Development of a Rail Brake Derived from Linear Motor Technology

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Studies have been carried out on a rail brake developed by applying a linear induction motor technology, called LIM-type rail brake. This brake is capable of generating braking forces without contact. In addition, this method decreases the rise in rail temperature, and on-board supply of electric power is not required by using dynamic braking. It is however necessary to install this brake in the limited space between front and rear wheels of the bogie. A prototype rail brake system was designed and built and its electromagnetic characteristics were examined on a test track in RTRI. These investigations revealed that the LIM-type rail brake could be applicable for practical use.

Keywords: rail brake, linear induction motor, prototype

1. Introduction

Eddy current rail brakes on rolling stock can generate non-contact braking forces that do not depend on the adhesion between wheels and rails [1]. Rail brakes however do have some advantages: one is a smaller decrease in braking force during high velocity running, while the adhesion braking force displays drooping characteristics along with increases in velocity; the other advantage is that the magnetic attracting force generated with the braking force can increase the contact pressure between wheels and rails resulting in an increase of adhesion braking force.

Applying the linear induction motor (LIM) technology to eddy current rail brakes makes it possible to energize the rail brake during malfunctioning of the feeder circuit, limiting the rise in rail temperature and enabling effective braking in an emergency, including during earthquakes. Stationary tests on a roller rig were carried out to determine the new design’s thermal and electromagnetic characteristics for speeds up to 300 km/h, to confirm the excitation system and its control method. The results demonstrated that in practice it met with design criteria [2]. In the subsequent study presented in this report, results of trials carried out on a prototype of the linear-motor-type (LIM-type) rail brake fitted to an actual railway vehicle-bogie and subjected to braking tests on tracks in a yard are described, and design considerations for practical use are discussed.

A bogie that had been used in revenue service was modified to produce a test bogie, and a prototype of LIM-type rail brake which was considered for installation in the test bogie was built. A control method for an excitation system shown in reference [2] was improved for practical use. These were installed in the test vehicle R291 [3], which was subjected to braking tests on yard tracks and the characteristics were evaluated.

This article reports on design considerations of the LIM-type rail brake, and the results of braking tests on yard tracks.

2. Outline of LIM-type rail brake

2.1 Armature

The LIM-type rail brake uses an armature of LIMs in place of the excitation pole of the conventional eddy current brakes. Figure 1 shows the composition. A support assembly for armatures is omitted in this figure. To install the armature in the limited space between the wheels, it is assumed that the armature core length and width are about 1.2 m and 0.065 m, respectively. “0.065 m” is width of the rail head on Japanese main lines. As mentioned previously, the air gap into which an electrical machine must fit is small and narrow. Since the secondary side is furthermore a bulk-iron rail, the composition is generally not conducive to good performance as an electric machine. The air gap is assumed to be 6 mm, on the condition that the bogie has a support assembly that can be lifted up when not being used, and lowered when being used. Under these restrictions, the target braking force is 5 kN per armature, 10 kN per bogie, for dynamic braking in the speed range of 50-300 km/h. A ring-winding armature was studied, and found to be an adequate armature that can generate this target braking force under such restrictions.
2.2 Excitation System

The LIM-type rail brake is equipped with a VVVF inverter as an excitation system for dynamic braking. Using an excitation circuit which depends on a feeder for the inverter control reduces its reliability as a brake system since the excitation circuit can encounter feeder malfunctions or regeneration cancellation. Consequently, the proposed excitation circuit is not connected to a feeder, and uses an auxiliary power supply as an energy source for initial excitation and as a power supply of inverter control. Figure 2 shows an example of such an excitation system for an LIM-type rail brake which is fixed to one car and two bogies. When triggered by a brake command, the inverter starts using the voltage of the auxiliary power circuit thereby immediately increasing the DC voltage of the smoothing capacitor by relying on the generated power. After reaching a preset DC voltage, it maintains the DC voltage required for its rated operation while maintaining the braking force by controlling and balancing the power generated and power required for excitation. In this operation method, the inverter works at high slip-frequencies, namely at low excitation-frequencies, and balances the generated power and the armature ohmic loss without making use of a braking resistor.

