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Experimental comparison of disturbance observer and inverse-based hysteresis compensation in 3D nanopositioning piezoactuation

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ABSTRACT

This paper presents an illustrative experiment-based comparison between different approaches for hysteresis compensation in piezoelectric actuators (X and Y axes). The focus is on 3D piezoactuation on some lab-made nanopositioning device, based on tunneling current phenomenon (Z axis). The experimental validation is done for two formerly developed methods – operator-based Modified Prandtl-Ishlinskii (MPI) inversion on the one hand and disturbance observer (DOB) affine hysteresis approximation on the other hand, as well as for the one corresponding to DOB based on MPI hysteresis approximation. It is shown that the modeling error introduced by MPI model is bounded and the MPI compensator in a forward path of the considered system can improve the performance of DOB. The results are given for tracking spiral patterns recently used in Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM).

1. Introduction

Due to their high resolution, high stiffness and fast response, piezoelectric actuators are widely used in micro/nano-scale applications like in STM [1] or AFM [2] and other nanopositioning applications [3,4]. However, they exhibit some adverse effects among which nonlinear hysteresis is the most prone to reduce the accuracy, especially in long-range positioning (e.g. imaging large samples). Moreover, the piezo can drift due to creep phenomenon, when positioned over extended periods of time [2].

A large number of works has been developed for eliminating these phenomena both in open-loop and closed-loop. Charge amplifiers [5] allow to linearize piezoelectric actuators (thus avoiding problems of hysteresis), but the cost and complexity of their circuit designs are often the main reasons for using voltage-based control. The open-loop feedforward control for both hysteresis and creep can be found for example in [6–8] (an inversion-based compensation). The most popular models used for hysteresis are operator-based Preisach [9,10] and Prandtl-Ishlinskii (PI) models [11,12]. Especially the latter model has been extensively used in real-time applications due to the fact that it is analytically invertible. However, due to the symmetry of elementary backlash blocks it uses, PI model in its classical form cannot properly capture asymmetric hysteresis loops. Therefore, several extensions have been proposed to overcome this limitation, for instance Modified Prandtl-Ishlinskii (MPI) model [13], or Generalized Prandtl-Ishlinskii (GPI) model [14]. The former model uses symmetric backlash and asymmetric one sided-dead zone operators as elementary building blocks, while the latter uses envelope functions to introduce asymmetry into the backlash operator. Both can successfully capture asymmetric hysteresis loops. These models are rate-independent, which means that their outputs do not depend on the rate of the excitation input. However, there exist in literature extensions for rate-dependent case (see for instance [15,16], respectively). The creep phenomenon, which is usually modeled as a transfer function [6,12], can be captured by the rate-dependent PI model as well as presented in [17].

Though computationally intensive, these methods are used when sensors are not available. On the other hand, closed-loop techniques are accurate and do not need model inversion, but the drawback is that they often require expensive sensors (such as a laser interferometer). Moreover, in closed-loop the measurement noise can deteriorate resolution, unless a high-end sensor is used. Due to ever-present uncertainties, external disturbances and modeling errors, the open-loop methods may not be robust enough and are combined together with closed-loop approaches. For instance,

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[18] used high gain feedback (for hysteresis and creep) with inverse-based feedforward vibration compensation. In [19] a robust H∞ control in the presence of sector bounded hysteresis uncertainty was considered. A disturbance observer (DOB) for hysteresis compensation was proposed in [20]. The idea behind this method is to give up hysteresis modeling and to consider it as a slowly varying disturbance on the input of a linear system, translate the difference between the response of the real plant and its model (through inversion of linear model) into observed disturbance and subtract it at the original input. In our previous works (see [21,22]), a similar DOB was implemented on some STM-like lab-made platform, with the difference that this disturbance is considered as a new entry of a state vector of linear system and reconstructed via state observer (direct compensation without model inversion). In [23] a GPI-based robust performance enhancement using DOB was considered in simulation.

The present paper comes in continuation of our previous work [22], where an experimental study of nanopositioning had been considered at low-frequency (1 Hz), with DOB-based hysteresis and creep compensation in the horizontal axes. Here indeed, we consider a similar experimental nanopositioning operation in 3D (in the presence of tunneling current in the vertical direction as in STM), at various frequencies. Various compensation methods are here compared: MPI, DOB based on an affine hysteresis approximation, and DOB based on MPI model of hysteresis. The creep effect modeling is here completely given up, avoiding more complex model, and instead, it is treated as a disturbance over the piezo displacement. It is thus part of a total disturbance including hysteresis modeling error as well, which is subsequently compensated via disturbance observer DOB. Our comparison shows that combining DOB with MPI improves the 3D nanopositioning (especially for higher frequencies).

