Improvement of Response and Efficiency of Railway Air Brake System by Modifying Software for Control

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Air brake systems are essential for the safety operation of railway vehicles. However, a certain amount of time is required to distribute compressed air through the pipe so that the brake cylinders fill. It is considered a more efficient system would produce significant benefits for safety, robustness, saving energy and labor for maintenance and so on. This study therefore proposes a new method for reducing response time of the system for supplying the compressed air, by controlling wheel slide protection (WSP) dump valves installed in recent railway vehicles. Attempts were also made to reduce air consumption in the air braking system, focusing on cases where a WSP system is applied. The benefits of the new approach were verified through actual railway vehicle tests and hybrid simulation method, etc. Results demonstrated that the proposed method reduced the response time and air consumption, and improved braking performance.

**Keywords:** air brake, air consumption, idle running time, wheel slide protection

1. Introduction

Recently, railway vehicle braking systems are designed to save energy and maintenance, leading to a preference for regenerative braking for electric railcars, and engine and hydro-dynamic brakes for diesel railcars. However, considering the possibility of these brakes failing to function effectively during a power outage or other emergency, air brakes, which use compressed air to press frictional material onto wheel treads or brake discs to produce a braking effect, are still considered an important system for stopping trains completely and safely.

In this context, this paper discusses methods for improving air brake response times and efficiency by upgrading the current software used in existing relevant vehicle systems. Specifically, this paper proposes one method for reducing the response time using WSP (wheel slide protection) dump valves and another method for reducing air consumption through WSP control, to save energy.

2. Air brake system for railway vehicles

Figure 1 illustrates an example of the standard compressed air system for railway vehicles. Air generated by the air compressor is stored in the main reservoir from which the compressed air is supplied through main reservoir pipes to relevant equipment installed on the train set including air brake, air springs for supporting vehicle bodies, and door operating equipment. Use of compressed air has been growing because of vehicle body tilting control and vibration damping systems for ride comfort, and with that, the volume of air required to operate these equipment has been increasing.

The air brake system is equipped with supply reservoirs and air reservoirs for the security brake, each with a dedicated check valve, to secure enough compressed air for braking in the event of the loss of main air reservoir pressure due to train separation or other emergencies.

Nowadays, many railway vehicles are equipped with the electric command brake system, which uses a BCU (Brake Control Unit) to convert driver inputs or electric command signals from the ATC, or other safety systems, into air pressure which is then distributed in the system. The BCU consists of a series of components including the followings:
- A brake electric control unit, which sends and receives electric signals, computes braking force and fulfills other functions.
- A load weighing valve detects air spring pressure.
- An electro-pneumatic valve and an emergency electromagnetic valve, both to send out compressed air based on electric signals received.
- A relay valve amplifies these pilot pressures before distribution.

The compressed air from the BCU is distributed to the bogies and brake cylinders through piping in the vehicle and further through the WSP dump valves near the bogies.
3. Improving responsiveness air brake

3.1 Higher responsiveness for enhanced braking performance

Out of braking time, the time having elapsed from a brake command until the specified degree of braking force starts being applied is defined as idle running time [1]. The specified degree here is not a uniquely defined concept, and idle running time can be determined in various ways, one of which is based on velocity waveform during braking [2]. By reducing idle running time through improved responsiveness, running distance (idle running distance) during idle running time is shortened, with the resultant effect being proportional to the initial braking speed.

This paper describes a study in which air brake responsiveness was evaluated in a stationary state. For that reason, idle running time was determined based on brake cylinder (BC) pressure [3], a method considered empirically almost equal to the velocity waveform-based method mentioned above, while a time constant representing the time that is required for BC pressure to reach 63.2% (= 1-e^-1) of a set point after receiving brake command input was used as the parameter for idle running time.

3.2 Factors impacting responsiveness and methods for improving responsiveness

With the standard air brake system shown in Fig. 1, the pilot pressure generation process for the service brake is different from that for the emergency brake while these brakes share a common circuit downstream of the relay valve. On the latest vehicles, the valves have been reduced in size and housed in mounting seats within a compact, one-piece BCU housing, and the volume of valve elements and interconnecting air lines has been reduced.

An air piping model, shown in Fig. 2, equivalent to that of a certain vehicle model was produced. The air pipe lengths and the arrangement of the piping equipment was based on that of the equivalent vehicle model. Actual parts were used for some of the components, including the BCU, (part of) the foundation brake rigging. On this air piping model, Fig. 3 shows BC pressure response during magnet valve-controlled braking that corresponds to emergency braking of 1067 mm gauge line trains. The time constant was 0.31 seconds at the relay valve outlet and 1.09 seconds at the circuit end. With the time constant at the circuit end more than three times greater than that at the relay valve outlet, it was presumed that the time taken to pressurize the circuit located downstream from the relay valve might account for a great portion of idle running time.

