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MultiRate Predictive Control of Piezoelectric actuators

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Abstract: Piezoelectric materials show nonlinear hysteresis behaviour when they are under high electrical field and mechanical load. Fundamental study of PEA depicts that the Hysteresis effect deteriorate the tracking performance of The PEA. This paper proposes a nonlinear model which quantifies the Hysteresis nonlinearity generated in Piezo-actuators in response to applied driving voltages. A novel perfect tracking control method based on multirate feedforward control is proposed which uses the nonlinear model to compensate mentioned limiting factors in PEA. In this study a multirate control method based on modified Prandtle-Ishlinskii operator as nonlinear model is implemented. It compensates rate dependant hysteresis nonlinearity in PEA. The controller structure has a simple design and can be quickly identified. The control system is capable to achieve suitable tracking control and it is convenient to use and can be quickly applied to the practical PEA applications. Experimental results are provided to verify the efficiency of the proposed method.

Keywords: Piezoelectric actuators, Hysteresis, Prandtle-Ishlinskii

1. INTRODUCTION

Properties of PEA make them efficient in positioning systems (Habibollahi et al. 2007). PEAs convert electrical energy directly to mechanical energy and consume low power. Motion in sub nano-meter is made possible and has fast response time. Consequently it takes to react only several micro seconds. PEAs have no moving parts in contact to each other to limit the resolution. Due to this effect PEAs show no wear and tear which causes a decrease in life time and precision. The advantages of PEAs make them suitable for electromechanical applications. Nowadays, there are increasing interests to piezoelectric and ferroelectric materials which are especially used in scientific and engineering applications such as Active vibration control (Carusoet al. 2003), needle-valve actuation and precision machining in precision mechanic applications. Atomic Force Microscopy (Croft et al. 2003) and cell manipulation in medical technology applications are other examples.

To achieve a precise tracking control in a PEA system, a model based controller design is necessary. The model should represent the PEA precisely. Many investigations have been performed to model the dynamics of PEAs (Carusoet al. 2003, Adriaens et al. 2002),

One of the critical fields in the study of PEA modeling is the hysteresis effect. Hysteresis occurs via applied voltage and induced displacement. The hysteresis is not a differentiable and nor a one-to-one nonlinear mapping. But it is a nonlinear operator with local memory. It means the output of the system depends not only on the instantaneous input value but also on the history of its operation (Maygergoyz 1991). The Nonlinear hysteresis effect can be corrected using charge control (Georgiou et al. 2005). However, charge control is inherently bulky, costly, uncommon, and offers limited sensitivity. It may lead to drift and saturation problems and reduces the operating range and life of PEA. Consequently, voltage control strategies for PEA proves to be more promising, economical and commercially acceptable control method.

Different models of the hysteresis have been utilized in various researches. The models of hysteresis can be divided to mathematical and nonlinear differential models. The Preisach model (Hu at al. 2003, Croft et al. 2001 and Ge et al. 1995) the Maxwell slip model (Georgiou at al. 2006, Goldfarb et al. 1997) are examples of the hysteresis mathematical models. The Preisach model uses first order recursive curve to approximate the hysteresis nonlinearity. It

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uses a large experimental database and time consuming parameter estimation procedure. Also, the Preisach model needs to spend much time on computation during the control process. In Maxwell slip model, the hysteresis model was approximated by using the motion dynamics. It is constructed by an applied force to one set of the massless bodies parallel to springs. In this model, relationships are in terms of the applied force, spring constants, and break forces to determine the hysteresis dynamics. The critical numbers of the employed springs and mass-less bodies which are necessary for accurately representing the hysteresis dynamics are very difficult to determine (Georgiou at al. 2006).The Duhem model (Stepanenko et al. 1998) and the Bouck-Wen model (Lin et al. 2006) are examples of the hysteresis nonlinear differential models. The differential models are ordinarily sensitive to noise measurement in practical applications.

(Croft et al. 2003) applied an integrated inversed approach to compensate the three adverse affects of creep, hysteresis, and vibration in Atomic Force Microscopy. Preisach model was used for hysteresis behavior and used linear high order spring-damper model for creep and vibration of PEA. Bashash and Jalili (2006) presented an on-line estimation strategy based on perturbation estimation .A nonlinear model was used with time varying coefficients to approximate the hysteresis nonlinearity in PEA. The sliding mode control to achieve the insensitivity against parameter uncertainties .Shieh et al. (2006) extended a friction model to represent the motion dynamics of PEA system. In fact their friction model contrasts a differential equation. An adaptive displacement tracking control was proposed with the parameter adaptation of parameterized hysteresis function. However the results depict growth of chattering when frequency or amplitude of input was increased.

The aim of present study is to compensate both the hysteresis nonlinearity and the effect of mechanical loading on PEA behavior. In order to compensate loading effect on PEA, a PID feedback control has been used in parallel with multirate control structure.

In many applications such as dynamic measurement for both sensing and actuating (Ling et al. 2005) and precision positioning in machining (Cuttino et al. 1999), external load should be considered in hysteresis model of piezoactuator. Hence, in most piezoelectric applications, there is a need to develop a model that accounts for hysteresis. It should describe both electrical and mechanical properties of piezoceramics. Along with the electromechanical coupling between the two domains. PEA can move or operate under high loads, up to several tons. The polarization in PEA is affected by both the applied voltage and external forces. When an external force is applied to poled piezoceramics, the dimensional change depends on the stiffness of the ceramic material and the change of remnant strain (caused by the polarization change). PEAs produce an electrical response (charge) when mechanically stressed in dynamic operation such as imprint applications. For high–accuracy positioning and tracking control in PEAs system subjected to mechanical loading, an electromechanical model of PEA must be used in controller design.

