Method to Improve Adaptation Speed of Control Parameters for Active Control Pantographs

Yoshitaka YAMASHITA  Shigeyuki KOBAYASHI  Takayuki USUDA
Current Collection Laboratory, Railway Dynamics Division

Arata MASUDA  Daisuke IBA
Kyoto Institute of Technology

In order to improve current collection performance as train running speeds increase, the authors have been working on the development of a feed-forward control technique for reducing contact force fluctuation, based on information about support spans and train running speed. The idea of the approach is to control the magnitude and phase lag in force control acting on the pantograph frame, allowing the force control to work after the controller has found the optimal magnitude and phase lag. The problem of this approach, however, is that finding the two optimal parameters using the steepest descent method is time consuming. This study proposes an improved approach in terms of parameter adaptation speed. An experimental result shows that the adaptation speed of the proposed method is about 20 times greater than that of the conventional one.

Keywords: pantograph, contact force, active control, feedforward control

1. Background

In order to meet the requirements associated with higher train speeds, many challenges must be overcome. Suppression of contact force fluctuation between the pantograph and catenary is one of them. The higher the train speed is, the greater the fluctuations will be [1]. Excessive fluctuation results not only in contact loss between the contact strip and contact wire, which interrupts stable electric supply to the train, but also in damage from arcing. It is well-known that an increase in the tensile force of the catenary is an effective way to decrease contact force fluctuation [2]. Another key challenge is to reduce aerodynamic noise emitted from pantographs. Smoothing the profile of pantograph components is one effective way to reduce aerodynamic noise, for example by removing the need for the plunger which gives elastic supports to the pantograph head. Such a measure however would make it difficult to maintain sufficient space for the stroke of the spring elements in the pantograph head, which could lead to poorer dynamic performance of the pantograph. Figure 1 illustrates the active control pantograph employed in this study. Taking electric insulation into account, a pneumatic actuator (hereafter, the actuator) is equipped for controlling the contact force in parallel with the raising mechanism of the pantograph. Figure 2 depicts the dynamic model of this pantograph. The masses $m_1$ and $m_2$ correspond to the masses or the equivalent masses of the pantograph head and frame, and $x_1$ and $x_2$ to the values of the vertical displacement of the masses. $k_1$ and $c_1$ are the stiffness and damping coefficient of the elements in the pantograph head, and $c_2$ is the damping coefficient of the pantograph damper. $P_0$ represents the static uplift applied by the raising mechanism and $u$ is the actuation force. $f_c$ is the contact force between the pantograph head and the contact wire. This pantograph is capable of measuring contact force.
by using the sensors embedded in the pantograph head [6]. Different from the sensors, the actuator is not installed in the pantograph head due to limited space. Therefore, the collocation of the contact force sensor and the actuator is not achieved. The actuator is driven by a command voltage signal which is output by the controller as a result of calculations based on the algorithm mentioned in chapter 3.

2.2 Software

For convenience, instead of sensors embedded in the pantograph head, a load cell installed between the pantograph and the vibration exciter which gives sinusoidal forced displacement to the pantograph head is utilized in this study. The measured contact force is input to the controller for calculating adequate actuation force. The controller consists of a phase locked loop (hereafter, PLL, Fig. 3) that extracts the contact force’s dominant frequency component around the target frequency (the free running frequency for the PLL). The target frequency is determined by the train speed and the fixed installation information such as span lengths, the loop for extracting the contact force’s amplitude at the above frequency (Fig. 4) and the block for determining the actuation force according to the following equation:

$$u = U e^{j \omega t} \quad \text{or} \quad u = A \sin(\omega t + \phi)$$

(1)

where $U$ is the complex amplitude of the actuation force, $j$ the imaginary unit, $A$ the amplitude of the actuation force and $\phi$ the phase of the actuation force. The control parameter to be regulated is $U$ (or $A$ and $\phi$) in (1). Where the contact force fluctuation due to the span length needs to be reduced, the target frequency is calculated by ‘train speed/span length.’ Practically, the controller outputs the command voltage to the amplifier of the actuator which means that the controller regulates the amplitude and the phase - not the actuation force - but of the command voltage. It is assumed however that the actuation force is almost proportional to the command voltage for simplicity, and the output of the controller is regarded as the actuation force in this study.