Then, assume two tanks connected to each other, one larger than the other. The larger tank is positioned up
stream from the smaller tank as shown in Fig. 4. The time taken for the downstream tank pressure to become equal to the upstream tank pressure after (A) is opened is expressed using (1) quoted from the reference [4]. (The numbers in (1) are in SI units whereas the corresponding numbers in the original equation are not.)

$$t = \left( 1.285 - \frac{101.3}{P_n} \right) \times 5.23 \times \frac{V_s}{S} \times \frac{1}{R} \sqrt{\frac{273}{T}}$$

(1)

Fig. 2 Configuration of equivalent air piping model

Fig. 3 BC pressure response in equivalent air piping model

Fig. 4 Tank pressurization

where \( t \) is time (s) taken for the downstream tank pressure to become equal to the upstream tank pressure; \( P_n \), upstream pressure (kPa); \( V_s \), downstream tank capacity (l); \( S \), sectional area (mm^2) of connection pipe; \( n \), specific heat ratio (1.4 for standard atmosphere); and \( T \), temperature (K). Upstream tank capacity \( V_{in} \) was ideally set at \( \infty \).

Based on the relationship defined above, shortening tank pressure equalization time, or improving responsive-ness, can be achieved by (a) increasing the upstream capacity and pressure, (b) increasing the connecting pipe diameter or (c) decreasing the downstream capacity. Achieving option (a) on actual vehicles on which (A) is the relay valve
3.3 Improving air brake responsiveness by using WSP dump valves

WSP dump valves are positioned near the bogie and consist of a pair of valves - a halt magnet valve (HV) and a release magnet valve (RV) - per axle. By combining the operations of these magnet valves, three statuses can be achieved: supply, exhaust and hold (Table 1). Energizing an HV closes the air line to the BC. Using this characteristic, the control software is modified to change the brake command procedures as follows (Fig. 5).

(1) The HV is energized to close the air line to the BC before a command is sent to the electro-pneumatic change valve (or the magnet valve).

(2) When braking force starts being applied, the HV is de-energized to open the air line to the BC.

At the stage (1), the RV can be in any state. If it is anticipated that unintended air pressure may stay in the BC by any chance, the RV can be simultaneously energized to positively and completely release air pressure from the BC.

Table 1 Response of WSP dump valves to commands

| Halt magnet valve (HV) | Release magnet valve (RV) |
|------------------------|---------------------------|
| Energized              | Energized                 |
| Exhaust                | De-energized              |
| Hold                   | Supply (Restore)          |

Out of braking response time, these procedures are expected to help to reduce the time having elapsed from a brake command up to the time when the air circuit between the relay valve and the WSP dump valves is pressurized.

3.4 Response performance test

BC pressure response was measured using the following methods (Fig. 6).

(1) Conventional control method that corresponds to emergency braking for 1067 mm gauge line trains, using an equivalent air brake circuit

(2) Responsiveness improving method, using an equivalent air brake circuit

(3) Responsiveness improving method, using an actual vehicle

BC pressure was measured at two points, F1 and F2 in Fig. 2, at the brake cylinder inlet. As shown on the horizontal axis in Fig. 6, the start time for the method (1) was at magnet valve open command and that for the methods (2) and (3) was at HV de-energization command. There was no involvement of jerk control in these tests. As the control software for an actual vehicle restricts brake operation in relation to the safety system and other vehicle functions, the measurements using the method (3) were conducted in test mode whereby the WSP dump valves were energized and de-energized by one axle at a time. Pressure set points for measurement were about 700 kPa for the equivalent air brake circuit, and about 530 kPa for the actual vehicle due to load compensating control.

As shown by the results of measurements using the methods (1) and (2) on the same equivalent air brake circuit, the time constant in the conventional braking was 1.09 seconds whereas that in the braking using the responsiveness improving method was just 0.23 seconds. The time constant in the method (3) using an actual vehicle was also just 0.26 seconds, which are nearly equal to the time constant for the equivalent air brake circuit in measurements using method (2).

