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Experimental comparison of rate-dependent hysteresis models in characterizing and compensating hysteresis of piezoelectric tube actuators

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ABSTRACT

An experimental study has been carried out to characterize rate-dependent hysteresis of a piezoelectric tube actuator at different excitation frequencies. The experimental measurements were followed by modeling and compensation of the hysteresis nonlinearities of the piezoelectric tube actuator using both the inverse rate-dependent Prandtl–Ishlinskii model (RDPI) and inverse rate-independent Prandtl–Ishlinskii model (RIPI) coupled with a controller. The comparison of hysteresis modeling and compensation of the actuator with both models is presented.

1. Introduction

Piezoelectric tube actuators are considered attractive for micro-/nano-positioning and micromanipulation applications [1]. These actuators, however, similar to other types of smart actuators exhibit rate-dependent hysteresis nonlinearities that increase with the excitation frequency of the applied input [2–5]. Formulating a rate-dependent hysteresis model that can account for the excitation frequency of the applied input is considered essential to expect the response of the actuator at various frequencies as well as to design controllers able to improve the tracking performance of smart actuators [6,7]. Different methodologies have been proposed in the literature for characterizing the hysteresis nonlinearities. One of the most popular methodologies is to employ a rate-independent hysteresis model (such as the classical Preisach, the classical Prandtl–Ishlinskii or the classical Bouc–Wen models [8,9]) coupled with linear dynamics which is the so-called Hammerstein model. Another methodology suggested recently in the literature is to formulate a hysteresis model such as the Prandtl–Ishlinskii that integrates the rate effect of the applied input in its parameters [10].

The primary goal of this study is to explore and compare the effectiveness of the rate-dependent Prandtl–Ishlinskii model (RDPI) and Hammerstein model in describing the dynamic hysteresis nonlinearities of piezoelectric actuator under different excitation frequencies. Since applying the inverse model would reveal the error due to characterization, a comparison is established on the basis of the compensation using inverse RDPI [10] and inverse RIPI coupled with a controller [11]. A laboratory experiment was carried out to characterize the voltage-to-displacement characteristics under different excitation frequencies and experimental data were employed to identify the parameters of the used models.

2. Characterization of hysteresis nonlinearities of piezoelectric tube actuator

2.1. The experimental setup

The experimental setup is represented in Fig. 1. It is composed of a piezoelectric tube able to deflect along two directions (*X* and *Y* directions), a computer with *Matlab/Simulink* software, two displacement sensors and two voltage amplifiers. In this experiment, only the *Y*-axis deflection is studied. The displacement sensors and

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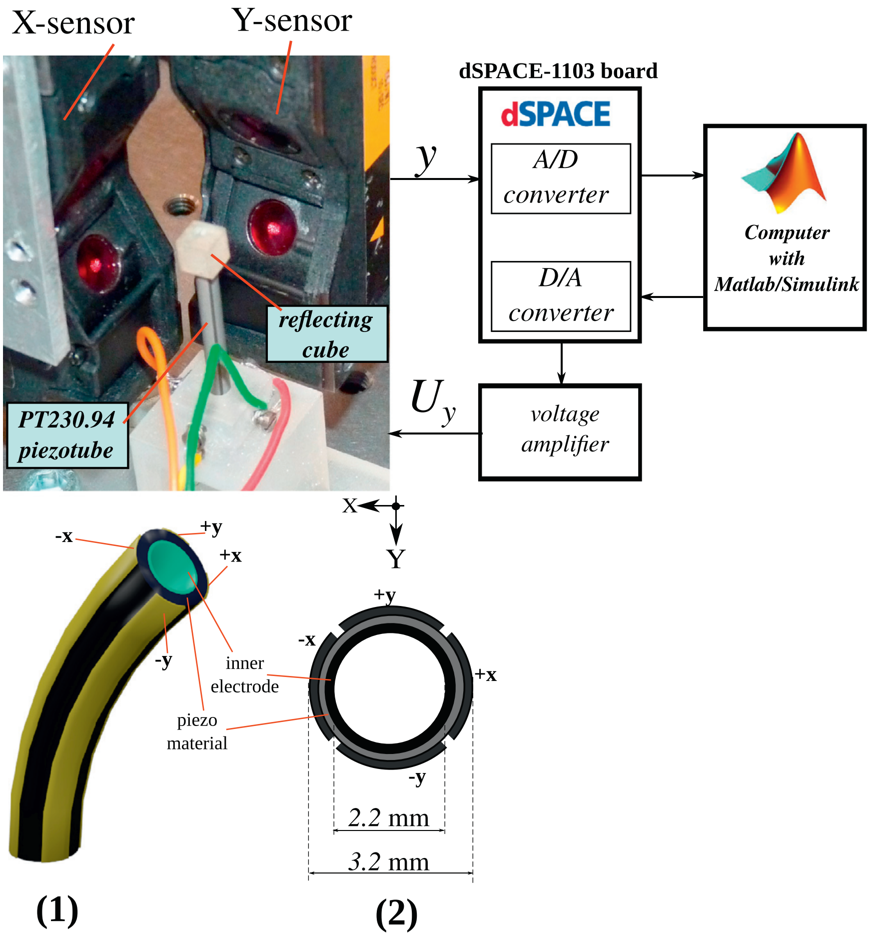

