The Electromechanical Coupling Dynamical Model of Active Maglav EMALS

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Abstract

EMALS is a take-off technology used in aircraft carrier. Now the technology is successful developed in US, which proves that it is possible. This paper put forward a design scheme in which the magnetic suspension technology is used in the EMALS. An electromechanical coupling dynamical model which not only includes the five degree of freedom controlled by maglev, but also includes the sixth degree of freedom of the linear motor will be set up in this paper. The model will be useful to the further study.
keywords: active maglev, EMALS, dnamics, model

1 Introduction

The technology of active magnetic suspension is one of a high technology which is admitted by the world. It is a new electromechanical coupling technology which takes advantage of controllable magnetic force to make the object suspend steadily. Its dynamic performance can be adjusted by controlling system. Research on it refers to mechanics, electromagnetics, electronics, dynamics, theory of modern control and computer science. It will be one of the most promising high technologies[1].

EMALS is also an advanced technology which is being researched in many developed countries now. It is a ejection system to make use of magnetic force to accelerate the plane to take off and is one of the important contents of electrification of the aircraft carrier. It is a great break through.

EMALS which is seen as catapult for the next generation is a hot research topic. In the early 1940's, The United States Navy once built and tested an electromagnetic catapult device. But because the cost is too high, and performance is not ideal, the development of electromagnetic catapulted research work was given up after World War II. In 1978, in order to solve the problem that the steam ejection can not meet the requirement of increasing weight and speed of carrier-based planes, the U.S. Navy developed again the electromagnetic catapult device. In 1999, they authorized General Atomics-Aeronautical Systems Inc. and Northrop Grumman to do the research. It was said that EMALS would be made about in 2012[2]. According to a news from "ifeng.com", the U.S Navy successfully finished the first taking off test of T-45 trainer aircraft by EMALS in naval station in Hurst lake on June 17 in 2011. According to another news from Xinhua net, the U.S Navy announced on November 28 in 2011 that electromagnetic ejection device success help a fighter take off in a test. The EMALS will be installed in the Ford-class aircraft carriers. It means that the first EMALS will soon be installed in American aircraft carriers.

In China, scattered research of the EMALS is still at the theoretical stage. Moreover, most research focused on the application of Electromagnetic emission technology in EMALS. A demonstration from the 713 Research Institute of CSIC shows that electromagnetic emission technology of Guide rail type and using DC power is possible. This demonstration is an important foundation[3]. Electromagnetic Emission is researched in NUDT. Meanwhile some research is done in HIT (Harbin institute of technology) [4]. Researchers from WHUT did some work to apply Maglev technology to EMALS. They also demonstrated the possibility using ANSYS [5,6].

In conclusion, at present there is theoretical research on active maglev EMALS only in WHUT of China in the world, while the dynamic characteristics of active maglev EMALS haven't been researched deeply. The work on theoretical analysis and experimental research of active maglev EMALS is very deficient. To design and manufacture active maglev EMALS to use in the carrier, research on its linear and nonlinear dynamic features is

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first of all necessary.

2 Specialty of active maglev EMALS

This paper puts forward a kind of thought for scheme design of electromagnetic catapult device by active magnetic levitation. It mainly refers to relative technologies from maglev train. The catapult platform contains magnetic suspension technology which can suspend the platform. The fighter is supported fully by the catapult platform. The friction can be eliminated completely. Just overcome the air resistance. So the performance of EMALS can be improved. Linear motor of high power which is easy to monitor is used to drive the catapult platform. What is different from maglev train is that the platform must be accelerated to adequate velocity in a very short time. There are three units to connect to the aircraft on the platform.
The specialty of EMALS this paper conceived is it have a wholly suspended catapult platform which eliminated the friction. When the plane is accelerated with platform it is only necessary to overcome air resistance. However, the piston of steam catapult is replaced only by linear motor of high power in the EMALS of USA. The aircraft is placed on deck and the friction between its wheels and deck is not eliminated. This can be proved from two aspects that the U.S. Navy video and many literatures do not mentioned the maglev. And the solution of this paper introduce maglev technology into EMALS besides using the linear motor as a driver. The active maglev EMALS eliminating the friction may be more advanced. The sketch is in Fig.1.

