The Pantograph Contact Force Measurement Method
in Overhead Catenary System

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Abstract
The author has started to research the quantitative effects of the contact force of the pantograph and the arc due to contact loss on the contact wire wear in order to clarify the mechanism of contact wire wear. For this purpose, the fundamental method of this research is comparing measurement results of the contact wire wear transition, the contact force and the arc between the specific area. However, the contact force of all pantographs, which generates the contact wire wear in a measurement area, must be measured for the purpose of these researches. It is insufficient that contact force of the pantograph is measured in the inspection car, because several types of pantographs pass the same line and train runs in each velocity. The author is under development of a method, which measures the contact force of every all pantograph, which pass the measurement area by placing sensors on catenary.

In this paper, the calculation results and the experimental results of this measurement method are reported. The results indicate that the measurement method with sensors placed on catenary can measure the contact force in frequency range DC - 15Hz in the case of arraying 2 accelerometers between a dropper span. It is also confirmed that the available frequency range of the contact force measurement depends on the number of sensors provided at the measurement area.

By applying this measurement method, the contact force including the uplift force, which affects the pantograph head, can be measured. Therefore, this measurement method is also useful for pantograph monitoring tools.

1. Introduction
Although wear of contact wire has been one of the most important problems in catenary system maintenance, the wear mechanism of contact wire is very complicated, and there are many unsolved matters. Contact wire wear depends on types of pantograph and contact wire, amount of the collecting current, velocity of trains, catenary type and its erection accuracy, surface condition of the contact wire, and others. These factors are mutually related. Especially, it is a known empirically that growth of the contact wire wear is strongly related to contact force of the pantograph and arc due to contact loss. However, quantitative evaluations of these contributions have not been clarified yet.

We have started to research the quantitative effects of the contact force and the arc on the contact wire wear in order to clarify the mechanism of contact wire wear. For this purpose, the fundamental method of this research is comparing measurement results of the contact wire wear transition, the contact force and the arc between the specific area. However, the contact force of all pantographs, which generates the contact wire wear in a measurement area, must be measured for the purpose of these researches. The term “measurement area” in this paper means data acquisition area of contact wire where the contact force, the arc and contact wire wear are acquired. It is insufficient that contact force of the pantograph is measured in the inspection car, because several types of pantographs pass the same line and train runs in each velocity. The author is developing the method, which measures contact force of all pantographs, which pass the measurement area by placing sensors on catenary.

In this paper, we report the calculation result and the experimental result of this measurement method.
2. Measurement theory

In this chapter, theory of contact force measurement on the overhead catenary system (OCS) as indicated in Fig. 1 is explained. To derive a equation of motion, the overhead catenary system is modeled as an infinite string supported by n droppers force $h_i$ ($i=1 \sim n$). The contact force $F$ is assumed to act on a point. The linear density of contact wire, the tension of contact wire, the position of the $i$-th dropper, and the velocity of train are described as $\rho, T, x_i, \text{and } v$ respectively. At the low frequency where we can neglect bending stiffness of contact wire, the behavior of contact wire $y(x,t)$ is expressed by the following equation.

$$\sum_{i=1}^{n} h_i \delta (x-x_i) + \rho \frac{\partial^2 y}{\partial t^2} - T \frac{\partial y}{\partial x} = F(i) \delta (x-vt)$$  \hspace{1cm} (1)

The length of the measurement area is defined as $L$. When the pantograph is in the measurement area, integrating Equation (1) over measurement area gives the following equation.

$$F(i) = \sum_{i=1}^{n} h_i \left( \frac{\partial y}{\partial x} - \frac{\partial y}{\partial x} \right) + \rho \frac{L}{2} \frac{\partial^2 y}{\partial t^2}$$  \hspace{1cm} (2)

