Development of Advanced OCS Inspection System Using Image Processing Technology

Seiji TABAYASHI, Makoto NIWAKAWA, Yusuke WATABE  
(Meidensha Corporation*)
Mitsuru IKEDA, Tatsuya KOYAMA, Kotaro NAKAMURA  
(Railway Technical Research Institute, RTRI**)  
2-1-1 Osaki, Shinagawa-ku, Tokyo 141-6004, Japan  
Tel: +81-3-6420-7111  
Fax: +81-3-5745-3037  
E-mail: tabayashi-s@mb.meidensha.co.jp  
Co-Authors: niwakawa-m@mb.meidensha.co.jp  
watabe-yu@mb.meidensha.co.jp  
mikeda@rtri.or.jp,koyama04@rtri.or.jp  
kotaro@rtri.or.jp

Keywords: image processing, contact force, wear

1. Abstract

To ensure the safe operation of electric railways, it is essential to maintain the soundness of contact wires, through which electric power is supplied to the vehicles. The overhead catenary system (OCS) is used to check the condition of the contact wires. The indices used include height, stagger, wear, gradient, contact force, and contact loss of the contact wires, all of which demonstrate the dynamic state of running vehicles. Measurements of OCS facilities and the pantograph itself include the shape of the collector head and horn of the pantograph and the installation status of pull-off arms and brackets. Conventional OCS inspection systems using a dedicated inspection vehicle have been supplied to many railway companies. The inspection vehicle is equipped with a laser-beam system for conducting dynamic measurement while running. We have developed a new OCS inspection system that is not based on conventional laser-beam measurement technology, but instead capitalizes on the advantages of cameras and advanced image processing technology. As a system for measuring the contact force between the pantograph and contact wire, we have developed a non-contact measurement system that does not use a special pantograph with integrated accelerometer and sensor such as a load cell.

This paper describes technical projects of wear measurement and contact force measurement using image processing, and describes how to install the developed system in practice and related items. Meidensha and RTRI have been conducting joint research for two years on the measurement of contact force. Some experimental results are also described here.
Challenge G: An even more competitive and cost efficient railway

2. Background

The following provides additional background information on the development of the system.

a) Non-contact measurement method not affecting dynamic characteristics

Conventional OCS inspection systems use a pantograph with a number of measuring instruments including a load sensor for measuring the contact force and an instrument for measuring installation angle from a pull-off arm. All of these instruments are mounted on the pantograph itself, and signal wires are attached to each instrument, which affects the dynamic characteristics of the pantograph. In addition, conventional OCS inspection system is required a huge installation space on the rooftop of the vehicle. The objective of our research is to obtain high-accuracy dynamic characteristics of the pantograph and catenary through non-contact measurement using a pantograph in an environment equivalent to commercial operations.

b) Optimizing maintenance using visual images

Since the laser system is based on numeric measurement, an on-site check of facilities must be conducted in the case of a suspected abnormality of OCS. The laser system performs measurement, receiving reflected light from the laser equipments. Since the cause of an abnormality could be noise or the effect of other contact wire devices (such as fittings), the results of numeric measurement alone are not sufficient for identifying the cause. This is why an on-site inspection is necessary.

But on-site work must be conducted during the night after service has ended, which increases the load on maintenance workers.

Meanwhile, with the system based on the image processing, all items are measured based on actual images, and the numeric values obtained and actual images are linked, allowing the defective position to be visually checked before performing on-site work.

Since the conventional OCS inspection system is installed in a dedicated vehicle, and since it uses a dedicated pantograph and dedicated sensors such as laser beams, measurement accuracy is high, but other equipment such as a mirror control device and high frequency power-supply unit must also be installed, in addition to a laser generator. Consequently, a large installation space is needed on the rooftop or inside the vehicle, which increases the set-up and maintenance costs. With the system using cameras, the devices are compact and can be installed not only in dedicated vehicles but also in-service vehicles during operation. A vehicle exclusively for measurement is not needed, which decreases the maintenance and operation costs, improves the measurement efficiency, and significantly decreases the maintenance cost for the entire inspection scheme.

c) Measuring contact wire wear and contact force employing image processing

Measuring wear:

