Performance of Linear Motor Type Rail Brake Using Roller Rig Test Bench

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1. Introduction

An intrinsic feature of eddy current rail brakes is that they guarantee a stable braking force unaffected by rail tread surface conditions, since they function without making contact with the rails. Application of such braking systems however gives rise to certain problems such as rail heating and difficulty in guaranteeing a power supply to energize the brake in the case of failure of the main train circuit. For these reasons, the system has not yet been commercialized in Japan [1]. A goal was therefore set to solve the problems related to use of eddy current rail brake systems, by applying linear motor technology [2, 3].

The proposed LIM-type rail brake includes an armature of linear induction motors (LIMs) instead of the DC-excitation-pole of the conventional system. The proposed rail brake generates braking forces by dynamic braking operation. This brake offers advantages, as illustrated in Fig. 1.

(1) For the same braking force, the increase in rail temperature in the case of the LIM-type rail brake is considerably less than that in the case of a conventional DC-type eddy current brake.
(2) The power required for excitation is obtained from the kinetic energy of the vehicle.

This paper describes the experimental verifications of the LIM-type rail brake system, which includes the armature and excitation system driven by “dynamic braking with zero electrical output.”

In order to generate power and maximize the braking force density despite the limited installation room on the bogie, studies were made to find a suitable design for the armature of LIM-type rail brake. To validate the proposed design, a prototype armature was constructed and its electromagnetic characteristics were examined on a test bench with a roller rig. These investigations revealed that the LIM-type rail brake could be applicable for practical use.

Keywords: rail brake, eddy current brake, linear induction motor, dynamic braking, rail heating

Fig. 1 Energy input and output in rail braking
2. LIM-type rail brake

2.1 Composition

In the LIM-type rail brake, an armature is installed in the bogie as shown in Fig. 2 and the rails used are assumed to be of a conventional composition. The armature consists of an iron core and a coil. An inverter device is installed in the car as a power converter for energizing the armature. A ring winding offering high electrical loading was adopted for the coil [4]. Given that existing rails are used as secondary conductors and have no design flexibility, the ring winding is the best means to obtain the maximum braking force with limited size.

Table 1 shows the specification of the LIM-type rail brake armature for a real machine. This specification is based on the short time rating S2 of the Japanese Electrotechnical Committee (JEC) [5]. The rating time was determined as the time needed to stop a train running at 160 km/h. It is assumed that the rail brake is fitted on 6 cars in a 9-car set (total weight 350,000kg).

Table 1. Performance demanded of a rail brake to be used in practice.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Demand</th>
</tr>
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<tbody>
<tr>
<td>Car speed</td>
<td>~160 km/h</td>
</tr>
<tr>
<td>Braking force</td>
<td>Over 10 kN / bogie</td>
</tr>
<tr>
<td>Reduction ratio of rail heating</td>
<td>Over 15%</td>
</tr>
<tr>
<td>Armature core length</td>
<td>1200 mm (typ.)</td>
</tr>
<tr>
<td>Armature core width</td>
<td>65-130 mm</td>
</tr>
<tr>
<td>Gap</td>
<td>Over 6 mm</td>
</tr>
<tr>
<td>Rating time</td>
<td>120 s (typ.)</td>
</tr>
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</table>

2.2 Excitation circuit and "dynamic braking with zero electrical output"

The main components of the LIM-type rail brake system are the armature and the power inverter. Figure 3 shows details of the excitation circuit including the power inverter. One car has two bogies and an armature is set to the right and left of each bogie, thus four armatures are fitted to one car. The front and rear bogies were equipped with armatures 1, 2 and 3, 4 respectively. The three-phase electrical circuit from the power inverter on the car was connected to the armature. The smoothing capacitor was connected with the power inverter in parallel and DC 100 V were supplied from the auxiliary circuit on the car to the power inverter as the control power source. Although the auxiliary circuit in this figure is assumed to be trouble-free, it is also possible to install a small Uninterruptible Power Supply (UPS) for the rail brake of each car. This configuration ensures that the LIM-type rail brake system is electrically separate from main circuit and can act as independent braking equipment.

By this excitation circuit configuration, when the power inverter receives the braking command, the power inverter provides a little initial excitation power (about 250 W, 0.4 s) from the auxiliary circuit to the armature. Once the rail brake activates the dynamic braking, the armature self-supplies itself excitation power. The time required for it to reach the regular braking force from initiation of excitation is two seconds or less, which is brief enough for train braking equipment.