Fig. 1. The experimental setup and description of the piezoelectric tube actuator, where (1) is the perspective view and (2) the top view.

voltage amplifiers are connected to the computer through a *dSPACE-1103* board. The piezoelectric tube scanner used is the PT230.94, fabricated by *Physik Instrumente* company. This tube has 30 mm of length, 3.2 mm of outer diameter and 2.2 mm of inner diameter. PT230.94 is made of PZT material coated by one inner electrode (in silver) and four external electrodes (in copper–nickel alloy), commonly named $+x$, $-x$, $+y$ and $-y$ (Fig. 1(a)). Voltages U_y and $-U_y$ can be applied on $+y$ and $-y$ electrodes in order to bend the tube along Y-axis. To allow a linear displacement measurement (which is not possible with the tubular shape of the piezoelectric tube actuator), a small cube with perpendicular and flat sides is placed on the top of the tube. The operating voltage range of the PT230.94 is ± 250 V for a deflection of ± 35 μm. Hence, voltage amplifiers are used to amplify the dSPACE board output voltages, for which the maximum range is about ± 10 V. The tube deflections are measured using LC-2420 displacement sensors (from *Keyence* company), which are tuned to have 10 nm resolution and a bandwidth of 50 kHz. Note that these displacement sensors are employed only for the characterization: the proposed control approach is exclusively feedforward and these sensors are not needed for tracking. Despite the capability of the actuator to move at least in two directions (*XY* scan), only the Y-axis has been considered due to the scalar nature of the considered model.

The output displacement of the actuator was measured under sinusoidal input of 200 V at 3 different excitation frequencies: $f = 10$, 50, and 100 Hz. This range of frequency incorporates excitations where the hysteresis is relatively rate-independent (lower than 10 Hz) as well as rate-dependent (beyond 10 Hz). The output displacement of the piezoelectric actuator corresponding to each excitation frequency is illustrated in Fig. 2(a). In addition, an experiment to measure the step response of the actuator was conducted to identify the dynamics of the actuator. Fig. 2(b) displays the output displacement of the actuator under step input of 200 V. The identified dynamics of the actuator will be employed to synthesis an H_∞ controller. In the next section the measured data is employed to identify the parameters of the used models.

3. Hysteresis modeling

The mathematical formulations of the RDPI model and modeling based on the Hammerstein model are revisited in this section.

3.1. The rate-dependent Prandtl–Ishlinskii model

The model is presented in details in [10]. For a discrete-time input $u(k)$ and for $i = 1, 2, \ldots, n$ where $n \in \mathbb{N}$ and $k = 1, 2, \ldots$, the output of the RDPI model is given as the superposition of several weighted rate-dependent play operators as

$$\Gamma[u](k) := \rho_0 u(k) + \sum_{i=1}^{n} \rho_i \Phi_i[u](k), \tag{1}$$

where ρ_i are constants representing the weights, Φ_i is the rate-dependent play operator with the dynamic threshold $r_i(v(k)) = \alpha_1 i + \alpha_2 |v(k)|$, where α_1 and α_2 are positive constants, and v is the rate of the applied input.