resistance of OCL connectors, this paper proposes measures against relative displacement and resonance which are the main factors contributing to their fatigue.

A fatigue-resistance design target of over $10^7$ was set for a new connector, against a relative displacement of 40 mm, as well as a primary natural frequency at 8 Hz or more. A new proposed connector, with improved fatigue resistance was developed by using the results of fatigue tests and finite element analyses of the lead wire. The prototype connector was tested on an active conventional revenue line for 190 days. Results confirmed that no strand disconnection of the lead wire had occurred, and that the new design had no significant influence on contact wire wear.

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