Rate-Dependent Prandtl-Ishlinskii Hysteresis Compensation Using Inverse-Multiplicative Feedforward Control in Magnetostrictive Terfenol-D based Actuators

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***Abstract*— In [1], a new technique based on the rate-dependent Prandtl-Ishlinskii model (RDPI) is presented to compensate for the rate-dependent hysteresis nonlinearities effects in piezomicropositioning actuators. In this paper the validity of the proposed compensator is further examined on a magnetostrictive Terfenol-D actuator under input current amplitude of 2.3 A applied at different excitation frequencies. The simulation and experimental results show that the proposed compensator can effectively compensate for the rate- dependent hysteresis nonlinearities in a high efficient manner without formulating an inverse model.**

I. Introduction

The Prandtl-Ishlinskii model is considered attractive for modeling and compensation of hysteresis nonlinearities due to its suitability and simplicity for real-time applications [1]–[10]. In a recent study, a rate-dependent Prandtl-Ishlinskii (RDPI) model and its analytical inverse have been developed [7] and efficiently applied for modeling and compensation of the rate-dependent hysteresis nonlinearities of piezoelectric and magnetostrictive actuators [10]–[12]. The hysteresis is considered rate-dependent when its shape or amplitude relies on the rate of the applied input signal. The RDPI model is able to track the measured hysteresis nonlinearities at low and high excitations of frequency, which is well suited for systems that exhibit rate-dependent hysteresis nonlinearities. A major advantage of the RDPI model is that the model can consider the rate-independent hysteresis nonlinearities (hysteresis found at low excitation frequency), the rate-dependent hysteresis nonlinearities (nonlinearities found at high excitation frequency) as well as the creep effects (nonlinearities found at very low excitation frequency). The compensation of the RDPI model is performed using a compensator calculated from the inverse of the initial model itself [7]. Both the model and the compensator are built based on the dynamic thresholds which are function of rate of the applied input. However, the exact inverse of the RDPI model can only be obtained if the dynamic thresholds satisfy the dilation condition, which restricts the formulation of an accurate model [7], [8].

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In [1], we proposed a new technique based on the rate-dependent Prandtl-Ishlinskii model (RDPI) to compensate for the rate-dependent hysteresis nonlinearities effects in piezomicropositioning actuators. Contrary to the existing compensator which is based on the direct inversion of the RDPI model [7], the proposed compensator ignores formulating the inverse model to derive the compensator. More precisely, the suggested compensator can be obtained through restructuration of the RDPI model using the inverse multiplicative structure. The model inversion is therefore avoided and no additional calculations are required. In addition, the compensator does not necessitate satisfying the dilation condition in [8]. Thus, the new approach provides more flexibility in formulating the dynamic compensator. In this paper, we go further on the analysis of this RDPI compensator for the magnetostrictive actuators. The proposed compensator permits to reduce the hysteresis nonlinearities for a wide range of excitation frequency and without formulating the inverse of the model of the magnetostrictive actuator. Notice that the RDPI has been employed to model magnetostrictive actuator [11] but not used to compensated for its strong hysteresis, which is the aim of this paper.

It is worth to notice that the inverse multiplicative structure has been initially employed to construct a hysteresis compensator in [13] for the classical Bouc-Wen model. It was afterwards extended to the multivariable classical Bouc-Wen [14], the generalized Bouc-Wen model [15], the classical Prandtl-Ishlinskii (RIPI) [9] and for the classical Preisach [16], [17]. All these results deal with rate-independent hysteresis whilst the aim of this paper is rate-dependent hysteresis where the hysteresis shape strongly depends on the rate or on the frequency of the input control.

The remainder of this paper is organized as follows. In section II, we recall the RDPI model as well as the inverse RDPI model used as compensator. In section III, we present the new inverse multiplicative scheme based compensation technique which permits to have a free-inversion RDPI compensator. The experimental applications to magnetostrictive actuator are then presented in section IV. Finally, the conclusions of the paper are given in section V.