3. Control parameter regulation method

3.1 Steepest descent method

In reference [5], a control parameter regulation method using steepest descent was proposed. Figure 5 shows the flow chart from this conventional method which is described in this section. The steepest descent method is applied to modify parameters to maximize the gradient of an objective function at individual iteration steps. Applying this to regulate the control parameters gives the equation shown below from iteration step $i$ to iteration step $i+1$:

$$\begin{bmatrix} A^{i+1} \\ \varphi \end{bmatrix} = \begin{bmatrix} A^i \\ \varphi \end{bmatrix} - \alpha \left[ \frac{\partial |F_c|^2}{\partial A} \right]$$

(2)

where $F_c$ is the complex amplitude of the contact force fluctuation, while the objective function of the optimiza-
tion problem is set to be $|F_c|^2$. $\alpha$ is the factor for updating the control parameters. In this method, control parameters are modified by neglecting the terms which are equal or higher than the 2nd order for the Taylor expansion of the objective function. However, when there is large variation in the control parameters, it is not appropriate to neglect those terms and can cause an increase in the objective function by changing the parameters while aiming at minimizing the objective function. In that case, the variation for the update is decreased so as to decrease the objective function. In this method, a certain period is required for evaluating the amplitude of the contact force fluctuation after the update of the control parameters, each of which is individually updated, so that it takes some time to obtain the optimal control parameters that minimize the contact force.

### 3.2 The proposed method

In this section, a new method (hereafter, the proposed method) for improving the adaptation speed of the control parameters is proposed. The contact force is expressed by:

$$f_c = F_c e^{i\omega t}$$  \hspace{1cm} (3)

and the relationship between the actuation force and the contact force fluctuation is expressed in a complex domain by:

$$F_c = B + HU$$  \hspace{1cm} (4)

where $H$ is the transfer function from the actuation force to the contact force fluctuation $F_c$, and $B$ is regarded as the complex amplitude of a disturbance, resulting from the unmodeled dynamics from (5), and it is considered to be applied to the pantograph head. In the proposed method, $B$ and $H$ are estimated using the known $F_c$ and $U$ to obtain the optimal value of $U$.

Here the complex amplitude of the actuation force and the contact force fluctuation are considered for the time interval $T$. Setting the complex amplitude of each force at time $nT$ to be $U(n)$ and $F(n)$ and assuming $B$ and $H$ to be invariants, (5) can be written as follows.

$$F_c(n) = B + HU(n)$$  
$$F_c(n-1) = B + HU(n-1)$$  
$$F_c(n-2) = B + HU(n-2)$$  \hspace{1cm} (5)

Considering the time $nT$ is the current time, it is possible to calculate the optimal actuation force $U(n)$ that makes the current contact force fluctuation ($F_c(n)$=0) zero by using the complex amplitudes of the actuation force $U(k)$ and the contact force fluctuation $F_c(k)$ ($k=n-1, n-2, ...$) of the last 2 steps. In case that the last 2 steps are utilized, $B$ and $H$ can be estimated by (6) and (7).

$$H = \frac{F_c(n-1) - F_c(n-2)}{U(n-1) - U(n-2)}$$  \hspace{1cm} (6)

$$B = \frac{F_c(n-1) - F_c(n-2)}{U(n-1) - U(n-2)}$$  \hspace{1cm} (7)

The optimal $U(n)$ therefore is obtained as follows.

$$U(n) = \frac{B}{H}$$  \hspace{1cm} (8)

When it is necessary to go back more than 3 steps, $B$ and $H$ can be estimated with the help of the least squares method.

In this proposed method, the variation of the control parameter for the update is calculated automatically in such a way that it would be optimal for the $N$ periods of the set time span. Therefore, it is unnecessary to regulate the factor $\alpha$ like in the conventional method. Furthermore, since the control parameter in this proposed method is the complex amplitude of the actuation force, the amplitude and the phase are regulated simultaneously. By using this method, the adaptation speed can be considerably reduced.

