

Design and Characteristic Analysis of LSM for High Speed Train System using Magnetic Equivalent Circuit

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Abstract

This paper describes design and characteristic analysis of long primary type linear synchronous motor (LSM) for high speed train system. LSM is designed using loading distribution method and magnetic equivalent circuit. For characteristic analysis of LSM, analytical and numerical methods are applied. Analytical method for solving the magnetic field distribution of the analytic model is based on the Maxwell's equations. Using the characteristic equation and magnetic equivalent circuit, we analyze the effect of variation of parameters, and then we validate the result by comparing with numerical method by finite element method (FEM). We compare the analytical method with numerical method for analyzing the effect by variable parameters. This result will be useful of design and forecast of performance without FEM.

Keywords : Linear synchronous motor(LSM), Magnetic equivalent circuit(MEC)

1. Introduction

The past, railway system is interest in the development of high speed train system with speed up to 500 km/h [1]. Wheeled vehicles and electric current collecting systems have severe problems such as pantographs and third rails. To overcome these problems, wheels can be eliminated by magnetic levitation and sliding contacts for feeding power can be eliminated by replacing conduction with induction or radiation at microwave frequencies, as the means for transferring electric power to the vehicle [2]. To achieving speed up to 500 km/h, vehicles are usually propelled by linear synchronous motors (LSM) on the both sides of guide way with 3-phase armature windings and DC excitation coils wound around salient poles on the vehicle.

LSM does not use the mechanical coupling for the rectilinear movement, thus structure of LSM is simple and robust as compared with the conventional rotary motor. LSM system is also called as non-adhesion drive system, this non-adhesion drive system has lots of advantages over

the adhesion drive system as follows; (1) Excellent acceleration and deceleration, (2) Capability of climbing steep gradients, (3) Less susceptibility to weather conditions, (4) Quiet and smooth running [3].

There are two types as follows; (1) Short primary type, (2) Long primary type. In this paper, we design and characteristic analysis of long primary type LSM for high speed train system. Design and characteristic analysis of LSM using simulation methods are very effective because of reducing time consuming. Thus, analysis of influence on design parameter and prediction phenomena are needed, for such a reason, reliability of simulation results is very important. Secure reliability of simulation results, various methods for verification are required. And in this paper, we verify the design and characteristics of LSM by magnetic equivalent circuit (MEC) and finite element method (FEM).

2. Design and Analyze Methods

2.1 Loading Condition

Before the design of LSM, estimating loading condition of system is needed for accurate design. Weights of bogies, LSM s, and so on are determined at first, and driving profiles of train system also are decided.

Figure 1 is shown speed vs. time curve for driving profiles.

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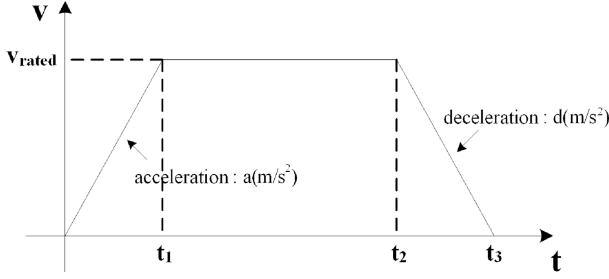


Fig. 1 Speed vs. time curve

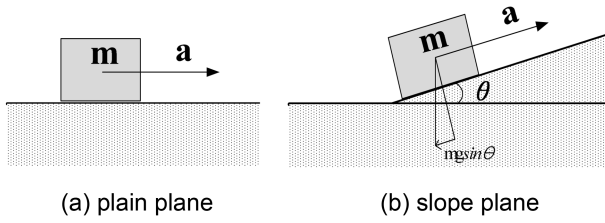


Fig. 2 Force for moving the mass

Speeds vs. time curve profiles such as Fig. 1 need some data as follows; acceleration and deceleration of LSM, total length of railroad, rated speed, and time.

As shown in Fig. 2, LSM when moving over slope plane needs more power than moving plain plane. Force when train is moving over slope plain with acceleration α is calculated as following Eq. (1).

$$F = m(g\sin\theta + \alpha) \quad (1)$$

where m is a total weight of train, g is an acceleration of gravity, θ is a slope angle, and α is a acceleration of train. And LSM with magnetic levitation has a drag force as following; (1) Aerodynamic drag force, (2) Magnetic drag force : this is similar to the rolling resistance of wheeled vehicle, (3) Linear generating drag force : this is created by the electric system producing auxiliary power for the train to feed levitation, air conditioning, lightning and so on [4].