The conventional laser-beam system provides high-accuracy measurement of wear, but equipment such as the laser generator, mirror reflector, and high frequency power-supply unit require a large installation space on the rooftop of the vehicle. In addition, a heavy, large-capacity power supply system must be installed in the vehicle, which is not possible in the existing commercial vehicles.
Furthermore, since a dedicated pantograph, on which various measurement sensors and cables are mounted, is necessary to measure the contact force, dynamic characteristics may be affected.

d) Measures for increased commercial service train speed

Since the start of commercial railway operations, travel speeds have continually increased for the convenience of passengers. This means that trains often travel with the tilting train, in which case some measurement items cannot be made using existing inspection vehicles. A suitable inspection vehicle would be prohibitively expensive, so it is necessary to perform dynamic inspection by installing an inspection system on an existing service vehicle or a test vehicle equivalent to the service vehicle.

3. Principle of OCS Measurement Methodology

3.1 System configuration and specifications

In this section, we describe the system configuration and specifications prior to introducing the principle of the OCS measurement methodology.

Figure 1 shows an example of both rooftop and on-board equipments for recording the image data. The vehicle seen in the figure is equipped with a rooftop cover similar to ones used on the Shinkansen cars. The rooftop equipment consists of CCD cameras located on the center sides close to the pantograph. These cameras are used to record the shape of the pantograph as it moves in a vertical direction. The line sensor (hereinafter “LS”) cameras are mounted vertically in order to scan the contact wire in the direction of the railway ties. The LS2 cameras measure the wear and stagger of the contact wire. The LS1 camera is mounted at an elevated angle in the direction to the pantograph in order to measure the height and gradient of the contact wire. The LS1 and LS3 cameras, which are mounted at an angle in the direction to the pantograph. These LS cameras record the vertical movement of the pantograph for measuring the contact force.

Lighting for the CCD cameras is set up to illuminate the entire pantograph, whereas the lighting for the LS2 cameras is set up vertically to illuminate the sliding surface of the contact wire. Lighting for the LS1 and LS3 cameras is set up at an elevated angle to illuminate the entire pantograph.

The pull-off arm sensors, which use the laser to detect the pull-off arm, are mounted on the right and left sides of the rooftop. The detection signals are transmitted to the on-board PC. (The pull-off arm sensors are omitted in Fig. 1)

The on-board PC stores the captured image data with the speed and location data imported from the vehicle. The image data is recorded to a portable hard disk, which is then transferred between the on-board PC and the station PC. The station PC is located in a control center or maintenance office and is part of a system that consists of a workstation and printer. The station PC executes image analysis and processing. After completion of analysis, the results are saved to the storage file for displaying charts, reports, and other data. The data can be output as a CSV file to check using other PCs.
Challenge G: An even more competitive and cost efficient railway

Table 1 shows the measurement items of the OCS, cameras, and sensors.

<table>
<thead>
<tr>
<th>Measurement item</th>
<th>Camera, sensor</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>LS</td>
<td>LS1 – 1 set</td>
</tr>
<tr>
<td>Stagger</td>
<td>LS</td>
<td>LS2 – 2 sets</td>
</tr>
<tr>
<td>Wear</td>
<td>LS</td>
<td>LS2 – 2 sets</td>
</tr>
<tr>
<td>Contact force</td>
<td>LS</td>
<td>LS1,3 – 2 sets</td>
</tr>
<tr>
<td>Gradient</td>
<td>LS</td>
<td>LS1 – 1 set</td>
</tr>
<tr>
<td>Contact loss</td>
<td>UV sensor</td>
<td>2 sets</td>
</tr>
<tr>
<td>Detection of obstacles</td>
<td>CCD</td>
<td>CCD – 2 sets</td>
</tr>
<tr>
<td>Pantograph horn shape</td>
<td>CCD</td>
<td>CCD – 1 set</td>
</tr>
<tr>
<td>Location</td>
<td>OBC on the car</td>
<td></td>
</tr>
<tr>
<td>Speed of the car</td>
<td>OBC on the car</td>
<td></td>
</tr>
<tr>
<td>Detection of pull-off arm</td>
<td>Laser sensor</td>
<td>2 sets</td>
</tr>
</tbody>
</table>