The proposed LIM-type rail brake can be operated in four modes by selecting the excitation frequency: 1) dynamic braking with zero electrical output, 2) power generation braking, 3) excitation power decrease braking and 4) direct current excitation braking. Of these modes, only "1) dynamic braking with zero electrical output" provides braking independently of the main circuit.

3. Braking test on test bench with roller rig

3.1 Test bench with roller rig

The test bench with roller rig was used to examine characteristics of the rail brake device. Originally, this test bench was used for friction brake testing, such as tread braking. The rail brake is fixed to the ground side of the test stand and the roller rig is installed as the wheel for simulating the rail (Fig. 4).

The rail brake on the ground side has rotational degrees of freedom. The reactive force between the rail brake and the roller rig can be measured directly by a load transducer. The roller rig is connected directly to the flywheel and the motor of 350-kW through the axis. When a braking test is performed, the flywheel and the roller rig are rotated by the motor. The rail brake is excited as the roller rig rotates and the braking force under virtual vehicle running conditions is measured. Tests were performed with a roller rig of diameter 1,110 mm and virtual running of 0-300 km/h in circumferential velocity.
3.2 Rail brake armature prototype

The armature of the rail brake installed on the roller rig test bench was curved in shape. Figure 5 is an external view of the test stand, Fig. 6 is a diagram of the configuration of the armature and Table 2 shows the armature's specifications.

The ring winding of the copper rectangular wire was adapted to the basic armature configuration given the limited space for brake systems on the bogie. The core length of the armature was one quarter of the circumference of the roller rig. The number of poles could be varied by changing the connection of the coil terminals because the coil was a ring winding. In this report, the four poles where the maximum braking force could be performed are described.

When braking forces are generated, large normal forces are also generated between the roller rig and the rail brake. The roller rig can only rotate around its axis; therefore, the gap length does not change under these accompanying normal forces. The test bench was also equipped with a load transducer, temperature sensors, ammeters and voltmeters.

3.3 Power inverter and controller

A specialized power inverter with a rating capacity of 90 kVA and rating voltage DC 600 V was used for the "dynamic braking with zero electrical output" braking tests. A power source of with a rating output of 300 W and rating voltage of DC 100 V was used as the above mentioned auxiliary circuit and was connected to the power inverter through the diode. This power source was utilized as both an initial excitation power source and control power source for the inverter. The analog signals of the frequency command and the output voltage command were output from the external controller. The power inverter received these signals and generated the PWM waveform voltage corresponding to the command.

<table>
<thead>
<tr>
<th>Table 2 Specification of the armature</th>
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<tbody>
<tr>
<td>Core</td>
</tr>
<tr>
<td>Width</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Slot</td>
</tr>
<tr>
<td>Width</td>
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<td>Depth</td>
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<td>Pitch</td>
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<td>Pole</td>
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<td>Pitch</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Gap</td>
</tr>
</tbody>
</table>

278 kg

6.5 mm

Fig. 6 Configuration diagram of the armature

Auxiliary circuit (DC 100V)
The rated output current of the power inverter was 100 A. Figure 7 shows the test control system diagram. Excepting “dynamic braking with zero electrical output” test, the external controller is not needed and a general-purpose power inverter with an output current of more than 350 A can be used for maximum braking force tests.

4. Test results

4.1 Braking force

Figure 8 shows the test results in which the braking force at each speed was measured on the test bench with a roller rig. The braking force of the rail brake achieved the target braking force of 10 kN/bogie in the 50-300 km/h speed range. The threshold limit values of adhesive braking force, generated by the wheel and rail are also shown in the figure. Braking force in adhesive braking decreases as train speed increases, whereas with rail braking, it does not. This is a specificity and advantage of rail braking. These tests confirmed that the braking force of the rail brake achieved target values and demonstrated the higher performance of non-adhesive braking over adhesive braking in the high-speed range.

![Fig. 8 Braking force](image1)

4.2 Brake control of “dynamic braking with zero electrical output”

Figure 9 shows the start-up control test of “dynamic braking with zero electrical output” in which the roller rig was rotated at simulated speed of 160 km/h. Armature current was increased in line with the brake command and a braking force was generated. The braking force stabilization time was approximately 1.4 s and satisfying the required specification. The DC voltage was also increased satisfactorily. A stable control of “dynamic braking with zero electrical output” was achieved. In addition, the electric power of the auxiliary circuit was measured under various conditions so that the first momentary control power for the start-up was 50-250 W and 0.2-0.4 s. This level of electric power is within the range which can be covered with an auxiliary circuit or a small storage battery.

