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Two Degree-of-Freedom Robust Digital Controller Design With Bouc-Wen Hysteresis Compensator for Piezoelectric Positioning Stage

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ABSTRACT The compensation of nonlinear hysteretic behavior is one of the mandatory requirements in order to achieve precise reference tracking performance from a piezoelectric positioning stage. A common practice of employing an inverse hysteresis model as a feed-forward compensator must deal with modeling complexity; consequently, real-time tracking performance suffers due to modeling errors. In this paper, a two degree-of-freedom robust digital feedback controller design scheme in the presence of a simple Bouc-Wen hysteresis feed-forward compensator is proposed to deal with the dual challenge of modeling complexity and modeling errors. The proposed control scheme takes into account the performance and robustness requirements simultaneously. The desired performance and robustness requirements are expressed by means of constraints on the shapes of closed-loop sensitivity functions (CLSFs). Then, pole placement with sensitivity function shaping methodology is adopted so that the CLSFs respect their respective constraints and the desired performance with robustness could be achieved. The presented experimental results verify the effectiveness of the proposed control scheme in achieving the peak-to-peak reference tracking error of 0.36% for the desired displacement of 12 μm with tracking frequency of 10 Hz, whereas the peak-to-peak tracking error of 4.33% is observed with a Bouc-Wen hysteresis feed-forward compensator (without the feedback controller). Overall, 91% improvement is achieved in reducing the reference tracking error with the proposed control scheme.

INDEX TERMS Bouc-Wen hysteresis compensator, piezoelectric positioning stage, system identification, two degree-of-freedom robust digital feedback controller.

I. INTRODUCTION

Piezoelectric actuators are very commonly used in micro/nanopositioning stages for different applications [1]. An important application of a positioning stage based on piezoelectric actuator is in Scanning Probe Microscopy (SPM). Here, a probe, attached with the piezoelectric positioning stage, is used to scan over the material's surface for its manipulation and interrogation at an atomic scale [2]. The probe movement is required with ultra-high positioning precision and speed. Piezoelectric positioning stages are also used for the servo system of hard-disk drives [3] as well as for probe-storage devices [4], where ultra-precise positioning at nanometer-scale is required. These positioning stages are also an important part of advanced lithography tools used in the manufacturing of semiconductor integrated circuits [5]. Piezoelectric positioning stage is also very vital in molecular biology for imaging and nano-manipulation as required in cell tracking and DNA analysis [6]. However, the requirement of ultra-precise positioning in all these vast ranges of applications is limited to a small displacement range due to the presence of nonlinear hysteresis effect in piezoelectric actuators. Hence, the compensation of nonlinear hysteresis effect is one of the mandatory requirements in order to achieve precise reference tracking performance for long range from a piezoelectric positioning stage. If the nonlinear hysteresis effect is not compensated, it may cause oscillations in the system response and even the closed-loop system can become unstable [7].

An accurate mathematical model of hysteresis is required in order to design the compensator for this nonlinearity.

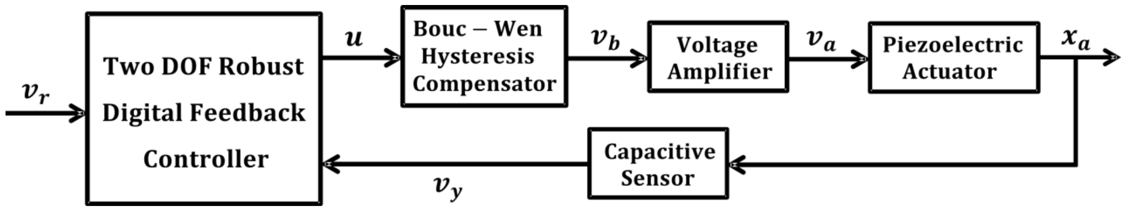

FIGURE 1. Closed-loop control scheme with two DOF feedback controller in the presence of Bouc-Wen hysteresis compensator.

For this purpose, a number of mathematical models have been analyzed in the literature to represent hysteresis nonlinearity of piezoelectric actuators [8]. Some of the famous hysteresis models are: Bouc-Wen model [9], Duhem model [10], Jiles-Atherton model [11], Krasnosel'skii-Pokrovskii model [12], Maxwell-based model [13], Prandtl-Ishlinskii model [14] and Preisach model [15]. Generally, two kinds of approaches are commonly adopted in the literature to compensate the nonlinear hysteresis effect. The first approach is to employ an inverse hysteresis model, as a feed-forward compensator, cascaded with a piezoelectric actuator in an open-loop system. Based on this first approach, many research papers have been written where authors have investigated the performance of a piezoelectric positioning stage in the presence of open-loop feed-forward compensator [16]–[18]. This approach of hysteresis compensation requires formulation of inverse hysteresis model which is often a challenging task. So, the modeling complexity is the main challenge of this first approach. Other than this modeling complexity, effective real-time tracking performance with an open-loop feed-forward compensator is difficult to achieve in the presence of unknown disturbances and modeling errors. The second approach of hysteresis compensation is to use a feedback controller with or without a feed-forward compensator. Usually, a feed-forward compensator is designed as an inverse hysteresis model to deal with hysteresis nonlinearity and then a feedback controller is designed to further enhance the tracking performance of the positioning stage. Different kinds of control algorithms, such as classical proportional-integral-derivative control [19], robust control [20], [21], fuzzy control [22], adaptive control [23], model-predictive control [24] and hybrid control [25] have been investigated in the literature without or with inverse hysteresis model as a feed-forward compensator to analyze the tracking performance of a piezoelectric positioning stage.

