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Dynamic and stability analysis of the linear guide with time-varying, piecewise-nonlinear stiffness by multi-term incremental harmonic balance method

Xiangxi Kong*, Wei Sun, Bo Wang, Bangchun Wen

School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, PR China

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ABSTRACT

The dynamic behaviors and stability of the linear guide considering contact actions are studied by multi-term incremental harmonic balance method (IHBM). Based on fully considering the parameters of the linear guide, a static model is developed and the contact stiffness is calculated according to Hertz contact theory. A generalized time-varying and piecewise-nonlinear dynamic model of the linear guide is formulated to perform an accurate investigation on its dynamic behaviors and stability. The numerical simulation is used to confirm the feasibility of the approach. The effects of excitation force and mean load on the system are analyzed in low-order nonlinearity. Multi-term IHBM and numerical simulation are employed to the effect of high-order nonlinearity and show the transition to chaos. Additionally, the effects of preload, initial contact angle, the number and diameter of balls are discussed.

1. Introduction

The linear guide consists of a mechanism in which steel balls are circulated infinitely to enable an infinite stroke of ball slides theoretically. Balls roll along the ball grooves formed on a rail and a carriage. Utilizing rolling contact via rolling elements (balls, rollers, etc.) to replace the sliding contact of traditional guide, the linear guide has lots of features: low friction force, low wear, high stiffness and good stability. Due to these advantages, the linear guide is widely used in high-grade machine tools, semiconductor manufacturing equipments or inspection apparatus [1–3]. As an important transmission component, the dynamic behaviors and stability of the system have a huge influence on the machining precision and stability of machine tools. Therefore, it is very significant to study the dynamic behaviors and stability of linear guide.

However, due to the strong nonlinearity of contact, it is difficult to develop a feasible model, which can reflect the static and dynamic behaviors of the linear guide accurately under complex external loads. A number of researchers have deduced a few static models to obtain the stiffness under external loads [4–6]. Dadalau et al. [4] treated the complex rolling contact as equivalent models by using Component Finite Element Method (CoFEM) and obtained the stiffness of the linear guide under different loads. Ohta et al. [5] created a static model of the linear guide considering the elastic of rail and carriage analytically and numerically and calculated the vertical stiffness by applying the static model with numerical simulation. Sun et al. [6] proposed a semi-analytical model corrected by experiment and verified by CoFEM. In their work, the vertical

* Corresponding author. Tel.: +86 24 83681620.
E-mail address: kongxiangxi007@163.com (X. Kong).

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stiffness of the linear guide was obtained correctly. However, in their works, to obtain the static stiffness of the linear guide accurately, the static models should be corrected by other ways and a full analytical model could not be obtained so that those were difficult to be used to study the dynamic behaviors. There are also lots of researches that describe models to analyze the dynamic behaviors of the linear guide [1,7–10]. Ohta et al. [7,8] treated the contact interfaces as spring-mass elements with constant stiffness and analyzed the natural vibration characteristics of the linear guide. Hung [1] adopted the same method with Ohta to obtain the natural vibration characteristics, but in his work the effects of loads on the stiffness were considered. Wu [9] created a full finite element model of the linear guide to obtain the stiffness, which was also used to analyze the natural vibration characteristics. We can find that they all analyzed the natural vibration characteristics and the effects of contact on these, but the more important dynamic behaviors and stability of the system in force vibration were not investigated, which influenced the cutting precision and stability directly.

The linear guide can suffer the high vertical loads and some low lateral and moment loads because of the characteristics of its structure. Especially, in the vertical direction, the linear guide has the high load capacity. However, under the high lateral and moment loads, the linear guide is not applicable. In our work, we study the dynamic behaviors and stability of the linear guide in the vertical direction. In the present research, a single-freedom dynamic model considering the contact stiffness is developed to investigate the dynamic behaviors and stability of the linear guide by multi-term IHBM. The outline of this article is the following. In the next section, we will create an approximate static model of the system to calculate the vertical stiffness under external loads. In Section 3, a single-freedom dynamic model is formulated, where the vertical stiffness is treated as a time-varying and piecewise-nonlinear one. In Section 4, multi-term IHBM is employed to study the nonlinear responses and stability of the system and compared with the linear system analysis. In Section 5, the numerical simulation is used to verify multi-term IHBM. The effects of the excitation forces and mean loads on the dynamic behaviors and stability of the system are studied and the transmission to chaos is presented by multi-term IHBM and numerical simulation in high-order nonlinearity. Moreover, we will change the parameters of the linear guide i.e. preload, initial contact angle, the diameter and number of balls to discuss the effects of those. Finally we will present our conclusions briefly.

2. Static modeling of the linear guide

The linear guide is a type of transmission assembly unit widely used in machine tools due to the low wear and friction for the ball bearings compared with the traditional guide. The transmission function is implemented based on the interactions of rail, carriage and balls. To analyze the dynamic behaviors of the linear guide, the stiffness should be obtained firstly. A simplified contact model is constructed as shown in Fig. 1, where the accessories are neglected for their few effects on its behaviors.

To calculate the stiffness of the linear guide, we presume that (1) when analyzing the interactions between balls and grooves, the contact of ball bearings is regarded as elastic contact; and (2) when calculating the displacement of carriage relative to rail, the carriage and rail are viewed as rigid.

In view of Fig. 1 again, the linear guide has four grooves expressed as i=1, 2, 3, and 4. θ_0 is the initial nominal contact angle, O_{ci} and O_{ri} are the groove curvature centers and r_c and r_r are the curvature radiuses of the carriage and rail respectively, usually r_c=r_r is represented with r, and δ_0 is the initial oversize of balls under preload P_0. The initial distance s_0 between O_c and O_r is

$$s_0 = r_r + r_c = 2r = d_0 + \delta_0, \quad \delta_0 > 0, \tag{1}$$

where d_0 is the initial diameter of ball. Under preload P_0, the balls will generate the elastic deformation. The oversize of ball δ_0 can be calculated by using the Hertz contact theory [5,6]:

$$\frac{\delta_0}{2} = \frac{3\mu}{2}\left(\frac{1}{12}\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)^2\left(\sum\rho\right)P_0^2\right)^{1/3}, \tag{2}$$

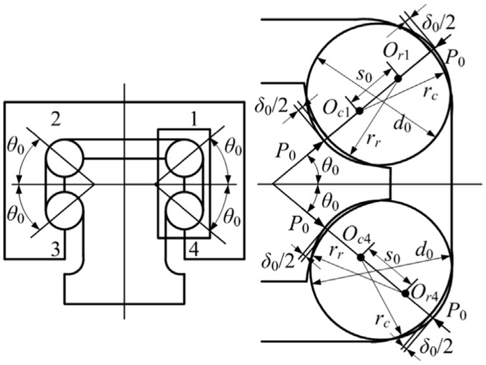

Fig. 1. Simplified model of the linear guide under preload.