# Multipurpose Design Optimization of Linear Induction Motors for EMS Type Maglev Vehicles

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**Keywords**

HSST, Linear induction motor, multipurpose design optimization

### Abstract

EMS Type Maglev vehicles including HSST that use linear induction motors for its thrust system have been in the stage of practical application. As linear induction motors are used widely and applied in high-speed operation, there is a problem of their end-effect, therefore optimization taken the effect into account at high-speed operation is needed. In this paper, we discuss optimization for high-speed linear induction motors.

## 1 Introduction

There are a number of linear motor application projects in several countries, and transportation system using linear motors, such as JR Maglev and HSST system in Japan, Transrapid in Germany and Linear Metro has been studied. In linear motors, linear induction motors have advantages of low cost, robust structure, direct drive etc., so HSST and Linear Metro use linear induction motors for its thrust system. The HSST system called ‘Linimo’ will be put to practical use in next year for the means of transportation of the 2005 world EXPO in Aichi, Japan. The top speed of this HSST system is assumed to be about 100km/h, and in the near future, the application for the transportation system where the top speed is 200km/h over is proposed. As the system using linear induction motors are used widely and applied in high-speed operation, their end-effect, which deteriorates the performance in high-speed, stand out and the calculation and the optimization that took their effect into consideration are needed. And some examples of optimization have been studied on the linear induction motor used for a linear metro and HSST-05 [1], [2]. But their studies assume their maximum speed 100km/h not over, so the end-effect in range of the speed hardly appears. In this paper, linear induction motor for high-speed (about 200km/s max) use like HSST-200 is analyzed and optimized on changing each parameters of its linear induction motor.

Fig.1 HSST (Linimo)

Fig.2 Linear Metro (Kobe city subway Kaigan Line)

## 2 LIM Analysis

In the analysis that takes end-effect into account of linear induction motors (LIMs), the space harmonic analysis method was used widely. In addition, there is a Fourier transformation technique and so on. While on the other hand, in this study, Two-Dimensional Finite-Difference-Method (FDM) analysis on the Cartesian coordinates with periodic boundary condition by quasi-stationary sinusoidal current supply, is applied. Moreover, for the calculation, LIM's parformances calculate by using MATLAB as its tool; i.e the calculation code is directly written as 'M-file' of MATLAB.

In the code used in this study or the space harmonic analysis method above, 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. This FDM method simulates near actually situation, but its calculation time is fairly required for a long time from the space harmonic analysis and the others.

### 2.1 The Basic Design Parameters

Design parameters of this calculation are set up on the basis of the HSST-200 vehicle parameters [3]. The dimension of this model is shown in Fig.3. Other parameters such as operation temperature, permitivity of secondary and so on, are summarized in Table I.