Comparison of the waveforms from methods (2) and (3) reveals that, while both the methods are designed for responsiveness improvement and have nearly the same time
constant, the transient response portions ((A) in Fig. 6) of the waveforms are different from each other. This appears to have been caused by the upstream flow having become full in the method (2) as the WSP dump valves on all four axles are energized at the same time whereas in the method (3), these valves are energized and de-energized one axle at a time. In Fig. 6, BC pressure dips a little in the portion (B) when the WSP dump valves on the adjoining axle are operated in test mode. This also appears to have been caused by restriction in the upstream flow rate.

3.5 Other applications of the responsiveness improving method

The proposed method for improving responsiveness uses the WSP dump valve that can be electrically controlled, and is positioned closest to the BC in order to shorten the time required for the compressed air to pressurize the circuit. The method is realized through modification of the control software. As for the method, the WSP dump valve is commanded to open or close the air line. Air pressure level still needs to be regulated through the control valves set in the BCU. This requires the braking force (notch) to be applied (selected) to be known before the proposed method is used.

In actual vehicles, there are instances where brake application is delayed until a judgment is made. On Shinkansen, for example, the power supply to overhead contact lines is suspended when there is an earthquake and trains apply the emergency brake and stop when they detect the power outage [5]. In that case, a delay is introduced between the voltage drop and the brake application to differentiate instantaneous power supply interruption due to the train passing a feed section or for other reasons [5]. The idle running time is then the sum of the delay and the time constant specific to the brake system. The proposed method of energizing and de-energizing the HV combined with a time delay feature similar to the Shinkansen’s offers a possibility to improve responsiveness of air brake (Fig. 7).

Simply improving responsiveness can generate shock loads from braking, negatively impacting ride quality and couplers and other equipment. Therefore, the method must be modified so as to eliminate such faults before being put to practical use.

4. Reducing air consumption for air braking

Brake cylinders may need to be made larger (volume increase) in the future to increase air braking force. However, the increased braking force may generate more wheel slides, resulting in higher frequency of WSP operation. These scenarios will likely lead to increased air consumption.

With that in mind, air consumption comparison between the slip rate WSP control method [6], which is one of the WSP control methods used in actual train operations, and the TL-type WSP control [7], which is an improved-deceleration version of the slip rate WSP, was made using a hybrid simulator consisting of an actual vehicle and simulation.

4.1 WSP control methods with less air consumption

4.1.1 Relationship between adhesion and braking force

The purpose of braking is to decelerate and stop translational motion of the vehicle. With the adhesive brake, which utilizes adhesion between wheels and rails, when braking force is simply increased or decreased while the train is slipping as shown in Fig. 8, effective braking force against translational motion stays within the adhesion limit for the period X during which braking force is greater than the adhesion limit, allowing the train to slip further. As the WSP control reduces braking force to the
extent that it is less than the adhesion limit, as in period Y, the braking force contributes to weakening translational motion, making the train slip less. Presuming that ideal brake control under such changing relationship between adhesion limit and braking force is to decelerate the train without causing it to slip while taking full advantage of wheel-rail adhesion, this can be expressed as continuously applying braking force that is equal to adhesion limit as shown in Fig. 9.

Furthermore, release is minimized by curtailing slide detection. Therefore, air consumption for WSP control is minimized by the following procedures:
- Controlling BC pressure to follow the adhesion limit curve as closely as possible
- Making slip less detectable while maintaining anti-wheel lock performance

**4.1.2 Slip rate WSP control method**

Figure 10 outlines slip rate wheel slide control [6] (hereafter SR-WSP), in which slip is handled in three states based on preset thresholds, namely "slide", "stay" and "re-adhesion (restoration)," while BC pressure is applied or released by the WSP dump valve operating according to state-specific rules. Slip is detected based on the logical sum of speed difference / slip rate detection (hereafter "ΔV detection") and deceleration detection (hereafter "β detection"). Speed difference ΔV (km/h) and slip rate η (%) are defined by (2) and (3) respectively.

\[
\Delta V = \text{Reference speed} - \text{Axle speed} \quad (2)
\]

\[
\eta = \frac{\Delta V}{\text{Reference speed}} \cdot 100 \quad (3)
\]

Reference speed indicates vehicle speed essentially. Either non-slipping axle speed or speed corrected for control application are practically substituted. In SR-WSP, a slip is processed as a complete cycle starting with generation, followed by attenuation and ending with re-adhesion, with the ultimate purpose of achieving re-adhesion without fail.

