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Integrated modeling and analysis of ball screw feed system and milling process with consideration of multi-excitation effect

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ABSTRACT

The present researches about feed drive system and milling process are almost independent with each other, and ignore the interaction between the two parts, especially the influence of nonideal motion of feed drive system on milling process. An integrated modeling method of ball screw feed system and milling process with multi-excitation effect is proposed in this paper. In the integrated model, firstly an analytical model of motor harmonic torque with consideration of asymmetrical drive circuit and asymmetrical permanent magnet is given. Then, the numerical simulation procedure of cutter/workpiece engagement during milling process with displacement fluctuation induced by harmonic torque is put forward, which is followed by the solving flow for the proposed integrated model. Based on the integrated model, a new kind of quality defect shown as contour low frequency oscillation on machined surface is studied by experiments and simulations. The results demonstrate that the forming mechanism of the contour oscillation can be ascribed to the multi-excitation effect with motor harmonic torque and milling force. Moreover, the influence of different milling conditions on the contour oscillation characteristics, particularly on surface roughness, are further discussed. The results indicate that it is necessary to explain the cause of the new kind of quality defect with a view of system integration.

1. Introduction

During milling process, the ball screw feed system of CNC machine tool is driven by the electromagnetic torque of control-servo drive system to participate milling machining for forming target parts [1]. Both feed drive system and milling process are the two bases for machining process, and any performance defect of each portion is easily to cause quality problem on parts. With the development of past decades, lots of related issues of feed drive system [2] and milling process [3,4] have already been discussed frequently, but what should be pointed out is that the vast majority of these researches focused on the two objects independently, and lacked consideration of the interaction mechanism between feed drive system and milling process. With the gradual improvement of requirements for part quality, it is difficult to explain the new kind of quality defect with traditional methods. Hence, it is necessary to study the issue from a view of system integration.

From the literature published, the researches on ball screw feed system mainly concentrated on the aspects of dynamic modeling and dynamic characteristic analysis of mechanical system [5,6], modeling and analysis of driving performance of

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Nomenclature

XYZ	global coordinate system
$X_{sw}O_{sw}Y_{sw}$	local static coordinate system of workpiece
$X_{sc}O_{sc}Y_{sc}$	local static coordinate system of cutter
$X_{dw}O_{dw}Y_{dw}$	local dynamic coordinate system of workpiece
$X_{dc}O_{dc}Y_{dc}$	local dynamic coordinate system of cutter
θ_r	mechanical angle of rotor coordinate rotating from stator coordinate
α	mechanical angle of rotor and stator
B_r	spatial distribution function of permanent magnet remanence of rotor
l_0	effective magnetization length of permanent magnet
$\delta(\alpha)$	effective air gap length
Z_s	number of stator cogging
e_a, e_b, e_c	three phase back EMF
i_a, i_b, i_c	three-phase current
Φ	magnetic flux through each phase winding
ω_r	rotation angular velocity of rotor
k_w	winding coefficient
L	axial effective length of coil
E_m	magnetic field energy
T_{cog}	cogging torque
$\tau_{e/m}$	torque resulting from symmetric part of drive circuit
$\Delta\tau_{e/m}$	orque resulting from asymmetric part of drive circuit
$h(i,j,t_k)$	instantaneous uncut chip thickness of the jth cutting element on the ith tooth at time t_k

servo system [10,11] and the control strategy [7–9]. For the mechanical system of ball screw feed system, FEM [5,6] and lumped mass method [12,13] are the two common methods to establish the dynamic model. The advantage of FEM is that it can exactly reflect local characteristics of the structure and precisely calculate multi-order dynamic characteristics of the mechanical system. By contrast, the advantage of lumped mass method is that the model is always simple and convenient, which is beneficial for parameters modification and regularity analysis. For the servo drive system, motor output torque is a excitation source for mechanical system, and its driving performance would directly affect the capability of mechanical motion. Actually, due to the limitation of design and manufacture in motor structure [14–16], and the influence of nonlinear characteristic of motor drive circuit [17,18], the motor torque is always unequal to the nominal value, and exists multiple harmonic components. For the ball screw feed system in a lathe, Liang et al. [19] analyzed the feed direction displacement fluctuation induced by the 6th-order current harmonic of a permanent magnet motor. Then with insert/workpiece geometric engagement, they further studied the influence of displacement fluctuate on the defect of machined surface, but this study ignored the mechanics and dynamic characteristics of cutting process, especially the excitation of turning force. Hence, it is difficult to explain the forming mechanism of quality defect on machined surface properly.

The study of milling process mainly focused on the cutting mechanics and dynamics [20,21], and it has achieved many important progresses in the milling of complex parts, such as curved surface [22–24] and thin wall parts [25,26]. During milling process, cutting force is one of the important excitation for the machining system, which acts on the cutter and workpiece and leads to the relative vibration and thus machining error. In the aspect of milling force study, some scholars have proposed milling force prediction method for 3-axis and 5-axis of sculptured surface [27,28]. In the aspect of milling chatter, the time domain and frequency domain methods for chatter prediction have also been presented [29–32]. In the aspect of machining quality, some researches had demonstrated the simulation method of machining error with consideration of dynamic excitation by milling force [33,34]. The attention of these studies almost concentrated on the cutter/workpiece engagement. Recently, Lee et al. [35] proposed a virtual simulation system of machine tool integrated with milling process, but in fact, there is no consideration of the interaction between the feed system and milling process. As far as it is concerned, all above researches considered the macro relative motion between cutter and workpiece as an ideal acceleration, uniform speed and acceleration process, and overlooked the micro displacement fluctuation induced by motor harmonic torque on milling process.

Literature reviews show that lots of researches have been done about the feed drive system and milling process, but the two parts of work are almost independent with each other. Actually, the motion of mechanical system would include displacement fluctuation resulting from harmonic excitation by motor torque. This kind of displacement fluctuation can further affect the milling process, especially cutter/workpiece engagement and milling force, and thus on part quality. Hence, this paper firstly proposes an integrated modeling method of ball screw feed system and milling process with consideration