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Precision positioning device using the combined piezo-VCM actuator with frictional constraint

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ABSTRACT

This paper presents a new actuating method for a precision sliding stage using the combined piezo-VCM (voice-coil-motor) actuator. The proposed method is to employ the VCM to keep a presliding state of the sliding stage and then to use the piezoelectric (PZT) impact force to achieve precise motion. By controlling the forward or backward presliding state, the stage might undergo either directional motion due to PZT impact force, and thus have one degree-of-freedom of motion ability. Through fundamental experiments, the sliding stage was demonstrated to have various step motions on the order of as precise as 10 nm or as large as 10 μm. In addition, operational parameters which affected the motion characteristics of the stage, including applied voltage, pulse width, and normal load, were demonstrated. A dynamic model of the positioning device was established and verified as effective by numerical simulations. Finally, position control was performed to show that the positioning device has both large operational range and high-precision positioning ability. Using a traditional proportional-integral (PI) controller, the sliding stage was successfully positioned by the VCM with forward and backward target positions of 300 μm and 100 μm, and with the rough accuracy of 30 μm. The final precise accuracy of 10 nm was obtained by the PZT impact force for both forward and backward position controls. According to these experimental and numerical examinations, the remarkable positioning performance of the proposed device was well demonstrated.

1. Introduction

Precision positioning is one of the most fundamental technologies for supporting the development of industrial manufacturing, and is a field of multidisciplinary engineering that includes sensors, actuators, controllers, and mechanical transmission elements. Recently, piezoelectric (PZT) actuators have been largely used in ultraprecision positioning devices, with applications found in optical devices, semiconductor related manufacturing facilities, ultraprecision machining tools, and various nanotechnology microscopes. Compared with traditional servo-motors or linear motors, the PZT actuators are superior with regard to their fast response, small sizes, and cost-effectiveness. However, the total displacement of a PZT actuator is only a few micrometers, and to overcome this drawback, a number of practical efforts have been made. Typical methods for amplifying the displacement include: (1) the lever-type displacement amplifying mechanisms using flexural hinges [1,2]; (2) the inchworm-like moving mechanisms composed of PZT actuators serving driving and clamping functions [3–7]; and (3) the impact drive mechanism (IDM) featuring self-moving ability that could be obtained by a single PZT actuator with a special control technique [8,9]. In addition, the PZT actuators coupled with usual mechanical elements to form hybrid actuators have been shown to be effective in enlarging their operational ranges while keeping the same precision actuating ability. The coupled mechanical elements can be given as (1) servo motor and linear motor [10,11]; (2) hydraulic actuator [12,13]; (3) pneumatic actuator [14,15]; (4) voice-coil-motor (VCM) [16,17]; and (5) even passive element of spring [18,19]. In this paper, an innovative actuating method that suitably employs the frictional characteristic of sliding surface is proposed for a precision positioning device using the combined piezo-VCM actuator.

Friction force in a precision positioning device is a nonlinear characteristic that degrades positioning accuracy. Notably, when a system is operated with a very low speed and within a small distance range, the nonlinear characteristics would appear in microscopic views. In this situation, a complex or accurate controller is required to compensate the nonlinear frictional effect in order to obtain a satisfactory accuracy [20–23]. However, in this paper the proposed method is to effectively use the inherent frictional force existing on the sliding surfaces of two contact objects, and no attempt is made to compensate for the harmful frictional effect. The main concept of the proposed method is to make use of the presliding state of a sliding stage subjected to a small

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frictional pre-load, and then an instantaneous actuation is performed by the PZT impact force to change the presliding state into sliding state. Benefiting from the precisely controllable PZT impact force, the sliding stage may undergo step motion having a displacement range on the order of several nanometers to several micrometers.

In a previous study concerned with the combined piezo-VCM actuator [16], there was a focus on using the VCM to substantially enlarge the operational range of the PZT actuator, as well as on using the PZT actuator to precisely adjust a target object via an intermittent contact force. This hybrid actuator, featuring both large operational range and 10 nm order actuating capabilities, was experimentally demonstrated in the same study. In addition, the optimal actuating parameters for the hybrid actuator were investigated using the nonlinear double-dynamic Taguchi method [24]. In that design, however, since the actuation for the target object was by means of a hammer-like block through the form of contact force, only one directional actuation was allowed. As a result, to precisely control a target object having one degree-of-freedom (DOF), two sets of the hybrid actuators had to be equipped [25]. This increases the complexity in controller design and also the problem of smaller size. Instead of the focus on a precision adjusting tool provided in previous studies, the method presented in this study is capable of actuating the sliding stage undergoing both forward and backward motions using only one hybrid actuator. This unique function is obtained by controlling the direction of presliding state, i.e., if a forward presliding state is maintained by the VCM, the sliding stage will move forward with step-like motion due to PZT impact force destroying the presliding state, and vice versa. The detailed actuating process is described in Section 2, and this is followed by the descriptions of the dynamic modeling in Section 3. The experimental setup is presented in Section 4, and the fundamental experiments are performed in Section 5. Simulation result and control performance are provided in Sections 6 and 7, respectively, while the conclusions are given in Section 8.

