Analysis of Linear Induction Motors for HSST and Linear Metro using Finite Difference Method

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Abstract An analysis of linear induction motor for HSST and Linear Metro using two-dimentional finite difference method is presented. This method is useful for analysis linear induction motor microscopically with small calculation cost. The biggest problem of a linear induction motor is the end-effect which appears in high-speed operation and deteriorate performance. The influence of effect has been analyzed.

Keywords: Finite Diffrenece Method, Finite Element Method, HSST, Linear Induction Motor, and Linear Metro

1. Introduction

There are a number of linear motor application projects in several countries, and transportation system using linear motors has been studied. In linear motors, linear induction motors (LIM) have advantage of low cost, robust structure, direct drive etc., so HSST system and Linear Metro use linear induction motors for its thrust system.

For the design and analysis of these LIMs, Fourier transformation technique and Space Harmonic Method has ever been used widely. These analysis methods calculate its performance from a macroscopic standpoint, so it can analyze rough performance, but it is difficult to calculate the distribution of the vector potentials, flux density and so on, in LIM's all analysis regions, *e.g.*, inside its primary core and secondary reaction plate. On the other hand, in order to solve these problems, there are Finite Difference Method and Finite Element Method. These methods analyze LIM microscopically. So, analyzing LIM's entire region's performance, it is useful for optimization of LIMs when its design parameters change.

Since the FDM is simpler, an analysis error increases in complex structure. However, LIM's shape can be partitioned as quadrilateral element, therefore an analytical error doesn't change so much compared with FEM, so the analysis need not be complicated in FEM.

The performance of LIM calculated by using FDM which have the advantage above is introduced in this paper and using this accurate calculation method, the influence of end-effect which appear appears in high-speed application been analyzed.

2. HSST and Linear Metro (1)

2.1 HSST[1] This system has been developed by Chubu HSST Deveropment Corporation and consists of LIM driven electromagnetically suspended(EMS) vehcle system for urban transportation.

In 1970, the first test vehicle HSST-01 recorded 300km/h with assist of jet propulsion. In 1989, HSST-05 had operated as a public transportaion system in the Yokohama Expo site. The first commercial application of the HSST system "Linimo" has been completed as a full-scale operation in 2005, which shceduled to be major access transportation system from Nagoya city to the site of the Aichi Expo, 2005.

The maximal speed of this HSST system Linimo is assumed to be about 100km/h, and in the near future, the application for the transportation system whose top speed is over 200km/h is being proposed for airport access.

2.2 Linear Metro A vehicle of the Linear Metro has wheel-rail system for its suspension and guidance, but driven by LIM's. This system has become to the major solution for a new subway in major cities in Japan.

One of the most significant purpose of Linear Metro is suppression of tunnel construction cost. Since the floor level of LIM driven train is lower than that of wheel driven convenbtional train and the tunnel section required to the LIM driven vehicle is smaller than that of conventional subway systems. The LIM driven trains can pass the severe slopes and curvature, where conventional type cannot. This is useful for increasing the freedom in planning a new line.

This Linear Metro is complete application at present. However, in the near future, improvements of a market competitiveness and a customer appeal will be needed. And as the one of the solution of this problem, there is the improvement of the maximum speed of Linear Metro up to 130km/h.

Thus, the application using LIM for high-speed operation is required and discussions about keeping the end-effect low-level is necessary.

Details of the computational method for calculating the LIM's end-effect are described in the following sec-

[1] High Speed Surface Transportation

tion.

3. LIM analysis using FDM

Space harmonic analysis method were used for evaluating the end-effect. There were some analytical approches like Fourier transformation technique [2]. These techniques were developed in 1970s, so the calculation is so small that the characteristic could be analyzed at very short time if it ware calculated by a present computer. The modelling error of these methods is a problem for the design and control method.

Two-Dimensional Finite-Difference-Method (FDM) on the Cartesian coordinates with periodic boundary condition by quasi-stationary sinusoidal current supply, has been applied in this study. The characteristics of LIM are calculated more precisely by solving Maxwell's electromagnetic field equations.