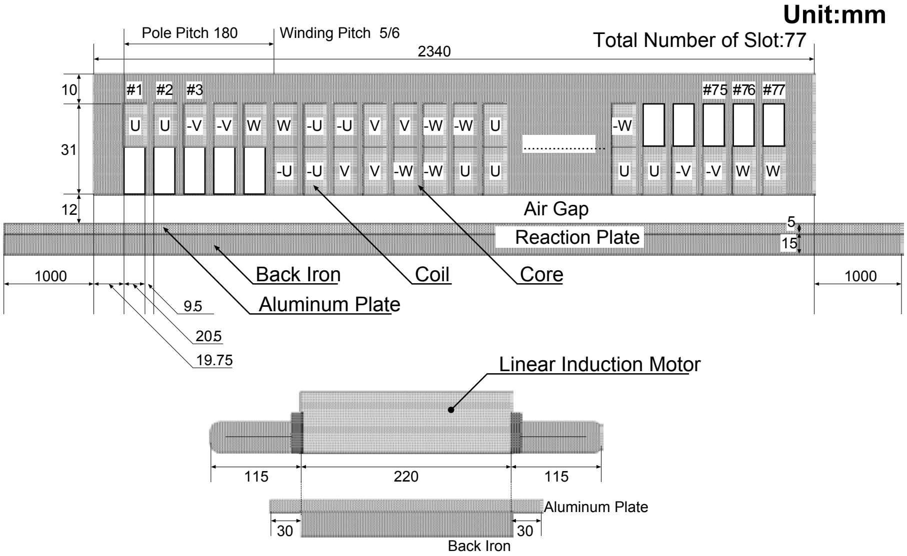

Fig. 3 Demention of LIM

Table I Parameters of LIM

| Condition | Value |
|---|---|
| Turns of Coil | 3 Turns |
| The material of Windings | Aluminium |
| Resistance par Coil (60% at 115 degree) | $2.44 \times 10^{-4}\ \Omega$ |
| Permitivity of Primary Core | $7.95773 \times 10^{2}$ |
| Conductivity of Secondary Conductor (Aluminium Plate, 60 % at 40 degree) | $2.29 \times 10^{7}\ (1/\Omega\mathrm{m})$ |
| Permitivity of Secondary Conductor (Al Plate) | $7.95773 \times 10^{5}$ |
| Permitivity of Back Iron | $7.95773 \times 10^{2}$ |

## 2.2 Base Performance Results

Under parameters of Fig.3 and Table I, keeping LIM's current 400A, thrust and normal forces on changing the frequency of power supply are shown in Fig. 4 and Fig. 5 respectively. The Fig. 6 illustrates the distribution of vector potential under conditions where slip frequency is set to 12.5Hz, operation velocity is 40m/s and current is 400A. These figures indicate that the calculation including the end-effect is possible for this MATLAB calculation code. And Fig. 7 shows the impedance of this LIM. This impedance is calculated from the vector potential value when the current of LIM is 1A.