II. Previous works on control of magnetostrictive actuators

Compared to other smart material based actuators, such as piezoelectric and shape memory alloys (SMA's), Terfenol-D magnetostrictive actuators exhibit rate-dependent hysteresis in symmetric as well as asymmetric fashion. Thus, at shallow levels of input amplitude, hysteresis nonlinearities of these actuators tend to be symmetric, while applying input at moderate and high levels of amplitude contribute asymmetric hysteresis nonlinearities. In addition, output saturation is evident in the hysteresis properties of these actuators at high excitations of input amplitude.

Due to the undesirable effects of hysteresis nonlinearities of magnetostrictive actuators, considerable efforts have been made in order to design controllers for compensation of hysteresis nonlinearities. The primary goal of these controllers is to cancel out the hysteresis effects associated with oscillations and poor tracking performance of the closed-loop system. The proposed control algorithms could be classified in two categories the non-inverse based control methods, which focus on the compensation of hysteresis nonlinearities without considering the inverse of the hysteresis model and inverse based control methods that employ the inverse of the hysteresis model.

In [18], as an example, a nonlinear differential equation coupled with an LQR controller has been suggested to compensate for hysteresis of magnetostrictive actuator described by the Jiles-Atherton physics-based hysteresis model. The study employed the model along with an inverse magnetization model involving solutions of the partial differential equations using numerical techniques.

A hybrid nonlinear optimal control design is experimentally employed on a magnetostrictive Terfenol-D actuator in [19] to improve the tracking control at high excitations of input frequency. The study employed a rate-dependent ferromagnetic homogenized energy model to describe the rate-dependent hysteresis of the actuator. The control design incorporated designing of proportional-integral (PI) feedback controller to account for the operating uncertainties.

In order to enhance the robustness of the steady-state response, a narrowband feedback design was utilized in [19] by dealing the hysteretic behavior as higher-order disturbances that can be cancelled-out by tuning a narrowband filter. A hybrid optimal controller was then incorporated to the control design with perturbation narrowband feedback.

A Preisach model and its inverse were employed in [20] for characterization and compensation of rate-independent hysteresis nonlinearities of magnetostrictive actuator. The parameters identification methodology suggested the adoption of both a fuzzy approximation and a feed-forward neural network procedure.

An inverse Preisach model was employed in [16] with an adaptive control system to compensate for hysteresis nonlinearities of a magnetostrictive actuator. The classic Preisach model was coupled with a second order system to quantify the rate-dependent hysteresis nonlinearities. In [21], an inverse modified Prandtl-Ishlinskii model was suggested for compensation of the rate-independent asymmetric hysteresis nonlinearity of a magnetostrictive actuator. The inverse model integrates inverses of a free memory function and a rate-independent Prandtl-Ishlinskii model.

A generalized Prandtl-Ishlinskii model and its analytical inverse has been suggested in [22] to compensate for asymmetric hysteresis nonlinearities of magnetostrictive actuators. The study utilized envelope functions for the classic play operator based Prandtl-Ishlinskii model for characterization of asymmetric hysteresis nonlinearities. The analytical inverse of the play operator-based Prandtl-Ishlinskii model together with the inverse of the envelope functions were formulated for compensation of rate-independent asymmetric hysteresis nonlinearities of the proposed model.

A recent study [12], has suggested compensation of symmetric rate-dependent hysteresis nonlinearities of magnetostrictive actuators using inverse rate-dependent Prandtl-Ishlinskii model. The model integrates the rate-dependent threshold function which is formulated as a function of the input rate to quantify the rate-dependent nonlinear hysteresis of the actuator. The study employs the inverse rate-dependent model in an open-loop feedforward manner as a rate-dependent compensator which is available when the threshold function satisfies the dilation condition. The study in [12] dealt with symmetric rate-dependent hysteresis found at shallow levels of input current.

Employing the inverse symmetric rate-dependent Prandtl-Ishlinskii model for compensation of asymmetric rate-dependent hysteresis nonlinearities obtained at high levels of input amplitude yields substantial errors in compensation. Consequently, the inverse symmetric rate-dependent Prandtl-Ishlinskii model was extended in [23] for compensation of asymmetric rate-dependent hysteresis of magnetostrictive actuators. The asymmetric rate-dependent model was formulated using a rate-dependent Prandtl-Ishlinskii model to account for the rate-dependent effect of the hysteresis, while an asymmetric memoryless function which a superposition of weighted deadband operators was employed to characterize the asymmetric behaviour of the hysteresis nonlinearities. The inverse model was formulated using both the inverses of rate-dependent Prandtl-Ishlinskii model and the memoryless function. The experimental implementation on the magnetostrictive actuator was afterwards carried-out in open-loop feedforward manner.

