Study on Miniaturization and Weight Reduction for the Application of LIM-type Eddy-current Rail Brakes to High-speed Trains

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To apply LIM-type eddy-current rail brakes to high-speed trains, it is necessary to miniaturize and reduce the weight of their armature mounted on bogies. This paper therefore considers reducing the volume of the iron core, taking into account the need to maintain braking performance at high speed, which has a great effect on braking distance. Electromagnetic field analysis was then used to verify the braking performance of the miniaturized armature by comparing it with armatures developed to perform well at low speed.

Keywords: high-speed rail, eddy-current rail brake, linear induction motor, FEM analysis

1. Introduction

Improving braking performance is very important to be able to increase train speed. Eddy-current rail brakes exert an electromagnetic braking force generated through electromagnetic interaction between an onboard electromagnet and induced eddy-current on a rail without adhesion. Therefore, this braking system is very effective for high running speeds where adhesive force decreases. The disadvantage of this braking system however, is that tracks can heat up because of the Joule-heating effect of the eddy current that is equal to the deceleration energy of the vehicle. To offset this disadvantage, a LIM-type eddy-current rail brake system (LIM-ECB) was developed that has an armature excited by three phase AC instead of a DC electromagnet [1-4]. This system operates as a linear induction motor (LIM) and generates the excitation power itself by using braking energy. This system therefore does not heat rails as much as conventional ECB, as shown in Fig. 1. Furthermore, it can exert braking force without output power, even in case of a power failure.

The aim of previous LIM-ECB development at RTRI, was to reduce the braking distance to be able to increase running speeds up to 160 km/h on 1067 mm gauge lines. Consequently, research focused on finding a LIM-ECB armature design which could maximize power generating performance while achieving the same level of braking force as strong electric and mechanical brakes, while at the same time reducing rail heating. To obtain this kind of performance, large and heavy armatures were designed.

This paper however describes the application of LIM-ECB to high-speed trains through miniaturization and reduction in weight of the armature. In new armature design, the focus was on reducing the iron core. The validity of this new design was confirmed using FEM analysis.

2. Overview of the LIM-ECB system

2.1 Configuration of the system

The LIM-ECB system is composed of an excitation inverter and an armature mounted on a bogie as shown in Fig. 2. Figure 3 shows the circuit structure and the flow of energy in the system. Figure 4 shows the ring-winding armature that was developed. In the ring-winding armature, a coil for each phase is simply wound around the yoke core.
They are independent and do not interfere with each other. The number of slots for each pole and phase that affect generating performance without changing exterior dimensions. A universal PWM inverter can be used to excite the armature, but inverter excitation frequency control needs to be more specific, i.e. controlled to ensure that power generation balances with total energy loss whilst the system is in operation.

2.2 Achievements from past developments

(1) Roller-rig bench tests
To evaluate the braking performance of the LIM-ECB system and verify the stability of the generating power control by changing the excitation frequency as shown above, roller-rig bench tests were conducted [1, 3] using an arc-shape armature as shown in Fig. 5. Satisfactory results were obtained for all the traveling (rotating) speeds that could be foreseen in operation. To evaluate the braking performance beyond the target limit in these bench tests, an armature which was larger than what is normally installed on a vehicle was used.

(2) Running tests on the RTRI test track
Running tests were carried out on the short test track at RTRI by mounting the LIM-ECB armatures shown in Figs. 2 and 6 on the bogie of the test vehicle [1, 2]. The roller-rig bench test armature was modified so that it could be installed on a bogie, added a waterproofed protective cover. Because of shortness of the test track, the braking performance of the straight shape armature confirmed at low speed.

3. Miniaturization and weight reduction of the armature

3.1 Strategy for miniaturization and weight reduction

An attempt was made to miniaturize the ring-winding armature to allow its installation on a high-speed train. The armature of a LIM-ECB must have a large magnetomotive force to ensure braking performance given the relatively large size of the magnetic gap between the armature and the rail. At the same time, external dimensions of the armature are very restricted because it has to be mounted in the limited space available on a bogie. Therefore, the magnetic flux density of the core should be close to saturation and the current density of the coil conductor should be close to the maximum thermal level admissible during operation. Under these excitation conditions, performance of the armature is proportional to both the cross section of the yoke core and the coil conductor. The cross section of the yoke determines the magnetic loading which is the coupling magnetic flux between the armature and the rail where the braking force originates. The total cross section of the coil conductor determines electric loading which is the magnetomotive force induced by the excitation current. A suitably balanced distribution ratio needs to exist between these two cross sections that depend on the external dimensions of the armature and electromagnetic characteristics of the rail. Armature design up until now aimed to reduce braking distances on 1067 mm gauge lines, by optimizing this distribution ratio.