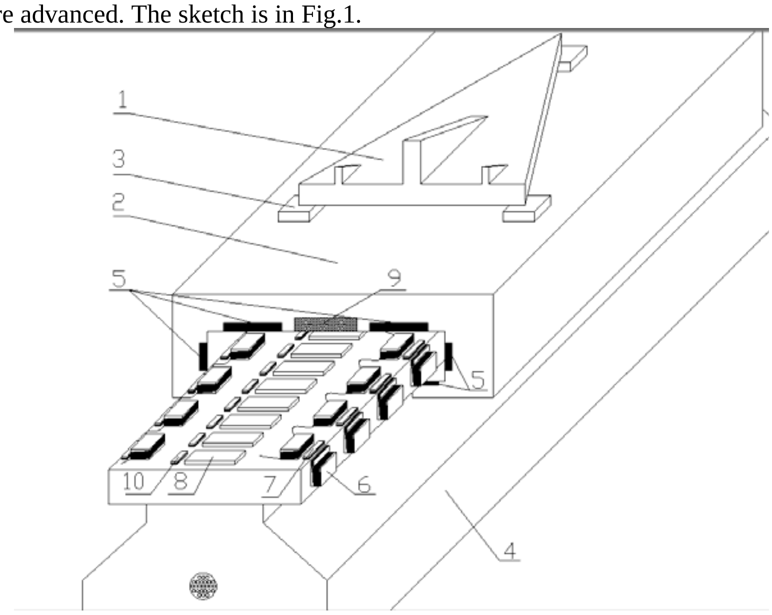

Figure 1: sketch of EMALS using active magnetic suspension technology

The dynamic features of active maglev EMALS depend on two kinds of parameters. The first kind is the mechanical properties parameters of platform itself. The second type is electromagnetic characteristics parameters of active maglev and linear motor. These two kinds of parameters together determine the synthesis static and dynamic mechanical behavior and quality of active maglev EMALS. As for situation of linear high speed motion, the various dynamic behavior of platform (such as ultra high-speed movement, passing the critical velocity, scope permitted maximum value of vertical or horizontal vibration, bear ability of transient impact load……) should be restricted to the condition of practical engineering application. As for active maglev EMALS, its load capacity, stiffness, damping and so on will be restricted by its physical factors. All these requirements and solution of the contradiction problem must be included in a plan as a whole and the consideration will not attend to one thing and lose another. Therefore, how to make the studies in the single one dispersed in the electromagnetism, electronics, mechanics, materials science, dynamics and modern control theory to bring into an unified model considered all kinds of effects, for the mechanical and electrical coupling dynamic characteristics analysis design and experimental research of active maglev EMALS, not only has important theoretical significance, but also has the practical engineering application value.
The catapult platform contains six degrees of freedom in the space. The acceleration which accelerates the platform in 70m to adequate velocity needs to be calculated. Also does the deceleration of the platform in the last 30m after

the plane takes off. In the accelerating and decelerating process the other five degrees of freedom should be supported without contact by maglev rail to make the transverse and lengthways vibration to least. This active maglev EMALS is an electromechanical coupling linear and nonlinear dynamic system which contains six degrees of freedom. So a corresponding theoretical model should be made and whose linear and nonlinear dynamic characteristics should be researched to well design linear motor and magnetic suspension system in EMALS.

3 Dynamic model of the maglev system with single degree of freedom

Now we introduce the working principle of the magnetic suspension system. Since the magnetic suspension system is a complex electromechanical system, proper model must be set up to analysis it. The magnetic suspension system is a nonlinear system whose exact mathematic model is hard to find out. So the mathematic model is often simplified to a linear one in the near equilibrium position.

Fig.2 is a schematic of the maglev system with one degree of freedom，the catapult platform is supported by a couple of electromagnets. The balance of the system is guaranteed by the adjustable magnetic forces.

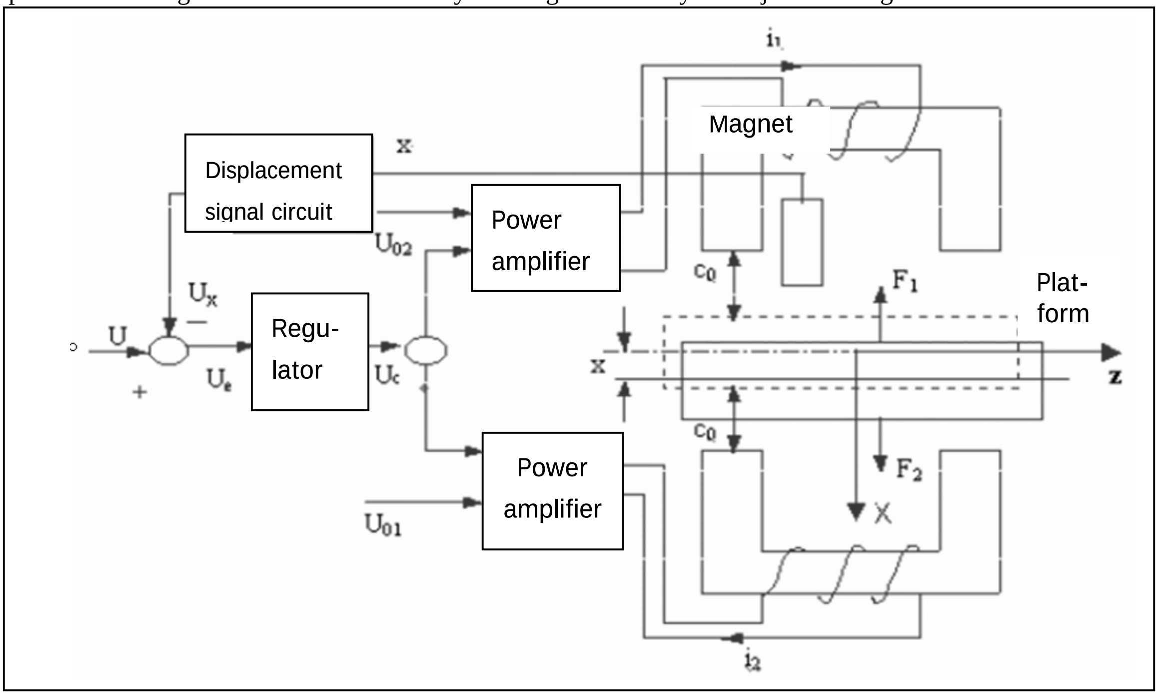

Figure 2: The schematic of maglev system with single degree of freedom

In Fig.2, the position of the maglev platform is controllable. Signal from displacement sensor will be converted to voltage signal when the platform has a displacement x. Voltage offset signal which is gotten by comparing is sent to adjuster. Electromagnetic forces are changed by control currents which are from power amplifier to force the platform back to the balance position.