III. Background

We remind the rate-dependent Prandtl-Ishlinskii (RDPI) model and the RDPI inverse model used as compensator in [7] which requires inversion and dilation condition. All the models and compensators are presented with the corresponding discrete form which is convenient for real time application.

Let us consider the control scheme illustrated in Figure 1 where the magnetostrictive actuator is typified by a rate-dependent hysteresis that can be represented by a RDPI Prandtl-Ishlinskii model. The main objective of this study is to design an inversion-free feedforward rate-dependent compensator for the magnetostrictive actuator of input u and output y, the desired displacement (reference) being y_r

A. The RDPI model

We deal with real absolutely continuous functions defined on the interval $(0,T)$. The space of such functions is denoted by $AC(0,T)$. For the input signal $u(t) \in AC(0,T)$ and for $i = 0,1,2,...,n$, where $n \in \mathbb{N}$ is an integer, let $r_i(\dot{u}(t)) \in AC(0,T)$ be given functions and called thresholds such that

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

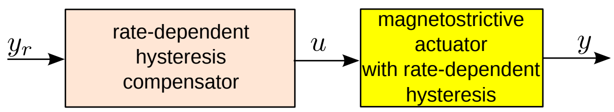


Fig. 1: Feedforward control scheme of the magnetostrictive actuator.

Let $\Phi_{r_i(\dot{u}(t))}[u](t)$ be a rate-dependent play (RDP) operator with output $\xi_i(t)$

$$\xi_i(t) = \Phi_{r_i(\dot{u}(t))}[u](t). \quad (2)$$

For input $u(t)$ and thresholds $r_i(\dot{u}(t))$ that are piecewise linear in each interval of a partition $0 = t_0 < t_1 < \cdots < t_l = T$, where $l \in \mathbb{N}$ is an integer, the output of the rate-dependent play operator for $t \in [t_{j-1}, t_j)$ is [7]

$$\xi_i(t) = \max\{u(t) - r_i(\dot{u}(t), \min\{u(t) + r_i(\dot{u}(t)), \xi_i(t_{j-1})\}\} \quad (3)$$

with initial condition $\xi_i(0) = \max(u(0) - r_i(0), \min(u(0) + r_i(0), x_i))$, where x_i are the initial states (memory) of the RDP operators and equal to 0. Finally, the output of the RDPI model is given as the superposition of several weighted RDP operators [7]

$$\Gamma[u](t) := \rho_0 u(t) + \sum_{i=1}^{n} \rho_i \Phi_{r_i(\dot{u}(t))}[u](t) \quad (4)$$

where ρ_0 and ρ_i are constants representing the weights. The thresholds $r_i(\dot{u}(t))$ being dependent on the input rate $\dot{u}(t)$, the formulation of the dynamic threshold governs the effect of the input and its rate on the output of the RDPI model. We use the following dynamic threshold function to formulate the RDPI model which is well convenient for magnetostrictive actuators [11]

$$r_i(\dot{u}(t)) = \delta_1 i + \delta_2 |\dot{u}(t)|, \quad (5)$$

where δ_1 and δ_2 are positive constants.

The discrete RDPI model can be represented with the sampling time T_s, where $T_s = t_k - t_{k-1}$, $k = 1,2,\ldots,K$, and $K \in \mathbb{N}$ is an integer. Then, the output of the discrete RDPI model is

$$y(k) = \Gamma[u](k) := \rho_0 u(k) + \Omega[u](k)\,, \quad (6)$$

where

$$\Omega[u](k) = \sum_{i=1}^{n} \rho_i \Phi_{r_i(v(k))}[u](k), \quad (7)$$

where $v(k)$ is the rate of the applied input and the discrete RDP (rate-dependent play) operator $\xi_i(k) = \Phi_{r_i(v(k))}[u](k)$ can be expressed as