OBC: On-Board Cpu

Major specifications of the imaging devices are as follows:

a. CCD Camera

Picture elements: 648 (H) x 492 (V) (max.)
Frame rate: 60 Hz
Sensor sensitivity: 0.23 Lx, Max gain, 50% Video

b. Line sensor camera

Picture elements: 7450
Scan rate: 4.73 KHz (max.)
Resolution: 4.7 micron

C. Floodlights; LED lights

d. UV sensor

Detect UV frequency: 206 – 226 nm
3.2 Measurement items and accuracy

The standard measurement items for the OCS system are as follows:

a. Contact wire height
b. Contact wire stagger
c. Contact wire wear
d. Contact force between pantograph and contact wire
e. Contact loss between pantograph and contact wire
f. Pantograph monitoring

The standard accuracy of each measurement item is shown in Table 2.

<table>
<thead>
<tr>
<th>Measurement item</th>
<th>Accuracy</th>
<th>Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>± 5 mm</td>
<td>Height range 4500–5400 mm</td>
</tr>
<tr>
<td>Stagger</td>
<td>± 5 mm</td>
<td>Stagger range ±350 mm</td>
</tr>
<tr>
<td>Wear</td>
<td>± 0.1 mm</td>
<td>Height range 400 mm/1 camera</td>
</tr>
<tr>
<td>Contact force</td>
<td></td>
<td>Based on EN standard</td>
</tr>
<tr>
<td>Contact loss</td>
<td>&lt;1 ms</td>
<td>Based on EN standard</td>
</tr>
<tr>
<td>Speed of the car</td>
<td></td>
<td>0–300 km/h</td>
</tr>
</tbody>
</table>

3.3 Measuring the height of the contact wire

Since the height of the contact wire will also be used for measuring contact force, higher spatial resolution is required compared to the measurement of contact wire stagger. The pantograph is therefore photographed using a line sensor camera (called a “line sensor”) having significantly higher one-line resolution than the CCD camera, and the top end of the pantograph is measured as the height of the contact wire assuming that the contact wire is touching the pantograph. The line sensor has image sensors laid out in rows, and with regard to the lineup direction of the sensors, has several times higher resolution than general CCD cameras. In addition, since the number of pixels used is significantly lower than that of CCD cameras, high-speed photographing is ensured. By shooting pantograph movement in the vertical direction using this line sensor, spatiotemporal images exhibiting the behavior of the pantograph can be obtained. The height of the pantograph is found by extracting pantograph images from the spatiotemporal images through image analysis. Based on the relative position between the line sensor and the pantograph, the actual spatial position is calculated from the imagery pantograph position, and output as the height of the contact wire.

3.4 Measuring the wear of the contact wire

The contact wires of which wear that can be measured using this system must have a round cross-sectional area with grooves. As wear progresses due to the passage of the pantographs, the bottom of the round shape becomes flat sliding face. If white light is irradiated onto this sliding surface of the contact wire, the sliding surface strongly reflects the light because it is flat. Meanwhile, the reflection from non-contacting surface is weaker because it is curved. Furthermore, since the contact wires mainly made of copper are exposed to long-term wind and rain, their surface is rusty. On the contrary, the sliding face maintains its metallic glare as a result of daily train operations. Consequently, if the contact wire irradiated with light is photographed directly from beneath it, the sliding face
Challenge G: An even more competitive and cost efficient railway appears to be only white, distinguishing it from the other faces. By measuring the width of the sliding face, the remaining diameter of the contact wire can be found. Since the measurement of the remaining diameter also requires higher spatial resolution, spatiotemporal images shot using a line sensor are used as in the measurement of the height of the contact wire.

LS2 line sensors shown in Fig. 1 are installed on the rooftop of the vehicle vertically facing upward, allowing the image sensors of the line sensor to line up in the direction of the railway ties. In this state, spatiotemporal images of the contact wire and surrounding area, including the sliding face of the contact wire, are photographed. From these spatiotemporal images, the threshold of brightness is set to distinguish the sliding face of the contact wire from the background area. Using this threshold, the spatiotemporal images are digitized. Since images photographed outdoors depend largely on the ambient environment (whether it is day or night, or the train is in a tunnel or open section), the brightness of the light is adjusted by calculating an appropriate value for each image by dynamically changing the brightness threshold. On the digitized spatiotemporal image, the sliding face of the contact wire appears white, whereas the background appears black. Images other than those of the contact wire are then subjected to processing such as noise removal, and the edge points representing the border of the sliding face of the contact wire are detected. From these edge points, the width of the sliding face of the contact wire on the images is calculated.