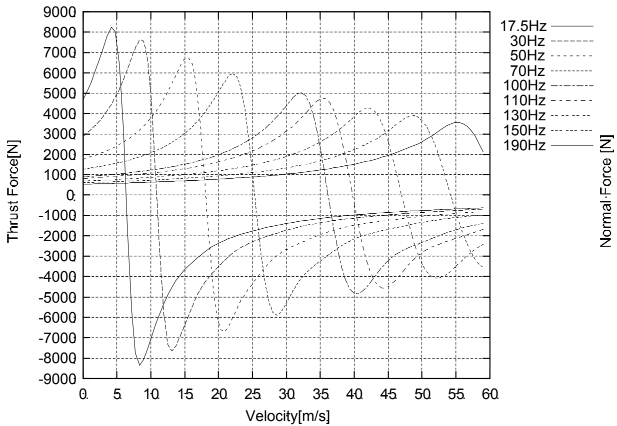

Fig. 4 Thrust Force

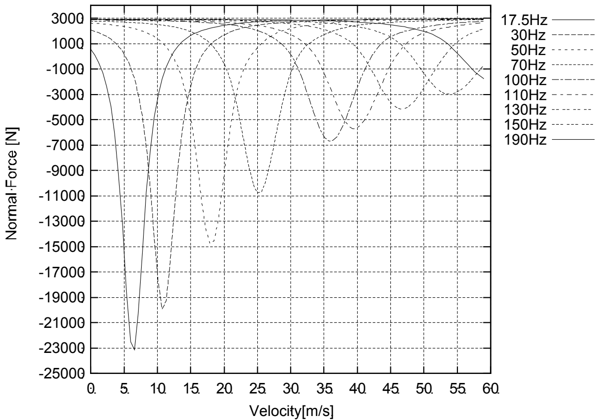

**Fig. 5 Normal Force**

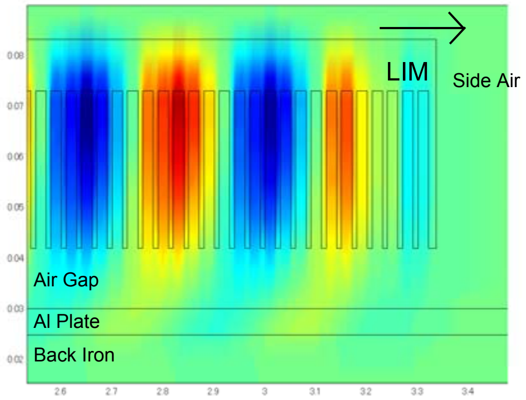

**Fig. 6 Distribution of Vector Potential**

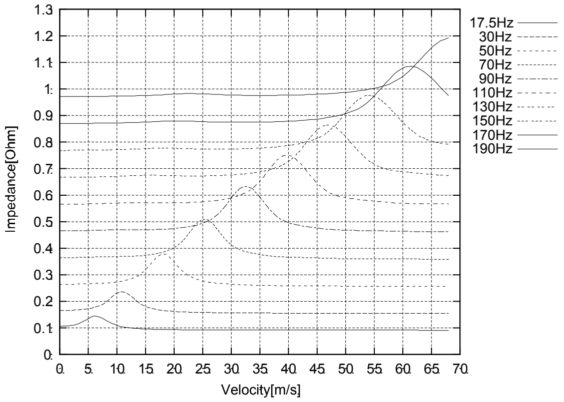

**Fig. 7 Impedance**

# 3 Velocity Control of LIM

## 3.1 Control Method

The LIM's velocity control method is the same method of rotary induction motors. The velocity control of LIM is based on constant slip frequency control under constant current in order to keep thrust force steady at low speed. At the same time, using this control the normal force is constant too. But as LIM's velocity is high, the frequency increases, so LIM's impedance becomes big (shown in Fig. 7). Because the output voltage of inverters for control of LIMs has been decided beforehand, when the voltage reach the maximum, it is necessary to change the mode in which its voltage is kept constant or the product of voltage and current is kept constant. After the velocity of the maximum voltage point, the primary current decrease, so the thrust force is reduced. In this study, after reaching the maximum voltage, the LIM is controlled by constant slip frequency under constant voltage.

The outline of thrust force, frequency, current and voltage value under this control is shown in Fig. 8. This figure does not include the end-effect.

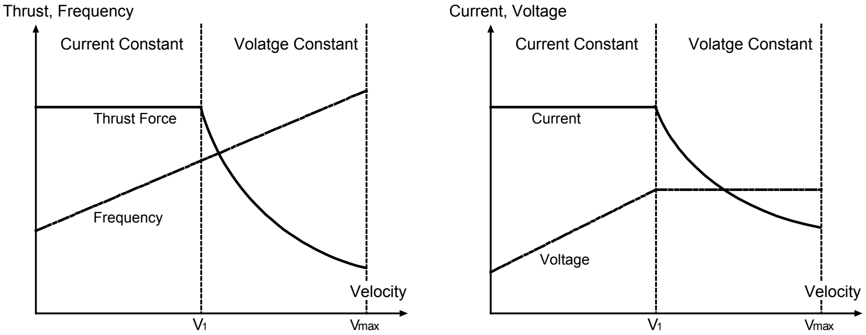

**Fig. 8 Charactaristics of Verocity Control under Constant Slip Frequency**

## 3.2 Power Supply Parameters

LIMs are driven by VVVF inverter. The parameters of inverter and configuration of the LIM are summrized in Table 2, and connection of LIMs is shown in Fig. 9.

Table II Paramters of Inverter and Configuration of LIM

| Condition | Value |
|---|---|
| Total LIMs per Inverter | 8 |
| Torolley Rail voltage | 1500V |
| Max inverter Line to Line Voltage | 1100V |
| Calculation Line Current of LIMs (rms) | 386A |

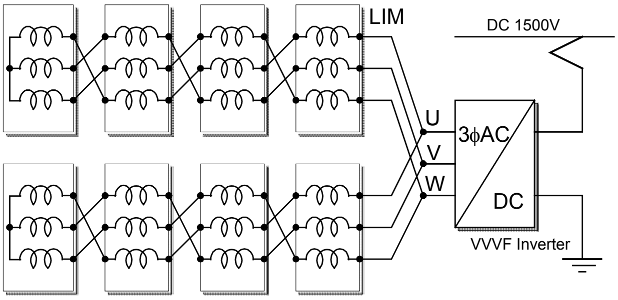

**Fig. 9 Connection of LIMs(4s-2p)**

### 3.3 Simulation Result

The result of calculation of the LIM using this constant slip frequency control taking the end-effect into account is shown in Fig. 10 and Fig. 11. The slip frequency is set to 14.5Hz.

