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Precision tracking control of a biaxial piezo stage using repetitive control and double-feedforward compensation

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ABSTRACT

This article presents precision tracking control of an *XY* piezo stage using repetitive control and double-feedforward compensation. The *XY* piezo stage is composed of two piezoelectric actuators within a leaf spring mechanism. The study applies two feedback controllers, a Proportional–Integral–Derivative controller and a repetitive controller, to achieve precision trajectory tracking and evaluate performance against benchmarks. Moreover, the investigation applies a double-feedforward compensation approach that integrates a Zero-Phase-Error-Tracking-Controller and an adaptive plant inversion compensator adapted by a Least-Mean-Square algorithm, based on an inverse Prandtl–Ishlinskii model, to improve tracking control performance further. Performance analysis and comparison of the experimental results demonstrate that the proposed control structure improves dynamic tracking accuracy of the *XY* piezo stage.

1. Introduction

The expanding development of semiconductors, biomedical science, precision mechanical, and nanotechnology has led to a rising demand for productivity and precision. High costs, huge volume, and lack of precision limit traditional chemistry processes, hydraulics, or pneumatics-driven equipment. Therefore, research now focuses more on mechanical type precision engineering.

In light of this need, various precision-demanding industrial applications such as optical inspection, precision positioning, and precision engineering require more attention. Hence, several research topics such as atomic force microscope (AFM) [1], nanoindentation [2], and fast tool servo (FTS) [3] have been very popular in recent years.

Because the demand for precision engineering is increasing, the piezo stage [4] becomes an important component due to its high efficiency, high resolution, large force, fast response, lack of moving parts, and flexibility in low temperatures and vacuum environments. However, the indigenous nonlinearities such as hysteresis, creep, and vibration always influence piezoelectric actuator performance [5]. As a result, these undesired phenomena of piezoelectric actuators constrain the performance of the *XY* piezo stage. To solve this problem, many control methods have been proposed to reduce the hysteresis effect and handle trajectory tracking tasks. For example, scientists use linear feedback controllers such as the Proportional–Integral–Derivative controller (PID) [6], the iterative learning controller (ILC) [7] and the repetitive controller (RC) [8] for trajectory tracking. Moreover, nonlinear control methods such as Neural-Network (NN) [9], fuzzy [10], and sliding model controllers (SMC) [11] are also fields on which researchers are actively working.

The use of a feedback controller with a feedforward compensator is another way to improve tracking performance. For piezo tracking control, one may choose a nonlinear inverse hysteresis model as the feedforward compensator. Researchers have commonly applied inverse hysteresis model compensation for hysteresis effect reduction, mainly because of its effectiveness and flexibility. In light of this, many researchers propose various hysteresis models such as the Prandtl–Ishlinskii model [12], the Bouc–Wen model [13], the Maxwell model [14], and the Preisach model [15] to compensate for this undesired behavior.

Because the above-mentioned PID controller is simple in algorithm and high in reliability, a number of researchers apply a PID controller integrated with an inverse hysteresis model compensator [16,17]. In addition to the general PID controller, a model based repetitive controller [8,18] is also widely used in the piezo stage applications due to their ability of periodic signal tracking such as triangular scanning of AFM [1] or precision positioning [11]. Therefore, we apply a discrete time repetitive controller for piezo stage contour tracking experiments. Designed by the internal model principle [19], a repetitive controller can improve the bandwidth of the closed loop system and thus improve the performance of periodic trajectory tracking or disturbance rejection [20]. Researchers also consider a repetitive controller integrated with an inverse hysteresis compensator as an attractive method to

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