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Adaptive positioning control of an ultrasonic linear motor system

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ABSTRACT

A 3PRR parallel precision positioning system, driven by three ultrasonic linear motors, was designed for use as the object stage of a scanning electron microscope (SEM). To improve the tracking accuracy of the parallel platform, the positioning control algorithms for the drive joints needed to be studied. The dead-zone phenomenon caused by static friction reduces the trajectory tracking accuracy significantly. Linear control algorithms such as PID (Proportion Integration Differentiation) are unable to compensate effectively for the dead-zone nonlinearity. To address this problem, two types of feedforward compensation control algorithms have been investigated. One is constant feedforward with the integral separation PID; the other is adaptive feedback and feedforward based on the model reference adaptive control (MRAC). Simulations and experiments were conducted using these two control algorithms. The results demonstrated that the constant feedforward with integral separation PID algorithm can compensate for the time-invariant system after identifying the dead-zone depth, while the adaptive feedback and feedforward algorithm is more suitable for the time-varying system. The experimental results show good agreement with the simulation results for these two control algorithms. For the dead-zone nonlinearity caused by the static friction, the adaptive feedback and feedforward algorithm can effectively improve the trajectory tracking accuracy.

1. Introduction

The micro-nano operating system is an important part in the field of precision operation. Such systems are usually comprised of compliant mechanisms and can fulfill the requirements of high-precision positioning but are unable to perform large-scale positioning [1]. The object stage of the micro-nano operating system is used to carry the samples for large-scale motions. Therefore, the object stage must meet the requirements of both large-stroke and high-precision positioning. A parallel mechanism usually accompanies the precision positioning system, so a 3PRR parallel precision positioning system driven by an ultrasonic linear motor has been designed and used as the object stage of a scanning electron microscope (SEM). The accuracy of the drive joints affects the accuracy of the end-effector. There are some nonlinearities, such as the friction, elastic deformation and backlash clearance, that will affect the joint positioning accuracy, or give rise to problems such as stick slip, limit cycle [2] and steady-state error [3], even leading to a bad working situation of self-excited vibration [4]. To the effect of the nonlinearities, there are two valid methods: one is to introduce less nonlinearity in the design process, while the other is to apply a nonlinear control algorithm to compensate for the nonlinearity [5]. Adaptive control is usually applied for the nonlinear control [6–8].

The ultrasonic linear motor is free of backlash clearance, and the clearance of the linear slider can be eliminated by preloading. Thus, the ultrasonic linear motor positioning system has no backlash clearance and less elastic deformation, and the main nonlinearity is the friction. Friction is always the main obstacle for high-precision positioning. Castillo-Castaneda has shown that friction influences accuracy much more than clearance [5]. Moreover, the static friction is the main factor affecting the trajectory tracking accuracy, leading to time delay and a dead-zone [9]. Friction compensation has been widely used for precision positioning. The friction model is a research hotspot and is not mature. There is as yet no perfect model to describe various friction behaviors [10]. The static friction behaviors are complex at the micro level and significantly affect the positioning accuracy [11–14]. The ultrasonic linear motor used in this 3PRR positioning system is a stick-slip type motor, and the two drive feet rub the rod at an ultrasonic frequency, allowing the motor to move forward. This design is different from other ultrasonic linear motors. The ultrasonic linear motor used in references [15–17] is the resonant vibration type motor, and the trajectory of the spacer is an ellipse. Different types of motor have different driving characteristics. The friction acts as a drive source and a resistance source at the same time, especially at low speed. The motor exhibits a strong nonlinearity that must be compensated. The neural network is an

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effective method for nonlinear control. References [15–17] control the ultrasonic linear motor using a neural network with good control performance, which is very enlightening regarding ultrasonic linear motor control. It can compensate for a part of the flat peak phenomenon but cannot eliminate it thoroughly.

Friction compensation can be divided into two types. One is based on a friction model; the other is a model-free method. The first step of the model-based compensation method is to build a suitable model of the friction, from a mathematical perspective. It is difficult to obtain a perfect model of the friction force. Many scholars have researched friction extensively and proposed many types of models, successively including the Coulomb model, the Stribeck model [18], the Dahl model [19], the LuGre model [10], the Leuven model [20] and so on. Because the LuGre model includes multiple types of friction behaviors such as Coulomb friction, pre-sliding friction, and friction lag, it is widely used in friction compensation [21,22]. Although the LuGre model is useful in friction compensation, it is not convenient for the friction compensation of an ultrasonic linear motor. Some of the model parameters cannot be identified, and it is difficult to express the friction behaviors under ultrasonic vibration. The static friction can be modeled as a dead-zone nonlinearity [9,14], so dead-zone compensation methods are also useful for static friction compensation [23–26]. The literature [27] has compared several control algorithms for the tracking control of an ultrasonic linear motor actuated stage; combinations with feedforward control exhibit better control performance.