Aerodynamic drag(F_A)

$$F_A = 2.8 \times v^2 \times (0.265 \times N + 30) [N] \quad (2)$$

Magnetic drag(F_M)

$$F_M = N \times (0.1 \times v^{0.5} + 0.02 \times v^{0.7}) \times 10^{-3} [N] \quad (3)$$

Linear generating drag(F_B)

$$F_B = 0 [N] (\text{for } 0 \leq v \leq 20 \text{ km/h}) \quad (4)$$

$$= N \times 7.3 \times 10^3 [N] (\text{for } 20 \leq v \leq 70 \text{ km/h})$$

$$= N(146/v - 0.2) \times 10^3 [N] (\text{for } 70 \leq v \leq 500 \text{ km/h})$$

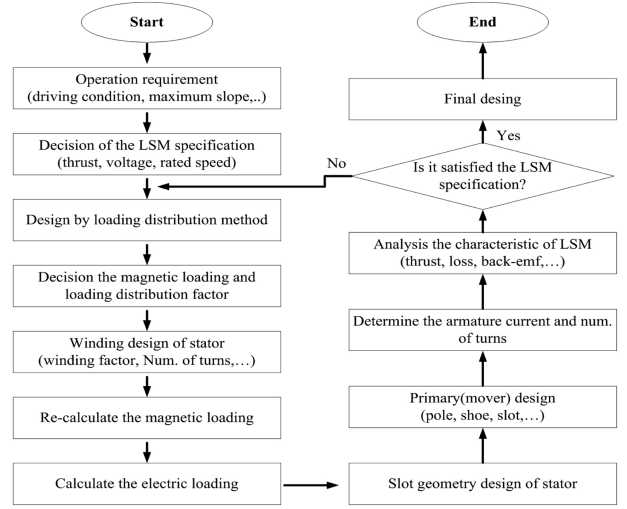


Fig. 3 Flowchart of design and analytic analysis procedure of LSM

where v is a velocity of train, N is a number of LSM, then, thrust force for train is calculated as following (5)

$$F_m = \frac{m(g\sin\theta + \alpha) + F_A + F_B + F_M}{N} \quad (5)$$

Capacity of LSM is established by following equation (6).

$$S = \frac{F_m \cdot V_{rated}}{\eta \cdot \cos\phi} \quad (6)$$

where η is an efficiency of LSM and $\cos\phi$ is a power factor. Supposing these factors are fixed, and then design process is performed.

2.2 Design of LSM

In previous section, we can determine rated speed, acceleration, and deceleration by driving profile and input voltage and frequency are limited by inverter specification. LSM is designed using loading distribution method and flowchart of design is shown in Fig. 3.

Foundation design of LSM is derived by design procedure and specification of LSM is shown in Table 1.

2.3 Characteristic Analysis of LSM

2.3.1 Analysis Method based on Analytic Approach

To solve characteristic analysis of LSM, Analytic approach method based on Maxwell's equations is developed in 1987 by Zesheng Deng and Ion Boldea[5,6]. Analytical model is developed for the simplified LSM for reducing computation. In deriving the analytical model, several assumptions are used. Slots and yokes of armature and filed is separated by two region, and then calculate magnetic flux density in airgap using boundary condition

Table 1 Specification of LSM

Parameter	Value	Unit
Rated Capacity	8	MW
Rated Thrust Force	57	kN
Frequency	270	Hz
Input Voltage	3 Φ 4,500	V
Input Current	935	A
Air gap length	10	Mm
Pole pitch	258	mm
Number of poles	230	
DC exciting current of mover	24	A
Lamination length	300	mm
Slots per poles per phases of Stator	1	