Some assumptions are put forward when the platform is under balance as follows: (1) Magnetic leakage of the winding is ignored. (2) Magnetic resistance of the iron core and the platform is ignored. (3) Magnetic lag and whirlpool of the magnetic material is ignored.

The resultant of the couple of electromagnetic forces acting on the platform is 0 in the balance situation. When there is a disturbance force which causes the platform to have a displacement x at a time such as in Fig.2, a control current $i_c= i_{x0}+i_x$ which will cause an increase of electromagnetic force I and an a decrease of electromagnetic force II must be added to make the platform back to the balance position. The two electromagnetic forces is:

$$F_1 = \frac{\mu_0 S_0 N^2 (I_0 + i_{x0} + i_x)^2}{4(c_0 + x)^2} \tag{1}$$

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$$F_2 = \frac{\mu_0 S_0 N^2 (I_0 - i_{x0} - i_x)^2}{4(c_0 - x)^2} \tag{2}$$

The resultant on the platform is:

$$\Delta F_x = F_1 - F_2 = \frac{\mu_0 S_0 N^2}{4}\left[\left(\frac{I_0 + i_{x0} + i_x}{c_0 + x}\right)^2 - \left(\frac{I_0 - i_{x0} - i_x}{c_0 - x}\right)^2 \right] \tag{3}$$

In this equation: $\boldsymbol{\mu_0}$—air-gap permeance ($4\pi\times10^{-7}$H/m) ; $\boldsymbol{S_0}$—sectional area of air-gap of poles (m^2); $\boldsymbol{N}$—the number of coil turn; $\boldsymbol{I_0}$—bias current of magnet coil (A), $\boldsymbol{x}$—disturbance displacement (m). Because it is differential motion, we can get: $\boldsymbol{i_1=I_0+i_{x0}+i_x}$, $\boldsymbol{i_2=I_0-i_{x0}-i_x}$. $\boldsymbol{i_x}$ is controlling current component caused by displacement in $\boldsymbol{x}$ direction. $\boldsymbol{i_{x0}}$ is current used to offset load in $\boldsymbol{x}$ direction.

When the platform is in balance position, i.e. x=0, i_x=0,

$$\Delta F_{x0} = \frac{\mu_0 S_0 N^2}{4}\left[\left(\frac{I_0 + i_{x0}}{c_0}\right)^2 - \left(\frac{I_0 - i_{x0}}{c_0}\right)^2 \right] \tag{4}$$

$\boldsymbol{\Delta F_{x0}}$ stands for static load in $\boldsymbol{x}$ direction (e.g. force in $\boldsymbol{x}$ direction from the mass of the platform and the aircraft). Then $\boldsymbol{i_{x0}}$ can be gotten:

$$i_{x0} = \frac{c_0^2 \Delta F_{x0}}{\mu_0 S_0 N^2 I_0} \tag{5}$$

The electromagnetic force of equation (3) is a nonlinear relationship one of current and air-gap. The linear part of equation (3) can be gotten by expanding equation (3) to Taylor series in the balance position (i.e. $\boldsymbol{x}$=0, $\boldsymbol{i_x}$=0) and ignoring high order small part:

$$\Delta F_x = \frac{\partial F}{\partial x} x + \frac{\partial F}{\partial i} i_x = k_{x\,x0} x + k_{i\,x0} i_x \tag{3a}$$

In equation (3a):

$$k_{x\,x0} = -\frac{\mu_0 S_0 N^2 (I_0^2 + i_{x0}^2)}{c_0^3} \tag{6}$$

$$k_{x\,i0} = \frac{\mu_0 S_0 N^2 I_0}{c_0^2} \tag{7}$$

$\boldsymbol{k_{xx0}}$, $\boldsymbol{k_{xi0}}$ are open loop coefficient of the displacement stiffness and the current stiffness, which are relative to the structure and working position of the electromagnet. When the structure and working position of the electromagnet is sure, $\boldsymbol{k_{xx0}}$, $\boldsymbol{k_{xi0}}$ are constant. According to Newton's second law, mechanics equation considering other forces acting on the object in $\boldsymbol{x}$ direction is:

$$m\ddot{x} + k_{xx0} x + k_{ix0} i_x = f_x \tag{8}$$

f_x is a resultant of nonlinear electromagnetic force and outer force.

4 Stiffness and damping characteristics of maglev system

Stiffness and damping are two main characteristics which are used to analysis the vibration of the mechanical system. Stiffness and damping characteristics decide dynamic characteristics of the maglev system, and decide the stability, vibration, and capacity of resisting disturbance. Stiffness of the maglev system can be classified by negative stiffness which is caused by structure and active stiffness which is caused by controller. The latter is much bigger in value. And along with the controller parameters changes, to the whole of the dynamic characteristics of the system has a good regulatory role.

