



Modeling and identification investigation of multi-field hysteretic dynamics in flexure-guided piezo platform

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ABSTRACT

The completely modeling and comprehensive identification approaches of the multi-field hysteretic dynamics in the flexure-guided piezo stage are proposed in this paper. First, the system description and the experimental setup are proposed. Next, the hysteretic dynamics is completely modeled in which the static Preisach hysteresis, creep, electrical and vibration dynamics are derived from the material, electrical and mechanical fields, respectively. Then, according to the model characteristics, a comprehensive identification approach is presented. A novel technique is provided to identify the electrical and vibration dynamics. Special inputs and sampling are proposed to identify the Preisach hysteresis. Finally, the experimental study is provided to demonstrate the effectiveness of the proposed modeling and identification approaches. The modeling and identification approaches in this paper will be beneficial to further developments and high-performance control of the flexure-guided piezo systems.

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1. Introduction

Piezo-based platforms are more and more appealing in precision engineering [1–6], but the control performance is limited by the hysteretic dynamics which belongs to multi-fields and multi-timescales. For flexure-guided piezo stages, the hysteretic dynamics is more complex. To enhance control performance of the one-degree-of-freedom flexure-guided piezo stage which can be in nano-positioning and intracytoplasmic sperm injection [3,7], the accurate modeling and identification will be investigated in this paper. Flexible joints and motion amplifying arms are often designed in piezo-based platforms. The flexible joints are used to avoid the friction and clearance nonlinearity. In this paper, to achieve larger displacement using lower driving voltage, low-stiff flexible joints are employed instead of high-stiff flexible joints. The proposed flexure-guided platform thus has lower resonant frequencies which increase the difficulty in the modeling and identification of the hysteretic dynamics. Additionally, to achieve larger displacement, a high-stiff arm is used to amplify the piezo displacement. To measure the displacement in the order of nanometers, this paper employs a capacitive displacement sensor because of its properties, including non-contact, high accuracy, high bandwidth and small size.

Compared with high-stiff piezo platforms, the hysteretic dynamics in the flexure-guided piezo platforms are much more complex due to the low-stiff flexible joints. The hysteretic dynamics results from the multi-field which consists of material

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field (i.e. hysteresis effect and creep effect [8]), electrical field, and mechanical field (i.e. mechanical vibration dynamics). First, the static hysteresis effect is a rate-independent nonlinearity which has global memories [9]. Classical Preisach model can be used to represent the static hysteresis [10]. Secondly, the creep, electrical and mechanical vibrations dynamics have different timescales [11].

The tracking accuracy can be degraded significantly due to the hysteretic dynamics [12,13]. Even at low frequencies, the tracking error of piezo platform can be as large as 15% of the travel span [14]. Various methods are investigated to model the hysteretic dynamics in piezoelectric actuators or platforms. For high-stiff piezoelectric actuators or platforms, the electrical and vibration dynamics are generally on the order of kHz, the creep dynamics and the hysteresis effect are much slower than the electrical and vibration dynamics. Thus, the hysteresis, creep and vibration dynamics can be treated separately. For instance, Song employed the static Preisach hysteresis to represent the piezo system without modeling the electrical and vibration dynamics [15]. We used a curve fitting technique to represent and reduce the creep effect while identifying the static hysteresis effect [14,16]. To apply modern robust control, Xu, Wu and Nikkhoo employed vibration dynamics to represent piezoelectric systems [17–19].

Additionally, the hysteretic dynamics can be investigated from the mathematical perspective. For instance, Mayergoyz presented a rate-dependent Preisach model with dynamic density functions [20], Ge presented a generalized Preisach model without the limitation of congruency property [21]. Janaideh modeled the dynamic hysteresis of piezo actuators using a rate-dependent Prandtl–Ishlinskii (P–I) model and identified the generalized P–I hysteresis by assuming the density function [22]. Jiang modified the P–I model to represent the asymmetric hysteresis of piezoelectric actuators [23], but it is difficult to use the pure mathematical models for further development of piezo platforms, because physical variables cannot be found in the pure mathematical models. Alternatively, hysteretic dynamics with some physical meanings is increasingly needed for the flexure-guided piezo platform. The full modeling of the hysteretic dynamics in flexure-guided platform is still not solved well. Hence, in this paper, the complete modeling of the hysteretic dynamics in flexure-guided platforms will be investigated.

To fully model the hysteretic dynamics, the multi-field domain is investigated for the piezo platform. The multi-field domains consist of the material, electrical and mechanical fields. Conveniently, the hysteretic dynamics in the flexure-guided platform can be achieved by combining the components which represent different dynamics and field effects. The dynamic interactions can be found in the proposed multi-field model. Tan presented a cascade connection using the Preisach hysteresis and non-hysteretic dynamics [24]. Conversely, Bree proposed a feedback combination of Duhem hysteresis and non-hysteretic dynamics to represent hysteretic dynamics [25], but it is difficult to identify parameters in the feedback combination. In this paper, the cascade connection is employed to combine the components of the effects and dynamics in the piezo platform. The hysteresis effect is represented by the classical Preisach model. The non-hysteretic creep, electrical and vibration dynamics are represented by transfer functions, such that it is easy for various researchers to employ the proposed hysteretic dynamics for further developments.

Following the modeling of the hysteretic dynamics, parameter identification will also be provided in this paper. Multi-timescales and couplings are significant limitations, especially for the flexure-guided piezo platform. The multi-field hysteretic dynamics exhibits multi-timescales which increase the difficulty in model identification. The creep dynamics is a slow timescale effect which is generally in the order of minutes. The hysteresis effect is a rate-independent nonlinearity which is independent of time [10]. For high-stiff piezo platforms, the timescale of vibration dynamics is in the order of milliseconds, but for the low-stiff piezo platform in this paper, the timescale of vibration dynamics is in the order of 100 ms. The decrease in the vibration frequencies increases the couplings among the components of the hysteretic dynamics. For low-stiff piezo platforms, the couplings are not fully treated while identifying the hysteretic dynamics. Rakotondrabe identified the hysteresis, creep and vibration dynamics without considering the couplings [26], Juhsz separately identified the Maxwell resistive capacitor hysteresis and vibration dynamics without considering the couplings and creep effect [28]. In this paper, the multi-timescales and couplings among the hysteresis creep, electrical and vibration dynamics will be considered while applying the identification.

In this paper, the flexible joints are much more soft which means the vibration dynamics will have lower frequencies. As a result, the couplings among the components of the hysteretic dynamics are much more significant. The further identification investigation of hysteretic dynamics in the flexure-guided piezo platform is also proposed in this paper. The comprehensive identification approach is designed according to the characteristics of the flexure-guided platform. A novel technique is developed to identify the electrical and vibration dynamics. Additionally, special input signals are designed to identify the static Preisach hysteresis.

This paper is organized as follows: First, system description and the experimental setup are presented in Section 2. Next, the complete modeling of the hysteretic dynamics in the flexure-guided piezo platform is proposed in Section 3. Multi-field effects and dynamics are contained in the hysteretic model. Then, the identification strategy is developed in Section 4. To further validate the proposed modeling and identification approach in this paper, the experimental study is proposed in Section 5. Additionally, the experimental results are discussed in Section 6. Finally, the conclusion of this paper is made in Section 7.

2. System description

The piezo-based platform, as shown in Fig. 1, comprises the PZT (i.e. $[\text{PbZr}_\lambda\text{Ti}_{1-\lambda}]\text{O}_3$, $0 \leq \lambda \leq 1$) stack, motion amplifying arm, working platform and capacitive sensor. The working platform moves along the flexure guide which consists of four

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