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Investigation on the displacement fluctuation of the linear motor feed system considering the linear encoder vibration

Xiaojun Yang [a,b], Dun Lu [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

Optical linear encoder is generally adopted to realize the full-closed loop control for the linear motor feed system. Its reading head installed on the worktable may vibrate as a result of the excitation of disturbance harmonics, which leads to the encoder's error. This study aims to investigate the mechanism of displacement fluctuation due to the encoder's error caused by the worktable vibration in the linear motor feed system. The vibrating modes of feed system are analyzed firstly, and then the influences of three torsional vibrations on encoder's errors are investigated. The transfer function between disturbance and output response is proposed to analyze the influence of encoder's error on the displacement fluctuation. The relationships among vibration, encoder's error, thrust harmonic and displacement fluctuation are discussed in detail. The results show that the encoder's error can produce obvious displacement fluctuation for the linear motor feed system, which is actually an electromechanical coupling process due to the direct drive and full-closed loop control. Finally, three effective measures are put forward to diminish the system displacement fluctuation.

1. Introduction

The linear motor feed system has a broad application prospect on high-speed and high-precision CNC machine tools because of its obvious advantages such as high speed/acceleration, large thrust and good dynamic characteristics [1–2]. However, many kinds of thrust harmonics in motors due to the nonlinearity of drive circuit and motor structure act on the mechanical system, and then deteriorate the motion stability of the feed system. Much research has been focused on the mechanism of thrust harmonics and compensation methods. Remy et al. [3] set up the model of permanent magnet linear synchronous motor (PMLSM) using causal sequence diagram (COG) considering the electromagnetic thrust harmonics, and then designed resonant controllers for the current control loop. Markovic et al. [4] presented an exact model for determining the cogging torque based on the con-formal mapping (CM) method, and got an optimal configuration with the minimal cogging torque. Hirasa et al. [5] and Gieras et al. [6] introduced the proportion coefficient to describe the end effect and analyzed the end force by establishing a new equivalent circuit. In addition, many literatures have been published on the control compensation strategy [7,7–12]. By using those methods mentioned above, the thrust fluctuation and dynamic precision of direct feed drives were greatly improved. The amplitudes of the thrust harmonics drop to less than 5% of the nominal thrust after the optimization and compensation.

For the linear motor feed system, however, the intermediate transmission parts are all cancelled. The mover is connected directly with the worktable. The thrust harmonics would cause significant displacement fluctuation which mainly affects the quality of the machining surface in spite of small amplitudes. Moreover, the thrust harmonics and other disturbances act on the mechanical system, leading to multi-modes vibrations. Especially when the frequency component of the thrust harmonics is close to the natural frequency of mechanical system, resonance would occur, resulting in a worse dynamic precision or even instability.

In the linear motor feed system, the linear encoder is widely used to realize full-closed loop control. Its dynamic characteristics have an important influence on the precision and stability of the feed system. The reading head of linear encoder is usually mounted on the worktable through a separate frame. The torsional vibration will cause the vibration of the reading head and hence result in encoder's error, leading to the displacement fluctuation of the feed system. Weck et al. [13] first found the influence of mechanical system on the feedback system in the direct drive and concluded that the motion stability can be improved obviously by

* Correspondence to: Room A315 of North Side, The west No.5 Building, Qujiang Campus, Xi'an Jiaotong University No.99, Yanxiang Road, Xi'an, ShaanXi 710049, China. Fax: +86 29 83399113.
E-mail addresses: xjyang518@163.com (X. Yang), whzhao@mail.xjtu.edu.cn (W. Zhao).

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Nomenclatures

ω_{0r}	frequency of roll vibration
θ_y	angular displacement of yaw vibration
ω_{0p}	frequency of pitch vibration
θ_r	angular displacement of roll vibration
$\Delta\delta_y$	encoder's errors caused by yaw vibration
θ_p	angular displacement of pitch vibration
$\Delta\delta_p$	encoder's errors caused by pitch vibration
$A_{\theta y}$	amplitude of yaw vibration
$\Delta\delta_r$	encoder's errors caused by roll vibration
$A_{\theta r}$	amplitude of roll vibration
d	the distance between sensor and scale in the light path
$A_{\theta p}$	amplitude of pitch vibration
β	included angle between reflected light and sensor, $\beta \in (0, 180^o)$
ω_{0y}	frequency of yaw vibration
α	refraction angle of light, $\alpha \in (0, 90^o)$
L_b	width of the worktable
L_m	distance between light source and sensor
L_a	length of the worktable
L_h	distance between the center of reading head and the worktable, $L_h \in (-L_a/2, L_a/2)$
F_δ	the amplitude of new thrust harmonic
$F_{6i\delta}$	the amplitude of new high-frequency thrust harmonic
K_p	proportional gain of position controller
K_v	proportional gain of speed controller
T_v	integral time constant of speed controller
K_F	force constant
m	load mass
M_p	thrust coefficient of pitch vibration
x_i	command signal
M_y	thrust coefficient of yaw vibration
x_o	output response
M_r	thrust coefficient of roll vibration
x_{oy}	displacement fluctuation caused by yaw
x_{or}	displacement fluctuation caused by roll
x_{op}	displacement fluctuation caused by pitch
K_A	equivalent gain of the current loop

