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Characteristic Analysis of a Linear Induction Motor for a Lightweight Train According to Various Secondary Schemes

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Abstract

This paper presents a performance characteristic analysis methodology for a linear induction motor used for a lightweight train. In general, an analytical method cannot provide accurate results in a linear motor because of large airgap, end effect, transverse edge effect, 3-dimensional configurations, large leakage, and so on. Besides, a numerical method requires lots of memory and solving time for transient analysis. However, the suggested methodology which is a kind of hybrid solution with an analytical method and a numerical method is very fast and accurate. Based on the methodology, 3-D FEM analyses for various design schemes of the secondary reaction plate have been done and from the analysis results, the best configuration for an urban railway transit is chosen.

Keywords : *End effect, Linear induction motor, LIM, Lightweight train, Reaction plate*

1. Introduction

As demands for cost-effective, less susceptible to weather, and reliable means of public transportation have increased, Korean government has taken into account the linear electric railway system (Linear metro) since the late twenty century. Linear metro gets the propulsion force from a liner motor different from a conventional rotary motor and it produces thrust force electromagnetically without using any friction force. Therefore, it does not use any mechanical coupling for the rectilinear movement.

The linear electric railway system is called as non-adhesion drive system, where as conventional railway system is called as adhesion drive system which gets the propulsion force from the friction between wheel and rail. This non-adhesion drive system has lots of advantages over the adhesion drive system as follows; (1) Excellent acceleration and deceleration, (2) Lower construction cost due to the small tunnel cross-section, (3) Capability of climbing steep gradients, (4) Enable flexible route planning (travel through sharp curves), (5) Less susceptibility to weather conditions, (6) Quiet and smooth running (No mechanical couplings), (7) Less maintenance cost. Consequently, the linear electric railway system is already in use in all over the world and continuously being extended.

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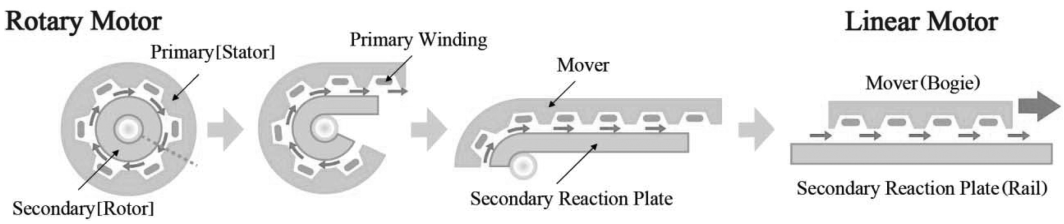
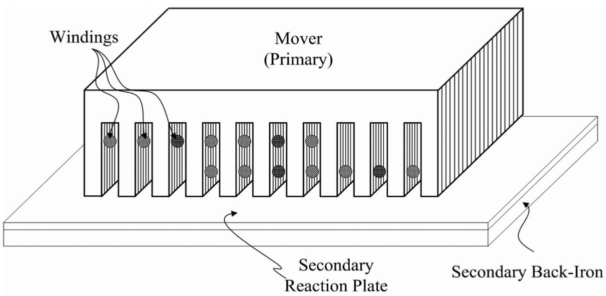


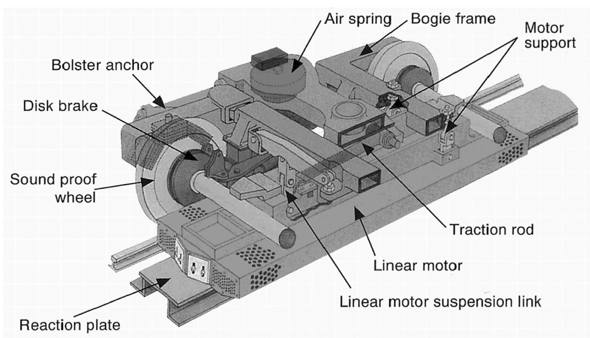
Fig. 1 Concept of a linear motor from a rotary motor [4]

through sharp curves), (5) Less susceptibility to weather conditions, (6) Quiet and smooth running (No mechanical couplings), (7) Less maintenance cost. Consequently, the linear electric railway system is already in use in all over the world and continuously being extended.

