Accuracy Improvement of Braking Distance by Deceleration Feedback Function Applying to Brake System

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Brake control systems used in current railways are generally open-loop structures. Braking performance can be affected by problems such as wheel slipping or the characteristics of friction components included in brake equipment. In order to automatically stabilize braking performance, we propose a new closed-loop system which can make train deceleration follow a set of target values which change with braking distance. We carried out running tests using rolling stock equipped with the proposed method. The results of the test showed that the method can contribute to reducing an increase in braking distance when there is temporary degradation in the brake.

Key words: brake system, deceleration control, train auto stopping control

1. Introduction

Brake control systems used in current railways are generally open-loop structures where the brake command is the input and variation of train speed is the output. In this structure, the brake control system input is not automatically controlled according to output.

However, because of wheel slipping or degradation in the friction coefficient of brake blocks, in wet conditions for example, train deceleration varies despite the same brake command being issued. In most cases, the loss of braking performance is compensated by re-adjusting the brake command, either by the driver or through an automatic control system, such as ATO.

In order to stabilize braking performance, we proposed a closed-loop structure as Deceleration control [1, 2] in which train speed is fed back to a newly added controller. This approach is a type of tracking control. The controller chooses the brake command automatically to make the train deceleration fit a target value which is defined as the demanded deceleration during the design phase. Deceleration control can therefore improve the accuracy of stopping distance because the closed-loop structure tries to precisely adjust the train deceleration to the target value.

This paper therefore proposes a new closed-loop system for deceleration control based on braking distance which ensures that train deceleration follows as set of target values which change according to the braking distance. We validated the proposed method through running tests using full-scale rolling stock.

2. Background

2.1 Railway brake system

The structure of a general brake control system currently used on railways is shown in Fig. 1. Most of the current brake systems just obey a brake command, which does not distinguish manual operation by a driver from an automatic one.

Brake commands generally have 7–8 notches. (Most automatic control systems, such as ATO and the train automatic stop control (TASC), have shorter notches.) Every notch defines a demanded deceleration. The demanded braking force is calculated based on the motion equation using demanded deceleration and the vehicle weight (including the payload) in proportion to the pressure of air springs supporting the car body. Then pneumatic brake and electrical brake devices work to provide the demanded braking force and reduce the train speed. However, the current brake control systems cannot detect whether the train deceleration actually matches the demanded one. A driver or ATO etc. is responsible for determining if the brake command has successfully achieved the demanded deceleration, adjusting the command again if necessarily. The current brake control systems are considered as an open-loop structure which have the brake command as input and the train deceleration as an output.

This means that current brake control systems cannot automatically compensate for factors not only unrelated to the vehicle, such as variations in track gradient, but also related to the vehicle, such as degradation of braking force, wheel slipping.

Fig. 1 Structure of general brake control system in current railways
2.2 Tracking control by train deceleration feedback

We previously proposed a closed-loop structure system as Deceleration control [2] (Fig. 2). In the previously suggested method, train deceleration is fed back to the controller and the brake control system tries to adjust the train deceleration to the demanded level defined by the brake command under any situation. (In practice, the applied feedback deceleration can be calculated from the train speed which can be measured even with the existent system.)

In this method, the target deceleration is defined by the brake command selected in the driving cab. The controller decides the controlled brake command based on the difference between the target deceleration and the measured train deceleration. The existent open-loop brake control system (shown in Fig. 1) can be used without modification. Compared to the current system, the only difference with the proposed method, is that a controlled brake command is substituted for the original brake command selected in the driving cab. We carried out running tests using rolling stock equipped with the system. As a result, the braking distance became more stable [2]. This paper describes how the previously developed deceleration control can be applied.

The problem with the previous deceleration control method, was that it could not reduce the increase in braking distance when the brakes suffered temporary degradation. Figure 3 shows an example of an increase in braking distance using the previous deceleration control. In the example, the train deceleration is restored to the target value by the controller after dropping temporarily. However, the braking distance increases because it is the second order integration of deceleration. This suggests that brake commands need to be updated in order to compensate for the increase in braking distance, similar to that encountered with the open-loop system.

3. Deceleration control based on the braking distance

This study therefore explains how we improved the previous deceleration control to prevent braking distance from increasing in case of a temporary drop in train deceleration.

The newly proposed control deceleration based on the braking distance, where the target deceleration is updated successively and automatically based on braking distance. Hereinafter, the proposed method is referred to as “Distance-based deceleration control”.

The symbols and the units used in the following are defined in Table 1.

3.1 Target deceleration based on the braking distance

Braking distance \( S_n \) between the train speed \( v_i \) and \( v_f (v_i>v_f) \) with the constant deceleration \( \beta_n \) can be calculated by (1):

\[
S_n = \frac{v_i^2-v_f^2}{2\beta_n} + \frac{v_f}{3.6} t_r
\]

where the second term on the right side means running distance during the free run time (so-called the response time) \( t_r \) which is from the time brake is initiated to when the braking force is fully established. We can set \( v_f = 0 \) if \( S_n \) considers the stopping distance.

