Control Engineering Practice 72 (2018) 29–41

Contents lists available at ScienceDirect

Control Engineering Practice

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

Internal model-based feedback control design for inversion-free feedforward rate-dependent hysteresis compensation of piezoelectric cantilever actuator

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ARTICLE INFO

Keywords:
Piezoelectric actuators
Rate-dependent hysteresis
Prandtl–Ishlinskii modeling
Inversion-free compensation method
Feedforward–feedback scheme
Internal model control

ABSTRACT

This study proposes a new rate-dependent feedforward compensator for compensation of hysteresis nonlinearities in smart materials-based actuators without considering the analytical inverse model. The proposed rate-dependent compensator is constructed with the inverse multiplicative structure of the rate-dependent Prandtl–Ishlinskii (RDPI) model. The study also presents an investigation for the compensation error when the proposed compensator is applied in an open-loop feedforward manner. Then, an internal model-based feedback control design is applied with the proposed feedforward compensator to a piezoelectric cantilever actuator. The experimental results illustrate that the proposed feedforward–feedback control scheme can be used in micro-positioning motion control applications to enhance the tracking performance of the piezoelectric cantilever actuator under different operating conditions.

1. Introduction

Smart materials-based actuators such as Shape Memory Alloys (SMAs), piezoelectric and magnetostrictive actuators are attractive for applications that require positioning/manipulating objects at micro and nano-scale levels (Pons, 2005; Rakotondrabe, 2013; Smith, 2005). However, these actuators exhibit rate-dependent hysteresis nonlinearities that increase as the frequency of the applied input increases. Such nonlinearities are known to cause oscillations and instabilities in open and closed-loop systems (Devasia, Eleftheriou, & Moheimani, 2007; Esbrook, Tan, & Khalil, 2013). Different feedback control methods have been used to reduce the hysteresis nonlinearities of smart materials-based actuators. However, synthesizing feedback controllers at high excitations of input frequency is a challenging task due to the presence of rate-dependent hysteresis nonlinearities. Furthermore, applying high levels of input amplitude to these actuators contributes asymmetric hysteresis nonlinearities which necessitate adequate consideration for the effects of input amplitude (Aljanaideh, Rakheja, & Su, 2014; Visone, 2008).

Implementing a rate-dependent compensator to reduce the effects of the rate-dependent hysteresis nonlinearities of a smart material-based actuator strongly facilitates the design of a linear or nonlinear feedback controllers. A few studies have suggested nonlinear control design such as adaptive control (Al Janaideh & Bernstein, 2013), energy-based control (Oates, Evans, Smith, & Dapino, 2009), hybrid control (Al Janaideh, Naldi, Marconi, & Krejci, 2012), optimal control (Oates, Zrostlik, Eichhorn, & Smith, 2010), robust control (Al Janaideh, Rakotondrabe, & Aljanaideh, 2016; El-Shaer, Al Janaideh, Krejci, & Tomizuka, 2013), and sliding-mode control (Edarar, Tan, & Khalil, 2012) to cancel-out hysteresis nonlinearities of smart materials-based actuators. Compared to other methodologies, a cascade arrangement of a rate-dependent hysteresis model and its rate-dependent inverse is known as an effective methodology for compensation of hysteresis nonlinearities in real-time system (Devasia et al., 2007; Leang & Devasia, 2007). However, deriving an analytical inverse model that is adaptive with the frequency involves difficulties that are associated with mathematical properties of the hysteresis model itself.

The Preisach and Prandtl–Ishlinskii models are among the most popular hysteresis models that have been used with their inverse models for modeling and compensation of hysteresis nonlinearities of smart material-based actuators (Das, Pota, & Petersen, 2007; Leang & Devasia,

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https://doi.org/10.1016/j.conengprac.2017.11.001
Received 22 November 2016; Received in revised form 30 October 2017; Accepted 4 November 2017

2007; Rakotondrabe, 2012a, 2013, 2017; Schitter, Stemmer, & Allgower, 2003; Tan & Baras, 2004; Visone, 2008; Yingfeng & Leang, 2013). Because of the exact inversion of the model, the Prandtl–Ishlinskii model is considered attractive for compensation of hysteresis nonlinearities in real-time applications (Rakotondrabe, 2012a, 2017). However, the Prandtl–Ishlinskii model is rate-independent hysteresis model. This problem has been addressed in Al Janaideh and Krejčí (2013) where the model and its inverse were extended to new versions that account for the rate of the applied input. The RDPI model and its inverse were applied for characterization and compensation of rate-dependent hysteresis nonlinearities of magnetostrictive (Aljanaideh, Al Janaideh, Su, & Rakheja, 2013) and piezoelectric (Al Janaideh & Krejčí, 2013) actuators. However, the inverse RDPI model is available only when the rate-dependent threshold function satisfies the dilation condition (Al Janaideh & Krejčí, 2013).

The mathematical conditions that are necessary to formulate an invertible RDPI model can be relaxed with the inverse multiplicative structure of the hysteresis model. Thus, the hysteresis compensator can be obtained by restructuring the hysteresis model that characterizes the hysteresis nonlinearities. This technique has been successfully applied to compensate for the hysteresis nonlinearities of the Bouc–Wen model (Rakotondrabe, 2011), the generalized Bouc–Wen model (Habineza, Rakotondrabe, & Le Gorrec, 2014), multivariable Bouc–Wen (Habineza, Rakotondrabe, & Le Gorrec, 2015), the Preisach model (Li, Su, & Chai, 2014; Oubellil, Ryba, Voda, & Rakotondrabe, 2015), the Prandtl–Ishlinskii model (Rakotondrabe, 2012a), the multivariable Prandtl–Ishlinskii model (Rakotondrabe, 2017) and recently the RDPI model (Aljanaideh, Al Janaideh, & Rakotondrabe, 2015).