![Figure 2](image_url)

**Fig. 2** Example of an excitation system of a LIM-type rail brake

2.3 Dynamic braking with zero electrical output

In the steady state of dynamic braking described above, the inverter has to control the charge-discharge power of the smoothing capacitor, and maintain a preset DC voltage. Therefore, the inverter has to control the active power that is transmitted between the AC and DC side, so that it converges to a zero value, and has also to supply the armature with reactive power simultaneously. In this article, this control method is called the “dynamic braking with zero electrical output” since the excitation system using this method does not depend on a feeder circuit for energizing the inverter and for dissipating of generated power, the system is not affected by feeder problems and cancelled regeneration. This system can therefore serve as a braking system independent from existing systems with the added merit of using non-adhesive forces. (See Table 1)

3. Design considerations

3.1 Requirement specifications

Here is an example of the requirement specifications for an express train model for operation on a Japanese meter-gauge line (3 motor cars, 6 trailer cars, and total weight of 350 tonnes).

- **Velocity**: 160 km/h or under,
- **Braking force** $F_r$: 5 kN per armature and over,
- **Reduction ratio of rail-heating** $\eta_r$: 18% and over (velocity dependence),
- **Armature core length** $l$: 1000-1200 mm,
- **Gap length** $g$: 6.5 mm,
- **Rated time** $t_{rated}$: 120 s,

where “reduction ratio of rail-heating” means the reduction rail heat compared with conventional rail brakes generating the same braking force. “Rated time” is defined as the required time for stopping the train using the braking force of LIM-type rail brakes alone, in which it is assumed that only 6 trailers of the train set have the rail brakes.

The short time rating $S_2$ specified in JEC-2137 [5] (Japanese Electrotechnical Committee) for induction machines is adopted as the limit for admissible temperature rise in the armature.

3.2 Armature

The excitation system using the “dynamic braking with zero electrical output” disposes of the kinetic energy of a vehicle as armature copper loss. This means that the armature also plays the role of a braking resistor. The design method of the armature in accordance with this system is shown below [6].

First, the mechanical input $P_m$ of the LIM-type rail brake is derived from the requirement specifications, and the armature copper loss $P_{arm}$ which equals the electric energy for energizing the brake, is calculated using the rail heat reduction ratio $\eta_r$:

$$ P_{arm} = P_m\eta_r = vF_r\eta_r. $$ (1)

Since the armature copper loss $P_{arm}$ is set to relatively high values in “dynamic braking with zero electrical output”, the temperature of the armature winding can be con-
sidered to rise while neglecting the heat radiation.

Under conditions of the rated time $t_{\text{rated}}$ and of the temperature rise limit $\Delta T_{\text{max}}$, the maximum current density $J_{\text{max}}$ and the minimum conductor mass $G_{c_{\text{min}}}$ which can be chosen are calculated as follows,

$$J_{\text{max}} = \frac{w_i C_s A \Delta T_{\text{max}}}{\rho_l J_{\text{rated}}} \quad (2)$$

$$G_{c_{\text{min}}} = \frac{w_i P_{\text{max}}}{\rho_c J_{\text{max}}} \frac{P_{\text{loss}}}{C_s A \Delta T_{\text{max}}} \quad (3)$$

where $w_i$ is specific gravity of the conductor; $C_s$, specific heat of the conductor; and $\rho_c$, resistivity of the conductor.

However, if the power factor of a circuit including both an excitation circuit and secondary circuit in a T-type equivalent circuit, called an equivalent secondary circuit, is represented by $\cos \phi_{2e}$, the apparent power $P_{2e}$ of the equivalent secondary circuit is obtained by the following formula:

$$P_{2e} = \frac{P_{\text{loss}}}{\cos \phi_{2e}} \quad (4)$$

In the excitation system using “dynamic braking with zero electrical output”, the number of poles $N_p$ and frequency $f_0$ are configured so that the synchronous watt equals the above-mentioned armature copper loss $P_{\text{loss}}$.