Then \( S_n \) considers the ideal braking distance when the demanded deceleration is always equal to constant \( \beta_n \). So we consider the \( S_n \) as the target braking distance (Fig. 4(a)).

The actual braking distance during braking \( S \) can be calculated by (2):

\[
S = \int v \, dt (= \sum (v \cdot \Delta t))
\]

where \( v \) is instantaneous speed and \( \Delta t \) is a sampling period of the controller.
In the end, the target deceleration based on the braking distance $\beta_d$ can be calculated by (3) and Fig. 4(b):

$$\beta_d = \frac{v^2 - v_f^2}{2(S_N - S)} \quad (3)$$

The term $S_N - S$ included in the denominator of the right side in (3) is considered as the remaining distance to the target. Therefore $\beta_d$ is considered to be the demanded deceleration to reduce the speed to the target $v_f$ over the remaining distance to the target. In this paper, we define a new algorithm for Distance-based deceleration control (shown in Fig. 5), in which the target value in the previous method (shown in Fig. 2) is replaced by $\beta_d$.

Equation (1) (2) and (3) are procedures for calculating target braking distance according to the initial braking speed $v_0$ and calculating the target deceleration based on braking distance by the controller itself. The proposed approach operates as TASC if the target braking distance is directly set.

3.2 Structure of the controller

In the controller of the proposed method, the input is the error between the target deceleration based on the braking distance and the measured train deceleration and the output is the controlled brake command. The inner structure of the controller is shown in Fig. 6. It consists of a PI controller and a Smith compensator, which is one effective approach for controlled objects with the dead time.

The parameter tuning of PI is made easier by the Smith compensator which estimates the output from the object by means of numerical models and cancels out the effect of the dead time. In this paper, the controlled object is equivalent to the part which has the brake command as input and the measured train deceleration as output (surrounded part by blue dotted line in Fig. 5). We model the object as the simple first-order lag system.

4. Running test

The proposed method can be applied to some types of trains,
such as EMU, DMU, and hauled train by locomotive, which have continuous brake system.

In this paper, running tests were carried out on the test track in Railway Technical Research Institute (RTRI) using a full-scale EMU in order to verify the proposed method.

4.1 Test condition

The test train was EMU consisting of two cars, one was a trailer (Tc car), the other was a motor car (Mc car) in the configuration shown in Fig. 7.

The Distance-based deceleration controller was installed on the Tc car, and the output of the tacho generator of the Tc was fed back as wheel circumferential speed as an input. The controlled brake command, which is the output from the controller, was converted into command signals (current value) to pneumatic control valves to be passed on to the brake cylinder (BC) pressure generator. The devices were installed on the test train as a function that can control the BC pressure independently of the original brake control system that usually operates by the demand of the driving cab. For the controlled brake command common to the Tc and Mc, the load-compensating function that changes the BC pressure for each vehicle according to the own payload was integrated into the software as part of the signal conversion function.

In addition, photoelectric sensors were installed under the floor of the Tc, and reflectors were fixed on the track. The brake command was automatically initiated when the sensors detected the passage if the train over the reflectors, ensuring that the brake initiation point was fixed. Since the driver manually operated the test train up to this braking initiating point, initial braking speed differed in each test.

4.2 Controller setting

In this paper, brake tests were carried out by means of following three type control methods; the Distance-based deceleration control is referred to as the proposed method, the previous deceleration control is referred to as the previous method and open-loop control which keeps BC pressure constant is referred to as the open-loop method. In addition, TASC simulation tests were also carried out under conditions where the target braking distance was fixed regardless of initial braking speed by means of the proposed method.

The proposed method can utilize the controller same as the previous method with the inner structure and set values (the proportional gain and the integral gain, the constant of the first-order lag model of the Smith compensator and the dead time.) In both methods, we set controlled brake commands with the common specification, in which the demanded deceleration (4.32 km/h/s) of the full service brake of the test train was evenly divided into 21 notches.

In addition, the following conditions were set to alleviate uncomfortable impact immediately after the start of braking and immediately before stopping.

(i) Feedback was not active during the 1.0 s after braking started, which ensured that all three methods applied the same operation.

(ii) In the previous method, the target value given to the controller was set as a constant value after (i) and until the train came to a stop.