In this paper, a Bouc-Wen hysteresis model, which is widely used to represent the nonlinear hysteresis effects of an actuator due to its accuracy [26], is directly used (without model inversion) as a feed-forward compensator to avoid modeling complexity. To further enhance the tracking performance of the considered piezoelectric positioning stage, a two degree of freedom (DOF) robust digital feedback controller is also used in the presence of Bouc-Wen hysteresis compensator. The main advantage of this feedback control design approach is that it takes into account the robustness and performance requirements simultaneously for the closed-loop system. According to author's knowledge, such a combination of Bouc-Wen hysteresis compensator with a two DOF robust digital feedback controller has never been investigated in the literature so far for the compensation of nonlinear hysteresis phenomenon and also for the tracking performance of a piezoelectric positioning stage. In order to demonstrate the effectiveness of the proposed control scheme, the experimental results are also presented in this paper. Better results are achieved with the proposed control scheme as compare to author's previous work [20], [21] for the same system.

Section 2 of this paper describes the working principle of the considered piezoelectric positioning stage with necessary details about the experimental setup. Bouc-Wen hysteresis model, feed-forward compensator design and system identification are presented in *Section 3*. Design methodology of two DOF robust digital feedback controller is presented in *Section 4*. Experimental results are given in *Section 5*. Finally, *Section 6* draws some conclusions.

II. PIEZOELECTRIC POSITIONING STAGE

In this section, working principle of the considered piezoelectric positioning stage with all the necessary details about the experimental setup is presented.

A. WORKING PRINCIPLE

The block diagram of the closed-loop control scheme is presented in Fig. 1. This control scheme has a two DOF robust digital feedback controller as well as a Bouc-Wen hysteresis compensator. The Bouc-Wen hysteresis compensator is designed to mitigate the effect of nonlinear hysteresis of piezoelectric actuator, whereas a two DOF robust digital feedback controller is designed to further enhance the tracking performance of the positioning stage with robustness and stability. Piezoelectric actuator has vibrational dynamics as well as hysteresis nonlinearity. The output displacement (x_a) of the piezoelectric actuator is sensed by a capacitive displacement sensor. The capacitive sensors are widely used in different micro/nanopositioning applications as they provide non-contact measurements with sub-nanometer resolution and high bandwidth. The output voltage (v_Y) of this sensor is given back to feedback controller. Another input for the feedback controller is the reference voltage (v_r) which corresponds to the desired displacement of the piezoelectric actuator. The feedback controller performs the necessary action and generates the control signal (u) for the Bouc-Wen hysteresis compensator. The output voltage (v_b) of the Bouc-Wen hysteresis compensator is amplified by a voltage amplifier in order to generate the input voltage (v_a) for piezoelectric actuator. Details about experimental setup are presented in the next sub-section.

B. EXPERIMENTAL DETAILS

The experimental setup consists of a micro/nanopositioning stage having a single-axis piezoelectric actuator (P752.21) and a non-contact capacitive displacement sensor (D015). The considered piezoelectric actuator provides a positioning range up to 35 μm with a resolution of 0.2 nm. The capacitive displacement sensor has a measuring range of 45 μm and a resolution of 0.01 nm with a bandwidth of 10 kHz. The capacitance of the sensor, which is directly related to the distance between the plates, is converted into a signal analogous to the displacement. The piezoelectric actuator is driven by a high-power piezo amplifier (E505.00) having gain of 10 and bandwidth of 3 kHz. The control algorithm is developed in a computer having LabVIEW environment for the real-time implementation. The amplifier and displacement sensor communicate with control computer through data acquisition card (PXIe6361). Fig. 2 shows the experimental setup and Fig. 3 shows the considered piezoelectric nanopositioning stage.

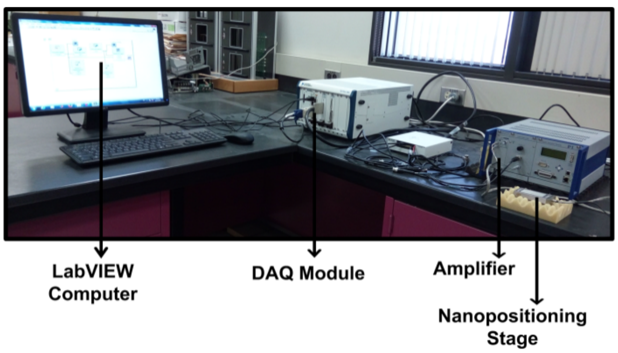

FIGURE 2. Experimental setup for piezoelectric positioning stage.

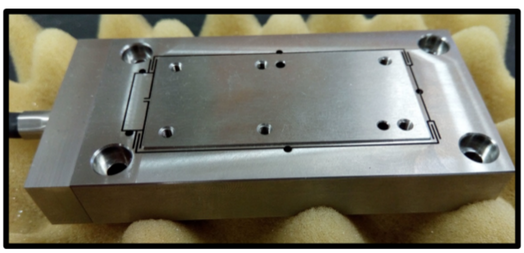

FIGURE 3. Piezoelectric nanopositioning stage (P-752.21).

III. HYSTERESIS MODEL AND FEED-FORWARD COMPENSATOR

In this section, the Bouc-Wen model is first presented to model the hysteretic phenomenon of the piezoelectric actuator. Then, the identification of different parameters of the hysteresis model as well as linear dynamics of the considered system is presented. Finally, a simple feed-forward compensator, based on Bouc-Wen hysteresis model, is also presented. The simulation results with the feed-forward compensator are also presented in this section.

