Mechatronics 24 (2014) 724–733

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

High-bandwidth tracking control of piezo-actuated nanopositioning stages using closed-loop input shaper

Mei-Ju Yang, Guo-Ying Gu, Li-Min Zhu *

State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

A R T I C L E I N F O

Article history:
Received 29 June 2013
Revised 23 February 2014
Accepted 28 February 2014
Available online 27 March 2014

Keywords:
Nanopositioning stages
Piezoelectric actuators
Tracking control
Closed-loop input shaper
Hysteresis compensation

A B S T R A C T

An integrated control strategy for piezo-actuated nanopositioning stages is proposed in this paper. The aim is to achieve high-speed and high-precision tracking control of nanopositioning stages. For this purpose, a direct inverse compensation method is firstly applied to eliminate the hysteresis nonlinearity without involving inverse model calculation. Then, an inside-the-loop input shaper is designed to suppress the vibration of the compensated system. A Smith predictor is introduced to prevent the potential closed-loop instability caused by the time delay of the inside-the-loop input shaper. Finally, a high-gain feedback controller is employed to handle the disturbances and modeling errors. To demonstrate the effectiveness of the proposed control method, comparative experiments are carried out on a piezoelectric actuated stage. The results show that the proposed control approach increases the tracking bandwidth of the stage from 22.6 Hz to 510 Hz.

1. Introduction

Nanopositioning stages are widely used in high-precision positioning and tracking applications, e.g., scanning probe microscopy [1], ultra-precision machine tools [2], and micromanipulator [3]. Most of these stages utilize piezoelectric actuators for actuation due to the excellent advantages of fast response time, high positioning precision, large output force, high stiffness, and small size. However, there are two factors limiting the speed and accuracy of the nanopositioning stage. One is the lightly damped resonances due to the mechanical dynamics, and the other is the inherent hysteresis nonlinearity of the piezoelectric material.

In order to achieve high bandwidth control of nanopositioning stages, many efforts have been made by the researchers to deal with the problem of the lightly damped resonances. One way to increase the operating speed is to build a piezo-actuated stage that is sufficiently stiff and lightweight [3]. A disadvantage of this approach is that its maximum traversal range is limited to a few microns. Furthermore, the operating frequency is still limited by the resonance frequency. Therefore, development of control techniques to suppress the vibrations becomes popular. Many damping control strategies are developed in the literature, such as the notch filter [4], input shaping [5–7], integral resonant control [8], and positive position feedback [9]. The input shaping control has been demonstrated as a simple and effective means to suppress the unwanted vibrations, and widely used in many applications, such as piezoelectric actuator [10,11], flexible manipulator [6,12–15], flexible spacecraft [16–18], and cranes [19,20]. The traditional input shaper is usually put in the forward path of the closed-loop system, which can be considered as a smart filter of the reference signal. However, this standard feedforward configuration does not have any impact on the control system response to immeasurable disturbances, noises, and uncertainty. In order to reduce this sensitivity effect, different kinds of closed-loop input shaping controllers were developed in the literature [21–26]. Kapila et al. designed a standard input shaper in conjunction with a full-state feedback controller to perform well despite of modeling errors in the timing of the impulses. [21]. Huey et al. developed a closed-loop input shaper [22,23]. They discussed the closed-loop stability utilizing input shapers inside the loop. They also investigated some useful applications of closed-loop input shaper. Using a structure already known from Internal Model Control, Staehlin and Singh transformed the outside-the-loop input shaper to the closed-loop input shaping controller [24]. Hung proposed a feedback input shaping configuration, which puts the input shaper within feedback loops [25]. This configuration takes advantage of the superior damping qualities of the input shaper, while reducing parametric sensitivity and uncertainty through the feedback controller. However, the main drawback of this approach is the existence of the time delays in feedback loops. It not only presents

* Corresponding author. Tel.: +86 21 34206545; fax: +86 21 34206086.
E-mail addresses: yangmeixianglian@sjtu.edu.cn (M.-J. Yang), guguoying@sjtu.edu.cn (G.-Y. Gu), zhulm@sjtu.edu.cn (L.-M. Zhu).

http://dx.doi.org/10.1016/j.mechatronics.2014.02.014
0957-4158/

a potential closed-loop instability, but also increases the implementation complexity of the linear control methods because of the irrational transfer function of the input shaper. Recently, a closed-loop input shaper based on the Smith predictor has been demonstrated as an effective means to prevent the instability issue due to the time delays in feedback loops. This technique has been successfully applied to damp the resonance mode of flexible beams [26].

It is worthy mentioning that the previous damping controllers are based on a linear description of the system, but the damping capabilities of the system can be greatly improved by considering the nonlinear phenomena present in the system. There are three main strategies for compensating hysteresis in piezoelectric actuators: charge control, feedback control, and feedforward control. The charge control [27] is based on the fact that the relationship between the displacement of piezo actuators and applied charge is nearly linear. However, this technique always increases the cost due to the requirement of charge amplifiers. The feedback control [28] is to reduce the hysteresis effect directly by feedback controller, where the hysteresis is considered as disturbance. However, in this category, a sophisticated control algorithm is generally required, such as H_∞ control, sliding model control, and robust adaptive control. Furthermore, due to nonsmooth and nonlinear behaviors of the hysteresis, the main difficulty for such feedback control techniques lies in the stability analysis of the whole closed-loop system. The feedforward control is the most widely used approach to reduce the hysteresis effect when actuated by voltage input. It generally consists of modeling the real hysteresis nonlinearity, identifying the model parameters to match the real hysteresis and constructing an inverse model as a desired compensator. A number of hysteresis models are available in the literature to describe the hysteresis nonlinearity, such as the Bouc-Wen model [29], Prandtl-Ishlinskii model [30,31], and Preisach model [32]. The challenges of this technique are the modeling complexity and lack of robustness to model uncertainty.

