Measurement of the Contact Force of the Pantograph by Image Processing Technology

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Contact force between a pantograph and catenary is one of the most important indices for evaluating the contact performance of the pantograph-catenary system. Hence, some contact force measuring methods have been developed. However, currently used measurement methods have some problems. Firstly, the installation of sensors in a panhead could affect the dynamic characteristics of the pantograph. Secondly, they need data transmitting equipment, because built-in sensors are set under high-voltage condition. Thirdly, some kinds of pantographs cannot be equipped with sensors in a panhead because of structural restriction. To eliminate these problems, the authors have developed a new contact force measuring method by using image processing sensors mounted on the rooftop of a train.

Keywords: pantograph, contact force, image processing, line sensor

1. Introduction

Overhead contact lines (OCL) are long structures installed along railway line at a height of approximately 5 m above the rail. Therefore, saving labor for maintenance work, reducing maintenance costs, and prolonging the lifetime of OCL through rational and available maintenance and management methods are definitely required. In addition, there is a need for more precise OCL installation along high speed lines. Having a good grasp of the contact conditions between a pantograph and contact wire is important for realizing these requirements. Contact force is utilized as one of the key indices [1, 2]. Some studies have been conducted to diagnose OCL conditions by utilizing contact force measurement results [3]. Some research institutes, including RTRI, have developed several contact force measurement methods (hereinafter abbreviated as currently-used methods) [4-7]. All of them, however, have some problems because they need sensors installed in and/or on the panhead of the pantograph. First of all the sensors and their cables could influence the dynamic characteristics of the pantograph. Secondly, measurement systems based on these methods need to use telemetry devices requiring electric power supply units because the sensors are installed in high-voltage conditions. Consequently these methods require a relatively large amount of space for fixing sensors and telemetry devices. Thirdly, the panhead on some pantographs cannot be equipped with sensors because of their design. To eliminate these drawbacks, the authors developed a new contact force measurement method, which can replace all these built-in sensors with image processing sensors.

2. The principles of the contact force measurement method

2.1 The outline of the contact force measurement method

Some contact force measurement methods have already been developed. Since many of them, including the present new method, are based on a force equilibrium equation, its outline is described in this section [6].

Figure 1 shows the analytical model of the pantograph. The pantograph is divided into two subsystems: subsystem 1 corresponds to the panhead, and subsystem 2 corresponds to the articulated frame with the panhead support. Contact force \( F_c \), inner force \( F_b \) acting upon the interface between subsystem 1 and subsystem 2, aerodynamic force \( F_a \), and inertia force \( F_I \) affecting on subsystem 1 equilibrate. The force equilibrium equation of subsystem 1 can thus be
obtained as follows.
\[ F_c = F_s + F_a + F_I \]  
(1)

Equation (1) indicates that contact force \( F_c \) can be evaluated as a summation of \( F_s \), \( F_a \), and \( F_I \).

There is, however, no practical method for measuring aerodynamic force \( F_a \), while the pantograph is sliding along the contact wire. Since the aerodynamic force \( F_a \) is proportional to the square of the flow velocity against the pantograph \( V_t \), \( F_c \) can be estimated by
\[ F_s = C_s V_t^2 \]  
(2)
where \( C_s \) is the proportionality constant which can be obtained by a wind tunnel test.

Hence, only the inner force \( F_s \) and inertia force \( F_I \) affecting subsystem 1 should be measured in order to evaluate the contact force.

In the case of the currently-used method, the inner force \( F_s \) can be obtained as follows.
\[ F_s = \sum_{i=1}^{n} F_{s,i} \]  
(3)
In the case of the currently-used method, the inner forces \( F_{s,i} \) are generally measured by built-in sensors such as loadcells or strain gauges set in the panhead [5, 6].

2.3 Measurement method for the inertia force

The inertia force \( F_I \) can only be evaluated in a low frequency range by the following approximate formula,
\[ F_I = ma \]  
(4)
where \( m \) is the mass of the panhead and \( a \) is its acceleration.

If the contact force must be measured up to a high frequency range, the inertia force has to be evaluated by the product of the accelerations of plural positions on the panhead and the corresponding equivalent mass \( m \). [6].
\[ F_I = \sum m_i a_i \]  
(5)

In the case of the currently-used method, the accelerations are generally measured by built-in accelerometers set into the panhead [5, 6].

3. Measuring the contact force by image processing technology

The authors developed a new contact force measurement method using image processing technology with line sensors, for which no built-in sensor is needed. This chapter explains the principle of this method.