Figure 1 shows the concept of a linear motor derived from a rotary motor. It is a conventional rotary motor whose stator, rotor and windings have been cut open, flattened, and placed on the guide way [1]. Even though the operating principle is exactly the same as a rotary motor, the linear motor has a finite length of a primary or secondary part and it causes 'end effect' and 'transverse edge effect'. Moreover, the large airgap lowers the efficiency. However, the linear motor is superior to the rotary motor in the case of rectilinear motion, especially for a railway transit.



(a) Configuration of a SP type linear induction motor



(b) Practical application for railway system [5]

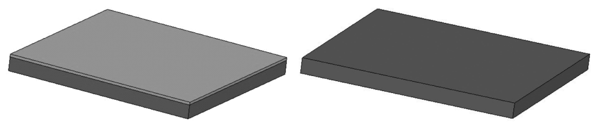
Fig. 2 Linear induction motor and a practical application

Among many kinds of linear motors, linear induction motor (LIM) is preferable to the urban railway transportation system because the construction cost is much lower than that of a linear synchronous motor (LSM), even though the efficiency and performance is little bit poor. The operating principle of a LIM is identical to a rotary induction motor. Space-time variant magnetic fields generated by the primary part cross the airgap and induce the electromotive force (EMF) in the secondary part, a conducting sheet. This EMF generates the eddy currents, which interact with the airgap flux and so produces thrust force known as Lorenz's force [1-3]. The Short-Primary (SP) type which is generally applied for a low-medium speed urban lightweight transit, is very easy to lay conducting sheets on the guideway and thereby reduces construction costs. However, the SP type has low energy efficiency because of the drag force and the leakage inductance caused from the end effect [1]. Figure 2 represents the configuration of a SP type linear induction motor and a practical application for railway systems.

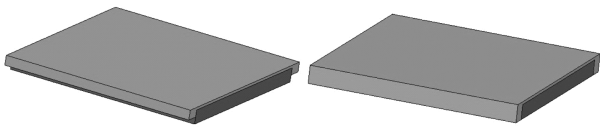
2. Issues of Characteristic Analysis

With the same primary design, the performance of the LIM directly depends on the secondary geometries and materials; in other words, magnetic flux path, eddy currents path, and plate conductivity. Therefore various secondary designs should be considered as many as possible. However, because we cannot build every case to test the performance of each LIM, analytical methods and numerical simulations are generally used to analyze the performance in each case. Figure 3 shows the various configurations of the secondary reaction plate.

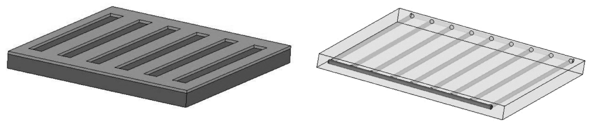
There are many analytical methods for electric machines; nevertheless, performance analysis of a LIM is quite different and difficult from that of a rotary machine. First of all, the LIM propulsion system has around 10[mm] large airgap with many restrictions such as construction tolerance, thermal expansion and bend of the reaction plate, abrasion of the wheel, and so on. This large airgap causes much larger flux leakage comparing with that of a rotary machine and lowers the accuracy of analysis after all. Sec-



