Mechanical Systems and Signal Processing 111 (2018) 492–508

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Investigation of the dynamic electromechanical coupling due to the thrust harmonics in the linear motor feed system

Xiaojun Yang, Hui Liu, Dun Lu, Wanhua Zhao *

School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710054, China

ARTICLE INFO

Article history:
Received 19 July 2017
Received in revised form 26 March 2018
Accepted 30 March 2018

Keywords:
Linear motor feed system
Electromechanical coupling
Thrust harmonics
Mechanical vibration
Displacement fluctuation

ABSTRACT

In the linear motor feed system, all the intermediate transmission components are cancelled. Lots of thrust harmonics caused by the nonlinearity of drive circuit and motor itself directly act on the mechanical system, leading to the vibrations. Meanwhile, the mechanical vibrations also affect the characteristics of motor thrust through the full closed-loop control. There is a close coupling between the servo drive and mechanical system, affecting the dynamic precision of the feed system. Therefore in this paper, an analytical method, which is used to present the mechanism of the electromechanical coupling caused by the thrust harmonics and its effects on the dynamic precision, is explored for the linear motor feed system. The thrust harmonics and mechanical characteristics are calculated firstly. The interactions between the servo system and mechanical system are analyzed afterwards. Then the coupled equation is established and the coupled process is analyzed. Moreover, the influence of the coupling on the displacement fluctuation is discussed. The results show that the thrust harmonics will produce significant displacement fluctuations, which is actually an electromechanical coupling process. In addition, its effects will aggravate with the increase of the velocity. At last several measures are put forward to improve the dynamic precision of the feed system. The displacement fluctuation caused by thrust harmonics is decreased more than 90% by implementing an integrated compensation strategy. This work will provide the theoretical support for the analysis and optimization of the complex electromechanical couplings, especially for the linear motor feed system.

1. Introduction

In recent years, with the growth of the demand for high-efficiency and high-precision machining, the linear motor feed system has a broad application prospect on the high-speed and high-precision computer numerical control (CNC) machine tools because of its obvious advantages, such as high speed and acceleration, large thrust, quick response and high precision [1,2].

At present, much attention about the linear motor feed system is paid to the thrust fluctuation. Zarko et al. [3] established the air-gap magnetic field model of permanent magnet and analyzed the motor thrust without considering the current input. Markovic et al. [4] presented an exact model for determining the cogging torque based on the conformal mapping (CM)

* Corresponding author at: Room A315 of North Side, The West No. 5 Building, Qujiang Campus, Xi'an Jiaotong University, No. 99, Yanxiang Road, Xi'an, Shaanxi, China.

E-mail addresses: xjyang518@163.com (X. Yang), whzhao@mail.xjtu.edu.cn (W. Zhao).

https://doi.org/10.1016/j.ymssp.2018.03.062

method, and got an optimal configuration with the minimal cogging torque. Remy et al. [5] set up the model of permanent-magnet linear synchronous motors (PMLSM) using causal sequence diagram (COG) and took into account the electromagnetic thrust harmonics. Lu et al. [6] described the equivalent circuit model and correction factors considering the end effect through theoretical analysis. Zeng et al. [7] presented an accurate and efficient analysis method for the PMLSMs considering the slotting effect, the end effect, and the magnet shape. Yang et al. [8] analyzed the multi-dimensional variation of each thrust harmonic under different motion parameters. In addition, many scholars had also focused on the control compensation strategy to improve the thrust fluctuations. Cho et al. [9] presented a novel disturbance compensation scheme to attenuate periodic disturbances on repetitive motion. It based on the assumptions that all measured states and disturbances were periodic and repetitive. Bascetta et al. [10] proposed a compensation scheme of force ripple based on a simple and compact model of the disturbance. Elfizy et al. [11] presented a controller design methodology which added the friction compensation, the force ripple compensation and a disturbance observer to model to improve the tracking performance for direct driven machine tools.

The above studies have played important roles in improving the thrust fluctuations and the dynamic precision for the linear motor feed system in the machine tools. However, the object of the above analysis is the linear motor itself. Although the amplitude of each thrust harmonic meets the requirements of the motor, the author team has found that these thrust harmonics with small amplitudes directly act on the mechanical system, still leading to obvious vibrations [12,13]. Especially the thrust harmonics have the cumulative effects, resulting in significant displacement fluctuations. What is more, the main compensation goals of the above methods are the tracking error and transient error. The displacement fluctuations during the uniform motion, which may affect the machining quality in the ultra-precision machining [14], are not considered. In addition, the dynamic characteristics of the mechanical system are ignored in the control model. In practice, the mechanical system is not an ideal single-inertia system. The thrust harmonics and other disturbances act on the mechanical system and then cause mechanical multi-modes vibrations. In the linear motor feed system, the linear encoder has to be used to realize full closed-loop control because of its direct driven structure. The mechanical vibrations will reversely affect the characteristics of motor thrust through the feedback system. There is a close coupling between the servo drive and mechanical system. Therefore, it is necessary to analyze the electromechanical coupling caused by the thrust harmonics and reveal its mechanism, which can provide the theoretical foundation for the improvement of the motion stability.

Aiming at the interactions between the servo system and mechanical system, Qiu [15,16] analyzed the electromechanical couplings among the rotor, the air-gap and the stator in large steam turbines and discussed the effects of electromagnetic parameters on the rotor vibrations. He et al. [17] found and analyzed four kinds of the electromechanical coupling behaviors of the complex electromechanical system. Kim and Chung [18,19] pointed out that the performance of the servo system mainly depended on the interaction between mechanical structure and servo drive. Szolc et al. [20] studied the dynamic electromechanical coupling effects in machine drive systems driven by asynchronous motors. The above research has important significance for understanding and analyzing the electromechanical couplings. However, these studies mainly focused on the motor rotor dynamics. There is little research on the mechanism and the effects of the electromechanical coupling between the servo system and mechanical system in the linear motor feed system on account of the neglect of the mechanical characteristics. Weck et al. [21] analyzed the interaction between servo drive and mechanical structure in various aspects including mechanical oscillation, bandwidth of current loop, up-limit of current and control parameters in the linear motor feed system. However, he only discussed the system stability under the influence of feedback errors and did not analyze the thrust harmonics and the displacement fluctuations. Yang et al. [22,23] analyzed the influences of air-gap fluctuation and encoder's errors on the displacement fluctuations and conducted preliminary research on two kinds of electromechanical couplings in the linear motor feed system.

In this paper, the electromechanical coupling caused by the thrust harmonics is analyzed for the linear motor feed system in machine tools. At first, the characteristics of the thrust and mechanical system are analyzed. Then the coupled equation is established and the coupled process is analyzed. In addition, the analytical expression of the displacement fluctuation caused by the coupling is deduced. At last the theoretical analyses are verified by the experiments and several measures are put forward to improve the displacement fluctuations of the feed system.

2. The electromechanical couplings in the linear motor feed system

The linear motor feed system consists of the numerical control (NC) system, servo drive and linear motor, mechanical system, feedback system and other accessories, as shown in Fig. 1.

The mover of the linear motor is directly connected with the driven component due to the direct-driven structure. The thrust harmonics and other disturbances directly act on the mechanical system, leading to vibrations. Meanwhile, the motor thrust is affected by the mechanical vibrations. There are obvious and complex electromechanical couplings involved multi-fields theories between the servo system and mechanical system in the linear motor feed system as shown in Fig. 1. The couplings have significant influences on the dynamic precision of the feed system, especially displacement fluctuations.

Based on the "force-displacement" equilibrium equation, the coupled equation between the servo system and mechanical system can be established as