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A two-dimensional nano-positioner: Design, modelling and experiments

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A B S T R A C T

In this paper, an X-Y nano-positioner driven by the shear piezoelectric actuators (SPAs) is proposed based on the friction-inertial theory. The nano-positioner can output a two-dimensional motion at a maximum speed of 0.187 mm/s within a 5 mm×5 mm workspace. In order to solve the contradiction between the motion velocity and the motion resolution, the coarse and the fine motion modes are first proposed on the SPAs application. The coarse motion and the fine motion are realized based on the power-function-shaped signal and the combined piecewise-curve signal respectively. The performance of the nano-positioner, e.g. the resolution, the velocity and the fluctuation, are analyzed and discussed based on different driving signals. Compared with other nano-positioners, the proposed system in this paper is superior in respect of compact size, high resolution, high velocity and two switchable motion modes. Furthermore, a prototype system of the proposed nano-positioner has been developed, which is evaluated by using a capacitive sensor based measurement system. Experiment results validate the effectiveness of the proposed methodology that can be employed and extended to a variety of SPA involved systems.

1. Introduction

The research aimed at precision engineering and nanotechnology develops significantly in recent years, which is widely used nowadays in nano-positioning, such as scanning probe microscopy and optics alignment etc [1,2]. The technological approaches to achieve the nano-positioning include compliance mechanism [3], inchworm actuator [4], and piezoelectric friction-inertial actuator (PFIA) [5], etc. Compared with others, the PFIA features the simple operation, and also solves the problem of the contradiction between the high accuracy and the long stroke [6–9].

According to the type of the piezoelectric actuator, the PFIAs have been categorized into the actuator with the SPA and the actuator with the piezoelectric stack [5]. The PFIAs with the piezoelectric stack always compose of driving object, slider, piezoelectric stack and sometimes compliant mechanism [10,11], which make the structure large and complex. On the contrary, the SPA based PFIAs are constructed by SPAs and a slider, which make the structure concise and compact. It is known that the miniaturization of the actuator can make the friction force/weight ratio larger due to the structural size decrease; on the other hand, can further improve the natural frequency [5,12]. In this paper, a planar two-dimensional nano-positioner driven by SPAs is proposed, which is more compact than the formerly developed systems with their size normally larger than 20 mm×20 mm [13–16].

The main working principle of the PFIA is based on the friction force between the friction element and the slider [17]. During every motion step, two clearly different phases are involved, i.e. the sticking phase and the slipping phase. The two motion phases determine the performance of the actuator, e.g. the motion velocity, the motion resolution and the step fluctuation etc. From the motion mechanism of the PFIA, it is easy to find that its integrated performance is a trade-off between the motion velocity and the motion resolution. To achieve a high motion velocity as well as a fine motion resolution, a framework including the coarse motion mode and the fine motion mode was proposed for the PFIA with the piezoelectric stack in previous literatures [17,18]. For the piezoelectric stack based PFIA, the coarse motion mode means that the actuator works in the “stick-slip” mode. In this mode, the piezoelectric actuator is actuated rapidly and repeatedly in a series of steps. Therefore the actuators can achieve a theoretically unlimited travel range and a significantly high motion velocity. On the other hand, in the fine motion mode, a slowly changed voltage is applied to the piezoelectric stack. The slider can move with the piezoelectric stack's movement without slipping, i.e., working in the “sticking” mode. Therefore, the slider can demonstrate the same positioning capability of the piezoelectric element within nanometer level. The travel range in this mode depends on the stroke of the piezoelectric stack. Therefore, the fine motion mode is also called scanning-mode [17–20].

However, the scanning-mode is not suitable for the PFIA with SPA due to the SPA's short stroke. Therefore, the coarse and the fine motion

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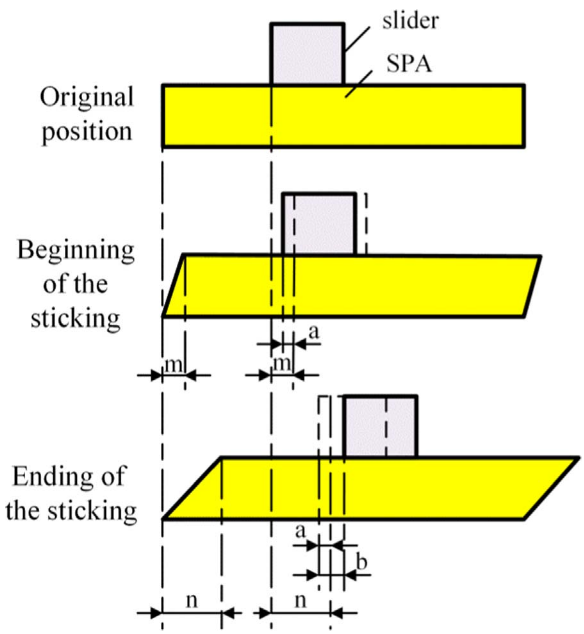

Fig. 1. Backlash generated in PFIA.

