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Robust independent modal space control of a coupled nano-positioning piezo-stage

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A B S T R A C T

In order to accurately control a coupled 3-DOF nano-positioning piezo-stage, this paper designs a hybrid controller. In this controller, a hysteresis observer based on a Bouc-Wen model is established to compensate the hysteresis nonlinearity of the piezoelectric actuator first. Compared to hysteresis compensations using Preisach model and Prandt–Ishlinskii model, the compensation method using the hysteresis observer is computationally lighter. Then, based on the proposed dynamics model, by constructing the modal filter, a robust H_∞ independent modal space controller is designed and utilized to decouple the piezo-stage and deal with the unmodeled dynamics, disturbance, and hysteresis compensation error. The effectiveness of the proposed controller is demonstrated experimentally. The experimental results show that the proposed controller can significantly achieve the high-precision positioning.

1. Introduction

Piezoelectric actuators (PEAs) are capable of providing precision motions and have attractive properties such as high stiffness, fast response, extremely low speeds, and high accuracy [1–3]. These make them very attractive for use in nano-positioning system. In recent years, many researchers focus on developing multi-DOF nano-positioning piezo-stages [4]. This paper concerns an control system design for high-precision positioning of a 3-DOF piezo-stage.

A disadvantage of the PEA is their hysteresis nonlinear behavior, which limits the piezo-stage performance such as giving rise to undesirable inaccuracy or oscillations, even leading to instability. The hysteresis can be compensated for by pre-shaping the input with the inverse hysteresis model. Various models such as Preisach model [5], Prandt–Ishlinskii model [6], neural network model [7], Maxwell model [8,9], Bouc–Wen model [10,11], have been widely used to model and compensate for the hysteresis.

Note that the complicated dynamics in piezo- stages, including the hysteresis compensation error, unmodeled dynamics and other perturbations, can be merged into the disturbances. Thus, Feedback techniques have been widely used to improve the accuracy and speed of piezo-stages, such as PID control [12,13], robust control [14,15], adaptive control [16] and sliding mode control [17,18].

In this paper, we extend our study in [19] and propose a novel control scheme that integrates hysteresis compensation into a H_∞ robust independent modal space control. The rest of this paper is organized as follows. Section 2 begins with a brief description of the piezo-stage and the structures of the dynamic model and controller are discussed. The hysteresis model

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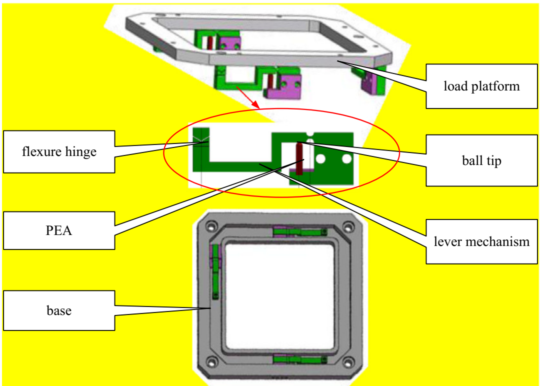
and compensation are proposed in Section 3. The mechanical model and H_∞ robust independent modal space control are given by Section 4. Section 5 shows the real time control experiments on the 3-DOF piezo-stage. Conclusion remarking is finally collected in Section 6.

2. Dynamic model

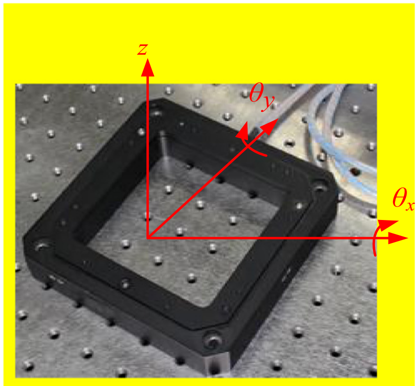
The schematic diagram of the 3-DOF piezo-stage (output range: z-axis, 0–50 μm; θ_x, 0–1 mrad; θ_y, 0–1 mrad) is shown in Fig. 1. The identical kinematic chains and PEAs in all axes guarantee the uniform characteristics within the workspace. In the proposed mechanism, the load platform is connected to three linkages through three lever mechanisms. Three PEAs with ball tips, whose displacements are amplified with the three lever mechanisms, are used to drive the platform.

Consider that a hysteresis force will be generated by the three PEAs under the input voltage, and will result in the forced vibration of the PEAs, flexible hinges, lever mechanisms, and load platform. Then, the comprehensive model of the piezo-stage is shown in Fig. 2. The sign conventions introduced in [19,20] and the number of each element is shown in Fig. 2.

In order to accurately and effectively control the outputs of the piezo-stage, a hybrid controller is designed and used. As shown in Fig. 3, in order to improve the positioning accuracy and reduce the complexity of the positioning control algorithm, the hysteresis of the PEAs is firstly feedforward compensated to realize the linear input-output relationship of the piezo-stage. Then, a H_∞ robust independent modal space controller is utilized to deal with the hysteresis compensation error, unmodeled dynamics, and disturbance.



(a) Schematic cross-sectional view



(b) photograph

Fig. 1. 3-DOF (z-θ_x-θ_y) piezo-stage.

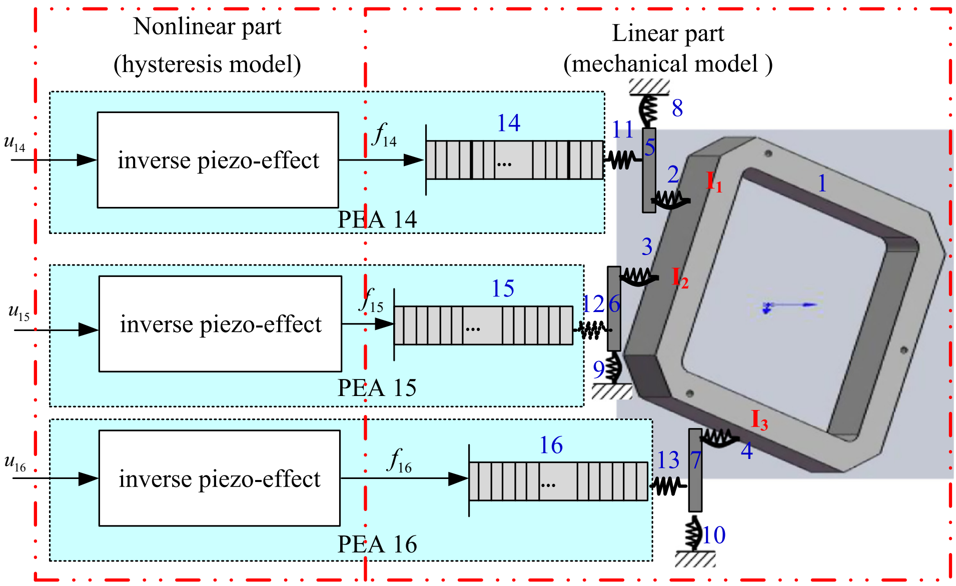


Fig. 2. Schematic comprehensive model of the piezo-stage.