The Dynamic Performance Analysis Model of EMS-MAGLEV System Utilizing Coupled Field-Circuit-Movement Finite Element Method

Yingying Yao, Youtong Fang, and Guanzhong Hu
Zhejiang University, China

Abstract

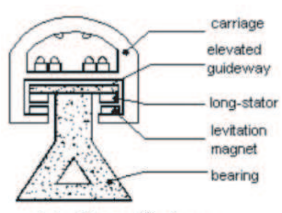
Many electro-mechanical motional systems include parts that can move relative to the others. EMS-Maglev system is one of the examples, which combines the devices for propulsion, levitation and on-board electric power transfer in a single electromagnetic structure. The analysis of its mechanical dynamic characteristics is very important for the design of the configuration and the control system. Because of the complexity of the time-varying magnetic configuration, analytical method can hardly obtain the dynamic performance. Therefore, analysis of the electromagnetic field is necessary. Moreover, with ordinarily transient finite element method, it is also difficult to consider the external power supply of linear synchronous motors and the working status of linear generator.

In this paper, a modified transient finite element algorithm for the performance analysis of magnetically levitated vehicles of electromagnetic type is presented. The algorithm incorporates external power system and vehicles movement equations into FE model of transient magnetic field computation directly. Sliding interface between stationary and moving region is used during the transient analysis. The periodic boundaries are implemented in an easy way to reduce the computation scale. Unfortunately, this directly coupled FE analysis is very time-consuming.

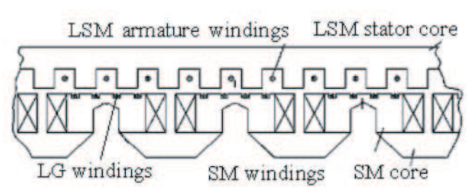
To overcome this problem, a fast solving technique for the mechanical dynamic characteristic of electro-mechanical motional systems is also proposed in this paper. Based on a sequence of finite element analysis, and a set of equivalent electrical circuit parameters extracted, the method incorporates electrical equation and vehicles movement equation into state equations. It is proved that this method can be used for both electro-motional static and dynamic cases. Through test of a transformer and an EMS-MAGLEV system, it reveals that the method gives reasonable results at very low computational costs comparing with transient finite element analysis.

1. Introduction

In electromagnetically levitated transport systems (EMS-Maglev), such as the German Transrapid, the propulsion is supplied by a long-stator linear synchronous (LSM) motor whose stator (armature) is fixed all along the guideway and the moving poles with the excitation (levitation magnets) are on the vehicle. The direct current exciting windings create main field and levitation forces. The LSM armature windings are energized by three-phase alternating voltage over a power supply section. And linear generator supplies the on-board electric power. Fig.1 gives the EMS-Maglev transport system in overall view and the configuration of LSM longitudinal section respectively. Obviously the excitation current has to assure the system of an accurate levitation force and a high power factor. To find the current and optimize the system, analysis of the mechanical dynamic characteristic is necessary. Due to the complexity of the time-varying magnetic configuration, a fully analytical



(a) Overall view



(b) The configuration of LSM longitudinal section

Figure 1: EMS-MAGLEV system.

approach enables to obtain only the mean value of the motor propulsion force, whereas the determination of the instantaneous value requires the recurrent utilization of a numerical code. Numerical analysis method such as finite element method employs time-stepping method to analyze the dynamic characteristics. Since the system matrix must be solved at each incremental time, this time-stepping method proves to be time-consuming.

To solve these problems, this paper presents a fasting solving method to analyze the dynamic characteristics, which can be used for both electro-mechanical static and electro-mechanical motional systems. In the method, the equivalent circuit parameters at each incremental time are extracted by using a sequence of finite element analysis. Then, the electro-mechanical coupled state equations are solved by Runge-Kutta method. To show validity of the proposed method, the dynamic performance of a transformer and an EMS Maglev system were tested. The results are compared with the time-stepping method using FEM.

2. Direct Coupled Field-Circuit-Motion Finite Element Analysis

The dynamic performanaces of a movable electrical device incorporated with power system are determined by external transient or periodic exiciting sources and the movement of the vehicle with constant excitation current. In this paper, it is assumed that a conducting part moving in only one direction with constant velocity u, and the conductor has an invariant cross section at right angles to the direction of motion. The governing equations of the eddy current problems considering movement of a conductivity material, external excitation and load, are writen as follows:

$$\nabla \times \nu \nabla \times A = -\sigma \frac{\partial A}{\partial t} + J_s + \frac{i_k N_k}{S_k} - \sigma \mu \times \nabla \times A \tag{1}$$

$$V_k = i_k R_k + \frac{d\psi_k}{dt} \tag{2}$$

$$M \frac{d^2 x}{dt^2} + d \frac{dx}{dt} + Kx = F \tag{3}$$

where A is the magnetic vector potential; μ the velocity of a moving conductor. i_k, R_k, ψ_k and V_k are the unknown current, total resistance in a power supply loop, the flux linkage linking the winding and the terminal voltage of k-th exciting coil respectively. σ is the electrical conductivity, J_s the current density excited in a filamentary conductors, ν the magnetic resistivity. x indicates the relative position of the moving part, t the time, M the mass, D the damping coefficient, K the spring constant. F represents the mechanically applied force F_m, the gravitational force F_g, and the electromagnetic force F_e, respectively. After applying standard Galerkin procedure to (1) and (2) except the last term on right hand of (1), a matrix equation is produced as:

$$\begin{bmatrix} K & -C_{12} \\ 0 & R \end{bmatrix} \begin{bmatrix} A \\ i \end{bmatrix} + \begin{bmatrix} M & 0 \\ D_{21} & L \end{bmatrix} \begin{bmatrix} \frac{dA}{dt} \\ \frac{di}{dt} \end{bmatrix} = \begin{bmatrix} F \\ V \end{bmatrix} \tag{4}$$

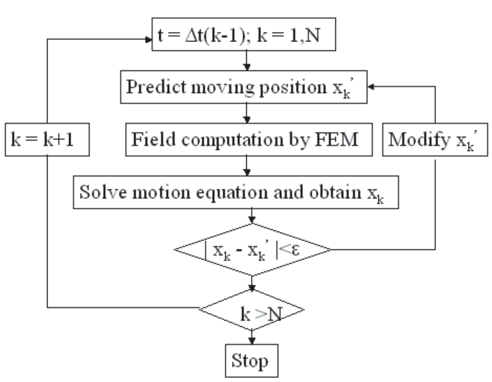


Figure 2: The flow chart of direct coupled method

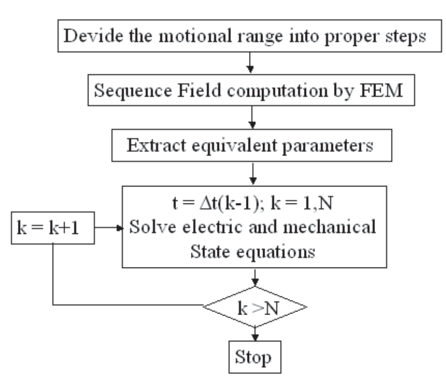


Figure 3: The flow chart of the fast solving technique

where, $K = \int_s \nu(\frac{\partial [N]^T}{\partial x}\frac{\partial [N]}{\partial x} + \frac{\partial [N]^T}{\partial x}\frac{\partial [N]}{\partial x})ds$, $M = \int_s \sigma [N]^T [N] ds$, $C_{12} = \int_s \frac{N}{S}[N]^T[N]ds$, Magnetic flux linkage on the coil is $\psi = \frac{N}{S}\sum_{i=1}^{Ne} S_i \int_i A \cdot dl$. Where S_i stands for the cross section area of the element i, Ne for the number of elements in the whole winding region, and li for the path fraction in element i. In 2D case, $D_{21} = kL_{ef}C_{12}$, L_ef is equivalent length in z direction. k is determined according to the phase circuits of exciting coils. The characteristic computing process of an electro-mechanical motional system, in which the governing equations are (1)∼(3), is shown in Fig. 2. From the computing flow chart, it is clear that during the dynamic characteristic evaluation, the electromagnetic field computation is recurrent many times.

3. Fast Solving Technique Based on Electro-Mechanical Equations Coupled Finite Element Analysis

In order to reduce the computation of the electro-mechanical motional system, a fast solving technique is proposed. To simplify the model, constant permeability of the ferromagnetic material is assumed. The loss in the iron core is neglected. For multi-windings, the flux linkage in (2) is then expressed in matrix form as follows:

$$[\psi] = [L(x,[i])][i] = [L][i] \tag{5}$$

where $[L]$ denotes the inductance matrix, which is consist of self inductance and mutual inductance. The parameters of $[L]$ are only dependent on the geometry of the system during movement. They are calculated according to magnetic energy. The electromagnetic force is obtained by the derivative of electromagnetic energy with respect to the position variable:

$$F_e(x,[i]) = \frac{\partial W_m(x,[i])}{\partial x} = \frac{1}{2}[i]^T \frac{\partial [L]}{\partial x}[i] \tag{6}$$

The state variables are chosen as the currents in each coil, relative position x and moving velocity μ. Equations (2) and (3) are converted into a set of state equations as follows:

$$\frac{d[i]}{dt} = [L]^{-1}[\mu] - [R][i] - \frac{\partial [L]}{\partial x}[i]\nu \tag{7}$$

$$\frac{d\nu}{dt} = \frac{F - D\nu - Kx}{M} \tag{8}$$

$$\frac{dx}{dt} = \nu \tag{9}$$

Above state equations (7)∼(9) are solved by using the Runge-Kutta method. During a time period, the inductance matrix [L] is calculated by FE method corresponding to the different position of the vehicle. When the Runge-Kutta method is applied to solve the state equations, the inductance and its derivatives are interpolated by Bspline method. The propulsion force F_x versus the vehicle position is calculated according to (6). The flow chart of this technique is shown in Fig. 3.