(a) Aluminum or copper flat sheet (b) Back-Iron only

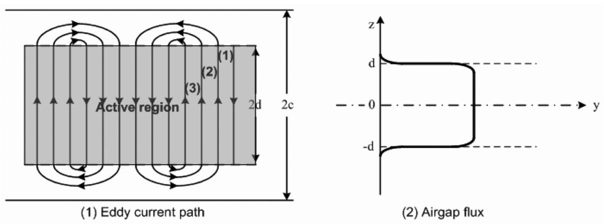


(c) Semi-Cap type (d) Full-Cap type

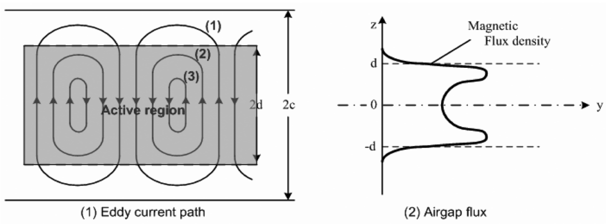


(e) Ladder type (f) Interior squirrel-cage type

Fig. 3 Various configurations of the secondary reaction plate



(a) 2-dimensional analysis model



(b) Real system

Fig. 4 Magnetic flux density of the 2D analysis and real system

ondly, end-effect of the primary side makes us not to use half- or quarter-modeling but full modeling. Thirdly, transient analysis modeling for long secondary reaction plate results in huge analysis model size and requires lots of time and computer memory. Besides, transverse edge effect and various configurations of the secondary reaction plate require 3-dimensional analysis of necessity. Figure 4 represents the eddy currents path and magnetic flux density of the 2-dimensional analysis model versus real system. Here, '2d' is active region, stack length of the primary and '2c' means width of the secondary reaction plate. As shown in the Figure 2-dimensional analysis cannot represent the airgap magnetic flux density properly.

After all, these considerations need much more time and capacity of computer memory, and lower the accuracy of the analysis.

3. Analysis Methodology

Even though characteristic analysis of a LIM requires 3-dimensional models to consider 'end effect', 'transverse edge effect', and '3-D configurations', transient analysis of the 3-dimensional full modeling is impossible for the present because of insufficient computer memory and solving time.

In order to analyze the performance with less time and memory, several steps are suggested in this paper as shown in Fig. 5. First of all, thrust force is calculated by using 2-dimensional full and one-pole models to compensate the end-effect as shown in Figure 6. Secondly, 3-D numerical models are used to consider the transverse edge effect and various configurations of the secondary reaction plate. Thirdly, from both 2-D and 3-D analysis, the equivalent secondary conductivities which are corresponding to each case can be calculated as following (1).

$$\sigma_e = k_e k_c \sigma_2 \tag{1}$$

σ_e is the equivalent secondary conductivity, σ_2 is the secondary material conductivity, and k_c is the 3-D correction factor, and k_e is the end effect correction factor.

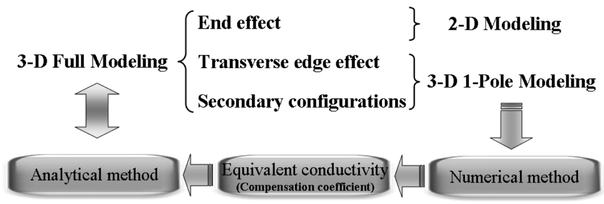
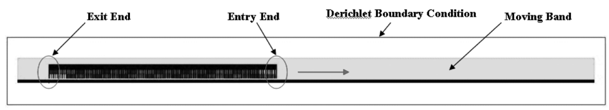
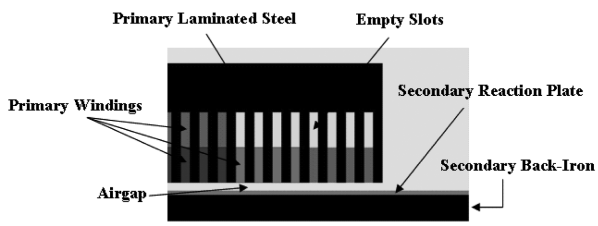


Fig. 5 Proposed analysis methodology



(a) Full modeling



(b) Magnified view of the end part

Fig. 6 2-dimensional transient analysis model

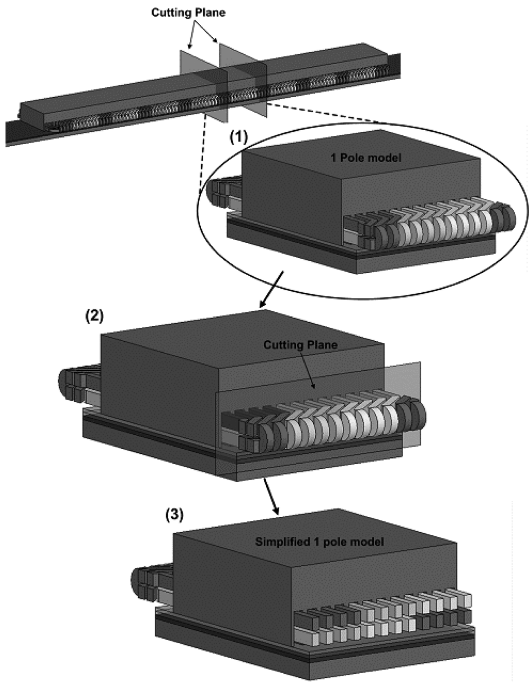


Fig. 7 3-dimensional one pole model (Extracting process from the full model)