A. BOUC-WEN HYSTERESIS MODEL

The reason of using the Bouc-Wen hysteresis model to represent nonlinear hysteresis effect of the considered piezoelectric actuator is its interesting simplicity in representing a large class of hysteresis with accuracy. Generally, this model can be described by the following differential equation:

$$\dot{\Phi}(t) = \alpha \dot{v}_a(t) - \beta \left|\dot{v}_a(t)\right| \left|\Phi(t)\right|^{n-1} \Phi(t) - \gamma \dot{v}_a(t) \left|\Phi(t)\right|^n \tag{1}$$

where Φ represents the hysteretic nonlinear term and $\dot{\Phi}$ is its first derivative with respect to time, v_a is the applied voltage to piezoelectric actuator, α, β, γ and $n \geq 1$ are the parameters which govern the shape and amplitude of hysteresis loop. Detailed discussion about effect of the Bouc-Wen model parameters can be found in [27]. The above presented hysteresis model can be transformed into discrete time for the purpose of designing a digital controller. So, a discrete time Bouc-Wen hysteresis model can be described by the following difference equation:

$$\begin{aligned}&\frac{\Phi(k+1)-\Phi(k)}{\Delta T}\\&= \alpha\frac{v_a(k+1)-v_d(k)}{\Delta T} - \beta\left|\frac{v_a(k+1)-v_a(k)}{\Delta T}\right|\left|\Phi(k)\right|^{n-1}\\&\quad \Phi(k) - \gamma\frac{v_a(k+1)-v_a(k)}{\Delta T}\left|\Phi(k)\right|^n\end{aligned} \tag{2}$$

where ΔT and k are sampling period and sampling instant, respectively. Now, the displacement of the piezoelectric actuator can be expressed as:

$$x_a(k) = g_P v_a(k) - \Phi(k) \tag{3}$$

where x_a represents the displacement of the piezoelectric actuator, g_P represents the piezoelectric coefficient and is strictly positive and Φ is hysteretic nonlinearity which can be described from (2) as follows:

$$\begin{aligned}\Phi(k) &= \Delta T\alpha\frac{v_a(k)-v_a(k-1)}{\Delta T}\\&\quad - \Delta T\beta\left|\frac{v_a(k)-v_a(k-1)}{\Delta T}\right|\left|\Phi(k-1)\right|^{n-1}\Phi(k-1)\\&\quad - \Delta T\gamma\frac{v_a(k)-v_a(k-1)}{\Delta T}\left|\Phi(k-1)\right|^n + \Phi(k-1)\end{aligned} \tag{4}$$

All the parameters (α, β, γ, n) of Bouc-Wen hysteresis model as well as the value of piezoelectric coefficient (g_P) are identified from the real-time experimental data. System identification is presented in the next sub-section.

B. SYSTEM IDENTIFICATION

In this sub-section, the identification of nonlinear hysteresis model parameters as well as the linear dynamics of considered piezoelectric positioning system is presented. A comparison of experimental and simulated results is also performed. The identified Bouc-Wen hysteresis model will be employed as a feed-forward compensator without performing model inversion.

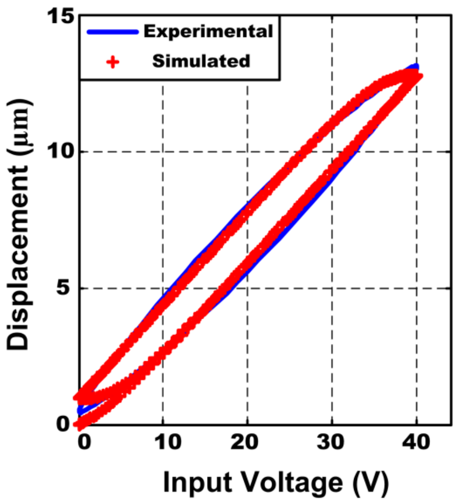

FIGURE 4. Experimental and simulated hysteresis loop with identified parameters of Bouc-Wen hysteresis model.

In order to identify different parameters (α, β, γ, n) of Bouc-Wen hysteresis model as well as piezoelectric coefficient (g_P), a sinusoidal input voltage of 40 V with a frequency of 10 Hz is applied to the piezoelectric actuator. The measured voltage from position sensor will generate the experimental hysteresis loop as shown in Fig. 4. In all the experiments, the real-time data acquisition is performed with a sampling frequency of 10 kHz. Now, to identify the parameters of Bouc-Wen hysteresis model, a nonlinear curve fitting problem is solved in a least-square sense by using the nonlinear least-square optimization toolbox in MATLAB. The identified parameters' values are: $\alpha = 0.7091, \beta = 2.0476, \gamma = 0.1949, n = 1$ and $g_P = 1.143$. After identification, simulated hysteresis loop is generated as shown in Fig. 4 based on identified parameters' values of Bouc-Wen hysteresis model. A close match between the experimental and simulated hysteresis loops can be observed which validates the presented Bouc-Wen hysteresis model for the considered piezoelectric actuator.

Now, in order to identify the linear dynamics of the considered piezoelectric positioning system, a sinusoidal chirp input signal of small amplitude (so that hysteresis effects are negligible) and increasing frequency is applied to the system. A recursive least square (RLS) parameter adaptation algorithm is used for estimating the parameters of the discrete time dynamic model of the considered system. Detailed discussion about RLS parameter adaptation algorithm can be found in [28]. The parameter adaptation algorithm uses the error between the actual system output and the output predicted by the model and modifies the model parameters at each sampling instant in order to minimize this error. The linear dynamic model will be used to design the proposed two DOF robust digital feedback controller. The identified 4$^{\text{th}}$ order discrete time dynamic model of the considered system is given as follows:

$$G\left(z^{-1}\right) = \frac{N\left(z^{-1}\right)}{D\left(z^{-1}\right)} = \frac{n_1 z^{-1} + n_2 z^{-2} + n_3 z^{-3} + n_4 z^{-4}}{1 + d_1 z^{-1} + d_2 z^{-2} + d_3 z^{-3} + d_4 z^{-4}} \quad (5)$$

where N and D are numerator and denominator polynomials of the plant. The identified parameters of these polynomials are: $n_1 = 0.652, n_2 = -0.806, n_3 = 0.398, n_4 = 0.0003, d_1 = -1.646, d_2 = 1.658, d_3 = -1.125$ and $d_4 = 0.387$. Experimental and simulated response with identified discrete time model for a chirp input is presented in Fig. 5. Again, a close match between the experimental and simulated responses can be observed which validates the identified model of the considered system. A small difference between these experimental and simulated plots will be dealt with the robustness of the proposed two DOF robust digital feedback controller.