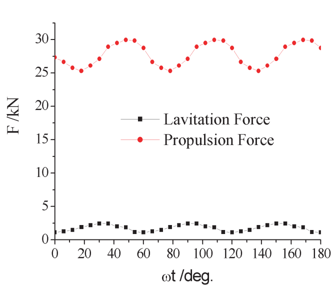


Figure 4: Levitation force versus the position

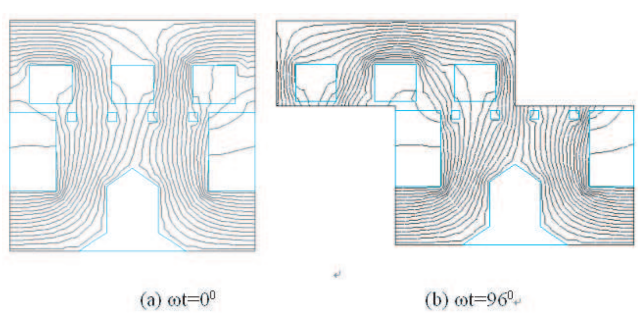


Figure 5: Flux at different time in electrical angle.

4. Numerical Results of Test Examples

Example 1: Transformer performance under short circuit experiment. Two-winding $240MVA$, $550/\sqrt{3}$: $20kV$ single-phase transformer, the turns of the primary and secondary windings are 508 and 32 respectively. To simulate the short circuit experiment of the transformer, the voltage sources applied to the primary and secondary terminal are $45.63222\sqrt{2}sin(100\pi t)kV$ and 0 respectively. The r.s.m. value of steady state currents in both windings calculated by directly coupled field-circuit method are 764.18A and 12127A respectively. The matrix [L] extracted through FE analysis is $[L] = \begin{bmatrix} 0.57605 & 9.1418 \\ 9.1418 & 145.27 \end{bmatrix}$ The r.s.m. value of steady currents in both windings calculated by Rung-Kutta method are 763.68A and 12126A respectively. The results reveal that the proposed fast solving technique is effective.

Example 2: The dynamic force characteristics of an EMS-MAGLEV system The suspending magnet of the test system is excited by 25×270[AT] direct current. The linear synchronous motors are energized by 3000V alternating voltage over 1200m in length. When the levitation magnet moves, electromagnetic forces, field distributions, and inductance are shown in Fig. 4∼Fig. 6. By comparing the propulsion force calculated by two methods, as shown in Fig. 7, it reveals that the fast solving technique can obtain reasonable mechanical dynamic characteristic with reduced computation.

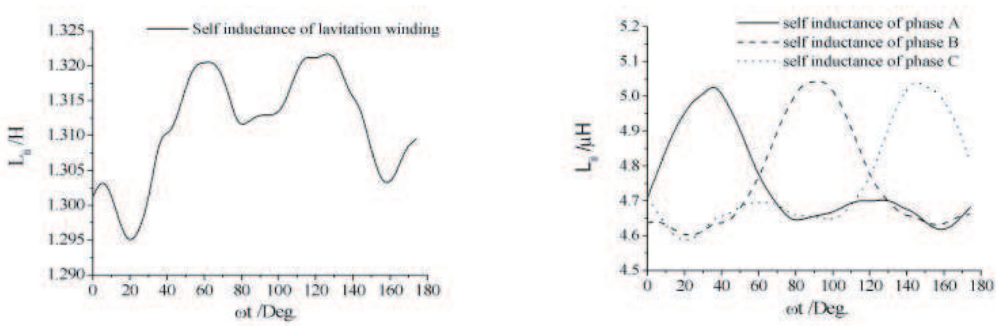


Figure 6: The Inductance versus the moving position

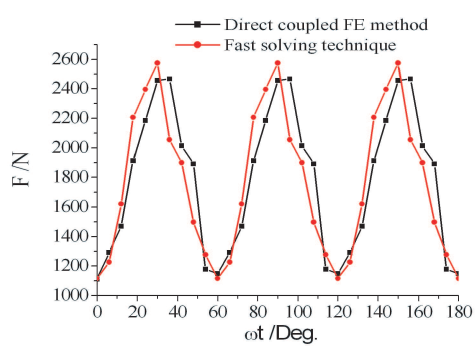


Figure 7: The propulsion force calculated by two methods

5. Conclusion

Two procedures for the simulation of electro-mechanical dynamic characteristics are describes. From the test examples, the fast solving technique, valid in conditions of linear magnetic circuit, gives reasonable results and requires a much reduced number of FE analyses.

6. Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 50477030).

REFERENCES

1. Andriollo, M., et al., "FEM Calculation of the LSM Propulsion Force in EMS-MAGLEV Trains," *IEEE Trans. On Magnetics*, Vol. 32, No. 5, 5064-5066, 1996.
2. Lee, Se-Hee, et al., "Fast Solving Technique for Mechanical Dynamic Characteristic in Electromagnetic Motional System by Electro-Mechanical State Equation Including Extracted Circuit Parameter," *IEEE Trans. On Applied Superconductivity*, Vol. 14, No. 2, 1926-29, 2004.
3. Takahashi, T. and E. Masato, "Dynamic Finite Element Analysis of a Magnetic Hammer with a New Composite Mesh Scheme," *IEEE Trans. on Magnetics*, Vol. 34, No. 5, 3339-3342, 1998.