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Dynamic electromechanical coupling resulting from the air-gap fluctuation of the linear motor in machine tools

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ABSTRACT

This paper investigates a dynamic electromechanical coupling resulting from the air-gap fluctuation of the linear motor in machine tools. The modes of the mechanical vibration are analyzed firstly in the linear motor feed system. Then the influence of mechanical vibration on the air-gap fluctuation is researched. Based on the Maxwell's equation and energy method, the analytical expression of the motor thrust is established considering the air-gap fluctuation. Then we discuss the effects of air-gap fluctuation on the motor thrust. At last, the dynamic electromechanical coupling caused by the air-gap fluctuation is theoretically analyzed and verified by experiments. The results show that the mechanical vibration can affect the characteristics of the motor thrust conversely causing the fluctuation of the motor air-gap. The air-gap fluctuation can produce new thrust harmonics. These new thrust harmonics excite mechanical system again, and then the electromechanical coupling loop is formed, leading to a worse dynamic precision of the feed system. In addition, the couplings will aggravate with the increase of velocity and load.

1. Introduction

Linear motor feed system is getting the promotion and application on high-speed CNC machine tools because of its obvious advantages such as high speed, acceleration, thrust and precision [1,2].

With the in-depth research, lot of problems are exposed in linear motor feed systems. The most popular of all are the thrust fluctuation and the interfering sensitivity. Zhu et al. [3] established the air-gap magnetic field model of permanent magnet and analyzed the motor thrust without considering the current input. Remy et al. [4] set up the model of PMLSM using causal sequence diagram (COG) and took into account the electromagnetic thrust harmonics. Zhu [5] and Zarko [6] established the analytical model of air-gap magnetic field using Maxwell tensor method which considered the motor cogging effect. Hirasa et al. [7] and Gieras et al. [8] introduced the proportion coefficient to describe the end effect and analyzed the end force by establishing a new equivalent circuit. In addition, there are a lot of other works focusing on the control compensation strategy [9–12].

The above studies have played important roles in improving the thrust fluctuation and dynamic precision in the machine tool direct feed drives. The amplitudes of thrust harmonics become less than 5% of the nominal thrust after optimization and compensation. However, all the intermediate transmission links are canceled in the linear motor feed system. The thrust harmonics directly act on the mechanical system and cause mechanical vibration. Especially when one frequency component of thrust harmonics is close to the nature frequency of mechanical system, resonance occurs, leading to a worse dynamic precision and even instability. The author team has found that in the direct drive system the electromechanical coupling may become more serious, especially in the high-speed and high-precision motion [13]. There is little research about the mechanism and the impact of the electromechanical coupling on the linear motor feed system. Most of studies only described the phenomenon [14], and did not reveal the mechanism of the coupling. In the relationship of coupling, lots of theories and methods can be used to analyze the mechanical vibration caused by the thrust harmonics. However there is little research on the adverse effect of mechanical vibration on the motor thrust. The analysis and calculation methods of motor thrust considering the mechanical vibration become the key to reveal this dynamic electromechanical coupling in the machine tool direct feed drives.

As mentioned above, the mechanical vibration, especially perpendicular to the feed direction, will affect the motor air-gap because the mover is connected directly with the driven parts. Air-

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gap is a key parameter to affect the performance of motor, and has a major impact on the output characteristics of the motor. In rotating machinery, the uneven air gap will generate unbalanced magnetic pull and lead to failure. Cameron et al. [15] and Belmans [16,17] expressed the permeance of the air-gap by Fourier series and obtained the analytical expression of unbalanced magnetic pull. Wang et al. [18] took magnetic material nonlinearity into consideration and discussed the effects of static and dynamic rotor eccentricity. Qiu [19] analyzed the influence of eccentricity on the motor torque. Im et al. [20] analyzed the dynamic behaviors of a BLDC considering the mechanical and electromagnetic interaction. The research on air-gap eccentricity in rotating machinery obtained very good effects. However air-gap change has not been concerned because of ignoring the oscillation of mechanical system in the linear motor feed system.

The aim of this paper is to reveal the mechanism of the electromechanical coupling considering the air-gap fluctuation. The modes of the mechanical vibration are analyzed firstly in the linear motor feed system. Based on the Maxwell's equation and energy method, the analytical expression of the motor thrust is established considering the air-gap fluctuation. At last, the dynamic electromechanical coupling caused by the air-gap fluctuation is theoretically analyzed and verified by experiments.

2. The calculation methods of the thrust considering the air-gap fluctuation caused by the mechanical vibration

2.1. Influence of mechanical vibration on the motor air-gap

The linear motor feed system consists of permanent magnet, motor primary, table, linear guide, grating and machine bed, as shown in Fig. 1. Ignoring the flexibility of table, the worktable has three linear vibrations along each axis and three rotational vibrations around each axis [21]. Assuming the displacements of linear vibration are x, y, z, respectively. The angle displacements of rotational vibration are θ_x, θ_y, θ_z respectively. The mechanical model can be established as:

$$\mathrm{M}\ddot{\mathrm{X}} + \mathrm{C_B}\dot{\mathrm{X}} + \mathrm{KX} = \mathrm{F} \tag{1}$$

where, M, $\mathbf{C_B}$, K are mass matrix, damping matrix and stiffness matrix, respectively. $X=[x\ y\ z\ \theta_x\ \theta_y\ \theta_z]^{\mathrm{T}}$ is displacement of the worktable. $\dot{\mathrm{X}}$ and $\ddot{\mathrm{X}}$ are the first and the second order derivative of X.