Equation (9) can be gotten by Laplace transform of Equ. (8).

$$ms^2 X(s) + k_{xx0} X(s) + k_{xi0} I_x(s) = F_x(s) \tag{9}$$

In the equation: $X(s) = L[x(t)]$, $I_x(s) = L[i_x(t)]$, $F_x(s) = L[f_x(t)]$

If $G_s(s)$ is the transfer function of displacement sensor, $G_c(s)$ is the transfer function of adjuster， $G_p(s)$ is the transfer function of power amplifier, we can get the closed loop transfer function of the maglev system in Fig.3 when input signal is zero.

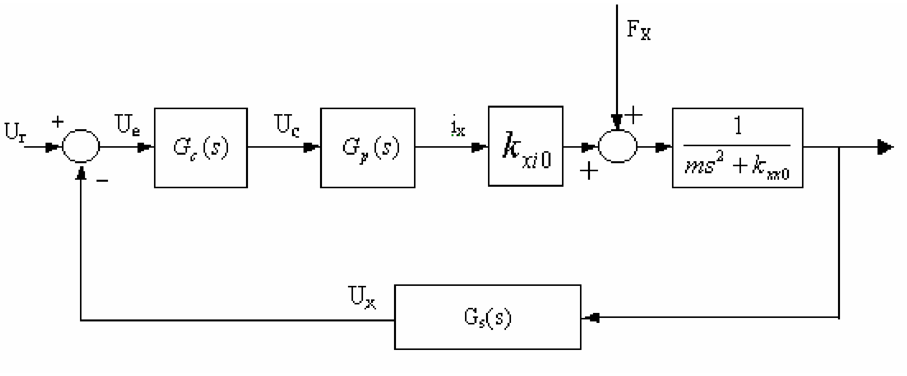

Figure 3: Diagram of transfer functions of the maglev system

Let： $G(s)=G_s(s)G_c(s)G_p(s)$, $G(s)$ is the transfer function of the controller. Then we can get closed loop transfer function of the system:

$$X(s) = \frac{F_x(s)}{ms^2 + k_{xx0} + k_{xi0}G(s)} \quad \textbf{(10)}$$

Let $s=j\omega$, the transfer function is :

$$X(j\omega) = \frac{F_x(j\omega)}{[k_{xi0}\,\mathrm{Re}(G(j\omega)) + k_{xxo} - m\omega^2] + j[k_{xi0}\,\mathrm{Im}(G(j\omega))]} \quad \textbf{(11)}$$

Dynamic equation of second order can be gotten according to theory of mechanics:

$$m\ddot{x} + c\dot{x} + kx = f_x \quad \textbf{(12)}$$

m, ***c***, ***k*** stands for mass, damping, stiffness. Then we can get through Laplace transform：

$$ms^2X(s) + csX(s) + kX(s) = F_x(s) \quad \textbf{(13)}$$

Let $s=j\omega$, equation (14) can be gotten:

$$X(j\omega) = \frac{F_x(j\omega)}{(k - m\omega^2) + j\omega c} \quad \textbf{(14)}$$

That is frequency response equation of mechanics system of second order.

After comparing (11) to (14) we know: k_{xx} is closed-loop stiffness of the maglev system which is corresponding to ***k*** ; c_{xx} is closed-loop damping of the maglev system which is corresponding to ***c***：

Stiffness： $$k_{xx} = k_{xx0} + k_{xi0}R_e[G(j\omega)] \quad \textbf{(15)}$$

Damping： $$c_{xx} = k_{xi0}I_m[G(j\omega)]/\omega \quad \textbf{(16)}$$

Linear part of increment of the electromagnetic force of equation (3a) is：

$$\Delta F_x = k_{xx}x + c_{xx}\dot{x} \quad \textbf{(3b)}$$

5 Dynamic model of active maglav EMALS

Dynamic model ignoring indeterminate problem will be set up. Firstly, the platform has six degrees of freedom, five of which is up to electromagnetic forces. The sixth one in catapult direction is up to linear motor. The force diagram is in Fig. 4.

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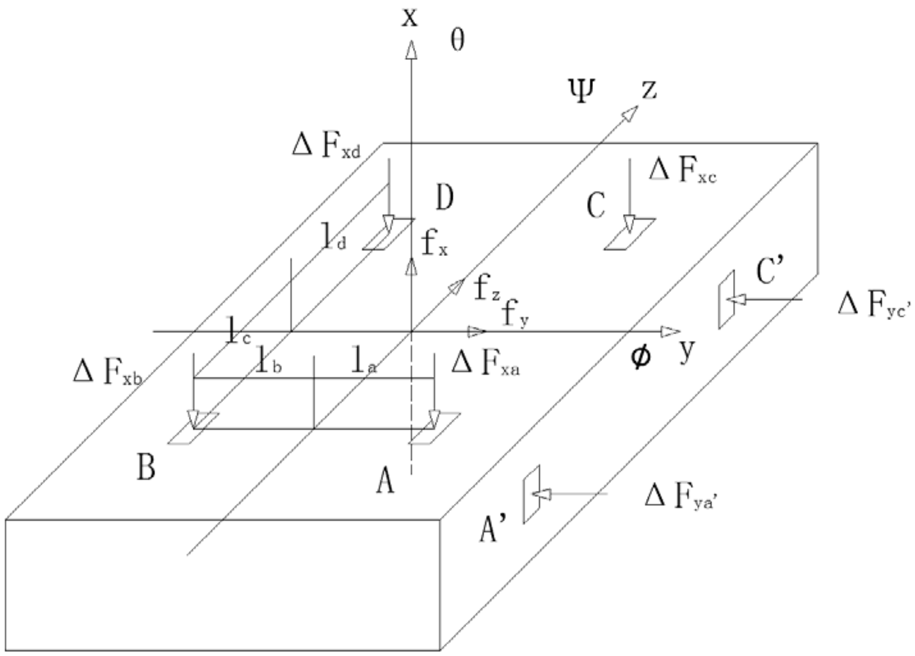