**4.1.3 TL-type WSP control method**

TL-type WSP control [7] (Fig. 11, hereafter TL-WSP) which is based on SR-WSP, is the one to be featured as follows:
(i) Uses estimated time up to wheel lock (\(T_L\)) (s) defined by (4) in place of \(\beta\) detection for slide detection.

\[
T_L = \frac{\text{Axle speed (km/h)}}{\text{Axle deceleration (km/h/s)}} \quad (4)
\]

(ii) Breaks up BC pressure release stages, and also sets a temporary-restoration point before re-adhesion and uses it as the phased supply start point.

(iii) Limits re-slips by applying pressure in stages during a restoration process from a slip.
Estimated time up to wheel lock, proposed in (i) above, is the parameter designed to secure enough time for BC pressure to be released completely before the wheel is locked. The control features (ii) and (iii) above are intended to prioritize hold and supply over exhaust in slips to maintain high BC pressure, which appears to be an effective strategy to prevent unnecessary exhaust and help reduce air consumption.

4.2 Air consumption measurement using an actual vehicle

4.2.1 Hybrid simulation

In hybrid simulation (Fig. 12) involving the RTRI type 291 test vehicle (hereafter “R291”), the volume of air consumed for WSP control was measured in a setup that considered a range of factors including foundation brake rigging and air piping length. With the R291, the auxiliary BC pressure generator can produce any BC pressure required for WSP control simulation. The R291 is equipped with air tubing, WSP dump valves and foundation brake rigging, all equivalent to actual vehicles, except that it has compressed air supplied from the main reservoir and double check valves positioned downstream from a relay valve. The simulation was conducted with no power applied on the vehicle while electric power and compressed air for measurement and control devices were provided from external sources.

Two simulators were used for the simulation. One is a vehicle dynamics simulator that computes each circumferential speed of axle and vehicle (translational motion) speed based on the actually measured BC pressure input, with the preset data containing specifications for foundation brake rigging including its cylinder diameter, brake block friction coefficient and vehicle weight. The other is a BCU simulator that executes WSP control based on simulated axle speed computed by the vehicle dynamics simulator at BC pressure generating command signal output.

Considering the capacity of the flow meter being used and the need to keep the air supply circuit from being restricted during braking, the flow rate of air exhausted from the WSP dump valves was measured as an indication of air consumption.

4.2.2 Simulation conditions

The simulation was conducted on a one-car Shinkansen train set using a BC pressure profile relative to train speed (Fig. 13). The R291, which was also involved in the simulation, was a 1067 mm gauge line unit which is different to the Shinkansen but shares some specifications including foundation brake rigging and air tubing length.

Adhesion limits, which could not be measured physically, were estimated by extrapolation of a function of the adhesion coefficient (Fig. 14). Adhesion limits were interpolated for other speeds as well while various adhesion coefficients were set up through a combination of sine waves and random numbers.

Table 2 shows the parameters used in the simulation of SR-WSP (hereafter “conventional control”) and TL-WSP (hereafter “proposed control”).
4.2.3 Test results

Hybrid simulation results are shown in Fig. 15 and Fig. 16. Figure 15 is an example of time-series charts while Fig. 16 indicates air consumption and mean deceleration.

In both the conventional and proposed controls, there was a trend that higher slip rates under the slide detection condition (hereafter detection slip rates) resulted in less air consumption. Figure 17 indicates that higher slip rates resulted in a lower number of slide detections, which implies that fewer detections correspond to lower air consumption. For the detection slip rate of 10 % or more, the proposed control achieved less air consumption than the conventional control, which releases and holds BC pressure longer than the proposed control, helping to reduce air consumption by the amount due to adhesion even with the conventional control, which releases with a slip rate of 8 % or less in Fig. 14) facilitating re-adhesion limit in the micro slip area (corresponding to the area of 5 %). This appears related to the relatively high adhesion control while in the proposed control, for which only β detections are shown, there was no wheel lock.

These results were reversed at the detection slip rate of 5 %. This appears related to the relatively high adhesion limit in the micro slip area (corresponding to the area with a slip rate of 8 % or less in Fig. 14) facilitating re-adhesion even with the conventional control, which releases and holds BC pressure longer than the proposed control, helping to reduce air consumption by the amount due to non-phased supply.

5. Conclusion

This paper proposes a method for reducing air brake response time using WSP dump valves and another for reducing air consumption in WSP control, in order to improve air brake performance by taking full advantage of the existing vehicle facilities and improving related software. For both methods, vehicles were retrofitted with WSP dump valves with control software modification. Simply improving responsiveness may generate shock loads from braking, negatively impacting ride quality inter alia. Further research will be conducted going forward to enable the proposals to be put to practical use while taking a closer look at possible effects, both positive and negative.

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