(iii) In the proposed method, after passing the period specified in (i), the target value was successively updated according to the procedure shown in Section 3.1 until the train speed was reduced to 3 km/h. Then the target value was fixed to the same constant value as in the previous method.
The degraded braking force condition was also set as a disruption to braking. Under this condition, when the train speed fell below 20 km/h, the braking force was intentionally degraded by completely exhausting BC pressure in the second axle in the direction of travel on both the Tc and Mc. Therefore, the braking force of the test train would theoretically decrease by 25%. Figure 8 shows the difference in responses expected depending on the applied control methods. In the open-loop method, deceleration remained low unless the brake command was re-selected. In the previous method, even when deceleration was restored to the target value after a transient response time by the controlled brake command change, the target value remained the same as before the decrease in deceleration. On the other hand, in the proposed method, in order to compensate the decrease in the train deceleration and the increase in braking distance due to the transient response time of the control, a higher target value was set and tracking control was achieved.

4.3 Result

Figure 9 shows an example of the proposed method under degraded braking force conditions, where the demanded deceleration was 1.5 km/h/s. Measured deceleration shown in figures was detected by the transducer installed on the floor of the Tc.

Immediately after the start of braking, as the measured deceleration overshot the target value, the subsequent target was smaller than the demanded one. Since the measured deceleration decreased because of a degradation in braking force when the train speed fell below 20 km/h, the measured deceleration was made to follow the updated target value which was larger than the demanded value to compensate the increase in braking distance. As a result, the measured braking distance calculated by time integration of train speed was 91.82 m, whilst the target braking distance from the measured initial speed 30.17 km/h to stopping with 1.0 s free run time and 1.5 km/h/s demanded deceleration was 91.83 m. (In this paper, the target deceleration smaller than the demanded one was allowed, as priority was given to the accuracy of braking distance. When a braking distance shorter than the target was allowed, for safety reasons the lower limit of the target deceleration was set as the demanded value.)

Figure 10 shows measured braking distance for each initial braking speed. The target braking distance in the figure was the theoretical stopping distance with 1.5 km/h/s deceleration after 1.0 s free run time from each initial speed. The assumed braking distance under the braking force degraded condition were theoretical values calculated with a deceleration of 1.125 km/h/s (25% drop of 1.5 km/h/s) below 20 km/h or less. In the proposed method, the measured braking distance almost matches the target one even under the braking force degraded condition and almost matches the fixed target deceleration. Therefore, the braking distance was accurately controlled.
get braking distance under the simulating TASC condition.

Figure 11 shows the error between the target braking distance and the measured one for each control method. Here, positive values mean that the measured braking distance exceeded the target.

In the open-loop method, the constant BC pressure is generally set so that the train can stop before the target braking distance to make an allowance for a safety margin. In our experiments, the test train stopped before the target braking distance even with degraded braking force, but it was extended by 8.40 m (mean value) compared to when braking force was not degraded.

In the previous method, the measured braking distances were closer to the target one compare to the results of the open loop method, and the increase in braking distance with degraded braking force was also reduced to 3.24 m (mean value) compared to when braking force was not degraded.

In the previous method, the measured braking distances were closer to the target one compared to the results of the open loop method, and the increase in braking distance with degraded braking force was also reduced to 3.24 m (mean value). However, in the previous method, the controller does not have a structure that can take into account errors in braking distance. Therefore, in order to further improve the accuracy of braking distance, it is necessary to tune the gains of the controller to make the measured deceleration follow the target value more strictly.

On the other hand, in the proposed method, the accuracy of braking distance was improved by successively updating the deceleration target value. As a result, it is possible to suppress the increase in braking distance to 0.16 m (mean value) braking force is degraded, although the controller settings are the same as in the previous method.

5. Conclusions

This study proposes a Distance-based deceleration control with the addition of a function to successively update the deceleration target value based on the braking distance in order to stabilize braking distance of rolling stock. The method improves the previously developed Deceleration control by adding a train speed feedback loop to the current brake control systems, which consists of an open-loop structure designed to track a certain target value.

Running tests using a full-scale test train confirmed that the proposed method ensured a high of accuracy in braking distance even when the braking force suffered temporary degradation.

In the proposed method, the controller utilizes deceleration which is differential value of the train speed and the braking distance which is the integrated value of the train speed. Therefore, we expect that the accuracy of the train speed greatly affects the control performance.

In this study, the output of a tacho generator of a specific axle in the train is fed back as the train speed. The circumferential speed of an axle may differ from the true train speed (ground speed) due to wheel slipping and differences of wheel diameters. In addition, tacho generators have the property that the output voltage drops at lower speed ranges, due to its structure.

In future, we are going to try to verify the effect of accuracy of train speed on the performance of the controller and try to improve the stability of the proposed method by means of the following:

- a method for selecting representative values from circumferential speeds acquired from several axles to ensure redundancy,
- a method able to acquire ground speed regardless of circumferential speed.

In addition, we are pursuing studies to adapt these findings for practical application, such as tuning control parameters to alleviate impulses in consideration of ride comfort.

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