Figure 4: Force diagram of the catapult platform of six degrees of freedom

In Fig.4, $\boldsymbol{\theta}$, $\boldsymbol{\phi}$, $\boldsymbol{\psi}$ stand for the platform's angular coordinates around ***x, y, z***. The six rectangles in the picture stand for positions where six electromagnetic resultants $\boldsymbol{\Delta F}$ are acting on.

In the picture above, ABCDA'C' stand for six electromagnets. Their resultants are ΔF_{xa}, ΔF_{xb}, ΔF_{xc} , ΔF_{xd}, $\Delta F_{ya'}$, $\Delta F_{yc'}$. Distances between planes AC, BD and coordinate surface ***xoz*** are l_a and l_b. Distances between planes AB, CD and coordinate surface ***xoy*** are l_c and l_d.

Taylor's first order linear equations about electromagnetic forces are：

$$\begin{cases} \Delta F_{xa} = k_{xx}^{a} x_a + c_{xx}^{a} \dot{x}_a \\ \Delta F_{xb} = k_{xx}^{b} x_b + c_{xx}^{b} \dot{x}_b \\ \Delta F_{xc} = k_{xx}^{c} x_c + c_{xx}^{c} \dot{x}_c \\ \Delta F_{xd} = k_{xx}^{d} x_d + c_{xx}^{d} \dot{x}_d \\ \Delta F_{ya'} = k_{yy}^{a'} x_a + c_{yy}^{a'} \dot{x}_{a'} \\ \Delta F_{yc'} = k_{yy}^{c'} x_a + c_{yy}^{c'} \dot{x}_{c'} \end{cases} \tag{17}$$

The coordinate transformation when the platform inclined is:

$$\begin{cases} x_a = x - l_c\phi - l_a\psi \\ x_b = x - l_c\phi + l_b\psi \\ x_c = x + l_d\phi - l_a\psi \\ x_d = x + l_d\phi + l_b\psi \\ y_{a'} = y + l_c\theta \\ y_{a'} = y - l_c\theta \end{cases} \tag{18}$$

The center for mass of the platform is chosen as the origin of the coordination. Dynamic differential equation for EMALS can be set up as follows.

$$
\left\{
\begin{array}{l}
m\ddot{x} + \Delta F_{xa} + \Delta F_{xb} + \Delta F_{xc} + \Delta F_{xd} = 0 \\
j_y\ddot{\phi} - \Delta F_{xa}L_c - \Delta F_{xb}L_c + \Delta F_{xc}L_d + \Delta F_{xd}L_d = 0 \\
j_z\ddot{\psi} - \Delta F_{xa}L_a + \Delta F_{xb}L_b - \Delta F_{xc}L_a + \Delta F_{xd}L_b = 0 \\
m\ddot{y} + \Delta F_{ya'} + \Delta F_{yc'} = 0 \\
j_x\ddot{\theta} + \Delta F_{ya'}L_c - \Delta F_{yc'}L_d = 0
\end{array}
\right\} \quad \textbf{(19)}
$$

In the equation ***m*** stands for the mass of the maglev platform. $\boldsymbol{j_x}$, $\boldsymbol{j_y}$, $\boldsymbol{j_z}$ stand for moment of inertia about axis of coordinates.

Equation (20) is gotten by putting equations (17) and (18) generation into equation (19).