Figure 2 shows the principle of measuring the remaining diameter of the contact wire. Assuming that the width of the sliding face of the contact wire is $N$ (pix), the height from the rail to the contact wire is $H$ (mm), the height from the rail to the sensor face of the line sensor is $H_s$ (mm), the focal distance of the lens is $F$ (mm), the sensor width of the line sensor is $S_{\text{width}}$ (mm), and the number of pixels of the line sensor used is $S_{\text{pix}}$ (pix), then the width of the sliding face of the contact wire in actual space $P$ (mm) can be calculated using Formula (1). In addition, assuming that the diameter of the contact wire is $d$ (mm), the remaining diameter of the contact wire, $R$ (mm), can be calculated using Formula (2).

$$ P = \frac{H - (H_s + F)}{F} \frac{S_{\text{width}}}{S_{\text{pix}}} \cdot N \quad (1) $$

$$ R = d/2 + \sqrt{(d/2)^2 - (P/2)^2} \quad (2) $$
3.5 Measuring the contact force

3.5.1 Contact force calculation formula

Since the contact force is a physical quantity acting between the contact wire and the pantograph, contact performance can be assessed directly by it. A method for measuring the contact force from line sensor camera images by image processing has been developed through this study. The developed non-contact method is not affected by the vibration properties of the pantograph, which is advantageous. The principle of this method using image processing is the same as that of measurement using a sensor such as an accelerometer (1). The contact force is given by:

\[ F_c = F_b + F_{inertia} + F_{aero} \] ..........................................................(a)

The contact force \( F_c \) is found by summing up the reaction force of the spring \( F_b \), inertia \( F_{inertia} \), and aerodynamic force \( F_{aero} \). The reaction force of the spring \( F_b \), inertia \( F_{inertia} \), and aerodynamic force \( F_{aero} \) is given by:

\[ F_b = k \times x \] ..................................................(b)
\[ F_{inertia} = M \times a \] ...........................................(c)
\[ F_{aero} = \frac{1}{2} C_L \rho V^2 S \] .........................................(d)

In Formula (d), \( C_L \) represents the lift coefficient, \( \rho \) represents the fluid density, \( V \) represents running speed, and \( S \) represents the reference area of the pantograph. Variables other than the expansion and contraction of the spring, acceleration, and running speed can be found experimentally, and the above three quantities must be measured through image processing.

Figure 7 outlines this method. As seen in the figure, light is irradiated onto the collector head of the pantograph and the spring of the pantograph is photographed using a line sensors, which are the cameras with rows of light-receiving elements. Using this line sensors, one-dimensional images can be obtained. By shooting continuously and laying out the obtained one-dimensional images in the direction of the temporal axis, high-resolution two-dimensional images are obtained.
These images are then processed to find the heights of the pantograph head and its support, and from these differences, the magnitude of expansion and contraction of the spring along with acceleration of the pantograph head are calculated. Traveling data coming from the train is recorded and used for calculating the running speed. The contact force is found by substituting the obtained expansion and contraction of the spring, acceleration, and running speed into Formulae (a) to (d). The method for detecting the height of the pantograph via image processing, and for calculating the expansion and contraction of the spring, acceleration, and contact force is detailed below.

3.5.2 Detecting the behavior of the pantograph

Figure 5 shows a typical obtained image. The white band in the image is the marker attached to the head of the pantograph shown in Fig. 4. Light is irradiated onto the collector head, which appears white in the photograph. Since the spring of the pantograph is included in the photograph, the upper and lower white bands in the image move when the spring is contracted, and the fluctuation in the height of the pantograph causes the white band to change shape in the vertical direction. To detect the behavior of the pantograph, a threshold value for distinguishing the collector head from the background is established, and digitization is performed. The contact wire, messenger wire, etc., are also photographed and appear in the image as noise, which must be removed. Since the width of the collector head is known, the width that does not fall within the set range is eliminated as noise. This method alone does not completely remove them if the contact wire is photographed when it is close to the width of the collector head. Noise can be completely removed by using the fact that the white band in the image appears as a continuous belt-like curve of a certain width. By removing the discontinuous part as noise, digitized images of only the background and the white band are created. The created digitized images are then subjected to edge processing to detect the displacement between the upper and lower band of the collector body shown in Fig. 5.
3.5.3 Calculating the contact force\(^1\)\(^2\)