$$\xi_i(k) = \max\{u(k) - r_i(v(k)), \min\{u(k) + r_i(v(k)), \xi_i(k-1)\}\}, \quad (8)$$

where

$$r_i(v(k)) = \delta_1 i + \delta_2 |v(k)|. \quad (9)$$

B. The RDPI inverse model

The output of the inverse RDPI hysteresis model which serves as compensator is [7]

$$\Gamma^{-1}[y_r](t) := b_0 y_r(t) + \sum_{i=1}^{n} b_i \Phi_{\hat{r}_i(\dot{y}_r(t))}[y_r](t). \quad (10)$$

where b_0 and b_i are constants, and $\hat{r}_i(t)$ is the dynamic threshold of the inverse model. More details can be found in [7], [11]

C. Input-output monotonicity of the RDPI model

In this section we consider input-output monotonicity between the input $u(k)$ and output $y(k)$, which is essential to present the convergence analysis for the new compensator in the future work. For $k > 1$, when the input $u(k)$ increases, we have $u(k) > u(k-1)$ and $\xi_i(k) > \xi_i(k-1)$, then the output of the model is $y(k) = \rho_0 v(k) + \sum_{i=1}^{n} \rho_i(u(k) - r_i(v(k)))$ and $y(k-1) = \rho_0 v(k-1) + \sum_{i=1}^{n} \rho_i(u(k-1) - r_i(v(k-1)))$. Let $\sigma_1(k) = u(k) - u(k-1)$ and $\sigma_2(k) = u(k-1) - u(k-2)$. Then

$$y(k) - y(k-1) = \sum_{i=0}^{n} \rho_i(\sigma_1(k) + \frac{\delta_2(\sigma_2(k) - \sigma_1(k))}{T_s}). \quad (11)$$

When the input $u(k)$ decreases, we have $u(k) < u(k-1)$ and $\xi_i(k) < \xi_i(k-1)$, then the output $y(k) = \rho_0 v(k) + \sum_{i=1}^{n} \rho_i(u(k) + r_i(v(k)))$ and $y(k-1) = \rho_0 v(k-1) + \sum_{i=1}^{n} \rho_i(u(k-1) + r_i(v(k-1)))$. Then

$$y(k) - y(k-1) = \sum_{i=0}^{n} \rho_i(\sigma_1(k) + \frac{\delta_2(\sigma_1(k) - \sigma_2(k))}{T_s}). \quad (12)$$

At very small sampling time T_s, we have $\sigma_1(k) = \sigma_2(k) = \sigma(k)$. Then, (11) and (12) can be written as

$$y(k) - y(k-1) = \sigma(k) \sum_{i=0}^{n} \rho_i. \quad (13)$$

Equation (13) shows the dependence of the output change on the weights $\sum_{i=0}^{n} \rho_i$ and sampling time T_s. Consequently, $\sum_{i=0}^{n} \rho_i$ and the dynamic thresholds $r_i(v(k))$ should be bounded and non-negative. The finite number of the RDP operators ensures that the slope at each point on the hysteresis loop is finite.

IV. The new inversion-free feedforward rate-dependent compensator

We present the new free-inversion RDPI compensator developed in our previous work [1].

1) The new free-inversion compensator: The free-inversion RDPI compensator, which is based on the rearrangement of the RDPI model following the inverse multiplicative structure, is given by [1]:

$$u(k) = \rho_0^{-1}\Big(y_r(k) - \Omega[u](k-1)\Big). \quad (14)$$

As we can see, the control law $u(k)$ contains the initial RDPI model $\Omega[u](k-1)$ and its parameter ρ. The advantage of the free-inversion compensator is therefore that there is no additional calculation required to obtain the compensator parameters. Thus, as long as the model is identified, the compensator is yielded. Also, no condition should be satisfied in order to ensure the invertibility of the RDPI model, such as the dilation condition.