Because secondary conductivity in a LIM directly affects to the thrust force, fourthly, the calculated equivalent conductivity is used as a parameter in an analytical method which replaces the 3-dimensional full model transient analysis. Figure 7 represents the 3-D one pole modeling which is extracted from the 3-D full model.

4. Analysis Results of Secondary Configurations

Figure 8 shows numerical simulation results of the thrust force according to the secondary conductivities. Because it is 2-D analysis, overhang of the secondary nor transverse edge effect could not be considered, but the results reveal the end effect very well. As shown in the figure, the end effect reduces the thrust force because of the dolphin phenomenon which acts like drag force. The end effect correction factor (k_e) is around 0.842 at the slip 0.2 (rated slip).

In order to analyze the transverse edge effect and overhang of the secondary, 3-D analyses of each case have been performed. Base model (No overhang, no-cap) and three cases of overhang with no-cap, semi-cap, and full-cap have been investigated respectively.

From the analysis, each equivalent secondary conductivity is calculated by using the effective eddy currents on the secondary of each model. In case of the base model, is 0.7086 and the others are shown in Table 1. And the percentage increase of the correction factor comparing with the base model has been plotted in the Figure 9. As shown in the figure, the equivalent conductivity increases as the overhang increases as expected. But, the amount of the aluminum used also increases dramatically.

#1~4 models have high percentage of (a)/(b), but the thrust force is low comparatively. #8~9 models have high thrust force but have low percentage of (a)/(b). In the last analysis, #6 model is selected for the light-

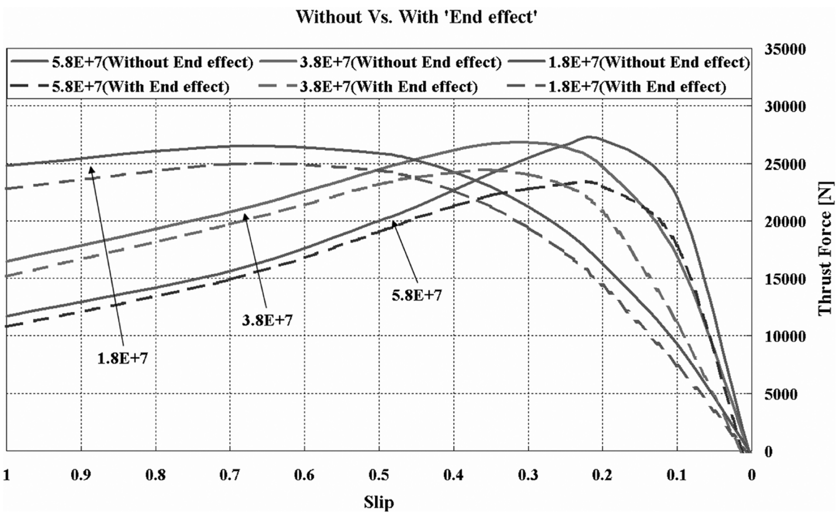


Fig. 8 Thrust force considering without & with 'End effect'

Table 1. Correction factor of Each case (k_c)

Cases	Correction factor
(0) No Overhang with no cap (Base model)	0.7086
(1) 1:1.1 Overhang with no cap	0.7777
(2) 1:1.2 Overhang with no cap	0.8224
(3) 1:1.3 Overhang with no cap	0.8604
(4) 1:1.1 Overhang with Semi-cap	0.8575
(5) 1:1.1 Overhang with Full-cap	0.8954
(6) 1:1.2 Overhang with Semi-cap	0.8776
(7) 1:1.2 Overhang with Full-cap	0.9059
(8) 1:1.3 Overhang with Semi-cap	0.9363
(9) 1:1.3 Overhang with Full-cap	0.9612