If the pole pitch $\tau$ is set to $b/N_p$, where $b$ is the armature core length, the frequency $f_0$ is obtained by the following formula:

$$f_0 = \frac{N_p P_{\text{loss}}}{2IF_0} \quad (5)$$

The specific capacity $S_{2e}/f_0$ of the equivalent secondary circuit is calculated from these parameters.

$$S_{2e}/f_0 = \frac{P_{2e}}{N_p f_0} = \frac{2IF_0}{N_p^2 \cos \phi_{2e}} \quad (6)$$

Here, if the magnetic flux density distribution in the air gap is assumed to be a sine wave in the direction of movement and average specific magnetic loading over the iron core width $b$ is set to $B$, the magnetic loading $q$ is given by the following formula:

$$q = \frac{2lnb}{\pi N_p} \quad (7)$$

The required electric loading $A$ and the specific electric loading $A$ are obtained by the following formula:

$$A = \frac{S_{2e}/f_0}{K_0} \quad (8)$$

$$A = \frac{\pi F_0 B}{K_0 h B \cos \phi_{2e}} \quad (9)$$

$$K_0 = \frac{\pi}{\sqrt{2}} k_4 k_p \quad (10)$$

where $k_4$ is a distribution factor and $k_p$ is a short-pitch factor of the winding arrangement. When the winding is arranged so as to be the distributed winding of the full-pitch in which the number of slots per pole and phase is about 2-3, then $K_0$ is about 2.1.

It is possible to design a specific arrangement of the armature with due consideration on the specific electric load-

In a high-speed range, the difference of performance is small.

Fig. 3 Graph showing the relationship between iron core weight and performance.
for accepting the magnetic loading. This electric loading is slightly larger and the magnetic loading is slightly smaller than the above-mentioned ones.

### 3.3 Control method of the excitation system

An excitation system performing “dynamic braking with zero electrical output” controls the braking force and DC voltage of an inverter. The slip-frequency in which LIM-type rail brake performs is completely different from that of a vector control and slip-frequency control for conventional induction motors. Wherein, a simple control method, shown in Fig. 4, was proposed, and it was demonstrated that the control method could be used in practice [4]. In this proposed control method, the braking force is controlled only by the output current, and the output DC voltage is controlled by the frequency.

In Fig. 4, the input part of the current command $I^{*}$ is provided with a pattern generator $P(I^{*})$. This pattern generator limits an initial excitation power $P_{in}$, that is provided by an auxiliary circuit during the start-up. The principle of power limitation is based on the management of the transient start-up state, in which the secondary current and the secondary flux have not risen while the primary current has. In concrete terms, the pattern generator generates the current command for the start-up $I_{up}$ by adding a new current command that performs like a ramp function to the current command $I^{*}$ for a least 1 second. In this process, the rate at which time changes in the current command for the start-up $I_{up}$ is adjusted to the maximum admissible value since the initial excitation power $P_{in}$ is proportional to the time rate of change in $I_{up}$. Additionally, the pattern generator calculates the maximum current command $I_{max}$ by referring to the DC voltage $v_{dc}$. The current $I_{max}$ can be output during a time $\Delta t$ only by using the stored energy of the smoothing capacitor that is charged by the difference in voltage $v_{dc}-v_{dc,max}$ between the auxiliary circuit voltage $v_{dc,max} (= 100 \text{ V})$ and the DC voltage $v_{dc}$.

$$\frac{1}{2} c (v_{dc}^2 - v_{dc,max}^2) = 3 r_{inv} I_{max}^2 \Delta t$$  \hspace{1cm} (11)

where $c$ is capacity of the smoothing capacitor and $r_{inv}$ is armature resistance. This maximum current command $I_{max}$ represents the current value that can be output only by using the stored energy of the smoothing capacitor, without power supply from the auxiliary circuit, regardless of the state of the secondary flux in the LIM-type rail brake. The time $\Delta t$ is treated as a coefficient of the maximum current command $I_{max}$ in practical use. After these processes, the pattern generator outputs the larger of $I_{up}$ and $I_{max}$, within the value of the original current command $I^{*}$, as the current command $I^{'}$ that is managed by initial excitation power.

$$P(I^{'}) = \min[I^{'}, \max(I_{up}, I_{max})]$$  \hspace{1cm} (13)

After the DC voltage $v_{dc}$ has risen to the desired level, the pattern generator outputs directly the original current command $I^{*}$ since the maximum current command $I_{max}$ becomes larger than the current command for the start-up $I_{up}$.

