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Dynamic performance analysis model of high-reliability EMS-Maglev system*

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Abstract: In this paper, a modified transient finite element (FE) algorithm for the performance analysis of magnetically levitated vehicles of electromagnetic type is presented. The algorithm incorporates the external power system and vehicle's 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. It is proved that this method can be used for both electro-motional static and dynamic cases. The test of a transformer and an EMS-Maglev system reveals that the method generates reasonable results at very low computational costs comparing with the transient FE analysis.

Key words: EMS-Maglev system, Field-circuit coupled, Movement finite element

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INTRODUCTION

In the electromagnetically levitated transport system (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 the linear generator supplies the on-board electric power. Fig.1 shows the EMS-Maglev transport system in overall view and the configuration of LSM longitudinal section. 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, an analysis of the mechanical dynamic characteristic is necessary (Andriollo *et al.*, 1996). Due to the complexity of the time-varying magnetic configuration, a fully analytical 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 (FEM) employs the time-stepping method to analyze the dynamic characteristics. Since the system matrix must be solved at each incremental time, this time-stepping method is time-consuming (Todaka and Enokizono, 1998; Lee *et al.*, 2004).

To solve these problems, this paper presents a fast 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 FE analysis. Then, the electro-mechanical coupled state equations are solved by Runge-Kutta method. To validate the proposed method, the dynamic performance of a transformer and an EMS-Maglev system was tested. The results are compared with the time-stepping method using FEM.

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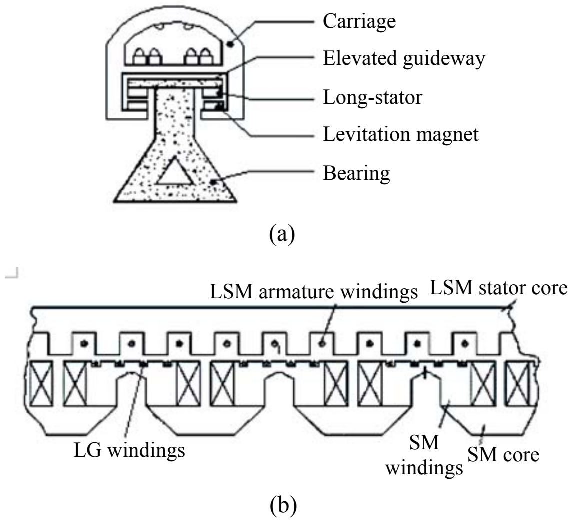


Fig.1 EMS-Maglev system. (a) Overall view; (b) The configuration of LSM longitudinal section

DIRECT COUPLED FIELD-CIRCUIT-MOTION FINITE ELEMENT ANALYSIS

The dynamic performances of a movable electrical device incorporated with a power system are determined by the external transient or periodic exciting 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 $\boldsymbol{u}$, 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 written as follows:

$$\nabla \times \nu \nabla \times \boldsymbol{A} = -\sigma \frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{J}_{\mathrm{s}} + \frac{i_k N_k}{S_k} - \sigma \boldsymbol{u} \times \nabla \times \boldsymbol{A}, \quad (1)$$

$$V_k = i_k R_k + \frac{\mathrm{d}\psi_k}{\mathrm{d}t}, \quad (2)$$

$$M \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + D \frac{\mathrm{d}x}{\mathrm{d}t} + Kx = F, \quad (3)$$

where $\boldsymbol{A}$ is the magnetic vector potential, $\boldsymbol{u}$ is 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 kth exciting coil respectively. σ is the electrical conductivity, $\boldsymbol{J}_{\mathrm{s}}$ 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 Eq.(1) and Eq.(2) except the last term on right hand of Eq.(1), a matrix equation is produced as:

$$\begin{bmatrix} K & -C_{12} \\ 0 & R \end{bmatrix} \begin{bmatrix} \boldsymbol{A} \\ \boldsymbol{i} \end{bmatrix} + \begin{bmatrix} M & 0 \\ D_{21} & L \end{bmatrix} \begin{bmatrix} \dfrac{\mathrm{d}\boldsymbol{A}}{\mathrm{d}t} \\ \dfrac{\mathrm{d}\boldsymbol{i}}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} F \\ V \end{bmatrix}, \quad (4)$$