The computational time of the FDM is longer than the time of the classical analytical approches, but is acceptable. This nummerical approch is also useful for evaluating the end-effect.

3.1 Basic Equation Fig. 1 and Fig. 2 show analysis models of a HSST and of a subway, respectively and the definition of coordinates. The equation which represents the performance of LIM is formulated as (1). This fundamental equation is set from Maxwell's electromagnetic equations. In this (1), A, ν, J_0, v_2 represent vector potential, magnetic resistance, current density and LIM's speed respectively.

$$\frac{\partial}{\partial x}\left(\nu_y \frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_x \frac{\partial A}{\partial y}\right) = -J_0+\sigma\left(\frac{\partial A}{\partial t}+v_2\frac{\partial A}{\partial x}\right) \quad (1)$$

In the method used in this study, the current is assumed to sinusodial and linear because LIM used for HSST and Linear Metro is designed with a certain amount of margin; there is no magnetic saturation. Therefore, (1) is rewritten as (2) by using $j\omega$-method, assuming quasi-stationary state and sinusoidal current supply. The "·" and ω show complex number and angler frequency of current.

$$\frac{\partial}{\partial x}\left(\nu_y \frac{\partial \dot{A}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_x \frac{\partial \dot{A}}{\partial y}\right) = -\dot{J}_0+\sigma\left(j\omega \dot{A}+v_2\frac{\partial \dot{A}}{\partial x}\right) \quad (2)$$

4. LIM Models

4.1 A LIM of a HSST The model LIM for HSST is based on HSST-200 proto-type vehicle [3] [4] [5]. This HSST-200 type is designed for the operation over 200km/h. That model is shown as Fig.1.

4.2 A LIM of a Linear Metro The model LIM for Linear Metro is based on the model of "Design Standardization for Subway System" which is determined by Japan Subway Association [6]. That model is shown in Fig.2.

Compared with HSST-LIM, the design for Linear Metro LIM is characterized in long motor length and pole pitch. Therefore it is said that Linear Metro-LIM is designed for reduction of end-effct.

4.3 The Other Parameters The other parameters, for example normal power, maximum volatage and so on, is summarized as shown in Table 1.

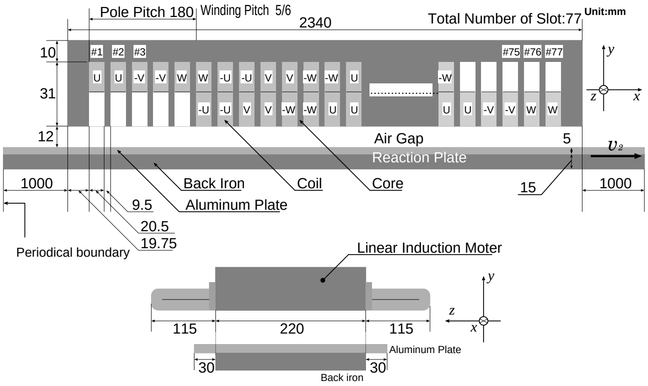

Fig. 1. HSST-LIM model

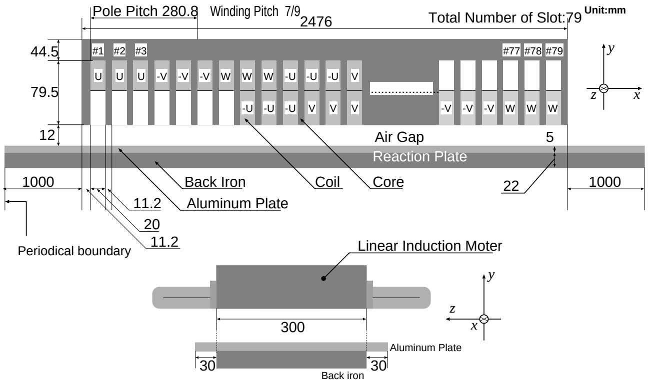

Fig. 2. Linear Metro-LIM model

Table 1. The other design parameter

Parameter	HSST	Linear Metro
Normal power(kW)	93	100
Maximum voltage(V)	275	1100
Maximum current(A)	400	150
Slip frequency(Hz)	12.5	4.5
Nominal speed(m/s)	40	12
Turns of coil	3	9
Material of Windings	Aluminium	←
Magnetic Resitance of Primary Core	7.9578×10^2	←
Conductivity of Secondary Conductor	2.29×10^7	←
Magnetic Resitance of Sec. Conductor	7.9578×10^5	←
Magnetic Resitance of Back Iron	7.9578×10^2	←

5. Calculated Results

Under conditions described previous section, analysis results are summarized as follows.