On the other hand, the inverter cannot output the sufficient AC voltage since the output voltage is restricted by the modulation factor at the low DC voltage during the start-up. In order to improve the response of the output current $I$, it is necessary that the relation between the responses of the output current $I$ and DC voltage $v_{dc}$ is taken into account, and that the effectual frequency $f_{eff}$ is chosen. Here, focusing on the relationship between the maximum output voltage $v_{max}$ of inverter and the charged voltage $v_{dc}$ of smoothing capacitor, the output current $I$ can be expressed by the following formula:

$$I = \frac{v_{max}}{Z_{m}}$$  \hspace{1cm} (14)

$$v_{max} = k_{m}v_{dc} = k_{m} \left( v_{dc} + \frac{6}{c} \int_{I_{up}}^{I} P_{in} |I^{'}| \cdot dt \right)$$  \hspace{1cm} (15)

where $Z_{m}$ is the impedance of the LIM-type rail brake; $r_{inv}$, the resistance component of $Z_{m}$, a coefficient that rep-
represents the relationship between the DC voltage and the maximum AC voltage; \( v_{\text{dc}} \), the initial charged voltage; and \( r_{\text{INV}} \), the equivalent resistance of the inverter. The following formula is obtained from these:

\[
\frac{dl}{dt} = \frac{3k_u}{c} \left[ \frac{r_{\text{in}} + r_{\text{INV}}}{Z_{\text{in}}^2} \right] I
\]

where \( \frac{r_{\text{in}} + r_{\text{INV}}}{Z_{\text{in}}^2} \) is the function of the frequency. By being operated at the frequency at which the value of \( \frac{r_{\text{in}} + r_{\text{INV}}}{Z_{\text{in}}^2} \) reaches the maximum, the most rapid response in the output current is achieved.

Moreover, in order to design a small and light weight armature suitable for practical use, a design in which an iron core reaches the magnetic saturation state in rated operation has to be adopted. Then, the impedance of a LIM-type rail develops strong nonlinearity in relation to the current value from magnetic saturation. For this reason, the impedance \( Z_{\text{in}} \) that is used for generating the forward voltage \( V_{\text{ref}} \) in the current control generates the non-linear forward voltage \( V_{\text{ref}} \) by referring to the current command \( I^* \) and frequency command \( f_{\text{ref}}^* \).

4. Braking tests on yard tracks

4.1 Test system

4.1.1 General outline

The two types of prototypes of the LIM-type rail brake were built and mounted onto the test bogie. This test bogie was installed into the test train R291 and was tested on the yard tracks at RTRI. Since it was not possible to perform "dynamic braking with zero electrical output" at low speed (45 km/h), the electric power was supplied to the excitation system from the SIV (auxiliary power unit).

4.1.2 Armature

The two types of armature sharing almost the same basic design and with only small differences in conductors and iron core arrangement were built. Figure 5 shows their exterior appearance and Table 2 shows their main specifications. The type A armature is a standard model according to the basic design, and the type B armature is a trial model for reduction in size and weight by reducing the amount of iron core and conductors. The designs of the support and protection elements are common to both types A and B. In order to support the armature in three points — at both the ends and in the middle — in the longitudinal direction of the armature core, the coils are arranged in irregular pitch. The support elements were designed with workability of maintenance, and were built to be strong so that the elements could resist the impact of a minor collision. As for the protection, the armature is also covered by a metallic stainless-steel mesh. Many of these parts were insulated from each other in order to minimize large eddy currents that would enclose the iron core.

Meanwhile, a six magnetic pole arrangement was deemed adequate based on the knowledge that pole pitch should be set to about 0.2 m. However, a four poles arrangement was adopted, even though performance degradation is slightly smaller than in a six poles arrangement for a large air gap, because of concern that the air gap between the armature and rail would become larger than the target values (6-7 mm) in the test bogie.

4.1.3 Bogie

A test bogie for the LIM-type rail brake was built by remodeling the trailer bogie of a commercial commuter train. Figure 6 shows the exterior appearance. Unlike the attachment of the armature described in the outline concepts of Section 2.1 that assumes practical use, the armatures in this test bogie are attached directly to the bogie frame. Therefore, the axle springs are made to have high rigidity...
to maintain the gap between the armature and the rail. The mass of the test bogie is 4,590 kg, of which 610 kg of LIM-type rail brake. The braking force was measured by a strain gauge attached to traction link between the car body and bogie.