V. Application to a Magnetostrictive Actuator

Magnetostrictive actuators are a class of smart material-based actuators that invariably exhibit symmetric as well as asymmetric rate-dependent hysteresis nonlinearities between the applied input current (magnetic field) and the output displacement [11], [12], [16]. These actuators are employed widely in actuating applications requiring large forces with small displacements. An experiment has been conducted on a Terfenol-D based magnetostrictive actuator from Etrema Inc. (model MFR OTY77) in order to characterize the hysteresis nonlinearities of the actuator under input current amplitude of 2.3 A applied at different excitations of frequency in the 50-250 Hz range. The configuration of the proposed actuator is presented in Figure 2. In addition, the details for the set-up are presented in [12]. The experimental results revealed the actuator show a constant sensitivity of 5.45 μm/A within the frequency band considered in the study. Figure 3 (a) shows the input current versus the output displacement of the actuator under sinusoidal harmonia input of 50, 100, 150 and 200 Hz excitation frequency. The figure illustrates the actuator exhibits symmetrical rate-dependent hysteresis loops. Thus, increasing the excitation frequency of the input current contributes an increase in the width of the hysteresis loop. The hysteresis loops of the actuator were further characterized under complex harmonic input 1.3sin(400$\times\pi$ t)+1.0sin(100$\times\pi t$). The output-input characteristics of the actuator under this input are illustrated in Figure 3 (b).

The discrete RDPI model was employed to describe the rate-dependent hysteresis of the actuator. The number n (of the play operators) has been selected as $n = 4$, which is sufficient to formulate a precise RDPI model able to describe the hysteresis loops which are presented in Figure 4 (a) and (b). The identified parameters of the model are: $\delta_1 = 0.4518$, $\delta_2 = 4.0986 \times 10^{-4}$, $\rho_0 = 0.7684$, $\rho_1 = 0.1521$, $\rho_2 = 0.1486$, $\rho_3 = 0.1453$, and $\rho_4 = 0.1421$. Figure 4 (a) and (b) display a comparison between both the output displacement of the actuator and the response of the RDPI model under same input. The effectiveness of the model was examined also under complex harmonic input 1.3sin(400$\times\pi$ t)+1.0sin(100$\times\pi t$). A comparison is presented in Figure 4 (c) which illustrated that the model

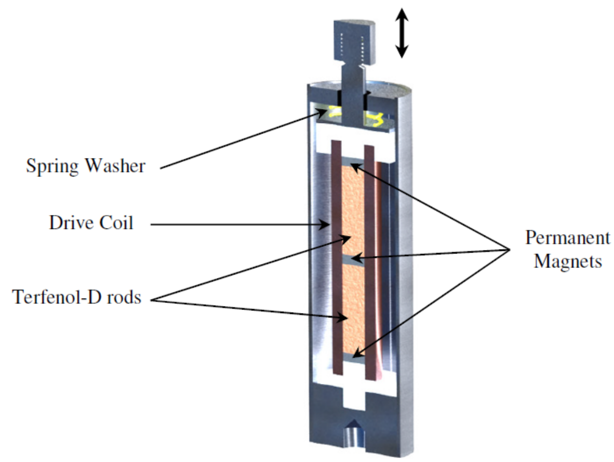


Fig. 2: The configuration of the magnetostrictive actuator experimented [12].