In this paper, an integrated strategy is proposed to achieve high bandwidth tracking control of the piezo-actuated nanopositioning stage. The control scheme is composed of three components: (1) a hysteresis compensator which effectively cancels the nonlinear hysteresis of the piezoelectric actuators; (2) a closed-loop input shaper including an inside-the-loop input shaper and a Smith predictor for vibration damping control of the stage; and (3) a feedback controller to handle the disturbances and modeling errors. Note that the closed-loop input shaper is not actually closed itself; it just means that it is included in the feedback loop, distinguishing itself from the commonly used open-loop input shaper. The proposed integrated controller is implemented and demonstrated to perform well in reference tracking and disturbance rejection on a piezo-actuated nanopositioning stage. To the best knowledge of the authors, this work is the first attempt at introducing the closed-loop input shaper to the domain of high speed and high precision control of the piezo-actuated nanopositioning stages. The contributions of this work are threefold:

1. Different from the common hysteresis compensation approaches, a direct inverse hysteresis model is constructed from the experimental data. Both the hysteresis modeling and its complex inversion calculation are avoided, and therefore the computation complexity is reduced significantly.
2. The input shaper used in this work is placed inside the feedback loop for vibration damping control. Compared with the traditional outside-the-loop input shaper, the inside-the-loop input shaper can not only eliminate the vibration induced by the reference, but also has the potential of disturbance rejection. By placing the input shaper in the closed loop, it is capable of reducing oscillations caused by both the input and the output disturbances without overly slowing the closed-loop system by increasing the closed-loop damping ratio. Furthermore, the inside-the-loop input shaper allows the use of higher gains in the feedback control laws.
3. The Smith predictor is introduced to prevent the potential closed-loop instability due to the existence of time delays in the feedback loop.

The rest of the paper is organized as follows. Section 2 describes the principle of the control strategy. The implementation of the controller on a piezo-actuated nanopositioning stage is presented in Section 3. Section 4 summarizes and discusses the experimental results, and Section 5 concludes the paper.

2. Control schemes

In this section, the integrated strategy for vibration damping and tracking control of piezo-actuated nanopositionig stages are proposed. In the following, the development of the individual components will be expressed in detail.

2.1. Hysteresis compensator

The hysteresis of the piezoelectric actuator is an inherent multi-valued nonlinearity with the asymmetric characteristic. In order to linearize the system, the hysteresis compensation is necessary. A common strategy on hysteresis compensation consists of modeling the real hysteresis nonlinearity, identifying the model parameters to match the real hysteresis and constructing an inverse model as a desired compensator. Different from the commonly used strategies, a direct inverse hysteresis compensation method proposed in our previous work [33] is utilized in this work, which compensates for the hysteresis nonlinearity by constructing an inverse hysteresis model directly from the experimental data. By this way, both the hysteresis modeling and its complex inversion calculation are avoided.

The block diagram of the hysteresis compensation is illustrated in Fig. 1. For a given desired trajectory, denoted as $y_d(t)$, the inverse hysteresis model will generate an input signal $v(t)$ which is applied to the piezoelectric actuator; the output of the piezoelectric actuator is denoted as $y(t)$. The model of the piezoelectric actuator is considered as a cascade of a rate-independent hysteresis submodel H and a linear dynamic submodel G [34]. When the input signal $v(t)$ is composed of low-frequency components, the system dynamic G is negligible. Hence, the output of the hysteresis model $w(t)$ is approximately equal to $y(t)$. If the inverse hysteresis model is ideal, the output $y(t)$ should follow the desired trajectory $y_d(t)$, that is $y(t) = y_d(t)$. Therefore, the input–output relationship of the inverse hysteresis model can be directly obtained by plotting $v(t)$ against $y(t)$, whereas the hysteresis model is obtained by plotting $y(t)$ against $v(t)$ as shown in Fig. 2. It can be observed that the inverse hysteresis loops and the hysteresis loops are symmetrical about the 45° line. Thus, the inverse hysteresis model can be directly derived from the experimental data just like the hysteresis

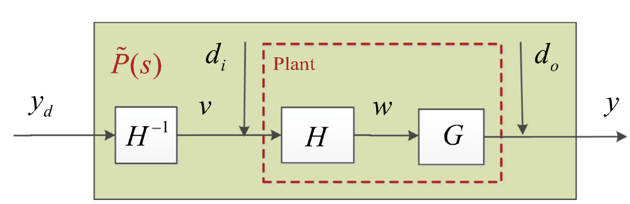

Fig. 1. The block diagram of hysteresis compensation.