### 4. Numerical verification

#### 4.1 Invariant excitation condition

The performance of the proposed control method is verified with the use of simulations. The pantograph model shown in Fig. 2 is used for the simulations, and those parameters are listed in Table 1. Figures 6(a) and (b) show the waveform of the forced displacement excitation with a frequency of 1Hz given to the pantograph head and a comparison of the contact force responses between the passive pantograph and the active control pantograph, respectively. In this case, it is assumed that the target frequency $(f_{\text{target}})$, which is given to the PLL shown in Fig. 3, is exactly consistent with the excitation frequency $(f_{\text{excitation}})$. The contact force responses remain steady from 10 secs. to 15 secs.

The abovementioned time span $T$ is set to be 2 secs., and therefore it can be seen that the optimal control parameter (the complex amplitude of the actuation force) is found by means of 5 to 7 updates (10 to 14 secs.). The fact that 50 updates, each of which needs 6 sec., are necessary to attain the optimal parameter under the conventional method emphasizes the effectiveness of the proposed method.

![Steepest descent method](image-url)
### Table 1 The parameters for the simulation

| Parameter | Value [Unit] | Parameter | Value [Unit] |
|-----------|--------------|-----------|--------------|
| $m_1$     | 3 [kg]       | $c_2$     | 100 [Ns/m]   |
| $m_2$     | 15 [kg]      | $k_1$     | 38000 [N/m]  |
| $c_1$     | 100 [Ns/m]   | $P_0$     | 54 [N]       |

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#### 4.2 Variant excitation condition

This section describes the verification of the performance of the proposed control method where the frequency of the excitation to the pantograph head (hereafter, the excitation frequency) varies during simulation. Figures 7(a) and (b) show pantograph head excitation displacement with a frequency that fluctuates after 10 secs from 1.0 Hz to 1.1 Hz, and the contact force responses to the displacement excitation, respectively. In the case of the active control pantograph, two results were obtained, firstly when the target frequency of the PLL was fixed at 1.0 Hz throughout (which means the target frequency has an error) and secondly when the target frequency of the PLL exactly followed the excitation frequency. The former and latter results are noted as "$f_{\text{target}} = 1.0 \text{ Hz}$" and "$f_{\text{target}} = f_{\text{ex}}$" in the legends of the figures. Comparing the results of the two cases, where "$f_{\text{target}} = f_{\text{ex}}$" the performance is very good in terms of the reduction in the contact force fluctuation. On the other hand, where "$f_{\text{target}} = 1.0 \text{ Hz}$," the contact force fluctuation exceeds that found with a passive pantograph right after the excitation frequency deviates from the target frequency. Furthermore, even though the contact force fluctuation is reduced once by means of the adaptation, fluctuation grows again beyond that of the passive pantograph. In this case, the controller cannot accept the temporal discrepancy between the excitation and the target frequencies and it becomes slightly unstable.

The PLL is modified as depicted in Fig. 8 in order to detect the variation of the excitation frequency and to force the target frequency to follow it. The difference from the Fig. 3 is emphasised by the dotted box in Fig. 8. The difference between the frequency output by the PLL (equivalent to the extracted frequency in Fig. 3) and the target frequency input to the excitation frequency follow-up loop is added to the target frequency at point B, and this makes the frequency input to the PLL at point A (equivalent to the target frequency in Fig. 3) follow up the excitation frequency. The 1\(^{st}\) order delay element is installed in order to avoid a sudden change in the actuation force due to the sudden change in the parameter.

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![Fig. 6](image6.png)  
*Fig. 6  Control performance with constant excitation frequency*

![Fig. 7](image7.png)  
*Fig. 7  Control performance with step variations in excitation frequency*

![Fig. 8](image8.png)  
*Fig. 8  PLL with frequency follow-up loop*
Figure 9 represents the control performance of the active control pantograph by means of the PLL with the follow-up function where the excitation frequency fluctuated. The result obtained from the pantograph with the PLL with the follow-up function is tagged as $f_{\text{target}} \approx f_{\text{excitation}}$ in the legend of Fig. 9. The abovementioned unstable behaviour was not observed when using the follow-up function.