where, $K = \int_s \nu \left(\frac{\partial [\boldsymbol{N}]^{\mathrm{T}}}{\partial x} \frac{\partial [\boldsymbol{N}]}{\partial x} + \frac{\partial [\boldsymbol{N}]^{\mathrm{T}}}{\partial x} \frac{\partial [\boldsymbol{N}]}{\partial x} \right) \mathrm{d}s$, $M = \int_s \sigma [\boldsymbol{N}]^{\mathrm{T}} [\boldsymbol{N}] \mathrm{d}s$, $C_{12} = \int_s \frac{N}{S} [\boldsymbol{N}]^{\mathrm{T}} [\boldsymbol{N}] \mathrm{d}s$.

Magnetic flux linkage on the coil is $\psi = \frac{N}{S} \sum_{i=1}^{N_{\mathrm{e}}} S_i \int_{l_i} \boldsymbol{A} \cdot \mathrm{d}l$, where S_i stands for the cross section area of the element i, N_{e} for the number of elements in the whole winding region, and l_i for the path fraction in element i. In 2D case, $D_{21} = kL_{\mathrm{ef}}C_{12}$, 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 Eqs.(1)~(3), is shown in Fig.2. From the computing flow chart, it is clear that the electromagnetic field computation is recurrent many times during the dynamic characteristic evaluation.

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 Eq.(2) is then expressed in matrix form as follows:

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

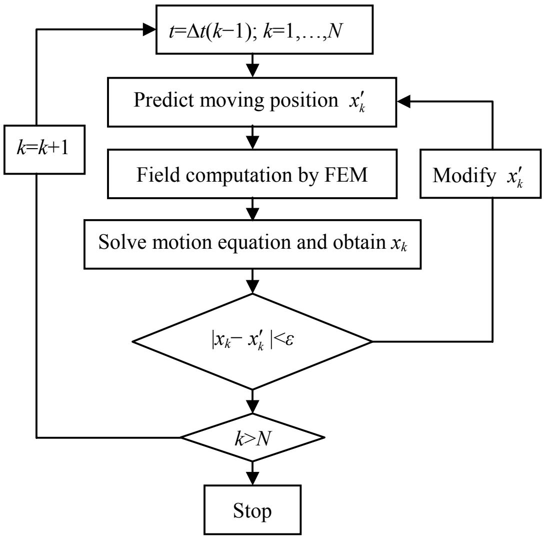


Fig.2 The flow chart of direct coupled method

where [***L***] denotes the inductance matrix, which consists 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:

$$F_{\mathrm{e}}(x,[\boldsymbol{i}])=\frac{\partial W_{\mathrm{m}}(x,[\boldsymbol{i}])}{\partial x}=\frac{1}{2}[\boldsymbol{i}]^{\mathrm{T}}\frac{\partial[\boldsymbol{L}]}{\partial x}[\boldsymbol{i}]. \tag{6}$$

The state variables are chosen as the currents in each coil, relative position x and moving velocity $\boldsymbol{u}$. Eqs.(2) and (3) are converted into a set of state equations as follows:

$$\frac{\mathrm{d}[\boldsymbol{i}]}{\mathrm{d}t}=[\boldsymbol{L}]^{-1}\left\{[\boldsymbol{u}]-[\boldsymbol{R}][\boldsymbol{i}]-\frac{\partial[\boldsymbol{L}]}{\partial x}[\boldsymbol{i}]v\right\}, \tag{7}$$

