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Compensation of dynamic mechanical tracking errors in ball screw drives

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ABSTRACT

Dynamic mechanical tracking errors occur in ball screw drives typically due to inertial, frictional and external forces. This results in axial elongation and compression of key components of the drive that deteriorate the dynamic tracking accuracy. In order to improve tracking accuracy, this paper presents a feedforward compensation method of dynamic mechanical tracking errors. A dynamic model is proposed to offset the position commands that are fed to the servo controller. The accuracy of the model can be improved by considering the torque transmission between the nut and the ball screw, which is not considered in existing models. To obtain the stiffness and friction parameters in the model, a new method of parameter identification is proposed. The method can simultaneously identify friction in key components leading to greatly improved efficiency and accuracy. The dynamic model and parameter identification method are validated by comparing simulation and experimental results for trapezoidal and sinusoidal trajectories. To validate the simulation results, the sinusoidal trajectories are used to compensate the tracking errors of the ball screw. The results confirm that most of the dynamic mechanical tracking errors are eliminated after compensation. Therefore, the compensation method based on the proposed dynamic model and parameter identification method is effective in improving the tracking accuracy of ball screw drives.

1. Introduction

Ball screw drives are widely used in computer numerical controlled (CNC) machine tools to position the workpiece relative to the tool because of their high stiffness, reliable operation and ability to mitigate the impact of inertial and cutting force variations [1–4]. Machining accuracy significantly depends on the tracking performance of the ball screw drives for a desired trajectory. Therefore, in order to meet the demands imposed by high productivity and high-precision parts, ball screw drives must exhibit good transient and steady tracking performance [5–7].

To improve tracking accuracy, position feedback is commonly used. If position feedback is obtained from a linear scale measuring the position of the working table, these problems can be, to a certain extent, alleviated during steady state positioning and low frequency movements. Compensation of the linear scale is always delayed because of processing of the control system. At high speed and high acceleration, the driving force of the motor increases, which results in increase of the force between components of the ball screw drive. Therefore, elastic deformation and vibration of some components become more serious with the increase of force. As the delay phenomenon of the control system is more apparent when dealing with high frequency signals, the delay of linear scale compensation becomes more serious in the situation. Therefore, the compensation effect of the linear scale is worsened with increase of speed and acceleration. Elastic deformation and vibration can deteriorate the dynamic linear accuracy of the ball screw drive with linear scale. [8–10] But if the errors can be estimated in advance, the delay problem can be eased. Therefore, in this paper, an error compensation method is proposed based on the position feedback obtained from a rotary encoder. The combination of the compensation method and a linear scale could also improve the dynamic linear accuracy of ball screw drives.

For ball screw drives with rotational feedback, tracking errors are composed of two parts, namely the control part and mechanical part. The difference between the motor position and the reference trajectory at each time instant is the control tracking error caused by the control system. Similarly, the difference between the working table and the motor position at each time instant is the mechanical tracking error caused by the mechanical system, and it mainly includes lead errors, elastic deformations and vibrations of the drive. As the lead errors are static, dynamic mechanical tracking errors are mechanical tracking errors without lead errors. In order to improve the tracking accuracy of drives both

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the control and the dynamic mechanical tracking errors needed to be decreased.

In order to reduce the dynamic mechanical tracking errors in ball screw drives in machine tools, various compensation features have been implemented in industrial numerical control systems, including geometric and thermal error compensation, torque compensation, feedforward compensation, notch filters, etc. [8]. In addition, elastic deformation of components also results in a difference between the motor position and the corresponding position of the working table. However, the compensation of dynamic mechanical tracking errors caused by the mechanical systems has received limited attention. In order to eliminate the dynamic mechanical tracking errors of ball screw drives, error compensation is always adopted. To determine the error compensation values, dynamic models are needed to evaluate/simulate the errors. Lim et al. proposed a method to reduce the errors of the working table's position without directly measuring the position of the working table [11]. A simple two-inertia model of the ball screw drive was proposed to estimate torsional deformations. It was assumed that the drive's stiffness is constant and friction is ignored in the model. The torsional deformation was compensated by means of the proposed torsional displacement feedback control. However, the stiffness of the active ball screw is relevant with the exact position of the nut, and the friction of components has an influence on the motion accuracy of the working table. Kamalzadeh et al. presented a new strategy for mitigating the detrimental effect of elastic deformations when only rotational feedback is available [8]. An elastic deformation model was developed and the position dependency of the drive stiffness was considered. The effects of viscous and Coulomb friction acting on the drive's rotating components were also considered. The compensation of the elastic deformation and lead errors was realized by using the proposed closed-loop scheme. However, in order to compute the elastic deformation, the model needs to input the real-time feedback control torque. Therefore, the application of the model was limited in some cases. Kamalzadeh and Erkorkmaz proposed a precision control strategy. Axial vibrations were modeled and actively compensated in the control law on the basis of a two-mass drive model [10]. In the model, the viscous friction in the rotary bearings and linear guideways and the damping induced in the nut were considered. The equivalent axial stiffness of the ball screw, the nut and supporting bearings was obtained. The axial stiffness and damping were identified by matching the frequency response of the model to the measured Frequency Response Functions. The compensation of axial vibration could actively attenuate vibration of the first axial model. But the model was not used to analysis and compensate the elastic deformation of ball screw drives. Zhu and Fujimoto proposed a novel mechanical model of a ball screw drive to analyze the elastic deformation dynamics under various motion conditions [12]. In their model, the torsional stiffness of the screw between the two end sides of the screw and the nut were differentiated. The stiffness of the supporting bearings and the friction in the guideway were also considered in the model. The model was used to analyze the elastic deformation characteristics and compensate the friction, but was not used to compensate for the elastic deformations in the moving process.

