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Analysis on the multi-dimensional spectrum of the thrust force for the linear motor feed drive system in machine tools

Xiaojun Yang [a,b], Dun Lu [a,b], Chengfang Ma [a,b], Jun Zhang [a,b], Wanhua Zhao [a,b,*]

[a] School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710054, China

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ABSTRACT

The motor thrust force has lots of harmonic components due to the nonlinearity of drive circuit and motor itself in the linear motor feed drive system. What is more, in the motion process, these thrust force harmonics may vary with the position, velocity, acceleration and load, which affects the displacement fluctuation of the feed drive system. Therefore, in this paper, on the basis of the thrust force spectrum obtained by the Maxwell equation and the electromagnetic energy method, the multi-dimensional variation of each thrust harmonic is analyzed under different motion parameters. Then the model of the servo system is established oriented to the dynamic precision. The influence of the variation of the thrust force spectrum on the displacement fluctuation is discussed. At last the experiments are carried out to verify the theoretical analysis above. It can be found that the thrust harmonics show multi-dimensional spectrum characteristics under different motion parameters and loads, which should be considered to choose the motion parameters and optimize the servo control parameters in the high-speed and high-precision machine tools equipped with the linear motor feed drive system.

1. Introduction

The linear motor feed drive system is getting the promotion and application on the high-speed and high-precision machine tools because of its high rigidity, speed, acceleration, thrust and precision [1–2].

With the in-depth research, lots of problems are exposed in the linear motor feed drive system. The most popular of all are the thrust force fluctuation and the interfering sensitivity. The motor thrust harmonics due to the nonlinearity of drive circuit and motor itself directly act on the mechanical system, affecting the motion stability of feed drive system. The research of many scholars has been focused on the forming mechanism of thrust force harmonics and the compensation methods. Proca et al. [3] presented the analytical model of the permanent magnet motors taking into account slotting which allowed the rated performance calculation but also such effects as cogging torque, ripple torque, back-emf form prediction. Remy et al. [4] set up the model of permanent-magnet linear synchronous motors (PMLSM) using causal sequence diagram (COG) and took into account the electromagnetic thrust harmonics.Jian et.al [5] investigated the cause of the detent force generation in the permanent magnet linear synchronous motor and calculated for the reduction of it. Zarko et al. [6] established the analytical model of air-gap magnetic field using Maxwell tensor method which considered the motor cogging

* Correspondence to: Xi'an Jiaotong University, Room A315 of North Side, The West No. 5 Building, Qujiang Campus, No. 99, Yanxiang Road, Xi'an, Shaanxi, China.
E-mail addresses: xjyang518@163.com (X. Yang), whzhao@mail.xjtu.edu.cn (W. Zhao).

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effect. Bazghaleh et al. [7] introduced the proportion coefficient to describe the end effect and analyzed the end force by establishing a new equivalent circuit. Zhu et al. [8] designed the auxiliary poles to reduce the detent force due to end effect. Lu et al. [9] described the equivalent circuit model and correction factors considering the end effect through theory analysis. In addition, there are a lot of other works focusing on the control compensation strategy [10–13].

The above studies have played important roles in improving the thrust force fluctuation and dynamic precision in the direct feed drives. However, in practice, the thrust force spectrum is not constant under different motion parameters. The linear motor feed drive system may do advance and return movement with high-speed, continuous uniform movement, or motion with an ever-changing load. In the motion process, the thrust force harmonics may vary with the position, velocity, acceleration and load, which affect the displacement fluctuation of the feed drive system. In addition, the mechanical system is not an ideal single-inertia system. In machine tools, the shaft driven by linear motor is usually coupled with other ones. The thrust force harmonics and other disturbances act on the mechanical system and then cause mechanical vibrations with excited numerous eigen modes. Especially when one frequency component of the thrust force harmonics is close to some natural frequency of the mechanical system, resonance occurs, leading to a worse dynamic precision and even instability [14–15].

Therefore, in this paper, the multi-dimensional variation of each thrust force harmonic is analyzed under different motion parameters oriented to the displacement fluctuation. Firstly, the spectrum of the thrust force is obtained by the Maxwell equation and the electromagnetic energy method. Then the multi-dimensional variation of each thrust force harmonic is analyzed. In addition, the model of the servo system is established oriented to the displacement fluctuation and the influence of the variation of the thrust spectrum on the displacement fluctuation is discussed. At last the experiments are carried out to verify the theoretical analysis above.

2. Analysis of the multi-dimensional variation of each thrust force harmonic

2.1. Calculation of the motor thrust force spectrum

The thrust force of linear motor, which drives the mechanical system to realize the movement, is produced by the interaction between the primary current and the magnetic field caused by the permanent magnet. However, the current is not the ideal sine wave and has lots of harmonics due to the nonlinearity of drive circuit. Meanwhile, the magnetic field contains many harmonics caused by the slot-effect, end-effect and magnetic linkage harmonics. As a result, the motor thrust force has many harmonic components. The 2-D model of the air-gap magnetic field is established as shown in Fig. 1.

where, 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 is the pole pitch, w_p is the width of permanent magnet, h_m is the height of slot, τ_s is slot pitch and w_s is tooth pitch.

The magnetic equation of the vector magnetic potential field is set up according to the Maxwell equations and the corresponding boundary conditions are applied. The air-gap magnetic field of permanent magnet can be obtained as:

$$B_y = \sum_{n=1,2,3...}^{\infty} B_{ny} \cos\left[\frac{(2n-1)\pi}{\tau}x\right] \tag{1}$$

The air-gap magnetic field of linear motor considering the slot-effect and end-effect can be obtained as [16]:

$$B'(x) = \lambda_s(x)\cdot\lambda_e(x)\cdot B_y(x, y) \tag{2}$$

where, $\lambda_s(x)$ and $\lambda_e(x)$ represent the relative permeance function between actual and ideal air-gap considering the slot-effect and end-effect, respectively.

The three-phase winding of motor is generally a star connection without the midline, which does not contain three times harmonics. Setting the initial phase current equal to zero, the armature current is given by [17]

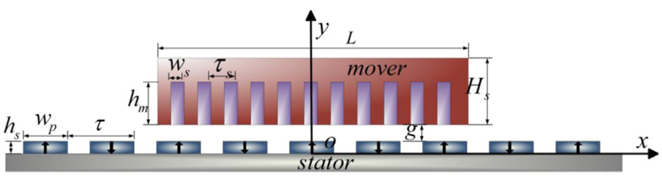

Fig. 1. The 2-D analytical model of the air-gap magnetic field.