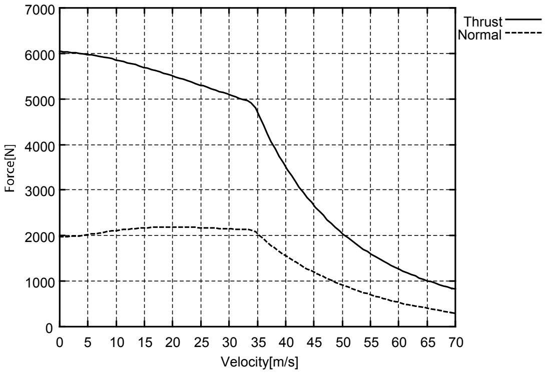

**Fig. 10 Thrust and Normal Forces**

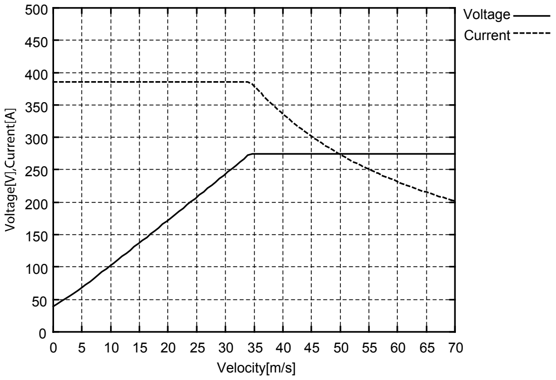

**Fig. 11 Voltage and Current**

In Fig. 10, the value of normal force is represented as absolute value. At constant current mode, the thrust force decreases with the increase of velocity because of the end-effect. The output voltage of inverter for control reaches in the maximum at about 34m/s (122km/h).

# 4 Multipurpose Design Optimization

## 4.1 Multipurpose Optimization Problem

Control variables and its environment become complication in multipurpose optimization problem, though there is especially no difficult theoretical if a simple case is enhanced. But, it is difficult to optimize what integrate them because they are estimated from many sides.

The multipurpose optimization problem is formulated into the following problems;

$$\text{Under constrained condition: } \begin{cases} g_i(\boldsymbol{x}) \geq 0 & (i = 1, 2, \cdots, k) \\ \vdots & \\ h_i(\boldsymbol{x}) \geq 0 & (i = 1, 2, \cdots, m) \\ \vdots & \end{cases}$$

$$\text{Objective function: } \{f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), \cdots, f_n(\boldsymbol{x})\} \quad \rightarrow \quad \text{minimize or maximize}$$

In order to solve this multipurpose problem, in this study, the method of convert objective function into *weighting addition* is used. That is to say, this problem is transformed as follows;

$$\text{Under constrained condition: } \begin{cases} g_i(\boldsymbol{x}) \geq 0 & (i = 1, 2, \cdots, k) \\ \vdots & \\ h_i(\boldsymbol{x}) \geq 0 & (i = 1, 2, \cdots, m) \\ \vdots & \end{cases}$$

$$\begin{cases} F = w_1 f_1 + w_2 f_2 + \cdots + w_n f_n \quad \rightarrow \quad \text{minimize or maximize} \ (w_i : \text{weight}) \\ \sum_{i=1}^{n} w_i = 1 \end{cases}$$

In this weighting addition method, the weighting coefficient $w_i$ is set for each objective function $f_i$. And all products of their objective function and their weighting coefficients are summed. Thus, this multipurpose problem is transposed to simplex objective optimization problem by minimizing or maximizing one function $F$ (called evaluation function) of sum of their products as objective function.

Making objective function based on this weighting method, each objective function must not be lumped into the same category because the unit and the order of their functions are different, so it is desirable that functions are normalized to decide weight coefficient before functions are summed. The decision of the weight coefficient is the most practicable present method, because converting into simplex purpose optimization problem solves optimal solution using the general mathematical program directly, but this decision is greatly depends on designer's experience and intuition.

## 4.2 Evaluation Method

### 4.2.1 Objective Function and Parameters

In this study, each objective function $f_i$ and design parameters vector $\boldsymbol{x}$ (= $x_1$, $x_2$, $x_3$) are set and summarized in Table III and Fig. 12 shows what each parameter $\boldsymbol{x}$ indicates in LIM.