To calculate the contact force, the expansion and contraction of the springs, accelerations, and running speed must be found. To find the expansion and contraction of the spring, relative displacement is calculated from the position of the upper and lower marker of the collector head obtained by the above method as shown in Fig. 5. The natural length of the spring is checked in advance, and the expansion and contraction can be found based on the difference between the natural length and the relative displacement. Acceleration is then calculated. Acceleration can be found by second-order differentiation. Actual traveling distance and time are recorded to calculate the running speed. Lastly, by substituting the obtained expansion and contraction of the springs, accelerations, and running speed into Formulae (a) to (d), the contact force can be found.

3.5.4 Experiment
a) Experimental environment

Using the experimental facilities at the Railway Technical Research Institute, experiments were conducted to assess the measurement accuracy of the contact force, using image processing. Relative and absolute displacements were found through image processing, and the expansion and contraction of the springs and accelerations were calculated. The aerodynamic force characteristics of the pantograph, based on the results of experiments conducted in a wind tunnel, are omitted here.

Figure 4 outlines the experiment. Of the two line sensor cameras, one photographed the center of the pantograph and the other photographed the position closer to the side end of the pantograph head. The images obtained were subjected to image processing to find the relative displacements, Then the expansion and contraction of the springs and the acceleration of the pantograph head were calculated, and the contact force was found using Formula (a).
b) Results of experiment and considerations

Figure 6 illustrates the frequency characteristics of the contact force measurement accuracy evaluated in the experiment. The horizontal axis represents frequency (Hz), and the vertical axis represents gain. Chart A) illustrates the inertia of the pantograph, and the transfer function of calculated inertia with the input excitation force was indicated.

Chart B) illustrates the reaction force of the spring, and the transfer function of calculated inertia with the input excitation force was indicated.

Chart C) indicates the contact force measurement accuracy. Table 3 show the accuracy between the measured and mandatory required accuracy on EN standard. These Measured accuracy calculated equation based on EN standard. Table 3 indicated, the measurement system have accuracy within the requirement accuracy on EN standard.

Table 3 The measurement accuracy of Contact force

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Measured Accuracy of pantograph force</th>
<th>Requirement Accuracy on EN standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~10Hz</td>
<td>12%</td>
<td>20%</td>
</tr>
<tr>
<td>0~20Hz</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>
4. Conclusion

(1) Expected Benefits

a. An inspector can quickly find an abnormality and examine the relevant images before making a site visit.

b. Having visual images helps to plan the necessary remediation work.

c. The dynamic contact force can be measured on any commercial train. Application of this method does not influence the dynamic characteristics of the pantograph.

d. A significant feature is the permanent linking of data between the various analyzed outputs, actual images, and location data. This function helps to identify the condition of the OCS including wear, corrugation or discoloration and makes it possible to sort abnormalities into different categories such as:
   - Error in measurement due to external influence
     This is a longstanding problem of traditional measurement methods that rely on numerical data. There is no way to determine whether the suspected abnormality is an actual defect or a measurement error without conducting a site visit.

(2) Impact on Railway Business

a. Measurement on a commercial train enables inspection during commercial service as opposed to expensive night work. This increases the efficiency of maintenance work.

b. This system can be installed on various vehicles and cars.

c. The compact design and combination of

* Meidensha Corporation.,
  515 kaminakamizo, higasimakado, numazu-shi, shizuoka 410-8588

** Railway Technical Research Institute.,
  515 hikari-cho, kokubunji-shi, tokyo, 185-8540

reconstructing dedicated measuring vehicle

* Mitsuru IKEDA : "A Study on the Method the Contact Force between Pantograph and Contact Wire (1st Report, Extension of the Frequency Range for Contact Force Measurement by an Improved Method of Evaluating the Pantograph Inertia Force)".

** Takamasa Hori : "A Method of Measuring the Contact Force between Pantograph and Contact Wire Using Image Processing"