5.1 Forces Characteristics of forces are calculated under the slip frequency constant control in all speed region as simplification. The LIM is controled with maximum current constant mode in low speed, *i.e.*, so LIM's thrust is expected to be constant. When inverter voltage reaches maximum, LIM is controled with maximum voltage constant mode. In this region, LIM's thrust is expected to be proportional to $1/v_2^2$.

5.1.1 HSST-LIM The characteristics of forces for HSST-LIM is shown as Fig. 3. The slip frequency is set to its nominal value 12.5Hz.

In Fig. 3, the value of attractive force is represented as absolute value. At constant current mode, the thrust decreases with the increase of velocity because of the end-effect.

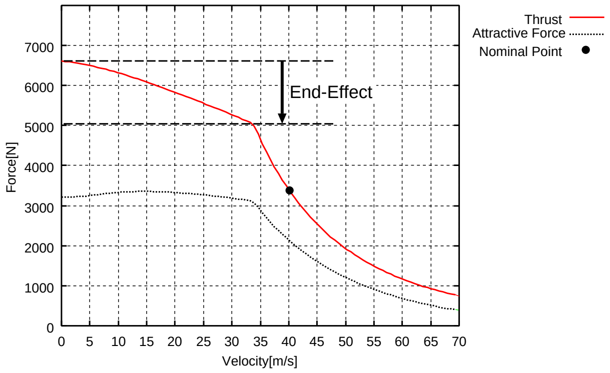

Fig. 3. Force performance of HSST-LIM

5.1.2 Linear Metro-LIM The characteristics of forces of Linear Metro-LIM is shown in Fig. 4. The slip frequency is set to its nominal value 4.5Hz.

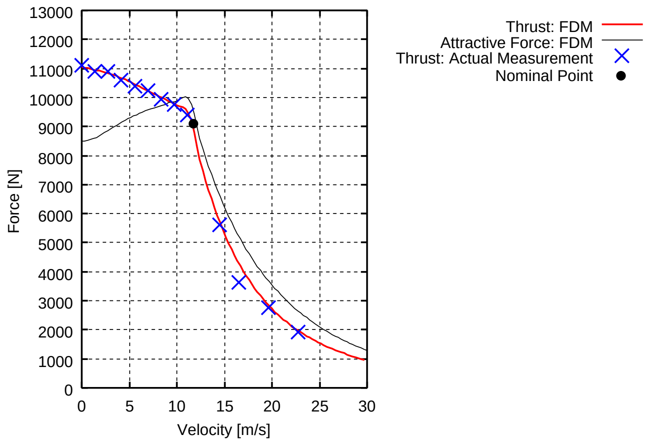

Fig. 4. Force performance of Linear Metro-LIM

In this case, the thrust decreases in current constant mode as same as the case of HSST-LIM. Compared with HSST-LIM, the LIM produces larger attractive force than that of HSST. There are thrust data actually measured in Linear Metro; the data are plotted by "×" in Fig. 4 [(7)]. The calculation is in good agreement with the measurements.

5.2 Flux density on surface of reaction plate Next, in order to observe the cause of end-effect, the flux density on surface of reaction plate is shown with slip frequency and LIM's speed changing. The slip freaqunecy f_s is set in the case of 0Hz(*i.e.*, slip=0), nominal and braking states. The secondary speed is set 0km, the half of nominal speed, nominal speed and the twice.

And the direction of movement of LIM is the right in figures.

5.2.1 HSST-LIM For the HSST-LIM, nominal slip frequency f_s is 12.5Hz. When slip frequency is set to $f_s = 0$Hz, 12.5Hz, -14Hz, flux density distributions are shown in Fig. 5, 6, 7 respectively.