$$\frac{\mathrm{d}v}{\mathrm{d}t}=\frac{F-Dv-Kx}{M}, \tag{8}$$

$$\frac{\mathrm{d}x}{\mathrm{d}t}=v. \tag{9}$$

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

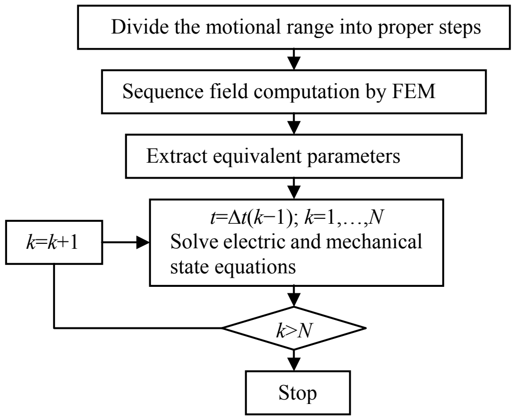


Fig.3 The flow chart of the fast solving technique

NUMERICAL RESULTS OF TEST EXAMPLES

Example 1 Transformer performance in the short circuit experiment

Two-winding 240 MVA, $550/\sqrt{3}:20$ kV 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 $45.6322\sqrt{2}\sin(100\pi t)$ kV and 0 respectively. The RMS value of steady state currents in both windings calculated by directly coupled field-circuit method are 764.18 A and 12127 A respectively. The matrix [***L***] extracted through FE analysis is $[\boldsymbol{L}]=\begin{bmatrix}0.57605 & 9.1418\\ 9.1418 & 145.27\end{bmatrix}$. The RMS value of steady currents in both windings calculated by Rung-Kutta method are 763.68 A and 12126 A 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 3000 V alternating voltage over 1200 m in length. When the levitation magnet moves, electromagnetic forces, field distributions, and inductance are shown in Figs.4~6.

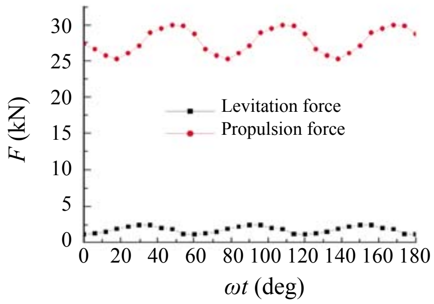
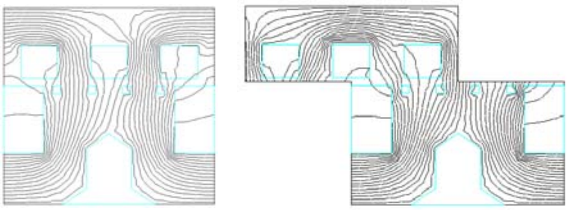


Fig.4 Levitation force versus the position



(a) (b)

Fig.5 Flux at different time in electrical angle. (a) ωt=0°; (b) ωt=96°

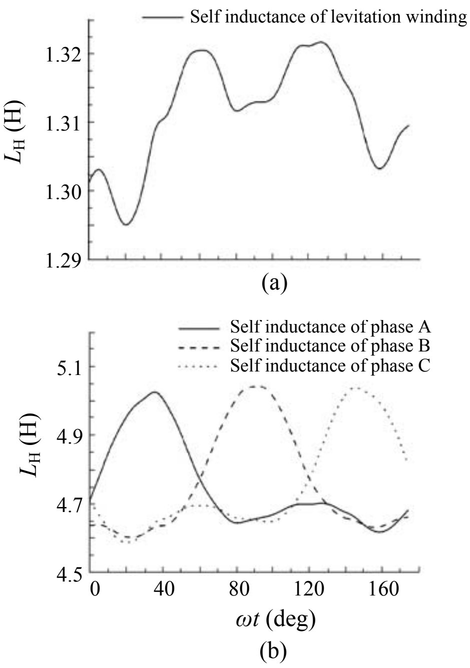


Fig.6 The inductance versus the moving position
(a) Self inductance of levitation winding; (b) Self inductance of phase A, B, C

The comparison of the propulsion forces calculated by two methods, as shown in Fig.7, reveals that the fast solving technique generates the reasonable mechanical dynamic characteristic with less computation.

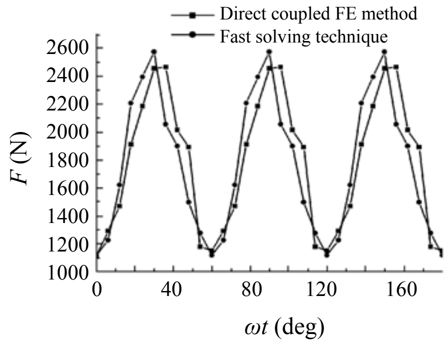


Fig.7 The propulsion force calculated by two methods

CONCLUSION

Two procedures for the simulation of electro-mechanical dynamic characteristics are described. The test examples show the fast solving technique, which is valid in conditions of linear magnetic circuit, generates the reasonable results with a much-reduced number of FE analyses.

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