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Design, testing and precision control of a novel long-stroke flexure micropositioning system

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ABSTRACT

This paper presents the design, modeling, analysis, testing and control of a novel compact long-stroke precision positioning stage. The stage is devised with leaf flexures to achieve a submicron-accuracy positioning with a stroke longer than 10 mm. Stage architectural parameters are designed to achieve the maximum natural frequency and then further improved to ensure a robust motion along the working axis. A voice coil motor and a laser displacement sensor are adopted for actuation and sensing of the fabricated stage, respectively. Both finite-element analysis and experimental tests confirm a motion range over 11 mm. To facilitate a rapid and precise positioning in front of nonlinear effects, a discrete-time sliding mode control (DSMC) algorithm based on a proportional–integral-derivative (PID) type of sliding function is devised. The DSMC guarantees the stability of the system in the presence of model uncertainties and disturbances. The effectiveness of the presented DSMC is verified through experimental studies. Results show that the DSMC is superior to PID algorithm in terms of both transient response speed and steady-state accuracy.

1. Introduction

In precision engineering applications, there is a growing demand for micro-/nanopositioning systems which are capable of delivering long-stroke (e.g., over 10 mm) precision motion yet possess a compact size at the same time. Such kind of applications range from scanning probe microscopy [1], lithography and fabrication [2], to cell micromanipulation [3], etc. For instance, in automated fish-embryo manipulation, a precise positioning stage with a long stroke is needed to execute an accurate operation [4]. A precision positioning stage with a compact size allows the application inside limited space [5]. Additionally, a compact physical size enables cost reduction in terms of material and fabrication. Hence, this research is concentrated on the design and development of a compact long-stroke micropositioning stage.

Piezoelectric stack actuators (PSAs) are extensively applied in micro-/nanopositioning stages [6]. However, PSA typically delivers a short stroke up to 0.1% of its length [7]. Although lever transmission mechanisms can be employed to amplify the output displacement [8,9], it is practically difficult to realize a positioning over 10 mm. In order to achieve a large motion range, the ball-screw drives are mostly employed [10]. Such kind of actuation produces a large motion range yet introduces the nonlinearity in terms of friction effect which may deteriorate the positioning accuracy. Hence, some friction-free drives have been employed, such as magnetic levitation motors [11], electromagnetic actuators [12], and voice coil motors [13,14]. These types of motors are lubrication free and vacuum compatible, which also fulfill the applications in ultraclean environment. Concerning the motion guiding mechanism of the stage, although the aerostatic bearings [15] and maglev bearings [16] are usually adopted, flexure bearings are more attractive in recent development of micropositioning systems, due to their merits in terms of low cost, no backlash, no friction, vacuum compatibility, and easy manufacture [17]. As compared with other mechanisms, flexures

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generate smooth motion by making use of elastic deformation of the material. Nevertheless, their motion range is constricted by the yield strength of the material, which poses a great challenge to achieve a long stroke.

In the literature, various profiles of flexure hinges (e.g., right-angle, right-circular, and elliptic) have been used to construct a flexure stage [18]. To accomplish a large motion range, the leaf flexure is employed in the current research. Intuitively, a longer stroke can be realized by using a longer and narrower leaf flexure. However, in practice, the length of the flexure hinge is constrained by the requirement of compactness and the width is restricted by the tolerance of manufacturing. Hence, it is challenging to design a flexure micropositioning stage with a long stroke and compact size simultaneously. In previous works, several designs have been proposed to tackle these issues. For instance, the compound parallelogram flexure (CPF) was employed to design an XY compliant stage [19]. More recently, the concept of multi-stage compound parallelogram flexure (MCPF) was proposed in [20] to achieve a larger pure translational motion. It has been demonstrated that, as compared with conventional CPF, the motion range of a MCPF is enlarged by N times, where N is the number of basic modules. In the current research, the MCPF concept is further developed and adapted to the design of a single-axis micropositioning stage driven by a voice coil motor (VCM). The stage is devised to deliver a robust long-stroke translational motion along the working axis while tolerating certain external loads.

Once the micropositioning stage is fabricated, the achievement of precision positioning is dependent on the control technique. Due to the low damping of the flexure-based system, a number of vibration modes exist and a high-order model is commonly identified for the system plant, which results in a high-order controller as a consequence. From the implementation point of view, a linear model of lower order (e.g., second order) is more desirable for practical realization of the control algorithm. However, the adoption of a low-order model means that the residual modes are not considered. Challenges exist in control design since the neglect of residual modes may cause control spillover and observation spillover [21]. Spillover is undesirable since it may cause instability and performance degradation of the system [22].

To account for these problems, various control techniques have been developed to maintain the robustness of the system in the presence of dynamic model uncertainties. In particular, the nonlinear sliding mode control (SMC) is popularly employed to deal with the unmodeled uncertainties and disturbances [23]. It is known that SMC is robust in the sliding phase even though uncertainties and disturbances exist. Furthermore, the discrete-time sliding mode control (DSMC) is more feasible for the implementation on sampled-data systems [24]. Most of existing DSMC techniques are developed based on the system state [25,26]. Nevertheless, in typical micropositioning systems, only the position information is supplied by the displacement sensors. In order to realize the DSMC scheme, a state observer needs to be designed to provide the state feedback. However, the realization of the state observer complicates the control design procedure. Moreover, an improperly designed observer may induce instability. Hence, from the viewpoint of implementation, it is desired to relieve the effort to construct a state observer.

To this end, a new DSMC algorithm is devised in the current research to accomplish a precision positioning with submicron accuracy. Different from existing DSMC strategies, the proposed one is developed based on a discrete-time second-order dynamic

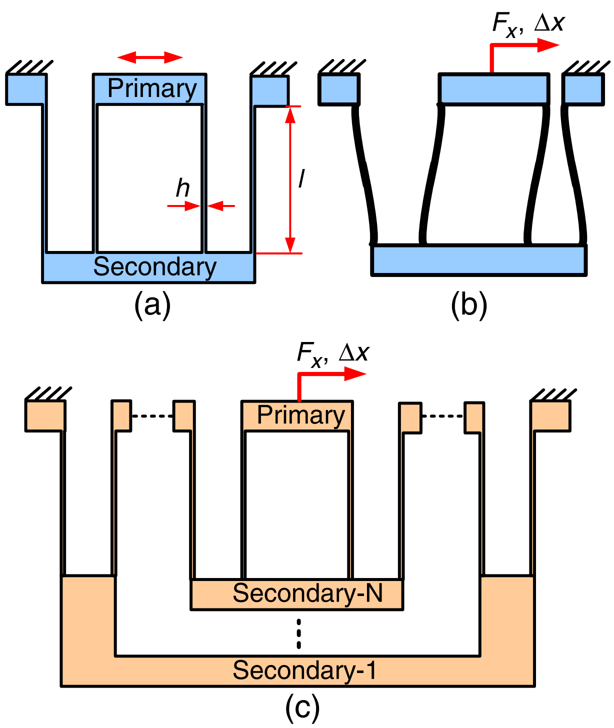

Fig. 1. (a) An ordinary CPF and (b) its deformation; (c) a MCPF with N modules.