The flux density decreases with the increase of LIM's speed at the entrance of LIM. This is the cause of the end-effects. Especially, in the effective-winding section, the grey part in those figures, this decrease mainly causes the effect. Because this HSST-200 is proto-type model LIM, at the nominal slip frequency and speed (12.5Hz, 40m/s), the end-effect appears dominantly although its slip frequency is set to large. There is still room for improvement for the HSST-200's LIM. The HSST system is maglev vehcle system. It is important for the LIM to be balance with its levitation system.

5.2.2 Lienar Metro-LIM For the Linear Metro-LIM, nominal slip frequency f_s is 4.5Hz. When slip fre-

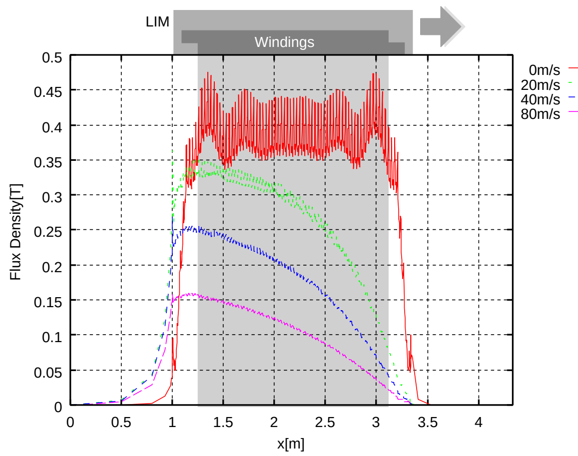

Fig. 5. $f_s = 0$Hz (slip = 0)

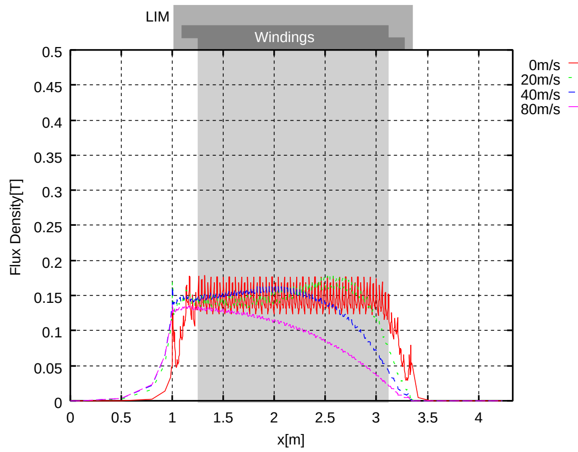

Fig. 6. $f_s = 12.5$Hz

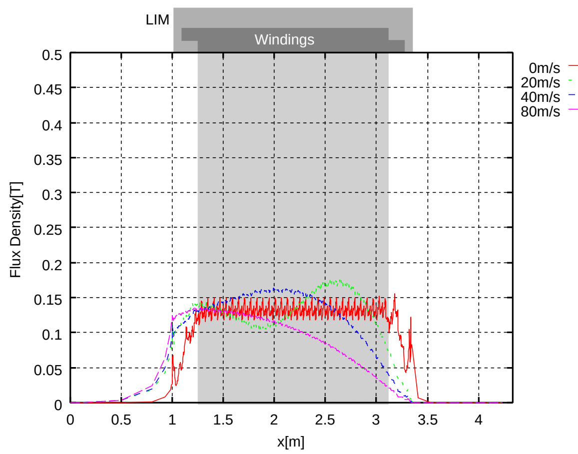

Fig. 7. $f_s = -14$Hz (regenerative braking state)

quency is set to f_s = 0Hz, 4.5Hz, −5Hz, flux density distributions are shown in Fig. 8, 9, 10 respectively.