The first term of the right-hand side of the Equation (2) is the sum of dropper forces in the measurement area. The second term is the vertical component of the tensile force of contact wire, and calculated by the gradient of the contact wire at both ends of the measurement area. The third term is the inertia force of the contact wire. In calculation of this term, continuous distribution of the vertical acceleration of the contact wire is necessary. However, generically it is difficult to measure the spatially continuous distribution of the contact wire vertical acceleration. Therefore, in this paper, the inertia force is estimated using the accelerations of the $p$ points, and the Equation (2) is approximated by the following equation:

$$F(i) = \sum_{i=1}^{n} h_i \left( \frac{\partial y}{\partial x} - \frac{\partial y}{\partial x} \right) + \rho \frac{L}{2} \frac{\partial^2 y_j}{\partial t^2}$$  \hspace{1cm} (3)

where $w_j$ is inertia force correction coefficient for the $j$-th acceleration measuring point. We can identify this value by excitation test or running test results. In sub-section 3.1, inertia force correction-coefficient is identified in the time domain so that contact force calculated from the Equation (3) agrees with contact force calculated by the numerical simulation. In sub-section 3.2, we identify the inertia force correction-coefficient in the frequency domain so that the contact force calculated from the Equation (3) agrees with contact force in experimental results.

A method to identify the inertia force correction coefficient in the frequency domain is described. Equation (3) can be transformed into frequency domain as follows.

$$F(\omega) = F_h(\omega) + F_v(\omega) + \sum_{j=1}^{p} w_j A_j(\omega)$$  \hspace{1cm} (4)

Dividing Equation (4) by $F(\omega)$, we get.

$$\frac{F_h(\omega)}{F(\omega)} + \frac{F_v(\omega)}{F(\omega)} + \sum_{j=1}^{p} w_j \frac{A_j(\omega)}{F(\omega)} = 1$$  \hspace{1cm} (5)

The real part of Equation (5) is expressed by the following equation,

$$\text{Re} \left[ \frac{F_h(\omega)}{F(\omega)} + \frac{F_v(\omega)}{F(\omega)} + \sum_{j=1}^{p} w_j \frac{A_j(\omega)}{F(\omega)} \right] = 1$$  \hspace{1cm} (6)

The imaginary part of Equation (5) is expressed by the following equation,

$$\text{Im} \left[ \frac{F_h(\omega)}{F(\omega)} + \frac{F_v(\omega)}{F(\omega)} + \sum_{j=1}^{p} w_j \frac{A_j(\omega)}{F(\omega)} \right] = 0$$  \hspace{1cm} (7)

$w_j$ can be identified from Equation (10) and (11) using the least squares method.
In this paper, the inertia-force correction coefficient has been identified from the data while the pantograph is running in the measurement area.

Contact force = Inertia force + Dropper force + Vertical components of tensile force

3. Measurement result of the contact force

3.1 Simulation results

The measurement method has been verified by numerical simulations. Dynamic behavior of the catenary in the pantograph passage is calculated by using the simulation. From this dynamic behavior of the catenary, the contact force is calculated using Equation (3). This contact force is compared with the contact force of the simulation results. In the simulation study, catenary type is a simple catenary, and the tension of contact wire and messenger wire are set at 9.81kN; the linear densities of contact wire and messenger wire are set at 0.99kg/m and 1.09kg/m. The static up-lift force of pantograph is set at 54N, and the velocity of train is set at 130km/h.

At first, sensor points, where acceleration, gradient and dropper force of simulation data are used for calculation of contact force, are arrayed as shown in Fig. 2 to validate contact force measurement method (case 1). The mounting interval of the accelerometer is 1m in order to avoid loss of accuracy in the inertial force correction. In addition, the gradient of the contact wire at both ends of the measurement area are obtained from the close 2 points displacements that are calculated from the quadratic integration of the acceleration. This measurement result of the contact force is shown in Fig. 3. Figure 3(a) is a comparative result in the time history, and Fig. 3(b) is a comparative result of the power spectrum of contact force. This result shows that the contact force is measurable at a high accuracy applying this method, when the interval for the measurement of the accelerometer is close enough.
Secondly, the interval of mounting the accelerometer is extended, and sensors are arrayed in two cases as shown in Fig. 4. Each point where the accelerometers mounted is shown in the following.

Case-2: The accelerometers are mounted at a distance of ±1.3m apart from the dropper point.
Case-3: The accelerometers are mounted at a distance of -1.3m and +2.5m apart from the dropper point.