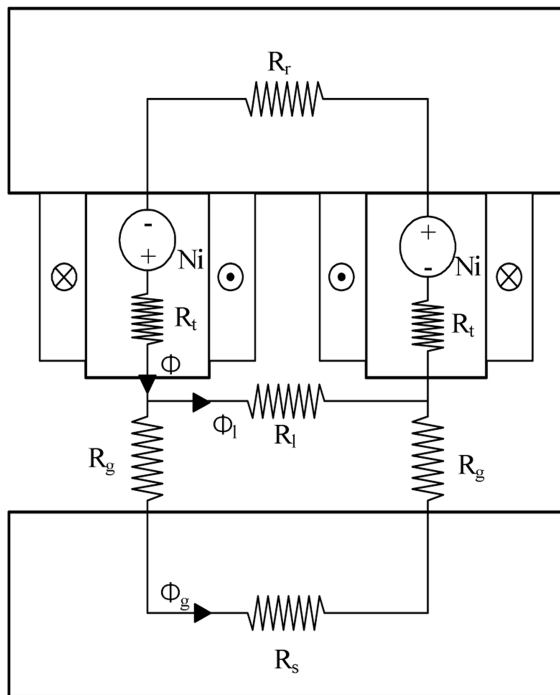


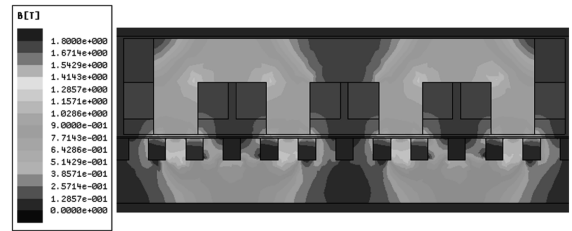
Fig. 4 Magnetic equivalent circuit for one pole of LSM

on each boundary surface. Using analytical method, we can analyze the distribution of magnetic flux density on temporal and spatial.

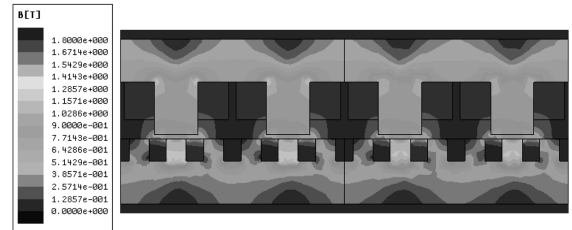
This method is very complicated and it is difficult to apply directly. Thus, characteristic analysis method is derived by coupling analytical method to MEC

2.3.2 Analysis method using MEC

MEC is a simple method for verifying the characteristic of electromagnetic phenomena, but Leakage fluxes and saturation of teeth and core are not considered correctly.

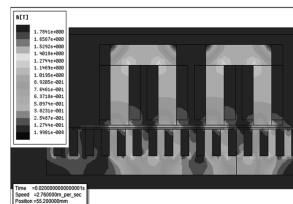


(a) Magnetic flux density considering with end effect

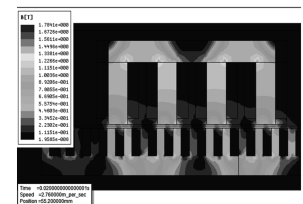


(b) Magnetic flux density considering without end effect

Fig. 5 Magnetic flux density considering with/without end effect



(a) Separated Yoke



(b) Connected Yoke

Fig. 6 Magnetic flux density considering yoke connection

MEC is useful ancillary analytical method to verifying method of design parameters. MEC for one pole model of LSM is shown in Fig. 4. To simplify geometry of Stator, stator slot and teeth are unified.

Unlike MEC of rotary type synchronous motor, magnetic flux of LSM flows from one pole to right next pole fully because of end effect. The end effect which is an important phenomenon in a linear motor has been considered by 2D FEM and magnetic flux density considering with/without end effect is shown in Fig. 5. Linear synchronous motor has a finite length of a primary, it causes end effect. Because of flux flows from one pole to next, MEC considering only one pole is suited for verification of characteristic of LSM. As shown in Fig. 6, results of characteristic analysis has 0.06% error either yoke of primary is separated or not.

Reluctance and electromagnetic force (EMF) is calculated as follow.