modes based on the SPA should be reconsidered. In this paper, for the SPA based PFIA application, two different curves of the driving signals are designed and employed to the two motion modes respectively. For the coarse motion, a high average velocity is the main concerned performance, so the power-function-shaped driving signal is selected as it is able to provide a large acceleration and also the curve shape can be tuned through one parameter only, i.e., the exponent n [6]. Literature [6] also demonstrates that the actuator step size is critically dependent on the instantaneous velocity at the ending stage of the sticking phase. Coincidently, compared with other driving curves, the exponential curve can realize an extremely high velocity at its ending stage. Therefore, the exponential curve is considered to be the best candidate curve for the coarse motion. On the contrary, for the fine motion, high resolution and low fluctuation are the basic and crucial required performance. Before discussing the fine driving signal in the SPA based system, the step loss and the overshoot phenomenon in the sticking phase should be noticed. As shown in Fig. 1, in the beginning of the sticking phase, the slider is expected to stick to the SPA without slipping. However, in practice, the slipping with a distance a exists due to the inertial effect. On the other hand, in the ending of the sticking phase, the slider should stop immediately but an overshoot b exists due to the inertial effect. The unexpected distances a and b are the uncontrollable uncertainties, which aggravates the motion fluctuation of the actuator [5,8,17]. Therefore, the signal design for the fine motion mode should be investigated seriously. In this paper, a driving signal combined with three piecewise curves is designed to realize the fine motion actuation. The proposed curve is comprised of the accelerating stage, the constant velocity stage and the decelerating stage, which can extremely reduce the uncontrollable uncertainties a and b, i.e., decrease the motion fluctuation in the fine motion. In this paper, an X-Y nano-positioner driven by SPAs with a compact size is designed and fabricated. The coarse and the fine motion modes are validated on this prototype, in which the fine driving signal is first proposed and employed on the SPA based nano-positioner system. The points mentioned above can be summarized as the main contribution of this paper.

The remainder of the paper is organized as follows. The design of the X-Y nano-positioner based on the SPA and the motion modelling is described in Section 2. The driving signals i.e., the power-function-shaped driving signal and the fine driving signal are designed in Section 3. The experiment system of the X-Y nano-positioner is introduced and the results are also presented in Section 4. Finally, some concluding remarks are summarized in Section 5.

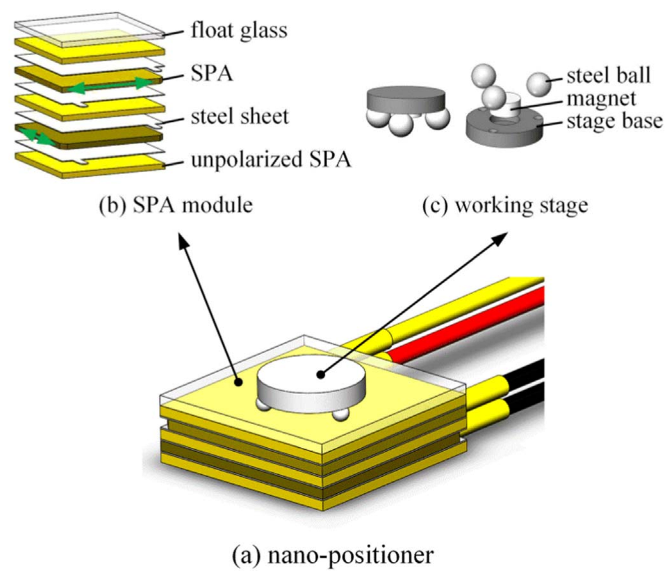

Fig. 2. An overview of the two-dimensional nano-positioner design.

2. Design and motion modelling

The proposed planar two-dimensional nano-positioner consists of a SPA module, a working-stage and a standard base, as shown in Fig. 2(a). In order to output a two-dimensional motion, the SPA module includes two SPAs which are perpendicularly arranged as shown in Fig. 2(b). In addition, each SPA is fixed with two steel sheets by copper conductive adhesives, so that the driving voltage can be applied on the SPA. Three unpolarized ceramic plates are glued to the steel sheets by epoxy resin to ensure the effective insulation. A piece of float glass with extreme flatness is pasted on the top of the module, which plays an important role, i.e., providing a perfect interface between the SPA module and the working-stage. The working-stage includes an end-stage, a permanent magnet and three steel balls, as shown in Fig. 2(c). In order to prevent the stage tipping, a flat design is proposed for the end stage so that the height of the gravity center is reduced as low as possible. The three steel balls are the balls from the same bearing, which assures that the friction ratio of the three points as close as possible when they contact the float glass.

The SPA module and the standard base are glued by the epoxy adhesive. Meanwhile, the working-stage floats on the top of the SPA module due to the gravity and the magnetic force. The mass m and the gravity force G of the total stage are 0.123g and 1.218mN respectively. Numerical analysis by Ansoft shows that the magnetic force between the magnet and four steel sheets is solved as 13.143mN with an error less than 5%. Due to the symmetry and annular structure of the stage, both of the gravity and the magnetic force are applied at the center line of the stage, which can be considered as the clamping force. Note that the value of the total clamping force has significant influence on the critical acceleration of the two motion phases, which can be calculated by the motion modelling described below and also is related with the magnet selection.

An inertia coordinate system $O\text{-}xyz$ is assigned as shown in Fig. 3, in which the motion of the SPA plate and the working-stage can be described as (x, y) and (x_m, y_m) respectively. The motion of the SPA plate is determined by the driving signal, and the working-stage moves according to the friction situation of the interface between the working-stage and the SPA. In this process, two distinct situations need to be analyzed, i.e., the sticking phase and the slipping phase. The condition of sticking phase in the moment t can be calculated firstly, which can be