$$
\left\{
\begin{array}{l}
m\ddot{x} + (c_{xx}^a + c_{xx}^b + c_{xx}^c + c_{xx}^d)\dot{x} + (-c_{xx}^a l_c - c_{xx}^b l_c + c_{xx}^c l_d + c_{xx}^d l_d)\dot{\phi} + (-c_{xx}^a l_a + c_{xx}^b l_b \\
-c_{xx}^c l_a + c_{xx}^d l_b)\dot{\psi} + (k_{xx}^a + k_{xx}^b + k_{xx}^c + k_{xx}^d)x + (-k_{xx}^a l_c - k_{xx}^b l_c + k_{xx}^c l_d + k_{xx}^d l_d)\phi \\
+(-k_{xx}^a l_a + k_{xx}^b l_b - k_{xx}^c l_a + k_{xx}^d l_b)\psi = 0 \\
\\
j_y\ddot{\phi} + (-c_{xx}^a l_c - c_{xx}^b l_c + c_{xx}^c l_d + c_{xx}^d l_d)\dot{x} + (c_{xx}^a l_c{}^2 + c_{xx}^b l_c{}^2 + c_{xx}^c l_d{}^2 + c_{xx}^d l_d{}^2)\dot{\phi} \\
+(c_{xx}^a l_a l_c - c_{xx}^b l_b l_c - c_{xx}^c l_a l_d + c_{xx}^d l_b l_d)\dot{\psi} + (-k_{xx}^a l_c - k_{xx}^b l_c + k_{xx}^c l_d + k_{xx}^d l_d)x \\
+(k_{xx}^a l_c{}^2 + k_{xx}^b l_c{}^2 + k_{xx}^c l_d{}^2 + k_{xx}^a l_d{}^2)\phi + (k_{xx}^a l_a l_c - k_{xx}^b l_b l_c - k_{xx}^c l_a l_d + k_{xx}^d l_b l_d)\psi = 0 \\
\\
j_z\ddot{\psi} + (-c_{xx}^a l_a + c_{xx}^b l_b - c_{xx}^c l_a + c_{xx}^d l_b)\dot{x} + (c_{xx}^a l_a l_c - c_{xx}^b l_b l_c - c_{xx}^c l_a l_d + c_{xx}^d l_b l_d)\dot{\phi} \\
+(c_{xx}^a l_a{}^2 + c_{xx}^b l_b{}^2 + c_{xx}^c l_a{}^2 + c_{xx}^d l_b{}^2)\dot{\psi} + (-k_{xx}^a l_a + k_{xx}^b l_b - k_{xx}^c l_a + k_{xx}^d l_b)x \\
+(k_{xx}^a l_a l_c - k_{xx}^b l_b l_c - k_{xx}^c l_a l_d + k_{xx}^d l_b l_d)\phi + (k_{xx}^a l_a{}^2 + k_{xx}^b l_b{}^2 + k_{xx}^c l_a{}^2 + k_{xx}^d l_b{}^2)\psi = 0 \\
\\
m\ddot{y} + (c_{yy}^{a'} + c_{yy}^{c'})\dot{y} + (c_{yy}^{a'} l_c - c_{yy}^{c'} l_d)\dot{\theta} + (k_{yy}^{a'} + k_{yy}^{c'})y + (k_{yy}^{a'} l_c - k_{yy}^{c'} l_d)\theta = 0 \\
\\
j_x\ddot{\theta} + (c_{yy}^{a'} l_c - c_{yy}^{c'} l_d)\dot{y} + (c_{yy}^{a'} l_c{}^2 + c_{yy}^{c'} l_d{}^2)\dot{\theta} + (k_{yy}^{a'} l_c - k_{yy}^{c'} l_d)y + (k_{yy}^{a'} l_c{}^2 + k_{yy}^{c'} l_d{}^2)\theta = 0
\end{array}
\right. \quad \textbf{(20)}
$$

Equation (20) consists five equations which stand for five degrees of freedom controlled by maglev system. Equation (21) can be gotten by tidying.

$$M_0\ddot{q}_0 + C_0\dot{q}_0 + K_0 q_0 = 0 \quad \textbf{(21)}$$

$\boldsymbol{q_0}$ is a generalized coordinate matrix, $\boldsymbol{M_0}$ is a generalized mass matrix, $\boldsymbol{C_0}$ is a generalized damping matrix, $\boldsymbol{K_0}$ is a generalized stiffness matrix.

$$q_0 = \left[x, \phi, \psi, y, \theta \right]^T \quad \textbf{(22)}$$

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$$M_0 = \begin{bmatrix} m & 0 & 0 & 0 & 0 \\ 0 & j_y & 0 & 0 & 0 \\ 0 & 0 & j_z & 0 & 0 \\ 0 & 0 & 0 & m & 0 \\ 0 & 0 & 0 & 0 & j_x \end{bmatrix} \tag{23}$$

$$C_0 = \begin{bmatrix} \begin{array}{c} c^a_{xx}+c^b_{xx} \\ +c^c_{xx}+c^d_{xx} \end{array} & \begin{array}{c} -c^a_{xx}l_c-c^b_{xx}l_c \\ +c^c_{xx}l_d+c^d_{xx}l_d \end{array} & \begin{array}{c} -c^a_{xx}l_a+C^b_{xx}l_b \\ -c^c_{xx}l_a+c^d_{xx}l_b \end{array} & 0 & 0 \\ \begin{array}{c} -c^a_{xx}l_c-c^b_{xx}l_c \\ +c^c_{xx}l_d+c^d_{xx}l_d \end{array} & \begin{array}{c} c^a_{xx}l_c^{\,2}+c^b_{xx}l_c^{\,2} \\ c^c_{xx}l_d^{\,2}+c^d_{xx}l_d^{\,2} \end{array} & \begin{array}{c} c^a_{xx}l_al_c-c^b_{xx}l_bl_c \\ -c^c_{xx}l_al_d+c^d_{xx}l_bl_d \end{array} & 0 & 0 \\ \begin{array}{c} -c^a_{xx}l_a+c^b_{xx}l_b \\ -c^c_{xx}l_a+c^d_{xx}l_b \end{array} & \begin{array}{c} c^a_{xx}l_al_c-c^b_{xx}l_bl_c \\ -c^c_{xx}l_al_d+c^a_{xx}l_bl_d \end{array} & \begin{array}{c} c^a_{xx}l_a^{\,2}+c^a_{xx}l_b^{\,2} \\ c^c_{xx}l_a^{\,2}+c^d_{xx}l_b^{\,2} \end{array} & 0 & 0 \\ 0 & 0 & 0 & c^{a'}_{yy}+c^{c'}_{yy} & c^{a'}_{yy}l_c-c^{c'}_{yy}l_d \\ 0 & 0 & 0 & c^{a'}_{yy}l_c-c^{c'}_{yy}l_d & c^{a'}_{yy}l_c^{\,2}+c^{c'}_{yy}l_d^{\,2} \end{bmatrix} \tag{24}$$