Based on the premise that LIM-ECB will be used in combination with adhesion brakes and that the goal is to improve braking performance at high-speed, there is the possibility of optimizing this distribution ratio by reducing the iron core, for the following reasons. At high speed the air-gap magnetic flux reduces due to a powerful reaction flux induced by a larger eddy-current generated on the rail as shown in Fig. 7. As a result, even if the cross section of each core tooth is reduced, it is predicted that braking force...
will not fall significantly at high speed. Conversely, the braking force at low speed falls proportionally with a reduction in the cross section of each core tooth. At low speed the LIM-ECB is used with adhesion brakes and together they exert a large braking force, which means that braking distance would not increase as much as shown in Fig. 8. Reducing the tooth cross section ultimately diminishes generation performance, however, excitation inverter capacity is adjusted accordingly since electrical capacity increases significantly with high braking energy, just as it does at low speed. Based on this premise, it can be concluded that reducing the core size not only reduces the outside dimensions and weight of the armature, but also allows scaling down of the whole system.

3.2 Scaled-down design of the armature with iron core reduction

This paper investigates the miniaturization of a ring-winding armature with an overall transverse width of 126.0 mm, which is half the width of the armature which was used on the Roller-rig, and a core lamination thickness set to 65.0 mm, which is equal to the width of the crown of a rail used on high-speed lines in Japan. Four armatures were designed, namely cases A, B, C and D, corresponding to the different reduced sizes of the core.

Table 1 shows the dimensions of each part corresponding to those shown in Fig. 9. To clarify the correlation between the core and braking performance, the values of the three parameters which most affect the performance of a LIM were kept the same, namely, the air gap between the armature and the rail, the slot pitch and the number of slots for each phase and each pole. Therefore, the pole pitch was the same in all the models. In addition, the margin of the lower part of each core tooth, materials used for the iron core and the coil conductor and the current density were also the same.
4. Verification of performance by FEM analysis

4.1 Outline of the analysis and FEM models

The performance of the scaled-down armature design shown above in the FEM electromagnetic analysis, was verified using the commercial software “JMAG.” Table 2 shows conditions applied for the analysis. Simple models were used for calculations in this analysis as shown in Fig. 10. They are are translationally symmetric in the longitudinal direction and had mirror symmetry in the transverse direction. Given that the purpose of the calculation was just to make a relative evaluation of the different designs, the ultimate impact of the armatures on the LIM was not taken into account.

### Table 1 Dimensions of armature components

| Armature size | Large (reference) | Miniaturized and reduced weight armatures |
|---------------|-------------------|-----------------------------------------|
| Armature type | Roller-rig test   | Case A | Case B | Case C | Case D |
| Reduction rate of core | 1   | 0.68 | 0.6 | 0.5 | 0.4 |
| Reduction rate of cross section coil conductor | 1 | 0.39 | 0.43 | 0.47 | 0.52 |
| Reduction rate of mass | 1 | 0.339 | 0.336 | 0.310 | 0.291 |
| Total height: H [mm] | 228.5 | 123.82 | 113.52 | 103.22 | 92.91 |
| Total Width: W [mm] | 252.0 | 126.0 (constraint condition) |
| Lamination thickness of the core: \( w_c \) [mm] | 95.0 | 65.0 (constraint condition) |
| Side overhang of coils: \( h_c \) [mm] | 78.5 | 30.5 |
| Yoke height: \( h_y \) [mm] | 70.5 | 70.5 | 61.82 | 51.52 | 41.22 |
| Tooth width: \( w_t \) [mm] | 11.5 | 11.5 | 10.08 | 8.4 | 6.72 |
| Slot width: \( w_s \) [mm] | 14.0 | 14.0 | 15.42 | 17.1 | 18.78 |
| Resistance of coil \( [m\Omega] \) | 6.04 | 1.32 | 1.38 | 1.39 | 1.61 |
| Slot pitch \( L_s \) [mm] | | 25.5 |
| Number of slots for each pole and phase | 2 |
| Pole pitch \( L_p \) [mm] | 153.0 |
| Tip margin height of tooth \( h_m \) [mm] | 1.0 |
| Air gap \( g \) [mm] | 6.5 |
| Current density \( [A/mm^2] \) | 12.0 |