The result of the contact force calculation in the time history is as shown in Fig. 5(a). This figure indicates the contact force calculated by the simulation and the contact force gained by this measurement method in the case-2 and 3. The power spectrum of the contact force is shown in Fig. 5(b). The results show that the contact force is estimable in the case-3 array of accelerometer up to 15Hz.
The effect of the accelerometer array position to measurement accuracy is described in the following. Using the simulation result, the cross spectrum of the acceleration of contact wire each point for the contact wire acceleration of the span center is calculated. Real parts of the cross spectrums are shown in Fig. 6. The horizontal axis of this figure indicates a position on the contact wire, which is correspondent with the catenary system as shown at the upper part of the figure; the vertical axis indicates frequency. In this figure, phase of contact wire acceleration at each point against the contact wire acceleration in a span center is as shown in the grayscale with respect to each frequency.

At point (a), the grayscale reversed against the next dropper span. It indicates that vibration of contact wire is an antiphase in 10Hz against the next dropper span. Therefore, it indicates that the half-wavelength is included between one dropper span in this vibration mode, and by measuring the contact wire acceleration at the dropper point center; it is possible to measure this vibration mode.

At point (b), a dark part and a light part can be observed every dropper span. Therefore, it indicates that a wavelength is included between one dropper span in this vibration mode, and by measuring the contact wire acceleration at a point of the quarter dropper span; it is possible to measure this vibration mode. From the verification of the above, the arrangement of the #case-3 accelerometer array has a superior quality than that of the #case-2 in the measurement of contact force.

![Fig. 6: Cross spectrum of contact wire vibration in simulation](image)

3.2 Experimental result

We also verify the measurement method experimentally. We carry out some experiments with the current collection testing equipment of RTRI in which a test car equipped with a pantograph runs the track of 500m long under overhead catenary system. The catenary type is as well as section 3.1, and the measurement area is set at 25m, sensors are arrayed as shown in Fig. 7. The scenery of this experiment is shown in Fig. 8. We measure dropper forces by strain gauges and acceleration of contact wire by accelerometer. At the same time, the contact force is measured in pantograph. The pantograph runs at the speed from 80 to 160km/h.

The static uplift force of the pantograph is 54N. In the calculation of the inertia force correction coefficient, the running results at the above-mentioned speed are used. The inertia force correction coefficient is identified in the frequency domain using Equation (6) and (7). The experimental results are shown in Fig. 9 and 10. In Fig. 9 outputs of all sensors and estimated contact force at 120km/h are shown. In this result, the contact force measured in overhead catenary system does not become 0N when the pantograph is outside of the measurement area. The reason is to include the error in the
inertial force as number of the acceleration measurement point of contact wire is insufficient. However, the result of the contact force is satisfactory when a pantograph is in the measurement area.

The result of the contact force, when a pantograph is in the measurement area, is as shown in Fig. 10(a) through (c). Each figure corresponds to pantograph running results at 80, 120 and 160km/h. 15Hz LP filter is applied to each contact force. This result indicates that the contact force, which is measured at the measurement area with the sensors installed in the overhead catenary system, is consistent with the contact force as measured with the pantograph. Consequently, the contact force is measurable by this method.

![Fig. 7: OCS and measurement points in experiment](image)

![Fig. 8: Scenery of experimental equipment](image)
Fig. 9: Measurement data in experiment

Fig. 10: Measurement results of contact force in experiment
4. Conclusion

This paper introduces the contact force measurement method on the overhead catenary system. We have confirmed the validity of the method by simulation and some experiments. We have also confirmed that the measurable frequency of the contact force depended on the number of sensor array placed at the measurement area. The result of the investigation indicates that the measurement method by placing sensors on the catenary can measure the contact force at the frequency from DC to 15Hz in the case of arraying 2 accelerometers between a dropper span. The final goal of this study is to clarify the wear mechanism of the contact wire, quantitative evaluation of the influence of the contact force and arc due to a contact loss on the contact wire wear, lifetime prediction of contact wire, and establishment of the criterion value of the contact force.

With application of the foregoing measurement method, the contact force including the uplift force, which affects the pantograph head, can be measured. In addition, it is conceivable that the foregoing method is applicable to the monitoring of pantographs.

References