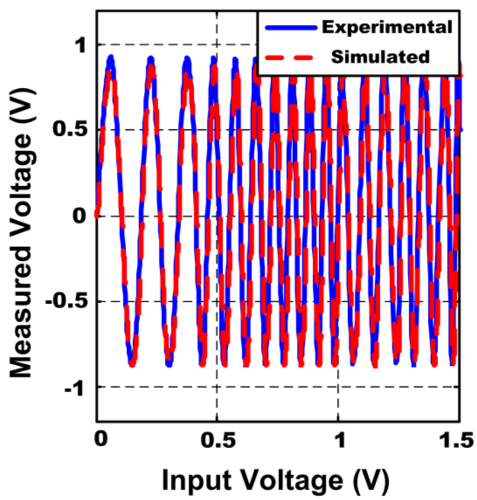

FIGURE 5. Experimental and simulated chirp response for the identification of linear dynamics.

C. BOUC-WEN HYSTERESIS COMPENSATOR

In order to compensate hysteresis nonlinearity of the considered piezoelectric actuator, a simple Bouc-Wen hysteresis compensator is designed based on identified hysteresis model (Φ) with identified value of piezoelectric coefficient (g_P) as shown in Fig. 6. In contrast to classical approach of hysteresis compensation where inverse hysteresis model is designed as a feed-forward compensator, here the presented approach does not require any inversion except for the piezoelectric coefficient (g_P) which is strictly positive. So the inverse modeling complexity can be avoided with the presented approach [26].

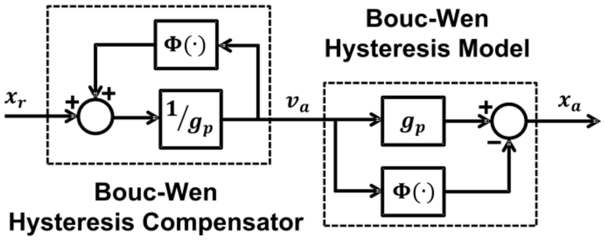

FIGURE 6. Block diagram of Bouc-Wen hysteresis model with compensator.

For Bouc-Wen hysteresis model, if x_a is the actual displacement of piezoelectric actuator and v_a is the applied voltage then the objective is to achieve $x_a = x_r$ (as shown in Fig. 6) where x_r is the input displacement for hysteresis compensator. Now, the equation for hysteresis compensator from (3) can be written as:

$$v_a(k) = \frac{1}{g_p}(x_r(k) + \Phi(k)) \tag{6}$$

where Φ represents the nonlinear hysteresis term which is used in feedback of the compensator as shown in Fig. 6. For this hysteresis compensator design, there is no need to perform inversion of actual hysteresis model.

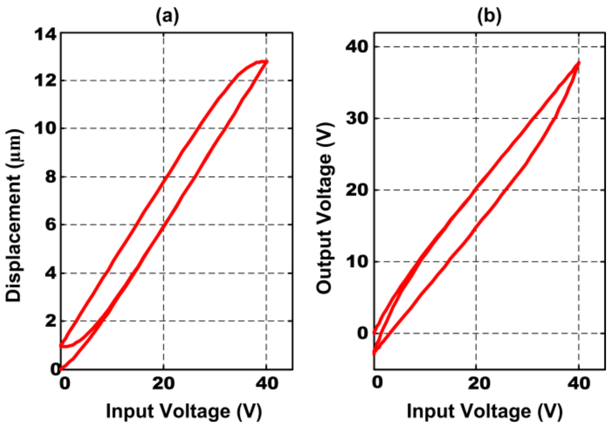

FIGURE 7. Simulation result of (a) hysteresis loop (b) output voltage of Bouc-Wen hysteresis compensator.

The simulation results of hysteresis loop and the output voltage of hysteresis compensator with identified Bouc-Wen hysteresis model are presented in Fig. 7(a) and Fig. 7(b), respectively. Fig. 8 shows the simulation result of hysteresis compensation with Bouc-Wen hysteresis compensator. This simulation result shows the capability of Bouc-Wen hysteresis compensator in compensating the hysteresis nonlinearity effectively. However, slight hysteresis nonlinear still can be observed during real-time experimentation with Bouc-Wen hysteresis compensator due to small mismatch between actual and simulated hysteresis loops. To further enhance the performance of considered piezoelectric positioning stage in terms of hysteresis compensation and precise reference tracking, a two DOF robust digital feedback controller in the presence of Bouc-Wen hysteresis compensator is analyzed and presented in the next section.

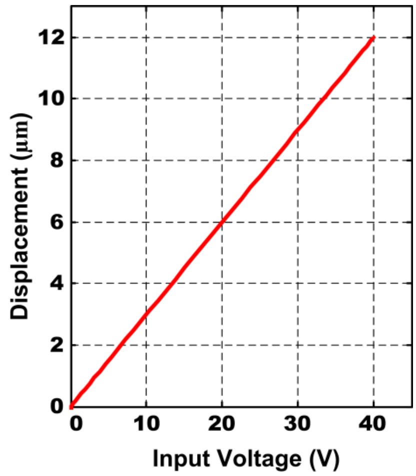

FIGURE 8. Simulation result of hysteresis compensation with Bouc-Wen hysteresis compensator.

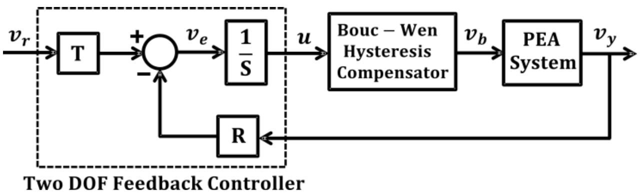

FIGURE 9. Block diagram of two DOF robust digital controller design for piezoelectric actuator (PEA) positioning stage.

IV. TWO DOF ROBUST DIGITAL CONTROLLER DESIGN

In this section, design methodology of a two DOF robust digital feedback controller, having three polynomials (R, S and T) as shown in Fig. 9, is presented. These three polynomials of the controller are designed by using pole placement with sensitivity functions shaping methodology [29]. The advantage of this methodology is that it can take into account the robustness and performance requirements simultaneously. The desired performance and robustness requirements are expressed by means of constraints on the shapes of closed-loop sensitivity functions.