$$R_r = \frac{\tau}{\mu_0 \mu_r (h_{yp} \times l_{pri})} \quad (7)$$

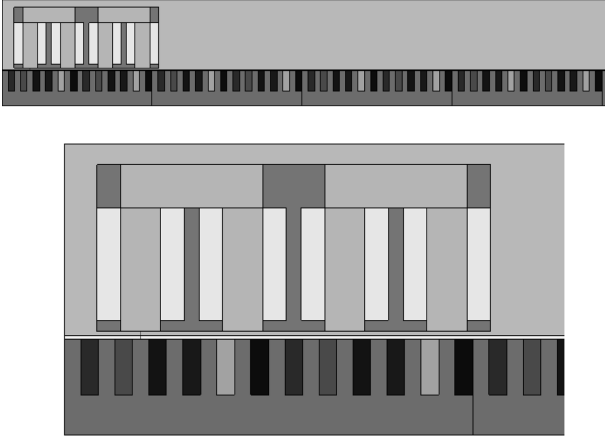


Fig. 7 2 dimensional periodic models for 2D FEM

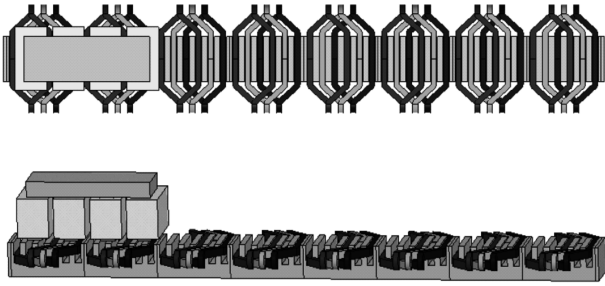


Fig. 8 3 dimensional periodic models for 3D FEM

$$R_s = \frac{\tau}{\mu_0 \mu_r (h_{ys} + h_{ts}) \times l_{stator}} \quad (8)$$

$$R_g = \frac{K_c \cdot g_0}{\mu_0 (w_{st} \times l_{pri})} \quad (9)$$

$$R_t = \frac{h_{tp}}{\mu_0 \mu_r (w_{tp} \times l_{pri})} \quad (10)$$

$$R_l = \frac{\tau}{\mu_0 (K_c g_0 \times l_{pri})} \quad (11)$$

where R_r , R_s , R_g , R_t and R_l are a reluctance at rotor yoke, stator, air-gap, rotor teeth, and leakage component and K_c is a carter's coefficient.

$$F = 2Ni = \Phi R_{eq} \quad (12)$$

$$R_{eq} = \{(2R_g + R_s) // R_l\} + R_r + 2R_t \quad (13)$$

$$\Phi_g = \Phi \times \frac{R_l}{(2R_g + R_s) + R_l} \quad (14)$$

We analyze characteristics using combination analytical method with MEC.

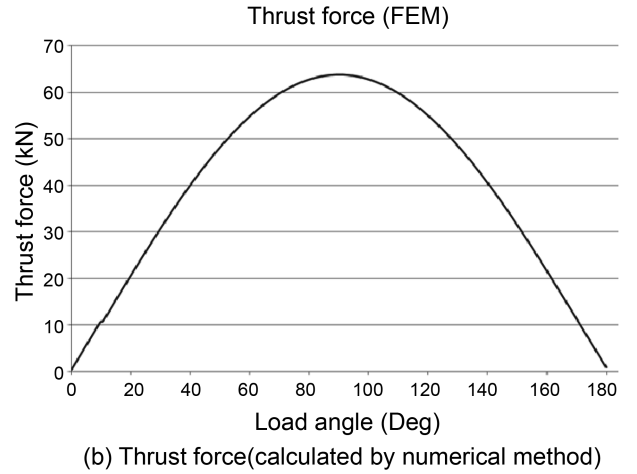
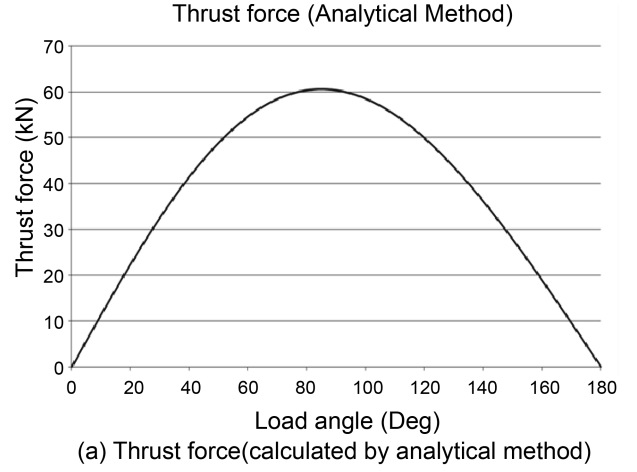