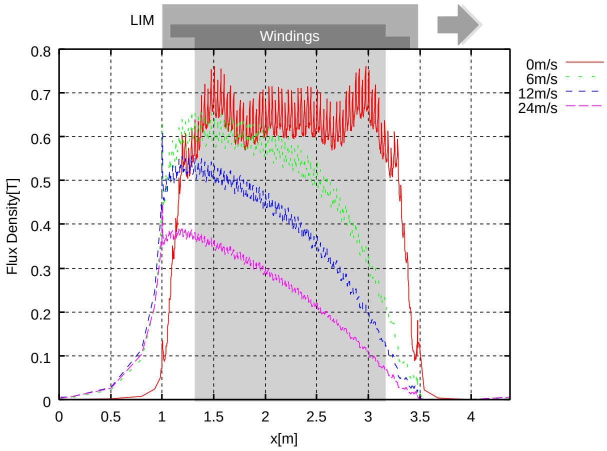

Fig. 8. $f_s = 0$Hz (slip = 0)

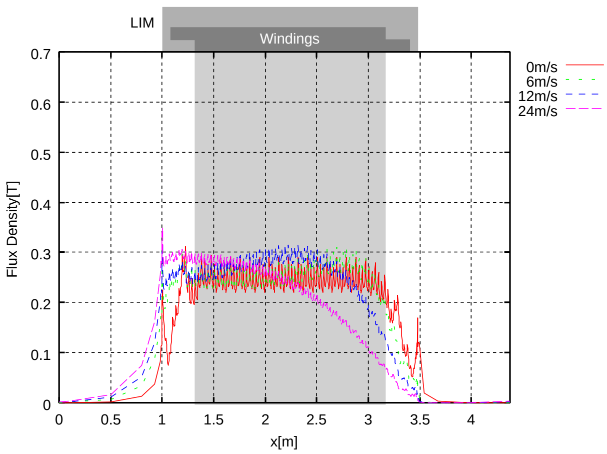

Fig. 9. $f_s = 4.5$Hz

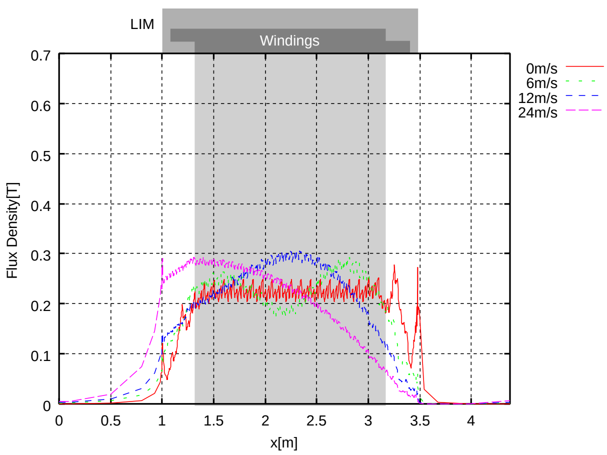

Fig. 10. $f_s = -5$Hz (regenerative braking state)

The same phenomea appear in Linear Metro. But compeared with HSST, at the nominal slip frequency and speed (4.5Hz, 12m/s), flux density distributions is smaller decrease than HSST although slip frequency is set to small. Linear Metro is low-speed application, so this LIM is high-quality finished form. That is confirmed by "Design Standardization for Subway System".

5.3 Discussion Seeing results of HSST and Linear Metro in Fig.5 to Fig 10, the LIM's end-effect mostly depends on speed of the LIM's. Therefore, the perfoemance of LIM as *induction motor* depends on speed too, and the model for control systems of a LIM cannot be fully realized using traditional induction motor model. A better model for a LIM must include the effect of speed.

And calculation time for one operation point is below two minutes even using Pentium-M prossessor 1.3GHz laptop PC. It is important that performance can be calculated with such small calculation cost.

6. Conclusions

In this paper, the calculation of LIM's for HSST and Linear Metro using two-dimentional FDM has been presented. Since the method can analyze LIMs microscopically, it can calculate the performance including flux density distribution, eddy current and so on, in all region of LIM for a short time with high accuracy. This is the advantage of the method in comparison with classical methods.

The results of flux density distributions of the surface of the reaction plate show charactaristics of LIM depend on its operation speed. A better model for LIM's controler design needs to formulate the substantial effects from operational speed. The new model will be useful to realize a new design method of a LIM and its control system.

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