The extracted frequencies from the PLL where $f_{\text{target}} = f_{\text{excitation}}$, $f_{\text{target}} = 1.0 \text{ Hz}$ and $f_{\text{target}} \approx f_{\text{excitation}}$ are plotted in Fig. 10. Where $f_{\text{target}} = 1.0 \text{ Hz}$, the extracted frequency synchronizes with the excitation frequency and reaches the mean value of about 1.1 Hz at the excitation frequency variation point. One can observe almost the same behaviour where $f_{\text{target}} \approx f_{\text{excitation}}$. The differences however are the extracted frequency from the PLL in case where $f_{\text{target}} = 1.0 \text{ Hz}$ deviates from the excitation frequency of 1.1 Hz, and the PLL outputs the extracted frequency which is around the mean value of the target frequency identical to the free running frequency of the PLL. Such a synchronization with and a deviation from the excitation frequency occurs repeatedly during the simulation. The authors confirm that smaller differences between the excitation frequency and the target frequency result in less frequent deviation between the excitation and the target frequencies.

5. Experimental verification

To verify the proposed method, experiments were carried out. In these experiments, the pantograph head was subject to forced displacement excitation. The time span $T$ was set to be 5 sec., and the PLLs shown in Fig. 8 were employed to make the target frequency follow the excitation frequency. Contact force fluctuation in cases where the excitation with a frequency of 1Hz and an amplitude of 30mm is given is shown in Fig. 11. In Fig. 11, the actuation force is applied to the pantograph after 10 secs., and the parameters are regulated by the proposed method. After 5 sec. of actuation, contact force fluctuation was already less than it would have been on a passive pantograph. After 20
sec. contact force fluctuation was 56% less than on a passive pantograph. The mean contact force shifting from 0N at 0secs. to 5 N at 35 secs. is caused by the mechanical hysteresis of the parts of the pantograph.

Figure 12 represents the comparison of the control parameter adaptation speeds between the conventional method and the proposed method. This figure shows that the proposed method significantly improves the control parameter adaptation speed. In this case, the adaptation speed of the proposed method is about 20 times greater than that of the conventional one.

6. Conclusion

A new method for improving the control parameter adaptation speed has been proposed to automatically regulate control parameters. The proposed method regulates the complex amplitude of the actuation force and estimates the optimal value in a set time span. The parameter regulation for the update of the control parameters, which is the amplitude and the phase of the actuation force, and the individual adaptation of the parameters are unnecessary in the proposed method, which leads to an outstanding improvement in adaptation speed. The numerical and experimental investigations show that the proposed method makes it possible to reduce contact force fluctuation in less time.

The proposed control method is suitable for application to active pantographs. Further research will be carried out on cases where train speed varies continuously, i.e. the excitation frequency varies.

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Authors

Yoshitaka YAMASHITA, Dr. Eng.
Senior Researcher, Current Collection Laboratory, Railway Dynamics Division
Research Areas: Catenary-Pantograph Interaction, Vibration Control

Arata MASUDA, Dr. Eng.
Professor, Kyoto Institute of Technology
Research Areas: Smart Structures, Vibration Control, Structural Health Monitoring, Energy Harvesting

Shigeyuki KOBAYASHI, Dr. Eng.
Assistant Senior Researcher, Current Collection Laboratory, Railway Dynamics Division
Research Areas: Catenary-Pantograph Interaction, Vibration Control

Daisuke IBA, Dr. Eng.
Associate Professor, Kyoto Institute of Technology
Research Areas: Active Mass Damper, Gear Vibration

Takayuki USUDA
Senior Chief Researcher, Laboratory Head, Current Collection Laboratory, Railway Dynamics Division
Research Areas: Catenary-Pantograph Interaction, Measurement Method, Maintenance Strategy