

# Experimental System Identification, Feed-Forward Control, and Hysteresis Compensation of a 2-DOF Mechanism

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## ABSTRACT

*Most of the micro/nano manipulation mechanisms and systems are commonly based on flexure-based monolithic structures, and are generally driven by piezoelectric actuators. In the presented work, experimental system identification, 1-DOF trajectory tracking with feed-forward control, and hysteresis compensation are investigated. An experimental research facility with laser interferometry-based sensing and measurement technique is established. System identification experiments were performed on a 2-DOF flexure-based mechanism to investigate its dynamics. The system identification procedure, experimental design, data acquisition, analysis and validation of the identified system are presented in details. A linear sine swept signal is applied to the system as an input and the corresponding response of the system is measured with laser interferometry-based sensing and measurement technique. The experimental results are used to evaluate the transfer function and the first natural frequency of the system in the X and Y axes. Experimental validation data is used to verify the accuracy of the identified model. Further, a feed-forward controller is established to track a 1-DOF smooth multiple-frequency trajectory. For hysteresis compensation, inverse PI (Prandtl-Ishlinskii) model is derived from classical PI model. The parameters of the inverse PI model is estimated and validated with the experimental data. Finally, inverse PI model is directly adopted as a feed-forward controller for hysteresis compensation of piezoelectric actuators.*

**Keywords:** *Hysteresis Compensation, Laser Interferometry-Based Sensing and Measurement, Micro/Nano Mechanisms, Motion Control, System Identification*

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## INTRODUCTION

Ultra-precision positioning and manipulation is required in many scientific applications in the area of engineering and medical sciences. In the applications such as atomic force microscopy, scanning electron microscopy, confocal microscopy, biological cell manipulation, micro/nano surgery, X-ray lithography, ultra-precise machining and micro component assembly, micro/nano manipulation plays an important role (Kwon et al., 2003; Mohd Zubir et al., 2009; Tian et al., 2011; Wang et al., 2009; Zubir et al., 2009). In these areas of engineering and scientific endeavors, the requirements for motion resolution, positioning accuracy and repeatability are within the nanoscale range. Piezoelectric actuator driven flexure-based mechanisms are the most appropriate platforms for the micro/nano positioning and manipulation (Jia et al., 2011; Qin et al., 2013; Tian et al., 2010, 2010; Tian et al., 2010; F. Wang et al., 2010; Yangmin et al., 2011). The flexure-based micro/nano mechanisms are generally monolithic structures comprising solid links and flexure hinges. These mechanisms offer several advantages such as unlimited motion resolution, negligible friction, zero backlash and low maintenance. On the other hand, piezoelectric actuators utilized as driving source possess non-linearities such as hysteresis and creep/drift (Cahyadi et al., 2006; Hall, 2001; Liaw et al., 2010; Tao et al., 2010). The presence of the non-linearities associated with piezo-actuation cannot guarantee positioning accuracy and precise motion tracking of the flexure-based mechanisms.

In the area of control, the objective of experimental system identification is to find dynamical model of the system from the input and the response data. Experimental system identification is primarily motivated by the desire to establish a more accurate description of the structure and its dynamical characteristics, and also for the purpose of developing appropriate control methodology for the desired tasks (Qin, et al., 2013; Yong et al., 2009). Generally, research towards precise and accurate motion tracking of a flexure-based mechanism falls

into: feed-forward control, feedback control and compound control. In the feed-forward control, system identification, hysteresis modeling and inversion calculation are important factors in defining and establishing effective and accurate control. In the feedback control, with the actual measurement of the displacement, the control can be implemented without any hysteresis model and system information. A better performance can be achieved with a combination of feed-forward and feedback control methods. Many appropriate closed-loop control strategies have been proposed to achieve the desired motion tracking of flexure based mechanisms driven by piezoelectric actuators (Bhagat et al., 2011; Liaw et al., 2008, 2009; Liaw et al., 2008; Xu et al., 2009).

An experimental research facility with a 2-DOF flexure-based mechanism and laser interferometry-based sensing and measurement setup is established and presented in next section. The experimental system identification methodology for a 2-DOF flexure-based mechanism is presented subsequently. Experimental results are used to identify the system parameters and further utilized for the validation of the identified system. Feed-forward control with identified system is established to track 1-DOF multiple frequency smooth motion trajectory. Further, PI inverse hysteresis model is obtained using the experimental results, and a direct inverse hysteresis-based feed-forward control is established for hysteresis compensation.

## EXPERIMENTAL FACILITY

Laser interferometry-based experimental research facility comprising a flexure-based 2-DOF mechanism is established. The 2-DOF flexure-based mechanism for micro/nano positioning and manipulation uses identical kinematic chains in the X and Y axes to guarantee uniform performance across the workspace. Optimal design and development of this decoupled 2-DOF flexure-based mechanism is presented in previous research (Qin et al.). Figure 1 shows the system architecture of the

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