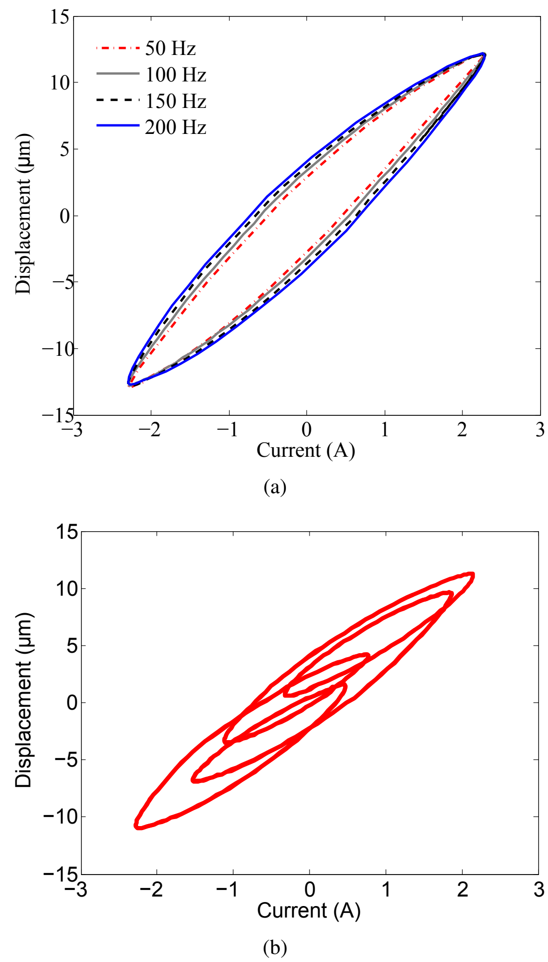


Fig. 3: (a) Hysteresis loops of a Terfenol-D magnetostrictive actuator, and (b) output-input characteristics of magnetostrictive actuator under complex harmonic input 1.3sin(400$\times\pi$ t)+1.0sin(100$\times\pi t$).

can effectively characterize minor hysteresis loops which are resulted due to complex harmonic input.

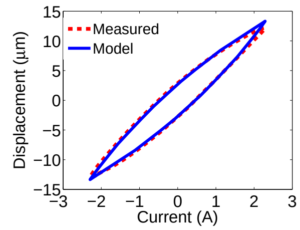
The compensation of the rate-dependent hysteresis non-linearities is investigated using the new free-inversion RDPI compensator presented in section-III. Several attempts have been carried out in the literature in order to achieve effective compensation of the hysteresis nonlinearities of the magnetostrictive actuators [19], [20], [24], [25]. These methods focus on designing closed-loop feedback controllers for compensation of rate-independent as well as rate-dependent hysteresis nonlinearities of magnetostrictive actuators. However, the compaction of hysteresis nonlinearities in open-loop feedforward manner without feedback sensors is highly desirable. In addition, installing feedback sensors in several micropositioning and micro-robotics applications represent challenging task due to the limited space in these environments. The proposed compensator was formulated based on the model itself and applied in an open-loop feedforward manner for compensation of the rate-dependent hysteresis of the RDPI model as illustrated in Figure 1. The compensation of the rate-dependent hysteresis was carried out at sampling time of $T_s = 10^{-5}$ second. The time history of the tracking error is illustrated in Figure4 (d) at the two excitation frequencies 50 and 200 Hz.

Let us now examine experimentally the robustness of the free-inversion compensator in (14) when the parameters of the identified model RDPI are uncertain. For that let us recalculate the free-inversion RDPI compensator by using the following parameters which are different from those of the initial model: $\delta_1 = 0.4$, $\delta_2 = 4.6666 \times 10^{-4}$, $\hat{\rho}_0 = 0.8$, $\lambda_1 = 0.0179$, $\rho_2 = 0.0200$, $\rho_3 = -0.0100$, and $\rho_4 = -0.0200$. Then we apply the calculated compensator to the initial magnetostrictive actuator. Figure 4(e) displays the tracking error when the compensator in (14) applied at sampling time of $T_s = 10^{-5}$ Sec and reference input frequency of 50 Hz and 200 Hz.

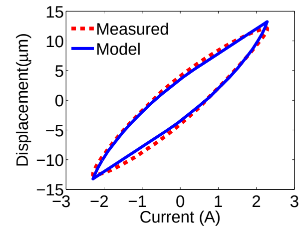
Evaluating the effectiveness of the proposed compensator under complex harmonic input 1.3sin($400\times\pi$ t)+1.0sin($100\times\pi t$) is presented in Figure5 which shows the time history of the tracking error when the complex harmonic input applied. These results demonstrate that the proposed methodology can be employed to compensate for rate-dependent hysteresis of smart material based actuators such as magnetostrictive actuators without formulating the inverse of the model. In addition, the results demonstrate that the proposed compensator can effectively compensate for minor hysteresis loops characterized under complex harmonic input without an inverse model.