3.1 The principle of the new method

As noted in chapter 2, if the friction force between the panhead and the panhead support is negligible, only the spring reaction forces \( F_{s,i} \) and the inertia force \( F_I \) have to be measured to obtain the contact force \( F_c \). According to Hooke’s law, the reaction forces \( F_{s,i} \) are obtained by the product of the spring coefficient and the spring deformation which corresponds to the relative displacement between the panhead and the panhead support. The inertia force \( F_I \) can be obtained by the product of the accelerations which can be obtained as the second derivative of the displacements of the panhead with respect to time and the corresponding equivalent masses of the panhead. This means that the contact force can be measured by evaluating the displacement of the panhead and the panhead support.

3.2 The displacement measurement method by image processing technology

A schematic drawing of this method is shown in Fig. 3. Some markers with black stripes are put on the surface of the panhead and the panhead support as a target for an image capture camera. Images of these markers are taken by line sensors with high time and spatial resolution mounted near the pantograph on the roof of the train. Lighting installed near the pantograph helps cameras to take clear images of the markers. Figure 4 shows a sample of the image of the marker taken by the line sensor camera.

Symbols, \( y_{ls} \), \( y_{lsn} \), \( y_{lsa} \) and \( y_{ls} \) in Fig. 3 are vertical displacements of the markers. These displacements are obtained by using image processing technology with the pattern matching based on the normalized cross-correlation (NCC) method. The NCC method enhances spatial resolution of displacement measurement. Figure 5 shows the displacement evaluated with/without the NCC method. This figure indicates that the spatial resolution can be improved by using the NCC method.
Equivalent mass (10) Acceleration of (6) (7)

**Fig. 3** Schematic view of the contact force measurement system with image-capture devices

**Fig. 4** Image of a marker taken by a line sensor camera

### 3.3 Measuring contact force

As mentioned before, the spring reaction force $F_{c,\text{applied}}$ of the panhead supporting spring can be evaluated by the product of the spring coefficient and the spring deformation which is taken by the method as described in section 3.2. If the friction force between the panhead and the panhead support is negligible, the inner force $F_{i}$ consists of spring reaction forces $F_{c,\text{applied}}$ alone.

Vertical accelerations $a_{u,i}, a_{u,R}$ and $a_{u,C}$ at the positions of the markers can be obtained as the second derivatives of the displacements $y_{u,i}, y_{u,R}$ and $y_{u,C}$ with respect to time. Thus, by identifying the equivalent masses in advance, the inertia force $F_{i}$ can also be obtained. The method for the identification of the equivalent masses is described below.

Excitation tests have to be carried out in order to identify the equivalent masses. In the tests, the inertia force $F_{i}$ can be estimated by (6):

$$ F_{ij} = (m_{i} + m_{c} + m_{s}) \begin{pmatrix} a_{u,i} & a_{u,R} & a_{u,C} \end{pmatrix} \begin{pmatrix} a_{u,i} & a_{u,R} & a_{u,C} \end{pmatrix}^T = F_{\text{capital},ij} - F_{c,\text{ij}} $$

where $m_{i}$, $m_{c}$ and $m_{s}$ are the equivalent masses at respective marker positions where displacements $y_{u,i}$, $y_{u,R}$ and $y_{u,C}$ are measured. $l$ $(i=1,2, \ldots , n)$ means excitation points. The superscript $T$ indicates the transposed matrix. $F_{\text{capital},ij}$ and $F_{c,ij}$ are the excitation force and the inner force, respectively. The frequency transfer function $G_{ij}$ of $a_{u,i}$ $(i=L, C, R)$ versus $F_{ij}$ is expressed as follows:

$$ G_{ij}(j\omega) = \hat{\alpha}_{u,i}/F_{ij} $$

where $j$ and $\omega$ are the imaginary unit and the angular frequency. $\hat{\alpha}_{u,i}$ and $F_{ij}$ indicate the Fourier transform of $a_{u,i}$ and $F_{ij}$. The frequency transfer function $G_{ij}$ can be written in a matrix form:

$$ G_{i} = \begin{pmatrix} G_{i,1}(j\omega_1) & G_{i,2}(j\omega_1) & G_{i,3}(j\omega_1) \\ G_{i,1}(j\omega_2) & G_{i,2}(j\omega_2) & G_{i,3}(j\omega_2) \\ \vdots & \vdots & \vdots \\ G_{i,1}(j\omega_{\text{max}}) & G_{i,2}(j\omega_{\text{max}}) & G_{i,3}(j\omega_{\text{max}}) \end{pmatrix} $$