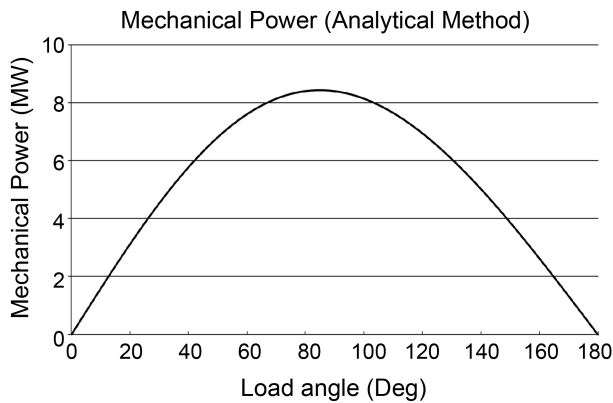
Fig. 9 Thrust force vs. load angle

2.3.3 Analytical method using FEM

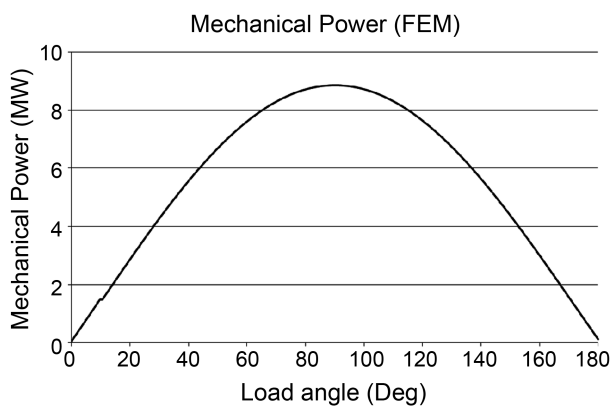
Characteristic analysis of a LSM requires 3 dimensional models and FEM to consider phenomena fully, but transient analysis of 3 dimensional full model is impossible for the present because of insufficient computer memory. Also, full model about LSM in this paper has 230 poles and is not impossible to calculate. Such as this reason, thrust force is calculated by using 2 dimensional periodic models, and 3 dimensional models are analyzed to be compared with 2 dimensional models. 2 dimensional and 3 dimensional models for FEM are shown in Fig. 7 and Fig. 8.

3. Analysis Results of LSM

Figure 9 shows analytical analysis result and numerical simulation result of the thrust force. Rated thrust force is determined 57 kN at load angle 85 deg in design process. Thrust force is 60.4 kN by using analytical analysis method and is 63.63 kN by using 2 dimensional FEM. As



(a) Mechanical Power(calculated by analytical method)



(a) Mechanical Power(calculated by analytical method)

Fig. 10 Mechanical power vs. load angle

shown in the figure, characteristic analyses of analytical method and FEM have similar results and error is within 5%. Error between results of analytical method and FEM is occurred as follow reasons: (1) Analytical method can't consider saturation and non linear characteristics of magnetic material. (2) Analysis model of analytical method is simplified for calculated easily.

Even though some reasons as above, analytical method is convenient for characteristic analysis easily and less time consuming. And mechanical power is shown in Fig. 10 and results are also similar to each other.

2 dimensional FEM is analyzed by transient state analysis method, but 3 dimensional FEM is impossible because of memories of computer and calculation time. Such as reason, steady state analyses of 3 dimensional models and 2 dimensional models are compared. Error is about 7% and time consuming of 3 dimensional FEM is 2 days for 14 steps and 2 dimensional FEM is only 2 hours for 14 steps. Thrust force of steady state analysis is larger than transient analysis because of steady state analysis is not

considered eddy current loss and hysteresis loss by time variant. In the time consuming aspect, 3 dimensional analysis is not more useful than 2 dimensional analysis.

4. Conclusion

In this paper, loading conditions and design method of LSM is presented and a characteristic analysis method for linear synchronous motor for a high speed train has been performed. A characteristic analysis method is derived by coupling analytical method based on Maxwell's equation to magnetic equivalent circuit. Thrust force which an important property of LSM is calculated by analytical method and numerical method and compared each case. Results of each case are within 5% error, thus analytical method is convenient for characteristic analysis easily and less time consuming. In various design cases for high speed train, analytical method of characteristic analysis is useful for time saving and for feedback results to new design consideration.

Acknowledgement

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Reference

1. Sen, P.C. (1975). "On linear synchronous motor (LSM) for high speed propulsion," IEEE Transaction on Magnetics, Vol. Mag-11, No. 5, pp. 1484-1486.
2. Levi, Enrico (1973). "Linear synchronous motors for high-speed ground train," IEEE Transactions on Magnetics, Vol. Mag-9, No. 3, pp. 242-248.
3. Lee, Hyung-Woo, Lee, Sung Gu, Park, Chanbae, Lee, Ju and Park, Hyun-June (2008). "Characteristic analysis of a linear induction motor for a lightweight train according to various secondary schemes," International Journal of Railway, Vol. 1, No. 1, pp. 6-11.
4. Kemp, Roger and Smith, Roderick (2007). "Technical issues raised by the proposal to introduce a 500 km/h magnetically levitated transport system in the UK," Department for Transport.
5. Deng, Zesheng and Boldea, I. (1986). "Fields in permanent magnet linear synchronous machines," IEEE Transactions on Magnetics, Vol. Mag-22, No. 2, pp. 107-112.
6. Deng, Z. and Boldea, I. (1987). "Forces and parameters of permanent magnet linear synchronous machines," IEEE Transactions on Magnetics, Vol. Mag-23, No. 1, pp. 305-309.