In the above six modes, the stiffness along the Y and Z directions of slide guide is high. The main frequency range concerned in this paper is less than 100 Hz. So it can be taken as rigid along the Y and Z directions. In the three rotational vibrations, the yaw vibration around z axis does not lead to the air-gap fluctuation. It is not the sensitive mode in the electromechanical coupling and will be discussed in other articles. The roll vibration around x axis is not excited directly by the motor thrust. The main type of coupling caused by roll is different from that discussed in this paper. So it is not considered here.

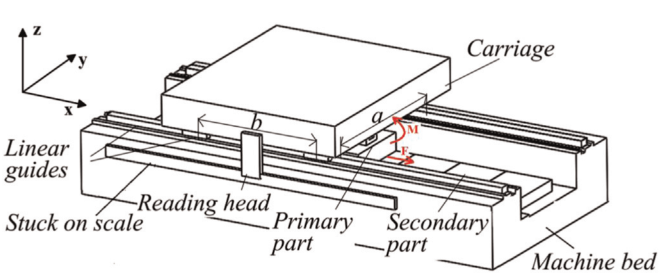

Fig. 1. The structure of the linear motor feed system in machine tools.

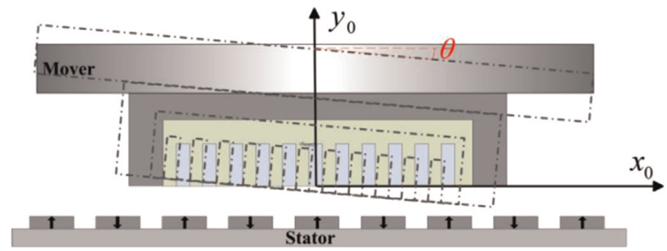

Fig. 2. The influence of pitch vibration on the air-gap.

The action line of motor thrust does not go across the center of gravity of the motor and worktable because of the structure of direct feed drives. So there is a negative moment (as shown in Fig. 1) which will cause pitch vibration.

Assuming the angular displacement of the pitch vibration is $\theta(t)$. θ is the periodic function of time. Under the excitation of periodic external force, $\theta(t)$ is given by

$$\theta(t) = A_\theta \ \sin(\omega_0 t - \phi) \tag{2}$$

where, A_θ is the amplitude of pitch vibration and its unit is rad. ω_0 is the frequency of pitch. ϕ is the initial phase angle.

Taking the center of mover as the origin, coordinate system is established as shown in Fig. 2. θ is defined as positive when the worktable vibrates clockwise. Because the amplitude of $\theta(t)$ is small, for any point on the surface of mover, air-gap g' is represented as:

$$g'(x_0, t) = g - x_0\theta(t) x_0 \in (-L/2, L/2) \tag{3}$$

where, g is the ideal air-gap. g' is the actual air-gap considering vibration. L is the length of motor primary.

In order to analyze the effect of air-gap fluctuation on the magnetic field, the relative permeance function between actual and ideal air-gap is introduced, viz

$$\lambda(x_0, t) = \frac{g}{g - x_0\theta(t)} x_0 \in (-L/2, L/2) \tag{4}$$

which can be expressed in the form of a Fourier series as follows:

$$\lambda(x_0, t) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\left(\frac{2n\pi}{L}x_0\right) + b_n \ \sin\left(\frac{2n\pi}{L}x_0\right)\right) \tag{5}$$

The high order terms are ignored in three coefficients because the angular displacement caused by pitch is very small. After simplified, they are equivalent to

$$a_0 = 1 + \frac{1}{3}\left(\frac{L\theta}{2g}\right)^2, \ a_n = 4\left(\frac{L}{2n\pi g}\right)^3 \theta^3, \ b_n = 2\left(\frac{L}{2n\pi g}\right)^2 \theta^2$$

2.2. The calculation of magnetic field considering air-gap fluctuation

The coordinate system of the mover does not coincide with that of the stator in the process of movement. So the coordinate system of permanent magnet magnetic field xoy and that of primary coil $x_0o_0y_0$ are set up respectively.

In Fig. 3, L is the length of mover, H_s is the height of mover, h_s is the thickness of permanent magnet, g is the thickness of air-gap,τ

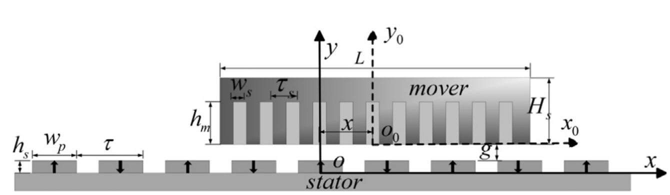

Fig. 3. The coordinate system of linear motor.