2. Actuating principle

Fig. 1 shows the schematic configuration of the positioning device and the driving process. The PZT actuator is mounted between the sliding stage and the moving shaft of the VCM. The sliding stage subjected to a pre-load F_n is set on the V-grooved base to perform 1-DOF of motion. The driving process for the sliding stage is carried out through the following steps:

(1) The beginning of the operation is shown in Fig. 1(a), the sliding stage is resting on the base and both the actuators are electrically neutral.
(2) In the forward rough positioning stage, as shown in Fig. 1(b), the VCM is actuated by applying a voltage to its coil which produces a forward electromagnetic force F_v. If the thrust force is larger than the maximum static friction force, the sliding stage will start to move with a large travel distance.
(3) In the forward precision positioning stage, shown in Fig. 1(c), the sliding stage is kept at the forward presliding state due to a small thrust force of the VCM, and then a pulse voltage waveform is applied to the PZT actuator to produce an impact force F_p, thus destroying the presliding state and causing a precise step motion of the sliding stage.
(4) The backward precision positioning stage, shown in Fig. 1(d), is similar to step (3), but with a small backward thrust force of the VCM, the sliding stage can move backward precisely due to the PZT impact force.

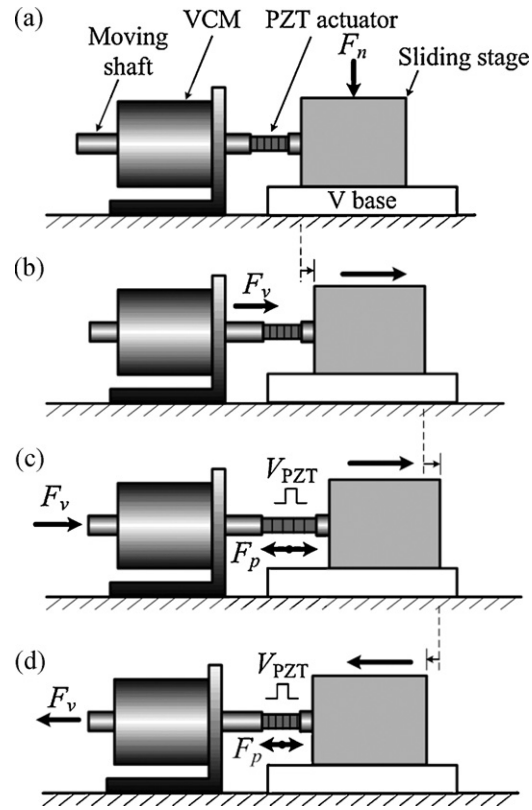

Fig. 1. Driving process including rough and precision positioning states.

The sliding stage can be actuated continuously to move in both forward and backward directions by repeating the steps (3) and (4). Therefore, compared with a previous study using two hybrid actuators [25], only one hybrid actuator can be used to obtain the same performance in this study.

3. Dynamic modeling

3.1. Physical model of the rough positioning state

Referring to the main component of the positioning device shown in Fig. 1(a), the schematic model is therefore represented as shown in Fig. 2. In the rough positioning state, as shown in Fig. 2(b), since the actuation is only dependent on the VCM, the dynamic equation is expressed as follows:

$$M'\ddot{X} = F_v - F_t - c_1\dot{X} \tag{1}$$

where M' is the total equivalent mass of the movable components, including the moving shaft of the VCM, PZT actuator, and sliding stage (M); X is the displacement of the sliding stage; F_v is a thrust force produced by applying a current to the coil of the VCM; F_t is the frictional load, and c_1 is the damping coefficient of the VCM.

Since the VCM can be regarded as a mechanical damper due to the nature of back electromotive force (BEMF), it can be represented by an equivalent electrical circuit, as shown in Fig. 3. Therefore, the input voltage V_{VCM} and the electromagnetic force F_v can be separately expressed as follows:

$$\begin{aligned} V_{VCM} &= RI + L\dot{I} + e_m, \\ F_v &= K_v I, \end{aligned} \tag{2}$$

where $e_m = K_m\dot{X}$, I is the coil current, R is the coil resistance, L is the coil inductance, K_m is the back-EMF constant, and K_v is the force constant.