In order to obtain better performance of dynamic mechanical tracking errors compensation, a formulated detailed dynamic model is proposed to improve the estimation accuracy of the dynamic mechanical tracking errors in this paper. In the model, the torque transmission between the nut and the ball screw is considered, which is not considered in existing models. The estimation accuracy of the dynamic models depends on the model formulation as well as the model parameter identification method used. Therefore, a new identification method of the key parameters of the dynamic model is also proposed to improve identification efficiency the method facilitates the simultaneous identification of both friction- and stiffness-related parameters. Based on the dynamic model and parameter identification method, the dynamic mechanical tracking errors can be largely compensated. The remainder of this study is organized as follows. Section 2 introduces the experimental setup. Section 3 describes the compensation method of tracking errors of the ball screw drive. In Section 4, the dynamic model is proposed. The method for the identification of the stiffness and friction parameters is presented in Section 5. Section 6 highlights the simulated and experimental dynamic mechanical tracking errors to show simulation accuracy, while in Section 7 a compensation experiment is presented to show the effects of compensation. Conclusion are drawn in Section 8.

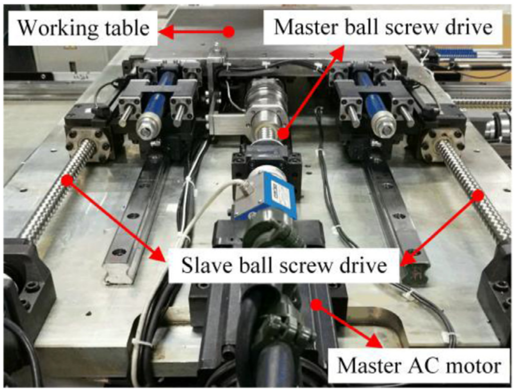

Fig. 1. Experimental setup.

2. Experimental setup

A ball screw feed drive system is constructed to study the compensation of dynamic mechanical tracking errors. In the constructed ball screw feed drive system, three ball screw drives are used, as shown in Fig. 1. The master ball screw drive is used to drive the working table. Table position measurement is obtained by a linear encoder. The body of the linear encoder is fixed to the base of the test bench with the scanning head mounted on the working table. The screw of the master ball screw drive is supported by a couple of angular contact bearings at the front end and a deep groove bearing at the rear end. The rotary position measurement of the motor is registered by a rotary encoder. The specifications of the master ball drive system are as follows: motor: Delta (Model: ECMA-C11020RS), driver: Delta (ASDA-A2), controller: DELTA TAU (Turbo PMAC2), linear encoder: HEIDENHAIN (LS177). The servo period of the controller is 442 µs and the servo frequency is 2262 Hz. The maximum data gathering frequency is 2262 Hz. According to the user manual, the bandwidth of the current loop of the controller is 200 Hz to 400 Hz. The resolution of the linear encoder is 0.125 µm and the resolution of the rotary encoder is 10,000 pulse/rev. The specification of the ball screw: pitch: 10 mm, diameter: 25 mm (product of Precision Motion Industries, INC., Taiwan). The resonant frequency of the ball screw drive is 130.6 Hz. The bandwidth of the experimental setup is 28.7 Hz.

3. Compensation of tracking errors of the ball screw drive

The common control strategy for ball screw drives is a PID servo filter, which contains a PID feedback filter and a PID feedforward filter, as shown in Fig. 2. The PID feedback filter consists of proportional (K_p), integral (K_i), and derivative (K_d) terms, each with its own contribution to the control effort. The PID feedforward filter has velocity (K_{vff}) and acceleration feedforward (K_{aff}) terms [8,13,14]. For a ball screw drive with rotational feedback, the position feedback in Fig. 2 is the real time position of the motor. Therefore, to improve the tracking accuracy, the feedforward compensation method can be adopted to reduce the effects of the mechanical system. In the common PID servo filter, there is an open interface which can be used to do feedforward compensation. The lead errors and dynamic mechanical tracking errors can be compensated via the open interface according to the commanded trajectory [15]. The lead errors are static and have nothing to do with the kinematic parameters of the working table, therefore, the test results of the lead errors