### Table 2 Conditions of the analysis

| Analysis method | \( A \rightarrow p \) method |
|-----------------|--------------------------|
| Transient Response |
| Traveling speed | 100 km/h, 300 km/h |
| Excitation frequency | 30Hz |
| Time interval | 0.09 ms (100 km/h) | 0.03 ms (300 km/h) |
| Number of elements | About 25-35 million |
4.2 Results

4.2.1 Braking force under the conditions used for the analysis

Figure 11 shows the resulting braking force and the relationship between the size of the core and the braking force. At low speed, i.e. 100 km/h, the results in cases A and B that had similar sized cores were almost the same, while in cases C and D that had relatively smaller cores the braking force was lower, as a result of the smaller cores. Compared with these results, the outcome in each case at high speed, i.e. 300 km/h was almost the same. This confirms the argument in Chapter 3. Figures 12 and 13 demonstrate the advantages of reducing core size for high speed in terms of per unit volume and weight of the armature and weight reduction.

Figure 14 shows the trends in the relationships between braking force at each speed and reduced core size. The braking force of the roller-rig armature at 300 km/h. Here, the armature volume is defined as the volume of the rectangular enclosing the armature. Figures 12 and 13 demonstrate the advantages of reducing core size for high speed in terms of per unit volume and weight of the armature and weight reduction.

Figure 14 shows the trends in the relationships between braking force at each speed and reduced core size.
Figure 14 shows that the decrease in the braking force ratio is smaller than the rate at which the core is reduced at high speed but that the opposite is true at low speed. This outcome could be explained by the strong reaction flux shown in Fig. 7 and the increased electric loading.

### 4.2.2 Generating performance and estimation of the apparent capacity in operation

Figure 15 shows the generated (induced) electric power and power consumption (the required power to excite) of the armature. In comparison with Fig. 11, similar tendencies appear for the generating power and braking force in each case. Power consumption however is inversely proportional to the core size reduction rate because the size of the coil conductor is increased. Therefore, when the core reduction rate is high, power consumption exceeds the excitation power.

Figure 16 shows the estimated apparent capacity at the operating point where generated power balances with power consumption as shown in the Chapter 2 for the current of the analysis conditions. In this paper the apparent capacity is estimated as follows: The generating power is approximately in proportion to the excitation frequency; so the apparent capacity at the operating point can be obtained by multiplying the result of the apparent capacity by the ratio of the power consumption to the generating power. Figure 16, shows that the apparent capacity increases in cases where the core reduction rate is high.

### 4.2.3 Estimated actual performance

In designing a whole LIM-ECB system, it is important to reduce the excitation inverter capacity. Figure 16 shows that the apparent required capacity changes with speed. Therefore, excitation system capacity for operation at 300 km/h was assumed, as shown in Fig. 16 for each case. The braking force was calculated on the basis of these assumed capacities for each case and the results are shown in Fig. 17. Compared with Fig. 11, the characteristic higher braking force at high speed than at lower speed in each case where the iron core has been reduced, is clearer in Fig. 17. In conclusion, miniaturization and weight reduction of the armature such as in cases C or D, when the iron core has been made significantly smaller appear to be a better design for braking performance at high speed. It should be noted however, that there is a tradeoff between miniaturization and weight reduction of the armature and electric capacity of the system, as shown in Fig. 16.

### 5. Summary

In this paper, in order to apply LIM-type eddy-current rail brakes to high-speed trains, miniaturization and weight reduction of the armature was investigated. Braking performance at high speed was considered to be a key goal, therefore the armatures were re-designed and made smaller and lighter weight by reducing the iron core based on the different characteristics of the air-gap flux density at high and low speed. Performance the new design was verified by FEM analysis. Results confirmed that reducing the core size had less influence on braking force at high speed than at low speed, which demonstrates the suitability of the principle of this design.

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