The inertia moment of the flywheel connected directly with the roller rig was set to the value corresponding to the inertial mass of the railway vehicle. The result of the “dynamic braking with zero electrical output” brake control test by is shown in Fig. 10. The initial moment of the flywheel was set to be 969 kgm² simulating the 40,000 kg of a vehicle’s inert mass equipped with four rail brake armatures. The roller rig was rotated to simulate a speed of 160 km/h. Within one second from commencement of free-running, a brake command of 100 A in current was applied to the external controller and the rail brake. In this brake control test, a constant deceleration was performed with stable values of output current at 100 A, braking force 1.5 kN and DC voltage 600 V. With regard to the braking force of this rail brake, there was a gradual peak at around 100 km/h and the braking force slightly increased with deceleration. When the simulated speed of the roller rig fell to under 50 km/h, the brake control stopped by virtue of the decrease in the DC voltage because power available was insufficient. Under real conditions, a vehicle would be decelerated at this speed with a mechanical brake such as a tred brake after the rail brake control stopped.

In this brake control test, the external controller was operated only by the control values corresponding to the

![Fig. 9 Start-up control test](image2)

![Fig. 10 Braking control test for “dynamic braking with zero electrical output”](image3)
impedance of the armature at the simulated speed of 160 km/h, without certain types of information such as sensed speed. Tests therefore confirmed that the control system using "dynamic braking with zero electrical output without speed sensor" could be achieved.

4.3 Reduced rail heating

Rail heating was estimated from the temperature rise of the roller rig in the braking tests. The inertial moment of the flywheel was set to an equivalent value of 40,000 kg of inert vehicle mass with four rail brake armatures. The temperature rises in the roller rig during deceleration produced by rail braking at simulated speeds of 65-30 km/h were measured. Figure 11 shows the maximum temperature rise during roller rig deceleration under the same average braking force with different excitation frequencies. Since the roller rig not the same as an actual rail and the same longitudinal section is heated repeatedly during braking tests, the test speed was limited. For the same reasons, absolute temperature rise values were not same as would be with an actual rail. The authors therefore evaluated the rail temperature rise through relative values based on the DC excitation modes for which temperature rises were the greatest. In these tests, because of the power inverter limitations, the direct current excitation was substituted by 1 Hz alternate current excitation called "DC excitation mode."

Figure 11 shows confirmation that the temperature rise of the roller rig is actually curtailed under dynamic braking. "Dynamic braking with zero electrical output" regulates the low frequency to balance the generated power and the armature copper losses. On the other hand, in case of the active dynamic braking, this type of rail braking helps to decrease roller rig temperature by about 50%. This confirms that LIM-type rail braking is effective in reducing rail heating.

5. Conclusion

Conventional rail braking raises certain problems such as it cannot operate when the main circuit on a train fails and can contribute to generating high rail temperatures. The authors therefore proposed the LIM-type rail brake, which resolves the problems found in conventional rail braking. This rail brake can reduce the rise in rail temperature rise by adjusting the frequency of the current to the armature. By using small an electrical power source to start braking, the rail brake generates the subsequent required power itself by virtue of dynamic braking and so no power source is needed to actually operate the rail brake. These methods overcome the problems caused by traditional rail braking.

The authors manufactured a full-scale rail brake prototype. Ring-winding was adopted in the armature used for investigations to attain the maximum braking force within a limited space. This rail brake prototype was tested with simulated running speeds up to a maximum of 300 km/h on a test bench with roller rig. The following results were obtained:

(1) It is proven that the target braking force of 10kN/bogie can be generated at a simulated running speed of 50-300 km/h.

(2) It is confirmed that the predetermined braking force is reached within two seconds, using only the auxiliary circuit.

(3) By using "dynamic braking with zero electrical output," the rail brake maintains a braking force within running speed range of 300-50 km/h, without either information from outside the inverter such as from speed sensors or the power supply from the main circuit.

(4) It is confirmed that rail heating is reduced by a ratio of 50% or more according to the temperature measurements taken on the roller rig while using the LIM-type rail brake.

The authors shall develop a "LIM-type rail brake" for application to a real bogie, based on the results of tests performed on the braking test bench with roller rig.

References