VI. Conclusions

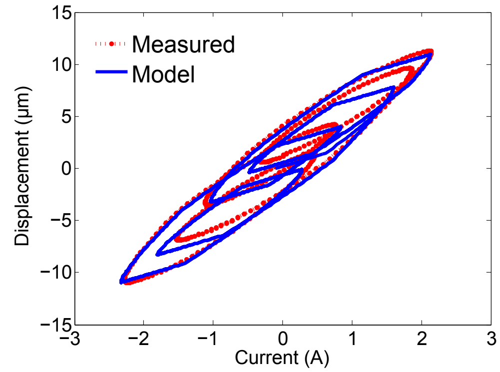
A new methodology for compensation of rate-dependent hysteresis of magnetostrictive actuators in open-loop feedforward manner was presented using RDPI model. The methodology suggested restructuring the model itself using the inverse multiplicative structure without synthesizing the inverse model. In addition, no mathematical conditions have to be satisfied to calculate an invertible rate-dependent model.



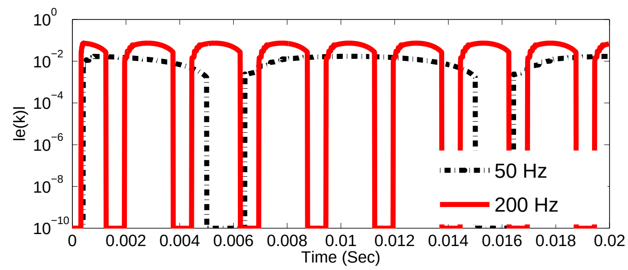
(a)



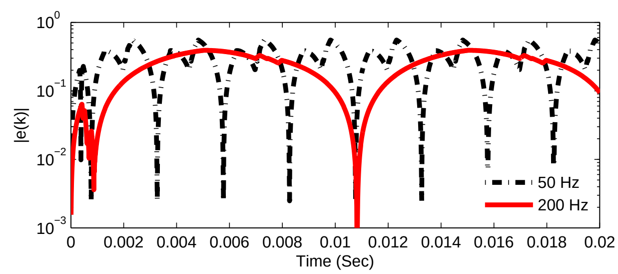
(b)



(c)



(d)



(e)

Fig. 4: (a), (b) and (c)comparison of the measured hysteresis loops obtained from a magnetostrictive actuator with the response of the RDPI model at 50 Hz, 200 Hz, and under complex harmonic input under complex harmonic input 1.3sin($400\times\pi$ t)+1.0sin($100\times\pi t$), respectively, and (d) the tracking error when using the compensator in (14) applied at sampling time of $T_s = 10^{-5}$ Sec and reference input frequency of 50 Hz and 200 Hz.

Experimental measurements obtained from a magnetostrictive actuator at different input waveforms (complex and simple harmonic) considering different excitations of

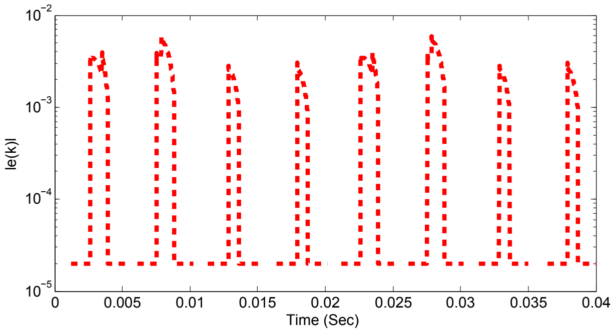


Fig. 5: The tracking error when the compensator in (14) applied at sampling time of $T_s = 10^{-5}$ Sec under complex harmonic input 1.3sin(400$\times\pi$ t)+1.0sin(100$\times\pi t$) .

frequency in the (50-200) Hz band were employed to verify the effectiveness of the new compensator in reducing rate-dependent hysteresis nonlinearities. The results demonstrated that the proposed compensator can be applied for compensation of rate-dependent hysteresis of a magnetostrictive actuator that exhibit rate-dependent hysteresis nonlinearities between input current and output displacement. Evaluating the proposed rate-dependent compensator under complex harmonic input showed that the proposed compensator can effectively compensate for the minor hysteresis loops without formulating a rate-dependent inverse model. The proposed methodology can cancel-out the dynamic hysteresis of smart actuators without synthesizing inverse rate-dependent model. In the future work, the proposed compensator will be extended for compensation of asymmetrical rate-dependent hysteresis loops.

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