$$K_0 = \begin{bmatrix} \begin{array}{c} k^a_{xx}+k^b_{xx} \\ +k^c_{xx}+k^d_{xx} \end{array} & \begin{array}{c} -k^a_{xx}l_c-k^b_{xx}l_c \\ +k^c_{xx}l_d+k^d_{xx}l_d \end{array} & \begin{array}{c} -k^a_{xx}l_a+k^b_{xx}l_b \\ -k^c_{xx}l_a+k^d_{xx}l_b \end{array} & 0 & 0 \\ \begin{array}{c} -k^a_{xx}l_c-k^b_{xx}l_c \\ +k^c_{xx}l_d+k^d_{xx}l_d \end{array} & \begin{array}{c} k^a_{xx}l_c^{\,2}+k^b_{xx}l_c^{\,2} \\ +k^c_{xx}l_d^{\,2}+k^d_{xx}l_d^{\,2} \end{array} & \begin{array}{c} k^a_{xx}l_al_c-k^b_{xx}l_bl_c \\ -k^c_{xx}l_al_d+k^d_{xx}l_bl_d \end{array} & 0 & 0 \\ \begin{array}{c} -k^a_{xx}l_a+k^b_{xx}l_b \\ -k^c_{xx}l_a+k^d_{xx}l_b \end{array} & \begin{array}{c} k^a_{xx}l_al_c-k^b_{xx}l_bl_c \\ -k^c_{xx}l_al_d+k^d_{xx}l_bl_d \end{array} & \begin{array}{c} k^a_{xx}l_a^{\,2}+k^b_{xx}l_b^{\,2} \\ +k^c_{xx}l_a^{\,2}+k^d_{xx}l_b^{\,2} \end{array} & 0 & 0 \\ 0 & 0 & 0 & k^{a'}_{yy}+k^{c'}_{yy} & k^{a'}_{yy}l_c-k^{c'}_{yy}l_d \\ 0 & 0 & 0 & k^{a'}_{yy}l_c-k^{c'}_{yy}l_d & k^{a'}_{yy}l_c^{\,2}+k^{c'}_{yy}l_d^{\,2} \end{bmatrix} \tag{25}$$

Dynamic model of linear motor is:

$$m\,\ddot{z} = f_z \tag{26}$$

Electromagnetic traction of the linear motor is:

$$f_z = \frac{m\,E_1}{(R_l^2+Z^2)}(Z\,U\sin\theta + R_l\cos\theta - E_1R_l) \tag{27}$$

Interactions between the active cell and the stator are：

$$f_x = \int_s \frac{1}{2\mu_0}[\,(B_x^2-B_y^2)n_x + 2n_yB_xB_y\,]d\,s \tag{28}$$

$$f_y = \int_s \frac{1}{2\mu_0}[\,(B_y^2-B_x^2)n_x + 2n_xB_xB_y\,]d\,s \tag{29}$$

In equations above: ***s*** stands integration path surrounding the air-gap; $\boldsymbol{n_x}$ and $\boldsymbol{n_y}$ stand for normal vector per unit and tangential vector per unit; $\boldsymbol{B_x}$ and $\boldsymbol{B_y}$ stand for normal vector and tangential vector of flux density ***B***; $\boldsymbol{\mu_0}$ stands for magnetic conductance.

Dynamic model of catapult platform of Active Maglav EMALS considering the linear motor is:

$$M\ddot{q}+C\dot{q}+Kq=F \tag{28}$$

But $\boldsymbol{q_0}$, $\boldsymbol{M_0}$, $\boldsymbol{C_0}$, $\boldsymbol{K_0}$ are replaced by $\boldsymbol{q}$, $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{K}$:

$$q=\left[x,\phi,\psi,y,\theta,z\right]^T \tag{29}$$

$$M=\begin{bmatrix} m & & & & & \\ & j_y & & & & \\ & & j_z & & & \\ & & & m & & \\ & & & & j_x & \\ & & & & & m \end{bmatrix} \tag{30}$$

$$C=\begin{bmatrix} \begin{array}{c} c^a_{xx}+c^b_{xx} \\ +c^c_{xx}+c^d_{xx} \end{array} & \begin{array}{c} -c^a_{xx}l_c-c^b_{xx}l_c \\ +c^c_{xx}l_d+c^d_{xx}l_d \end{array} & \begin{array}{c} -c^a_{xx}l_a+C^b_{xx}l_b \\ -c^c_{xx}l_a+c^d_{xx}l_b \end{array} & 0 & 0 & 0 \\ \begin{array}{c} -c^a_{xx}l_c-c^b_{xx}l_c \\ +c^c_{xx}l_d+c^d_{xx}l_d \end{array} & \begin{array}{c} c^a_{xx}l_c{}^2+c^b_{xx}l_c{}^2 \\ c^c_{xx}l_d{}^2+c^d_{xx}l_d{}^2 \end{array} & \begin{array}{c} c^a_{xx}l_al_c-c^b_{xx}l_bl_c \\ -c^c_{xx}l_al_d+c^d_{xx}l_bl_d \end{array} & 0 & 0 & 0 \\ \begin{array}{c} -c^a_{xx}l_a+c^b_{xx}l_b \\ -c^c_{xx}l_a+c^d_{xx}l_b \end{array} & \begin{array}{c} c^a_{xx}l_al_c-c^b_{xx}l_bl_c \\ -c^c_{xx}l_al_d+c^a_{xx}l_bl_d \end{array} & \begin{array}{c} c^a_{xx}l_a{}^2+c^a_{xx}l_b{}^2 \\ c^c_{xx}l_a{}^2+c^d_{xx}l_b{}^2 \end{array} & 0 & 0 & 0 \\ 0 & 0 & 0 & c^{a'}_{yy}+c^{c'}_{yy} & c^{a'}_{yy}l_c-c^{c'}_{yy}l_d & 0 \\ 0 & 0 & 0 & c^{a'}_{yy}l_c-c^{c'}_{yy}l_d & c^{a'}_{yy}l_c{}^2+c^{c'}_{yy}l_d{}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{31}$$