Table III Objective Functions and Design Parameters

| Objective Function | Remark |
|---|---|
| $f_1$ | Thrust force (0 speed) |
| $f_2$ | Thrust force (200 km/h) |
| $f_3$ | Power fuctor (160 km/h) |
| $f_4$ | Cost index |
| Design Parameters | |
| $x_1$ | Coil pitch |
| $x_2$ | Core height |
| $x_3$ | Aluminum plate thickness |

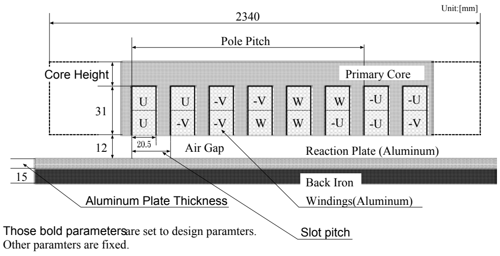

**Fig. 12 Design Paramters**

Other design paramters are set as fixed parameters shown in Fig.3. When Objective functions $f_i$ are formulated for the function of design parameters, LIM's parformances such as thrust force, normal force, power fuctor and so on, are calculated by using two-dementional FDM which is described section 2 and section 3. The power factor $f_3$ is related to operational cost and this HSST system is designed for the average speed of 160km/h, so the value of power factor is set at 160km/h. The cost index $f_4$ shows the material cost index which includes costs of secondary Aluminum plate (reaction plate), primary core and Aluminum windings, but not back iron because it is set as fixed parameter. The objective function $f_4$ is the inverse of actual material costs in order to maximaize evaluation function $F$. So, the bigger cost index is better.

### 4.2.2 Evaluation Function

The Evaluation function $F$ is formed as follow Eq.1.

$$F(\boldsymbol{x}) = w_1 f_1(\boldsymbol{x}) + w_2 f_2(\boldsymbol{x}) + w_3 f_3(\boldsymbol{x}) + w_4 f_4(\boldsymbol{x}) = \sum_{i=1}^{4} w_i f_i(\boldsymbol{x}) \tag{1}$$

The coefficients $w_i$ are weighting coefficients for each objective function $f_i$. Each objective function is normalized under the condition $\boldsymbol{x}_0$ = (30, 10, 5), which is HSST-200 LIM's basic parameter; i.e. their functions are calculated based on the increase or decrease ratio to the basic condition. The value of

LIM’s performances is shown in Table IV and how to normalize objective functions is shown as follows. And slip frequency is set to 14Hz.

Table IV The Performances of LIM under $\boldsymbol{x}_0 = (30, 10, 5)$

| Performances | Value |
|---|---|
| Thrust force (0 speed) at $\boldsymbol{x}_0$ | 4123N |
| Thrust force (200 km/h) at $\boldsymbol{x}_0$ | 1578N |
| Power fuctor at (160 km/h) at $\boldsymbol{x}_0$ | 0.2376 |
| Cost index at $\boldsymbol{x}_0$ | 1/14215 |

How to normalize:

$$f_1(\boldsymbol{x}) = \frac{\text{Thrust force (0 speed) at } \boldsymbol{x}}{\text{Thrust force (0 speed) at } \boldsymbol{x}_0}$$

### 4.2.3 Constrained Condition

Constrained conditions $g_i$ are summarized in Table V.

The condition $g_1$ is designed for compact levitation system and minimizing effects to its system. The $g_2$ is needed for the loaded HSST vehicle to start up at 10% uphill gradient, on the other hand $g_3$ is need for the loaded vehicle to climb up at 3.3% uphill gradient at the speed of 200 km/h. Conditions $g_2$, $g_3$ are set under calculation of HSST-200’s travel resistance added the margin. This resistanse $D$ is defined as Eq. 2. This travel resistance draws like Fig.13 for the loaded HSST vehicle and 3.3% uphill gradient. The curve of the Fig. 13 is set up as summation of Eq.2 and gravity at uphill gradient. In order to keep the increase of cost within1.05%, the condition $g_4$ is set. And the conditions for design paramters $\boldsymbol{x}$ are shown in Table VI.

Table V Constrained Condition

| Constrained Condition | | Evaluation |
|---|---|---|
| $g_1(\boldsymbol{x})$ | Normal force at 0 speed | $\lvert g_1 \rvert \le 0.7$ |
| $g_2(\boldsymbol{x})$ | Thrust force at 0 speed | $g_2 \ge 0.85$ |
| $g_3(\boldsymbol{x})$ | Thrust force at 200km/h | $g_3 \ge 1.004$ |
| $g_4(\boldsymbol{x})$ | Cost Index | $g_4 \ge 0.9524$ |