($\omega_1 \sim \omega_{\text{max}}$ are angular frequencies of Fourier transform. $\omega_1$ and $\omega_{\text{max}}$ are minimum and maximum angular frequencies of the angular frequency range required to measure the contact force. By (6) and (8), the equivalent masses $m_{i}$, $m_{c}$ and $m_{s}$ are calculated as follows:

$$ (m_{i}, m_{c}, m_{s}) = G^{+}V $$

The superscript $+$ indicates the generalized inverse matrix. Matrix $G$ and vector $V$ are expressed as follows:

$$ G = \begin{pmatrix} G_{1} & \cdots & G_{n} \end{pmatrix}, \quad V = (v_{1}, \cdots , v_{\text{max}})^{T}, \quad v_{1} = \cdots = v_{\text{max}} = 1 $$

As stated above, the inner force and the inertia force required to measure the contact force can be evaluated by

**Fig. 5** Displacement of a marker evaluated by the NCC method (True value is measured by a displacement sensor)

**Fig. 6** Flow chart illustrating the measurement method for the contact force by image processing technology
using the image processing technology with line sensor cameras. Substitution of these forces in (1) and using (2) give the contact force. Figure 6 indicates the measurement procedure for this method.

4. Test for verification of the new method

The authors carried out an excitation test on the pantograph in order to verify measurement accuracy of the new method. Figure 7 shows a photo of the test.

A single-arm type pantograph was used in the test. An exciter was placed under the panhead and a loadcell was put on the panhead to measure the excitation force $F_{\text{c,appplied}}$. $F_{\text{c,appplied}}$ was compared with the force $F_{\text{c,measured}}$ measured by the new method.

Two line sensor cameras (pixels: 7450 pix, sampling frequency: 4.73 kHz) and lighting were mounted near the pantograph. Three markers were set on different surfaces of the panhead and the panhead support. One line sensor camera captured images of two markers put on the surface of the pantograph and the pantograph support to evaluate the spring reaction force of the panhead supporting springs and the inertia force at center of the panhead. The other line sensor camera took images of a marker put on the surface of the panhead to evaluate the inertial force on side of the panhead.

The test results are shown in Fig. 8. This figure indicates the gain and phase of the frequency transfer function of the measured contact force $F_{\text{c,measured}}$ versus the exciting force $F_{\text{c,appplied}}$.

The European Standard (EN 50317) provides the tolerance of the measurement accuracy of the contact force by using the following formula [8]:

$$\left\{1 - \frac{1}{(f_2 - f_1)} \sum_{k=1}^{n} (f_k - f_1) \right\} \frac{F_{\text{c,measured}} - F_{\text{c,appplied}}}{F_{\text{c,appplied}}} \times 100\%$$

where $f_1$ and $f_2$ are the maximum and minimum measurement frequencies. Figure 8 indicates that the new contact force measurement method has satisfactory measurement accuracy, which meets the requirement of the standard expressed in (11).
5. Example of application

This chapter shows an application example of the contact force measurement system based on the new method. This system was installed on a high-speed commercial train whose maximum speed is 300 km/h. Figure 9 shows a general view of the system.

This train set had two pantographs connected by a bus line. Contact force measurement equipment and measurement devices for contact wire wear, contact wire deviation, contact loss and pantograph height were installed around one pantograph (hereinafter abbreviated as pantograph A). Only a contact loss measurement system however was installed around the other pantograph (hereinafter abbreviated as pantograph B).

Figure 10 shows an example of the measurement result at 280km/h. This figure shows that the measured contact force was almost zero where contact loss was detected. However, since this train had a bus line, there were some cases where the contact loss did not occur at positions where the contact force equaled zero. In addition, contact force tended to increase when the pantograph height was decreasing. Therefore, the results of contact force measurements were consistent with the results from other measurements.

The contact force measurement result shows that there is nothing wrong with the configuration of the overlap section (vicinity of 126.08 km), because extremely large contact force is not observed at the section. Furthermore, the result also indicates qualitative influence of contact force fluctuation on contact loss. As shown above, contact force measurement helped to gain insight into the interaction between the pantograph and catenary.
6. Conclusions

The Authors developed a new contact force measurement method using image processing technology, which needs no built-in sensors such as loadcells. Excitation tests confirmed that this method has the satisfactory measurement accuracy to meet the requirements in EN 50317. The contact force measurement system based on this method uses only contactless measurement devices and is easily installed on a train set. Therefore, the new contact force measurement system can be installed in many kinds of train set. The system was installed on high-speed commercial train and has been used in periodic inspections. It is expected that this method will help the maintenance of the OCL.

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