changing the installation position of linear encoder. However the mechanism of encoder's error was not discussed. The effects of installation deviation, thermal deformation and mechanical static deformation on encoder's error have been performed in much research [14–16]. Moreover, the performance of the encoder under dynamic vibration was paid much attention in recent years. Alejandre and López [17,18] analyzed the loss of accuracy of the encoder because of mechanical vibration under different mounting conditions and discussed the sensitivity of mechanical vibration for encoder's errors under different mounting dimensions. However, the influence of encoder's error on displacement fluctuation of the feed system was not discussed in their papers.

Therefore in this study, the displacement fluctuation resulting from encoder's error is analyzed. The influence mechanism of encoder's error on displacement fluctuation is explored. The vibrating modes are analyzed firstly in the linear motor feed system. Then the influence of mechanical vibration on the encoder's error is researched. The Electromechanical coupling model is established and the new thrust harmonics are obtained considering the nonlinearity of the drive circuit. The transfer function between disturbance and output response is proposed to analyze the influence of encoder's error on the displacement fluctuation. The relationships among vibration, encoder's error, thrust harmonic and displacement fluctuation are analyzed. At last, several effective measures are put forward to diminish the displacement fluctuation.

2. Displacement fluctuation model based on thrust harmonics resulting from encoder's errors

2.1. Calculation of encoder's errors caused by the mechanical dynamic vibration

The linear motor feed system generally consists of permanent magnet, motor primary, worktable, linear guide, linear encoder and machine bed, as shown in Fig.1. Ignoring the flexibility of the worktable, the worktable has three linear vibrations along each axis and three rotational vibrations around each axis [19]. In the above six modes, the stiffness along the Y and Z directions of the slide guide is very high. Their vibrating response can be ignored in this paper.

The optical linear encoder is usually mounted on the worktable through a separate frame as shown in Fig.1. The frequency of the vibration of the frame is very high, which is not discussed in this paper. The reading head is difficult to mount in the center of worktable due to the limitation of the structure space. The torsional vibration of worktable may lead to the vibration of reading head. The optical path will change because of the vibration of linear encoder with photoelectric scanning principle. And then encoder's error is generated, leading to the displacement fluctuation of feed system.

2.1.1. Effect of yaw vibration of the worktable on the encoder's error

The angular displacement of mechanical yaw vibration $\theta_y(t)$ is the periodic function of time under the excitation of periodic external force, that is

$$\theta_y(t) = A_{\theta y}\sin(\omega_{0y}t - \phi_y) \quad (1)$$

The reading head of the linear encoder is usually mounted on the side of the worktable as shown in Fig.1. The change of optical path in reading head caused by the yaw vibration of the worktable is shown in Fig.2. The solid line represents normal status and dashed line represents the status considering vibration.

The yaw vibration causes the deflection between reading head and scale in vertical direction, leading to encoder's error $\Delta\delta_y$ in photoelectric sensor. The encoder's error caused by yaw vibration can be obtained by the geometric relationship in Fig.2(c) as follows:

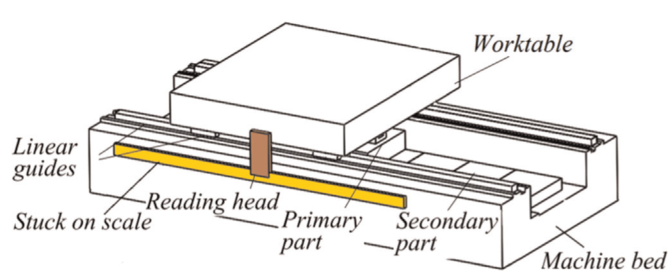

Fig. 1. Structure diagram of the linear motor feed system.