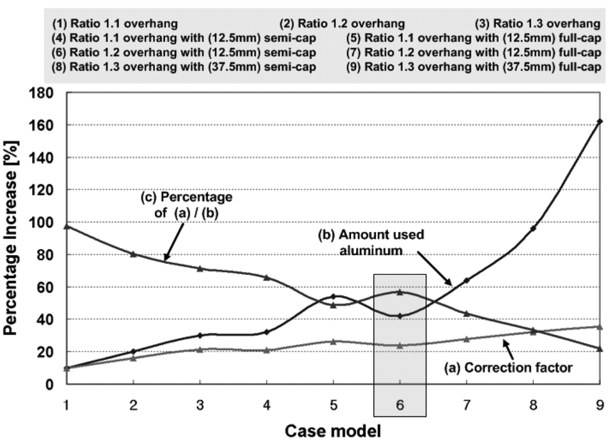


Fig. 9 The equivalent secondary conductivities of each case

weight train. The #6 model is shown in the Figure 10 and the performance analysis is plotted in the Figure 11.

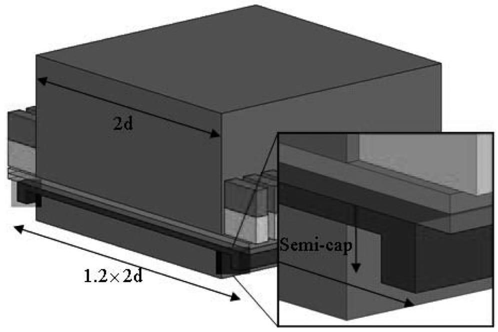


Fig. 10 Ratio 1:1.2 overhang with semi-cap model

5. Conclusions

A characteristic analysis methodology for a linear induction motor for a lightweight train has been performed in this paper. The end effect which is an important phenomenon in a linear motor has been considered by using 2-D numerical method and the correction factor is calculated. In addition, the transverse edge effect and the 3-dimensional reaction plate configurations are also considered by using 3-D numerical method and the correction factors are obtained in each configuration. Based on the numerical simulation results, the equivalent conductivities of the secondary reaction plate in each case have been applied to the analytical method to figure out the performance of the various design schemes of the LIM.

In case of copper reaction plate, ladder type or interior squirrel-cage type, it is expected that the performance will be better than aluminum plate. But the construction cost will also be much higher than the aluminum plate and so it is impractical to the railway system. Ultimately, the best

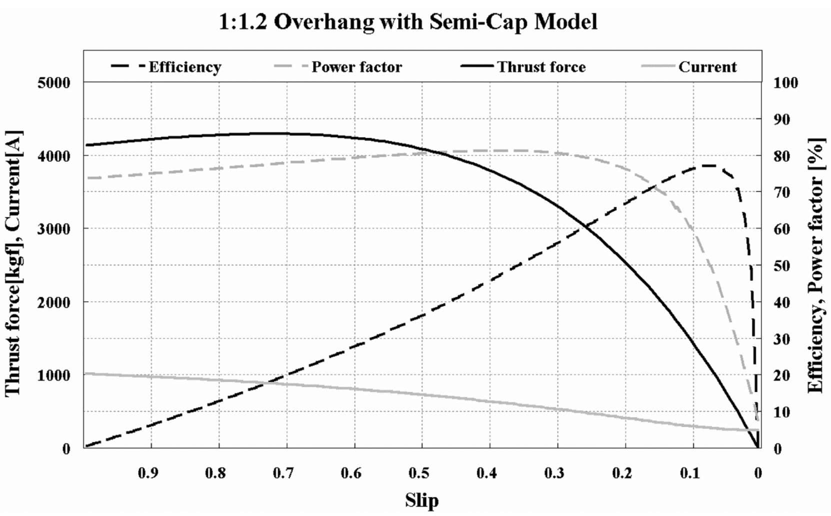


Fig. 11 Characteristic analysis result of the #6 model

configuration (#6 model) for an urban railway transit is chosen from the analysis results.

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