This study aims to solve the flat peak phenomenon when the system is tracking a sine wave trajectory. The flat peak phenomenon is caused by static friction and is difficult to compensate for via feedback control alone [5,28], so feedforward control is introduced to improve the tracking accuracy. Aiming at cases of unknown friction models, the model-free method for friction compensation was developed. This method is designed for this motor type and treats the friction nonlinearity as the disturbance, compensating for it in real time. Two feedforward control algorithms are utilized: one is constant feedforward combined with PID control, while the other is adaptive feedforward combined with the MRAC. Constant value compensation with the integral separation PID control is studied. It is a modified PID control method that can compensate for the time delay and the flat peak of the sine wave trajectory tracking. This method can improve the trajectory tracking accuracy of the system. However, it cannot adjust the compensation parameter adaptively when there is a disturbance or uncertainty in the friction interface. The adaptive feedback and feedforward algorithm is applied to solve this problem. The experimental results demonstrated that both model-free methods can effectively compensate for the friction.

The rest of this article is organized as follows. Section 2 presents the system description and problem statement. Section 3 introduces the constant feedforward with integral separation PID method and describes the simulation. Section 4 introduces the adaptive feedback and feedforward algorithm and describes the simulation. Section 5 presents the experimental results of the control algorithms. Section 6 draws the conclusions and summarizes the proposed work.

2. System description and problem statement

The 3PRR planar parallel mechanism has been designed and built as an object stage for the SEM. The trajectory tracking precision requires improvement, so it is necessary to investigate control methods for the ultrasonic linear motor positioning system. Due to the high response and precise performance of the ultrasonic motor [29], mechanisms driven by ultrasonic linear motor can accomplish the requirements of high speed, high precision and no magnetic field. The static friction in the system decreases the trajectory tracking accuracy, and the phenomenon of static friction has been investigated in subsequent experiments.

2.1. System description

The parallel 3PRR precision positioning system has been designed to meet the demands of precision positioning, shown in Fig. 1(b). It consists of the ultrasonic linear motor positioning system shown in Fig. 1(a). The ultrasonic linear motor positioning system is an electromechanical system including a computer and control card, motor driving unit and motor. The computer is used as the host and calculates the control value through a specified control algorithm. Then, the control value is sent to the control card, which translates it to a voltage signal. The motor driving unit receives the voltage signal and translates it to a high-frequency, high-amplitude driving voltage to the PZT inside the ultrasonic linear motor case. Therefore, the motor moves in a specified velocity carrying the linear encoder, the displacement and the velocity feedback to the control card and the computer, making up closed-loop system.

According to the design method described above, the ultrasonic linear motor positioning system was constructed as an experimental apparatus to verify the control methods for reducing nonlinearities. It is well known that simpler and more reliable mechanisms introduce fewer errors, such as the assembly error and machining error. Furthermore, because the simple mechanism consists of fewer parts, less nonlinearity is introduced. The ultrasonic linear motor driven system is a direct drive system. It does not include a ball screw and gear reducer, and it is driven by preloaded friction, with less backlash clearance. The ultrasonic linear motor positioning system is also free of magnetic fields. Therefore, it is adapted to environments without magnetic fields, such as the SEM chamber, as shown in Fig. 1(c).

The driving principle of the ultrasonic linear motor is shown in Fig. 2. The low-speed high-thrust characteristic makes it suitable for direct drive with no gear reducer transmission mechanism, and the linear type of ultrasonic motor moves straight without connecting to a ball screw, so it has no backlash clearance. The ultrasonic linear motor is a piezoelectric motor powered by the ultrasonic vibration of the stator, placed against the rotor. This system uses the motor model type U-264 made by PI German. The rod of the motor acts as the stator, and the two drive feet in the motor case act as the rotor.

2.2. Problem statement

1) The uncertainty of the friction interface on the motor rod leads to different running states in different travel ranges and different times. The parameters of the friction model are difficult to identify.

The friction model shows that the state of the friction interface, such as roughness and lubrication, can affect the friction parameters [30]. The ultrasonic linear motor is driven by friction. Two PZT units are connected to the driving feet and clamped to the motor rod. When applying the control voltage signal to the motor drive unit, the motor drive excites the feet to rub the rod, causing motion. The drive principle of the motor is shown in Fig. 2. Hence, the friction interface of the motor on the motor rod is the key factor affecting the running state.

The uncertainty of the friction interface includes two aspects: the slow time-varying and the inconsistency of the friction interface. The rod is exposed to the air, so environmental changes such