To the authors' knowledge, such an experimental comparison has not been reported in the literature before. In paper [23], a theoretical study is done in 1D only, for improving the performance of the actual GPI by adding a disturbance observer (DOB), and only illustrated in simulation. In our 3D operation, the motion in Z direction is based on the quantum phenomenon of tunneling current [25], which makes the device similar to STM, but including here in addition a tracking control, based on pole placement with sensitivity functions shaping (see also [22,26]).

In summary, contributions of the present paper are as follows:

(1) A comparison between various approaches for hysteresis compensation is given, starting from some conventional feedforward compensation, based on MPI model, going on with an observer-based method (DOB), up to a less conventional method, which combines both of them (MPI + DOB).
(2) Experimental validations of the above mentioned methods are given in an original context of 3D nanopositioning.
(3) The modeling error with MPI hysteresis description is analyzed and shown to be bounded (similarly to the boundedness study of Preisach and Krasnoselskii-Pokrovskii (KP) hysteresis operators of [10], or the boundedness of inverse compensation error with GPI model of [23,24]).

The paper is organized as follows: the experimental setup is given in Section 2. Sections 3–5 are devoted to inverse-based MPI, DOB, and combined DOB + MPI, respectively, applied in X and Y axes. Section 5 provides additionally the proof of boundedness of the modeling error introduced by MPI model. Section 6 describes Z axis modeling and control of tunneling current. In Section 7 all the configurations are compared for spiral trajectories [27] of different scanning frequency in X–Y plane in the presence of tunneling current in the Z direction. Finally, Section 8 concludes the paper.

2. Experimental setup

The researches in this paper are carried out on tunneling current-based platform of GIPSA-lab shown in Fig. 1. The algorithms are developed in Matlab & Simulink™ software on a development PC, and downloaded via Ethernet interface into a Target PC. Two acquisition cards (one for control and one for measurement signals) connected with Target PC through PCI bus are used together with two anti-aliasing Butterworth filters with cutoff frequency of 20 kHz. Three piezoelectric actuators are driven by control signals from 16-bit D/A converter of the control card, amplified by a high voltage amplifier E-240-100 of gain 15 (V/V) and bandwidth 4 kHz. A platinum/iridium (Pt–Ir) tunneling tip is moved along metallic surface in X and Y directions by piezoelectric actuator Tritor T-402-00 of gain 235 (nm/V) and bandwidth 630 Hz while much smaller and stiffer piezoelectric actuator of gain 1.2 (nm/V) and bandwidth 120 kHz moves the tip in Z direction as shown in Fig. 2. Two capacitive sensors CS005 with capaNCDT 6500C device (gain 200 (V/mm) and bandwidth 8.5 kHz) are used to measure the displacements along X and Y axes. In the Z direction, the distance between tip and surface (<1 nm) is determined by the value of tunneling current (nA), measured via high gain (10^9 [V/nA]) sensor. These three analog outputs are converted into digital values by 16-bit A/D converter of the measurement card and used subsequently by the real-time application working in Target PC with the sampling rate f_s of 20 kHz.

3. Modified Prandtl-Ishlinskii model

In this section the MPI approach is recalled. A modeling for both X and Y directions is considered, however, only the equations of motion for X direction are presented for brevity (Y being similar).

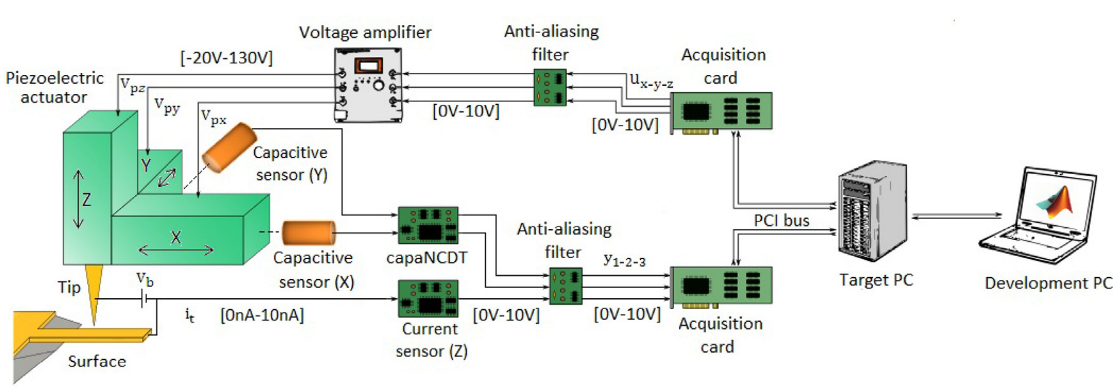

Fig. 1. Experimental setup.