The desired performance of the piezoelectric positioning stage is to achieve peak-to-peak reference tracking error of less than 1% for the desired displacement of 12 μm. This precise tracking performance is indeed required with robustness and stability. Three closed-loop sensitivity functions are considered here which are given as follows:

$$S_0\left(z^{-1}\right) = \frac{D\left(z^{-1}\right)S\left(z^{-1}\right)}{D\left(z^{-1}\right)S\left(z^{-1}\right)+N\left(z^{-1}\right)R\left(z^{-1}\right)} \tag{7}$$

$$T_0\left(z^{-1}\right) = \frac{N\left(z^{-1}\right)T\left(z^{-1}\right)}{D\left(z^{-1}\right)S\left(z^{-1}\right)+N\left(z^{-1}\right)R\left(z^{-1}\right)} \tag{8}$$

$$KS_0\left(z^{-1}\right) = \frac{D\left(z^{-1}\right)R\left(z^{-1}\right)}{D\left(z^{-1}\right)S\left(z^{-1}\right)+N\left(z^{-1}\right)R\left(z^{-1}\right)} \tag{9}$$

where S_0 is output sensitivity function, T_0 complementary sensitivity function and KS_0 is input sensitivity function. R, S and T are three polynomials of the controller, and N and D are polynomials of the plant. The considered constraints on the shapes of closed loop sensitivity functions are described in Table 1.

TABLE 1. Considered constraints on the shapes of sensitivity function.

Constraint	Condition	Reason
Constraint 1	$\|S_0\|_\infty < 6\ dB, \forall\omega$	For sufficient stability and robustness margin
Constraint 2	$\|T_0\|_\infty < 3.5\ dB, \forall\omega$	
Constraint 3	$\|KS_0\|_\infty < 20\ dB, \forall\omega$	To avoid instability due to actuator saturation
Constraint 4	$\|S_0\| < -30\ dB,$ $0 < \omega < \omega_T$	To achieve maximum of 1% peak-to-peak tracking error with maximum tracking frequency of $\omega_T = 10$ Hz
Constraint 5	$\|T_0\| < -10\ dB,$ $\omega > 10^3\ Hz$	To attenuate noise at system output

The constraints mentioned in Table 1 are used for the controller design as well as for the performance analysis of the considered piezoelectric positioning stage. A proper shaping of closed- loop sensitivity functions is required so that each sensitivity function respect its respective constraint. This shaping of closed-loop sensitivity functions can be done by appropriate selection of desired closed-loop poles and pre-specified polynomials in the controller polynomials. The desired closed-loop poles are specified by a polynomial C of the form:

$$C\left(z^{-1}\right) = C_D\left(z^{-1}\right) \cdot C_A\left(z^{-1}\right) \tag{10}$$

where C_D represents the desired dominant poles and C_A represents the auxiliary poles of the closed-loop system. Three polynomials of the controller are considered as follows:

$$R\left(z^{-1}\right) = P_R\left(z^{-1}\right) \cdot U_R\left(z^{-1}\right) \tag{11}$$

$$S\left(z^{-1}\right) = P_S\left(z^{-1}\right) \cdot U_S\left(z^{-1}\right) \tag{12}$$

$$T\left(z^{-1}\right) = R(1) \tag{13}$$

where P_R and P_S correspond to pre-specified polynomials of R and S polynomials of the controller respectively and T polynomial is considered as $R(1)$ in order to ensure steady-state unity gain between the reference and output of the system. The unknown polynomials of the controller U_R and U_S are obtained as a solution of the following polynomial (Bizout equation):

$$C\left(z^{-1}\right) = D\left(z^{-1}\right) \cdot S\left(z^{-1}\right) + N\left(z^{-1}\right) \cdot R\left(z^{-1}\right) \tag{14}$$

where C polynomial can be taken as given in (10) and R and S polynomials of the controller as given in (11) and (12) respectively. The controller design procedure is summarized in Fig. 10.

In order to design the two DOF robust digital feedback controller, the desired dominant closed-loop poles are placed

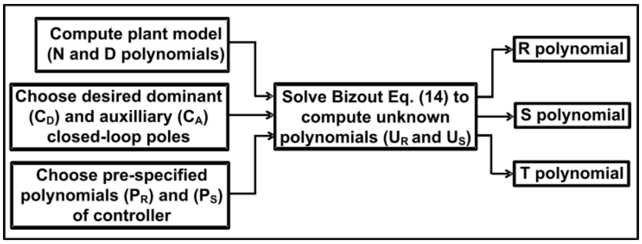

FIGURE 10. Block diagram of controller design procedure.

at 800 Hz with damping coefficient of 0.7 so that the closed-loop and open-loop natural frequencies remain almost the same. Four high frequency desired closed-loop auxiliary real poles are added at 0.3 in order to enhance the robustness of the closed-loop system and also to shape the output sensitivity function. In order to shape the input sensitivity function, a real zero has been introduced at $0.5f_S$ (where f_S is sampling frequency) as a pre-specified polynomial (P_R) of the controller. An integrator is also used as a pre-specified polynomial (P_S) of the controller. Now, after solving (14), following polynomials of the two DOF robust digital feedback controller are achieved:

$$R\left(z^{-1}\right) = r_0 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3} + r_4 z^{-4} + r_5 z^{-5}$$

$$S\left(z^{-1}\right) = 1 + s_1 z^{-1} + s_2 z^{-2} + s_3 z^{-3} + s_4 z^{-4} + s_5 z^{-5}$$

$$T\left(z^{-1}\right) = t_0$$

where $r_0 = 0.6691, r_1 = -1.0195, r_2 = 0.2919, r_3 = 0.7968, r_4 = -0.8738, r_5 = 0.3099, s_1 = -1.3074, s_2 = 0.0093, s_3 = 0.6172, s_4 = -0.3188, s_5 = -0.0002$ and $t_0 = 0.1745$. Closed-loop sensitivity functions with designed two DOF robust digital feedback controller are presented in Fig. 11. It can be observed that all closed-loop sensitivity functions respect their respective constraints as mentioned in Table 1. Respecting the constraints by the sensitivity functions indicate that the desired performance is achieved with the proposed controller. The desired performance at higher tracking frequency with the proposed control scheme can also be achieved if the constraints on the shapes of the closed-loop sensitivity functions and the pre-specified polynomials of the controller are chosen accordingly. Real-time experimental results are presented in the next section.

V. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, real-time experimental results of the considered piezoelectric actuator system are presented. For all presented experimental results, a sinusoidal reference input displacement of 12 μm with a tracking frequency of 10 Hz is considered. Data acquisition is performed with sampling frequency of 10 kHz.

Three different cases are thoroughly examined here in order to analyze the performance of the piezoelectric

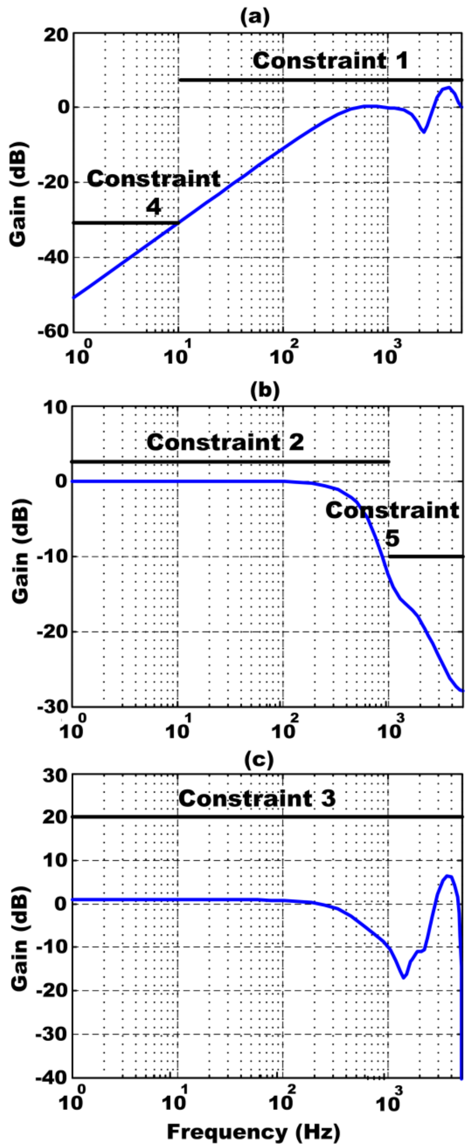

FIGURE 11. (a) Output sensitivity function (b) Complementary sensitivity function (c) Input sensitivity function.

actuator system in terms of hysteresis compensation and reference tracking. The considered three different cases are:

Case I: Open-loop system without any compensator.

Case II: Open-loop system with feed-forward Bouc-Wen hysteresis compensator.

Case III: Closed-loop system with proposed two DOF robust digital controller in the presence of feed-forward Bouc-Wen hysteresis compensator.

The experimental results which are achieved in above mentioned three cases are discussed below:

Case I: Fig. 12(a) and Fig. 12(b) show the experimental results of hysteresis loop and reference tracking error respectively, in open-loop configuration without any compensator. A large hysteresis loop with hysteresis percentage of 20.82% can be observed in the output displacement of

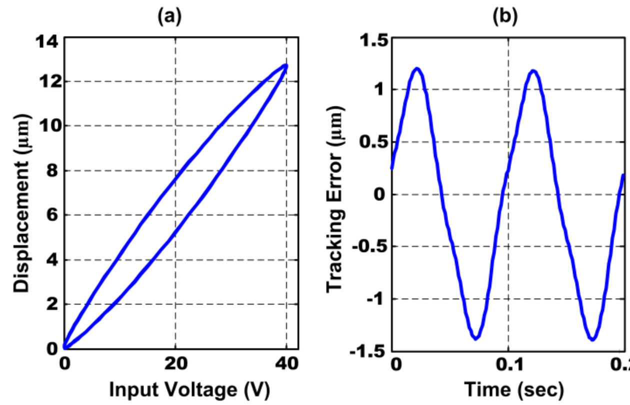

FIGURE 12. CASE I: Experimental results in open-loop without any compensator (a) hysteresis loop (b) reference tracking error.

piezoelectric actuator. Similarly, a large peak-to-peak tracking error of 2.6 μm, which is 21.67% of the desired displacement (12 μm) of piezoelectric actuator, is also observed. These experimental results demonstrate the necessity of designing a compensator for hysteresis nonlinearity, which will also reduce the reference tracking error.

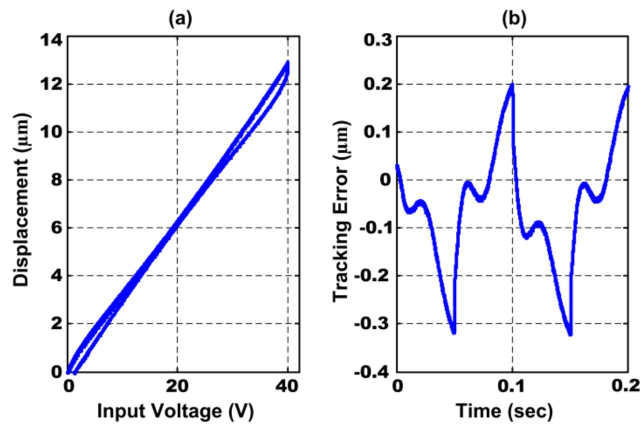

FIGURE 13. CASE II: Experimental results with Bouc-Wen feedforward compensator (a) hysteresis loop (b) reference tracking error.