Although employing the inverse multiplicative structure is effective for compensation of hysteresis nonlinearities in open-loop feedforward manner, synthesizing feedback control techniques is essential to maintain or to improve the tracking performance in presence of internal and external disturbances such as: modeling uncertainties and environmental influence. However, feedback control designs necessitate adequate consideration for the compensation error of the feedforward compensator and the boundedness of compensation error. Thus, exploring the compensation error facilitates applying feedback control architectures such as proportional–integral–derivative controller, internal model-based feedback, hybrid control, or robust control, as examples, with the inverse multiplicative structure. This study presents a feedforward and feedback control scheme to improve the performances of smart materials based actuators over a wide range of input frequency. The feedforward controller (compensator) is based on the combination of the inverse multiplicative structure and the RDPI model and a thorough analysis of the tracking error is developed. The feedback controller is based on the internal model control scheme which permits to consider remaining compensation errors, model uncertainties and eventual external disturbance. Finally, the whole is applied to a piezoelectric cantilever actuator that is characterized by a rate-dependent hysteresis, a creep phenomenon and badly damped oscillations. The main contributions of the study can be summarized as follows:

- A rate-dependent feedforward hysteresis compensator for compensation of hysteresis nonlinearities of smart materials-based actuators without formulating inverse rate-dependent models is derived. The compensator is based on the rearrangement of a rate-dependent Prandtl–Ishlinskii (RDPI) model. Additionally to the Lipschitz continuity analysis of the model, we also investigate the bound of the tracking error from the compensation as well as the condition on the sampling period to make this bound valuable.
- From a linear model with error derived from the previous analysis, we augment the feedforward control system by a feedback controller. The aim of this feedback is to cancel the remaining error and to reject eventual disturbance that a feedforward would not allow. For that we suggest the internal model control (IMC) which permits to consider model uncertainties in the new linear model, additionally to the error and to the external disturbance.
- Finally, the proposed RDPI-feedforward and IMC-feedback control scheme have been applied to a piezoelectric actuator classically used in micromanipulation applications. The efficiency of the feedforward–feedback scheme is particularly compared with the result from a feedback-only scheme.and is shown to demonstrate higher bandwidth.

The paper is organized as follows. Section 2 includes a description for the proposed compensation scheme and the formulation of RDPI model. In this section, the discrete RDPI model is also presented with the Lipschitz continuity property. Section 3 introduces the development of rate-dependent feedforward compensator on the basis of the inverse multiplicative scheme. This section also presents the boundedness of the error between the reference input and the output of the RDPI model when the proposed compensator is applied. Section 6 is devoted to the application to a piezoelectric cantilever actuator. Its characterization, RDPI modeling and RDPI compensation are detailed in the same section. Section 5 presents synthesizing and applying of an internal model-based feedback control design to enhance the tracking performance of the compensated piezoelectric cantilever actuator. The conclusions of the paper are summarized in Section 6.

2. Background

Among the available smart material-based actuators, SMAs, magnetostrictive and piezoelectric types are considered the most popular for micro- and nano-positioning tasks. Due to their fine resolution and fast response, piezoelectric actuators for example, are employed in atomic force microscopy and also for manipulating small objects at micro- and nano-scale (Rakotondrabe, 2013). SMAs are another example of smart material-based actuators that are attractive for applications where flexibility and generation of large deformations are required. These actuators are integrated in the modern aircraft wings and the buildings structures to resist earthquakes vibrations (Hu, Smith, & Ernstberger, 2012; Smith, 2005; Smith & Hu, 2012). These actuators show rate-dependent hysteresis nonlinearities between applied harmonic input and output displacement (Al Janaideh & Krejci, 2013). Such nonlinearities are considered relatively rate-independent at shallow levels of input frequency. However, applying harmonic input at high excitations of input frequency contributes a significant increase in the hysteresis nonlinearities. These nonlinearities cause high positioning errors and instabilities in the closed-loop control systems. Enhancing the tracking performance of smart material-based actuators necessitates selecting an appropriate model that can account for the hysteresis nonlinearities that these actuators exhibit. The Prandtl–Ishlinskii model is a flexible hysteresis model that can describe rate-independent as well as rate-dependent hysteresis properties of smart material-based actuators. The mathematical formulation of this model is presented in this section along with investigation for the Lipschitz continuity property of the model.

2.1. The RDPI model

A rate-dependent version of the Prandtl–Ishlinskii model has been proposed in Aljanaideh et al. (2013) and Al Janaideh and Krejčí (2013) for characterizing the rate-dependent hysteresis nonlinearities of magnetostrictive and piezoelectric actuators. The model is represented as a summation of weighted rate-dependent play operators. Each of these operators integrates a rate-dependent threshold that is formulated as a function of the input rate. We deal with real absolutely continuous functions that are defined on the interval $(0, T)$, such that the space of these functions can be denoted by $AC(0, T)$. Let us consider also the input $z(t) \in AC(0, T)$. For $i = 0, 1, 2, \ldots, n$, where $n \in \mathbb{N}$ is an integer, the $r_i(\dot{z}(t)) \in AC(0, T)$ are considered as thresholds such that

$$0 = r_0(\dot{z}(t)) \leq r_1(\dot{z}(t)) \leq r_2(\dot{z}(t)) \leq \cdots \leq r_n(\dot{z}(t)). \quad (1)$$