The gaps between the armature and the rail were set to 6 mm in the type A and 7.5 mm in the type B armature, after several pretest runs.

4.1.4 Excitation system

As described above, electric power is supplied to the excitation system from the SIV in this braking test. On a trial basis, each of the two inverters was arranged to excite one armature. The rated voltage and capacity of test inverters were 440 V and 514 kVA respectively. The inverters received the frequency command and output voltage command from an external controller. This controller was implemented with the control method described in “3.3 Control method in excitation system.”

4.2 Test results

4.2.1 Braking performance

Figure 7 shows time-waveforms of output current and braking force. The braking force was measured as a load of the traction link while LIM-type rail brake was excited during vehicle’s coasting operation at a target velocity. It was confirmed that the braking force was generated according to the output current.

Figure 8 shows the braking force characteristics corresponding to the slip-frequency. Although a measured value is in the slip-frequency range lower than the practical use range, the measured value agrees with the designed value and the estimated value from bench tests [2] [4]. This shows that the LIM-type rail brake would be able to generate the target braking force of 5 kN in future practical use.

4.2.2 Power generation performance

Figure 9 shows synchronous watts corresponding to the slip-frequency, in which the LIM-type rail brake is regarded as a linear generator. The LIM-type rail brake cannot generate an electrical output as a generator because of the low velocity when running on yard tracks. However, the LIM-type rail brake can reduce the excitation power supplied from the inverter by using induced power (synchronous watts) in the armature. The synchronous watts shown in Fig. 9 are the reduced quantity of the excitation power. The measured value agrees with the designed value. It was also estimated that the reduction ratio of rail heating agreed with the designed value since the synchronous watts agreed well with the designed value.

4.2.3 Excitation control

As for a testing the excitation control, tests were only performed to verify the control of the output current without verification of power generation because of the low velocity running on yard tracks. Figure 10 shows the output current when various current values are commanded during deceleration from 42 km/h. In spite of large changes in impedance corresponding to current values caused by magnetic saturation in the iron core, the output current was well stabilized.

Furthermore, various tests concerning the excitation control were performed on the bench test apparatus [7],...
which produced the expected outcomes.

5. Conclusions

This article reported on the design considerations for a LIM-type rail brake, and results of braking tests on yard tracks. Prototypes of the LIM-type rail brake were mounted on a test bogie and tested using the test train. As a result, knowledge of this brake's assembly in a bogie was obtained and confirmation was obtained that the braking force and excitation performances generally agreed with the design values. Furthermore, an excitation method that could perform during feeder circuit malfunctions was also demonstrated in the previous articles [2] [7].

These results proved that the target braking force of 10 kN per bogie can be generated and that this brake can perform by self-excitation without being energized by feeder circuit.

References

[1] Obara, T., et al., "An Emergency Brake System for Conventional Lines," Proceedings of the International Symposium on Railroad Cybernetics, pp. 252–256, 1991 (in Japanese).
[2] Sakamoto, Y., et al., “Performance of Linear Motor Type Rail Brake Using Roller Rig Test Bench,” Quarterly Report of RTRI, Vol. 53, No.1, pp. 41–45, 2012.
[3] http://www.rtri.or.jp/rd/division/rd42/rd4220/rd42200301.html
[4] Sakamoto, Y., et al., "Excitation Method of Linear-Motor-Type Rail Brake without Using Power Sources by Dynamic Braking with Zero Electrical Output," IEEJ Trans. IA, Vol. 131, No. 2, pp. 219–226, 2011 (in Japanese).
[5] Japanese Electrotechnical Committee of IEE Japan, Standard of the Japanese Electrotechnical Committee JEC-2137 Induction Motor, Denkishoin, 2000 (in Japanese).
[6] Sakamoto, Y., et al., “Design Considerations and Experimental Verification of a Rail Brake Armature Based on Linear Induction Motor Technology,” IEEJ Trans. IA, Vol. 131, No. 1, pp. 127-134, 2011 (in Japanese).
[7] Sakamoto, Y., et al., “A Study on the Start-up Control of Dynamic Braking in Linear-Motor-Type Rail Brake,” The Papers of Technical Meeting on Linear Drives, IEE Japan, LD-11-056, 2011 (in Japanese).

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