Case II: Fig. 13(a) and Fig. 13(b) present the experimental results of hysteresis loop and reference tracking error respectively, in open loop configuration in the presence of Bouc-Wen hysteresis compensator. Hysteresis percentage of 1.25% is still observed in the output displacement of the piezoelectric actuator as shown in Fig. 13(a). The observed slight hysteresis nonlinearity is due to a small mismatch between the measured experimental hysteresis loop and the output of identified hysteresis model. In the presence of a Bouc-Wen hysteresis compensator, the observed peak-to-peak reference tracking error, shown in Fig. 13(b), is 0.52 μm which is 4.33% of the desired displacement (12 μm) of piezoelectric positioning stage. Overall, the Bouc-Wen hysteresis compensator has improved the performance of the considered piezoelectric actuator system in suppressing the hysteresis nonlinearity by 93.9% and in reducing the peak-to-peak tracking error by 80.1% from the open-loop system without any compensator (Case I). In order to further enhance the performance of piezoelectric positioning stage in terms of hysteresis compensation and reducing the reference tracking error, a closed-loop configuration with two DOF robust digital feedback controller in the presence of the feed-forward Bouc-Wen hysteresis compensator is analyzed in Case III.

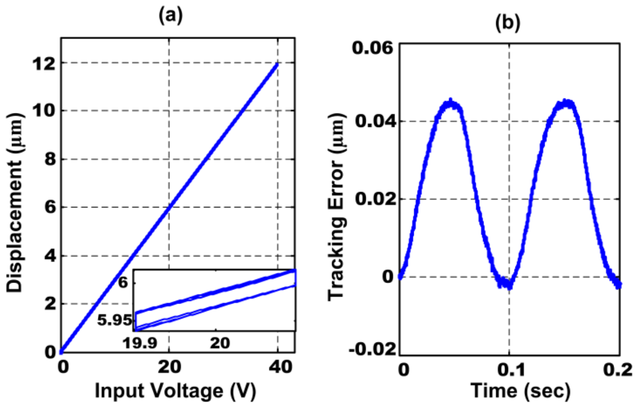

FIGURE 14. CASE III: Experimental results with 2 DOF robust digital feedback controller in the presence of Bouc-Wen feed-forward compensator (a) hysteresis loop (b) reference tracking error.

Case III: Fig. 14(a) and Fig. 14(b) present the experimental results of hysteresis loop and reference tracking error respectively, in closed-loop configuration with two DOF robust digital feedback controller in the presence of feed-forward Bouc-Wen hysteresis compensator. Better results in terms of hysteresis compensation and reference tracking are observed in this Case III. A very small hysteresis loop with hysteresis percentage of 0.16% can be observed in the output displacement of piezoelectric actuator as shown in Fig. 14(a). Overall, the proposed two DOF robust digital controller with Bouc-Wen hysteresis compensator has improved the performance of considered piezoelectric actuator in suppressing the hysteresis nonlinearity by 99.2% from the open-loop system without compensator (Case I) and by 87.2% from the open-loop system with feed-forward Bouc-Wen hysteresis compensator (Case II). Better compensation of hysteresis nonlinearity will accordingly reduce the reference tracking error. A very small peak-to-peak reference tracking error of 0.043 μm, which is 0.36% of the desired displacement (12 μm) of piezoelectric positioning stage, is observed in this Case III as shown in Fig. 14(b). As compared to Case I and Case II, the reference tracking error is reduced in Case III by 98.3% from the open-loop system without any compensator and by 91.6% from the open-loop system with a feed-forward Bouc-Wen hysteresis compensator.

The summary of achieved results in Case I, Case II and Case III is presented in Table 2.

TABLE 2. Summary of achieved experimental results.

	Case I	Case II	Case III
Hysteresis	20.82%	1.25%	0.16%
Improvement in hysteresis compensation from Case I	–	93.9%	99.2%
Improvement in hysteresis compensation from Case II	–	–	87.2%
Tracking error	21.67%	4.33%	0.36%
Improvement in reducing tracking error from Case I	–	80.1%	98.3%
Improvement in reducing tracking error from Case II	–	–	91.6%

VI. CONCLUSION

In this paper, the tracking precision of a piezoelectric positioning stage has been analyzed in three different cases: open-loop configuration without any compensator (Case I), open-loop configuration with a Bouc-Wen hysteresis feed-forward compensator (Case II) and finally, closed-loop configuration with two DOF robust digital feedback controller in the presence of Bouc-Wen hysteresis feed-forward compensator (Case III). Before analyzing the performance of piezoelectric positioning stage, the linear dynamic model of considered piezoelectric actuator system with different parameters of Bouc-Wen hysteresis model have been identified from the real-time experimental data. The achieved experimental results in Case III demonstrate improved performance in terms of suppressing the hysteresis nonlinearity and reducing the tracking error as compared to Case I and Case II. Hysteresis percentage of 0.16% has been achieved in Case III, which is almost 99% improvement from Case I and 87% improvement from Case II. As far as peak-to-peak reference tracking error is concerned, 0.36% of the desired displacement of 12 μm has been achieved in Case III, which is almost 98% improvement from Case I and 91% improvement from Case II. All these achieved experimental results demonstrate the effectiveness of the proposed control scheme.

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REFERENCES

[1] S. Devasia, E. Eleftheriou, and S. O. R. Moheimani, "A survey of control issues in nanopositioning," *IEEE Trans. Control Syst. Technol.*, vol. 15, no. 5, pp. 802–823, Sep. 2007.

[2] G. Binnig and D. P. E. Smith, "Single-tube three-dimensional scanner for scanning tunneling microscopy," *Rev. Sci. Instrum.*, vol. 57, no. 8, pp. 1688–1689, Aug. 1986.

[3] U. Boettcher, R. A. De Callafon, and F. E. Talke, "Modeling and control of a dual stage actuator hard disk drive," *J. Adv. Mech. Des., Syst. Manuf.*, vol. 4, no. 1, pp. 107–118, 2010.

