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Integrated modeling and analysis of the multiple electromechanical couplings for the direct driven feed system in machine tools

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ABSTRACT

The complicated electromechanical coupling phenomena due to different kinds of causes have significant influences on the dynamic precision of the direct driven feed system in machine tools. In this paper, a novel integrated modeling and analysis method of the multiple electromechanical couplings for the direct driven feed system in machine tools is presented. At first, four different kinds of electromechanical coupling phenomena in the direct driven feed system are analyzed systematically. Then a novel integrated modeling and analysis method of the electromechanical coupling which is influenced by multiple factors is put forward. In addition, the effects of multiple electromechanical couplings on the dynamic precision of the feed system and their main influencing factors are compared and discussed, respectively. Finally, the results of modeling and analysis are verified by the experiments. It finds out that multiple electromechanical coupling loops, which are overlapped and influenced by each other, are the main reasons of the displacement fluctuations in the direct driven feed system.

1. Introduction

In the direct driven feed system, all the intermediate mechanical transmission parts are cancelled. Comparing with the traditional ball screw feed system, the backlash and friction are reduced. Therefore, the linear motor has lots of advantages, such as large thrust, high stiffness, high speed, acceleration and precision, and has a broad application prospect in the machine tools [1,2]. However, the zero transmission structure also has many problems. The most prominent ones are thrust fluctuation and interference susceptibility, which have been studied by a lot of scholars [3–11]. Zeng et al. [3] presented a Schwarz-Christoffel mapping-based method for accurately predicting the thrust force of the permanent magnet linear motors (PMLM) and calculated the cogging force due to the slotting effect and end effect. Tavana et al. [4] used the magnet arc shaping technique to improve the performance of the permanent magnet linear synchronous motor (PMLSM). Vaez et al. [5] presented an alternative method to model the air-gap flux density distribution taking into account the end teeth effects and magnetic saturation of iron core. Yang et al. [6] analyzed the multi-dimensional variation of each thrust harmonic under different motion parameters. Kazan et al. [7] presented a new analysis method for air core PMLSM, which replaced most of the finite-element analysis (FEA) steps with an analytical model of the motor consisting of nonlinear equivalent magnetic

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Nomenclature

E_{mk}	back electromotive forces without load/V
v	speed of the mover/m/min
N	coil turns
H_s	the height of mover/mm
g	the thickness of air-gap/mm
w_s	the tooth pitch/mm
M_{ab}	the mutual inductance between a phase and b phase/mH
a_0	electromagnetic coefficient considering slot effect
τ	pole pitch/mm
a_i	electromagnetic coefficient considering slot effect, $i = 1, 2, 3, \ldots$
C_n	electromagnetic coefficient considering end effect, $n = 1, 2, 3, \ldots$
w	width of mover/mm
μ_0	$\mu_0 = 4\pi \times 10^{-7}$ (H/m)
X_L	distance away from mover end/mm
ε	asymmetric inductance coefficient
I_m	amplitudes of the current harmonics/A
J_x	moment of inertia around x axis/Kg m^2
J_z	moment of inertia around z axis/Kg m^2
k_s	servo stiffness in feed direction/N/m
$k_{\theta z}$	torsional stiffness around z axis/N m/deg
F_{Tr}	thrust harmonics/N
S_y	coefficient between yaw and displacement fluctuation/μm/arcsec
$A_{\theta p}$	amplitude of pitch vibration/arcsec
ω_{p0}	frequency of pitch/Hz
ω_{y0}	frequency of yaw/Hz
K_v	proportional gain of speed controller/As/m
K_F	force constant/N/A
x_i	command signal/mm
K_p	proportional gain of position controller/s^{-1}
ω_{gri}	frequency of displacement fluctuation caused by air-gap/Hz
D_{eri}	amplitude of displacement fluctuation caused by encoder's error/μm
φ_{eri}	phase of displacement fluctuation caused by encoder' error/rad
F_{other}	other outside disturbances/N
D_{cri}	amplitude of displacement fluctuation caused by cutting force/μm
M_{my}	coefficient of thrust on yaw direction
M_{op}	coefficient of other force on pitch direction
M_{or}	coefficient of other force on roll direction
L_m	distance between light source and sensor/mm
L_h	distance between the center of reading head and the worktable/mm, $L_h \in (-L_a/2, L_a/2)$
L_b	width of the worktable/mm
g'	the air-gap considering vibration/mm
T	the motion time/s
E_{lk}	back electromotive forces with load/V
i_k	armature current/A
k	three-phase windings, $k = a, b, c$
l	width of the coil/mm
h_s	the thickness of permanent magnet/mm
w_p	the width of permanent magnet/mm
L_{a}	the self-inductance of a phase winding/mH
M_{ac}	the mutual inductance between a phase and c phase/mH
F_{6i}	amplitudes of ripple thrust/N, $i = 1, 2, 3, \ldots$
B_i	electromagnetic coefficient/mT, $i = 1, 2, 3, \ldots$
A_n	electromagnetic coefficient considering end effect, $n = 1, 2, 3, \ldots$
τ_s	pitch/mm
λ_0	permeability, $\lambda_0 = \mu_0/g_e$
g_e	equivalent air-gap coefficient/mm
L	length of mover/mm
L_{a0}	amplitude of the inductance/mH
m	mass of the mover and worktable/kg