$$K=\begin{bmatrix} \begin{array}{c} k^a_{xx}+k^b_{xx} \\ +k^c_{xx}+k^d_{xx} \end{array} & \begin{array}{c} -k^a_{xx}l_c-k^b_{xx}l_c \\ +k^c_{xx}l_d+k^d_{xx}l_d \end{array} & \begin{array}{c} -k^a_{xx}l_a+k^b_{xx}l_b \\ -k^c_{xx}l_a+k^d_{xx}l_b \end{array} & 0 & 0 & 0 \\ \begin{array}{c} -k^a_{xx}l_c-k^b_{xx}l_c \\ +k^c_{xx}l_d+k^d_{xx}l_d \end{array} & \begin{array}{c} k^a_{xx}l_c{}^2+k^b_{xx}l_c{}^2 \\ +k^c_{xx}l_d{}^2+k^d_{xx}l_d{}^2 \end{array} & \begin{array}{c} k^a_{xx}l_al_c-k^b_{xx}l_bl_c \\ -k^c_{xx}l_al_d+k^d_{xx}l_bl_d \end{array} & 0 & 0 & 0 \\ \begin{array}{c} -k^a_{xx}l_a+k^b_{xx}l_b \\ -k^c_{xx}l_a+k^d_{xx}l_b \end{array} & \begin{array}{c} k^a_{xx}l_al_c-k^b_{xx}l_bl_c \\ -k^c_{xx}l_al_d+k^d_{xx}l_bl_d \end{array} & \begin{array}{c} k^a_{xx}l_a{}^2+k^b_{xx}l_b{}^2 \\ +k^c_{xx}l_a{}^2+k^d_{xx}l_b{}^2 \end{array} & 0 & 0 & 0 \\ 0 & 0 & 0 & k^{a'}_{yy}+k^{c'}_{yy} & k^{a'}_{yy}l_c-k^{c'}_{yy}l_d & 0 \\ 0 & 0 & 0 & k^{a'}_{yy}l_c-k^{c'}_{yy}l_d & k^{a'}_{yy}l_c{}^2+k^{c'}_{yy}l_d{}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{32}$$

$$F=[f_x,0,0,f_y,0,f_z]^T \tag{33}$$

The characteristic number of the magnetic suspension catapult platform system can be gotten by solving (28).

$$\lambda_r=u+v\,i \tag{34}$$

The u, v are real part and the imaginary part of the eigenvalue. Stability of the catapult platform system can be known according to the real part of the eigenvalue. When the real part is negative, the system is stable. The imaginary part of the eigenvalue is the natural frequency of the system. The dynamic quality of EMALS such as acceleration, plural eigenvalue, plural modal, critical velocity, instability velocity and so on can be gotten by solving equation (28).

6 Conclusion

The electromagnetic ejection catapult platform supported by active maglev contains six degrees of freedom.

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Suppose (x,y,φ,ψ,θ) is five degrees of freedom supported by active maglev. Active levitation force can be unfolded to linear force of first order in small perturbation range and nonlinear force of second order or higher order in large perturbation range. Then the linear and nonlinear dynamic models are made. The z-coordinate stands for the sixth degree decided by the linear motor. The dynamical model of this direction is made according to the desire of EMALS. The electromechanical coupling dynamical model of Active maglev EMALS is finally expressed as

$$M\ddot{q} + C\dot{q} + Kq = F \tag{28}$$

In the equation above, q=[x, φ, ψ, y, θ, z]^T is a generalized coordinate, M is a matrix containing the mass of the platform m and rotary inertia j_x, j_y, j_z around coordinate axes, C stands for damping coefficient matrix, K is stiffness coefficient matrix, F is a matrix containing nonlinear part of f_x, f_y, f_z exerted by active magnetic suspension and linear motor to platform and nonlinear incentive force f'_x, f'_y, f'_z exerted by outer body to platform. The dynamic characteristics such as acceleration, deceleration, plural eigenvalue, plural modal, critical velocity, instability of speed, and forced vibration response containing bifurcate and chaotic phenomenon under the action of resonant force and nonlinear force and so on can be calculated according to equation (28).

This paper set up a whole electromechanical coupling dynamical model for active maglev EMALS and it can be used to research the electromechanical coupling dynamic characteristics of active maglev EMALS with six degrees of freedom.

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