[4] E. Eleftheriou, "Nanopositioning for storage applications," *Annu. Rev. Control*, vol. 36, no. 2, pp. 244–254, Dec. 2012.
[5] E. Mehdizadeh and S. Pourkamali, "Deep submicron parallel scanning probe lithography using two-degree-of-freedom microelectromechanical systems actuators with integrated nanotips," *IET Micro Nano Lett.*, vol. 9, no. 10, pp. 673–675, 2014.
[6] J. Andrecka *et al.*, "Nano positioning system reveals the course of upstream and nontemplate DNA within the RNA polymerase II elongation complex," *Nucleic Acids Res.*, vol. 37, no. 17, pp. 5803–5809, 2009.
[7] C. Ru, L. Chen, B. Shao, W. Rong, and L. Sun, "A hysteresis compensation method of piezoelectric actuator: Model, identification and control," *Control Eng. Pract.*, vol. 17, no. 9, pp. 1107–1114, 2009.
[8] L. Ma, Y. Shen, J. Li, H. Zheng, and T. Zou, "Modeling hysteresis for piezoelectric actuators," *J. Intell. Mater. Syst. Structures*, vol. 27, no. 10, pp. 1404–1411, 2016.
[9] D. Habineza, M. Rakotondrabe, and Y. Le Gorrec, "Bouc–Wen modeling and feedforward control of multivariable hysteresis in piezoelectric systems: Application to a 3-DoF piezotube scanner," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 5, pp. 1797–1806, Sep. 2015.
[10] G. Wang and G. Chen, "Identification of piezoelectric hysteresis by a novel Duhem model based neural network," *Sens. Actuators A, Phys.*, vol. 264, pp. 282–288, Sep. 2017.
[11] M. A. Zaman and M. A. Matin, "Optimization of Jiles–Atherton hysteresis model parameters using Taguchi's method," *IEEE Trans. Mag.*, vol. 51, no. 5, May 2015, Art. no. 7301004.
[12] M. Zhou, S. He, B. Hu, and Q. Zhang, "Modified KP model for hysteresis of magnetic shape memory alloy actuator," *IETE Tech. Rev.*, vol. 32, no. 1, pp. 29–36, 2015.
[13] L. Cao, Y. Li, G. Tian, B. Liu, and Y. Chen, "Time domain analysis of the fractional order weighted distributed parameter Maxwell model," *Comput. Math. Appl.*, vol. 66, no. 5, pp. 813–823, 2013.
[14] Y. Qin, X. Zhao, and L. Zhou, "Modeling and identification of the rate-dependent hysteresis of piezoelectric actuator using a modified Prandtl–Ishlinskii model," *Micromachines*, vol. 8, no. 4, p. 114, 2017.
[15] P.-B. Nguyen, S.-B. Choi, and B.-K. Song, "A new approach to hysteresis modelling for a piezoelectric actuator using Preisach model and recursive method with an application to open-loop position tracking control," *Sens. Actuators A, Phys.*, vol. 270, no. 1, pp. 136–152, 2017.
[16] R. Changhai and S. Lining, "Hysteresis and creep compensation for piezoelectric actuator in open-loop operation," *Sens. Actuators A, Phys.*, vol. 122, no. 1, pp. 124–130, 2005.
[17] M. Al Janaideh and P. Krejčí, "Inverse rate-dependent Prandtl–Ishlinskii model for feedforward compensation of hysteresis in a piezomicropositioning actuator," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 5, pp. 1498–1507, Oct. 2013.
[18] Y. Qin, Y. Tian, D. Zhang, B. Shirinzadeh, and S. Fatikow, "A novel direct inverse modeling approach for hysteresis compensation of piezoelectric actuator in feedforward applications," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 3, pp. 981–989, Jun. 2013.
[19] H. Tang and Y. Li, "Feedforward nonlinear PID control of a novel micromanipulator using Preisach hysteresis compensator," *Robot. Comput.-Integr. Manuf.*, vol. 34, pp. 124–132, Aug. 2015.
[20] I. Ahmad and A. M. Abdurraqeeb, "Tracking control of a piezoelectric actuator with hysteresis compensation using RST digital controller," *Microsyst. Technol.*, vol. 23, no. 6, pp. 2307–2317, 2017.
[21] I. Ahmad and A. M. Abdurraqeeb, "H-infinity control design with feedforward compensator for hysteresis compensation in piezoelectric actuators," *Automatika*, vol. 57, no. 3, pp. 691–701, 2017.
[22] Z. Chi and Q. Xu, "Precision control of piezoelectric actuator using fuzzy feedback control with inverse hysteresis compensation," in *Proc. IEEE NEMS*, Xi'an, China, Apr. 2015, pp. 219–224.
[23] Q. Xu and M. Jia, "Model reference adaptive control with perturbation estimation for a micropositioning system," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 1, pp. 352–359, Jan. 2014.
[24] Y. Cao, L. Cheng, X. B. Chen, and J. Y. Peng, "An inversion-based model predictive control with an integral-of-error state variable for piezoelectric actuators," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 3, pp. 895–904, Jun. 2013.
[25] J. N. Yang, Z. Li, A. Danielians, and S. C. Liu, "Aseismic hybrid control of nonlinear and hysteretic structures II," *J. Eng. Mech.*, vol. 118, no. 7, pp. 1441–1456, 1992.
[26] M. Rakotondrabe, "Bouc–Wen modeling and inverse multiplicative structure to compensate hysteresis nonlinearity in piezoelectric actuators," *IEEE Trans. Autom. Sci. Eng.*, vol. 8, no. 2, pp. 428–431, Apr. 2011.
[27] F. Ikhouane, V. Mañosa, and J. Rodellar, "Dynamic properties of the hysteretic Bouc–Wen model," *Syst. Control Lett.*, vol. 56, no. 3, pp. 197–205, 2007.
[28] I. D. Landau, R. Lozano, and M. M'Saad, "Recursive plant model identification in open loop," in *Adaptive Control*, 2nd ed. London, U.K.: Springer-Verlag, 2011, pp. 153–190.
[29] I. D. Landau and A. Karimi, "Robust digital control using pole placement with sensitivity function shaping method," *Int. J. Robust Nonlinear Control*, vol. 8, no. 2, pp. 191–210, 1998.

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