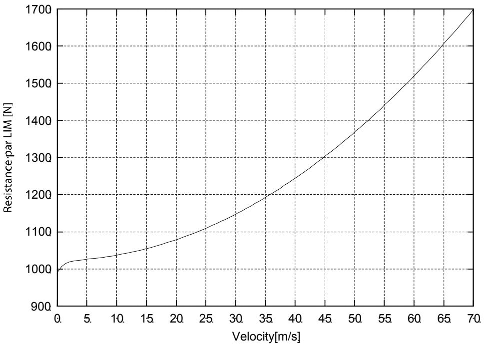

Fig. 13 Travel Resistance

$$D = \text{Magnetic Resistance} + \text{Air Resistance} + \text{Pantographic Resistance} \tag{2}$$

Table VI Condition for Design Parameters

| Design Parameters | | Condition |
|---|---|---|
| $x_1$ | Coil Pitch | $25.956 \le x_1 \le 35.54$ [mm] |
| $x_2$ | Core height | $10 \le x_2 \le 25$ [mm] |
| $x_3$ | Aluminum plate thickness | $4 \le x_3 \le 12$ [mm] |

#### 4.2.4 Weighting Coefficient Ratio

Weighting coefficients are set to two cases as shown in Table VII. The case I is the case of weighting total cost that includes material cost and power factor, which is related to operational cost. In the case II, thrust forces are weighted.

Table VII Weighting Coefficients

| Case | $w_1$ | $w_2$ | $w_3$ | $w_4$ |
|---|---|---|---|---|
| I | 0.10 | 0.10 | 0.40 | 0.40 |
| II | 0.40 | 0.40 | 0.10 | 0.10 |

### 4.3 Optimization Result and Discussion

Based on the condition that has been described above, the Evaluation function $F$ is maximized as shown in Eq. 3.

$$\begin{cases} \max F(\boldsymbol{x}) = \sum_{i=1}^{4} w_i f_i(\boldsymbol{x}) \\ \sum_{i=1}^{4} w_i = 1 \end{cases} \quad \text{under } g_i(\boldsymbol{x}) \ (i = 1 \cdots 4) \tag{3}$$

This optimization problem is calculated by using optimization toolbox in MATLAB. The optimization results are summarized in Table VIII.

Table VIII Optimization Result

| Weighting Case | $x_1$[mm] | $x_2$[mm] | $x_3$[mm] | $f_1$ | $f_2$ | $f_3$ | $f_4$ |
|---|---|---|---|---|---|---|---|
| I | 32.813 | 10.0 | 4.360 | 0.8924 | 1.1897 | 1.1192 | 1.0232 |
| II | 32.843 | 13.554 | 4.2885 | 0.8906 | 1.2065 | 1.1289 | 0.9570 |

Seeing this result, $f_1$ which means thrust force at 0 speed decrease, on the other hand, $f_2$ which means thrust force at 200km/h increase in the both case. It is found that HSST-200 LIM's basic parameter $\boldsymbol{x}_0$ = (30, 10, 5) is the design that put weight on low-speed performances.

The case I means that the parformance of this LIM on 200km/h can be improved holding down cost rather than a basic design, at the same time power fuctor at 160km/h can increase.

In the case II, since thrust forces was weighted, there is a margin in 200km/h in this design, and the thrust force at 200km/h becomes about 1900N in this case. In this case, the loaded HSST vehicle can climb up at about 5.0% uphill gradient at the speed of 200 km/h, taking the increase of LIM's weight into account.

But, looking overall, it turns out that the characteristic of the case I is excellent because the rate of the increase of thrust force at 200km/h is lower than that of the cost.

## 5 Conclusion

In this study, linear induction motors performances for HSST-200 Maglev vehicles are optimized based on multipurpose optimization problem by using Two-Dimensional Finite-Difference-Method for analysis of LIM. It is found that this method can calculate LIM's parformances including end-effect.

From optimize result, in the case of weighting LIM's total cost, the thrust force at 200km/h can be improved to 119% keeping the material cost 97.7% from basic HSST-200's design by analyzing the optimal design. At the same time, the power fuctor at 160km/h is improved to 112%, on the other hand, thrust force at 0 speed decreases. However, this thrust force value satisifies the constrained condition for thrust force at 0 speed in order to start up at 10% uphill gradient.

In this study, two-dementional FDM is used for the analysis of LIM, but actually the three-dimentional or quasi-three-dimensional analysis is needed for taking "transverse edge effect" and so on into account. And LIM's performances and optimization should be calculated on the basis of the analysis. This will be the next study based on this paper.

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