The experimental results in (Hu et al. 2003) show that the classical Preisach model offers excellent modeling accuracy when the actuator is subject to an excitation voltage signal at a low frequency without any load. The accuracy of the Preisach model is shown to rapidly deteriorate as the load being applied to the PEA is increased or the range of frequencies contained in the voltage excitation signal gets wider. However the classical PEA remains a good model for hysteresis in piezoceramic actuators in applications where the load fluctuation is relatively small and the range of frequencies in the excitation is limited. Therefore the classical Preisach model can potentially be used when the variation in the load applied to the actuator is small or when the load applied to the actuator itself is small as is the case in numerous applications PEA (Lin et al. 2006, Croft et al. 2001, and Leang et al. 2006)

A comprehensive model of PEA should account for the hysteresis behavior inherent to the material of piezoceramics it also has to characterize the electromechanical effect on PEA. In this paper the Prandtel–Ishlinkii operator is utilized to describe hysteresis behavior. It uses a multirate scheme to produce desired control input

2. MODELING OF THE PEA DYNAMIC

This section describes the modeling of hysteresis using the modified PI operator proposed by Kuhnen and Janocha (2002).

2.1Prandtl-Ishlinskii (PI) Operator

The PI model is a superposition of elementary play or stop operators, which are parameterized by a single threshold variable (Kuhnen et al. 2002). The elementary operator in the PI hysteresis model is a rate-independent backlash or linear-play operator. It is commonly used in the modeling of backlash between gears with one degree of freedom. A backlash operator is defined by

$$y(t) = H_{\mathrm{r}}[x, y_0](t) = \max\{x(t) - r, \min\{x(t) + r, y(t-T)\}\} \quad (1)$$

Where x is the control input, y is the actuator response, r is the control input threshold value or the magnitude of the backlash and T is the sampling period. The initial consistency condition of (1) is given by

$$y(0) = \max\{x(0) - r, \min\{x(0) + r, y_0\}\} \quad (2)$$

Where y_0 is usually but not necessarily initialized to 0. Multiplying the backlash operator H_r, by a weight value w_h, the generalized backlash operator is obtained:

$$y(t) = w_h . H_r[x, y_o](t) \quad (3)$$

The weight w_h defines the gain of the backlash operator and may be viewed as the gear ratio in gear mechanical play analogy. Complex hysteresis nonlinearity can be modeled by a linear weighted superposition of many backlash operators with different threshold and weight values,

$$y(t) = w_h . H_r[x, y_o](t) \tag{4}$$

Where

$$H_r[x, y_0](t) = \tag{5}$$

$$\left[H_{r0}[x, y_{00}](t) \quad \cdots \quad H_{rn}[x, y_{0n}](t) \right]^T$$

With the weight vector $w_h^T = \left[w_{h0} \quad \cdots \quad w_{hn} \right]$, with the threshold vector $r = \left[r_0 \quad \cdots \quad r_n \right]^T$, where $0 = r_0 < \quad \cdots \quad < r_n$ and the initial state vector $y = \left[y_0 \quad \cdots \quad y_n \right]^T$. The control input threshold values r_i are usually chosen to be equal intervals between maximum and minimum of PEA displacement.

2.2Modified PI Operator

The PI operator inherited the symmetry property of the backlash operator about the center point of the loop formed by the operator. The fact that most real actuator hysteretic loops are not synonymic weakens the model accuracy of the PI operator. To overcome this restrictive property, a saturation operator is combined in series with the hysteresis operator. A saturation operator is a weighted superposition of linear-stop or one-sided dead zone operators. A dead zone operator is a non-convex, non-symmetrical, and memory free nonlinear operator given by

$$S_d[\mathbf{x}](t) = \begin{cases} \max\{x(t) - d, 0\} & d > 0 \\ x(t) & d = 0 \end{cases} \tag{6}$$

$$z(t) = w_s^T . S_d[x](t) \tag{7}$$

Where y the output of the hysteresis operator is, z is the actuator response. $w_s^T = \left[w_{s0} \quad \cdots \quad w_{sm} \right]$ Is the weight vector. $S_d[x](t) = \left[S_{d0}[x](t) \quad \cdots \quad S_{dm}[x](t) \right]$ With the threshold vector $d^T = \left[d_0 \quad \cdots \quad d_n \right]$. Where $0 = d_0 < \quad \cdots \quad < d_n$. Thus the modified PI operator is

$$\Gamma(t) = w_s^T . S_d[w_h^T . H_r[x, y_0]](t) \tag{8}$$

d_i Are usually chosen to be equal intervals between maximum and minimum of hysteresis operator output.

3. MULTIRATE CONTROL

Multirate Sampled-data control has received significant attention in recent years. See (Ahrens et al. 2006) and the references therein for efforts in this direction. In (Dabroom et al 2001) an output feedback controller is implemented by discretizing a controller designed under continuous-time state feedback and using a discrete-time high-gain observer to estimate the system states. In (Ahrens et al. 2006) a multirate output feedback control scheme for a class of nonlinear systems based on discrete-time high gain observers was introduced and the stability of a system under sampled-data output feedback was studied, where the control rate is fixed by the sampled data state feedback design, while the output sampling rate is faster. In this paper we are motivated by applications to smart material systems that may employ computationally demanding controllers such as hysteresis inversion algorithms (Habibollahi et al. 2007). In addition, difficulty in measuring system states in smart material applications points to a tracking control method based on multirate feedforward. The block diagram shown in Fig. 1 schematically represents the multirate control strategy for a PEA.

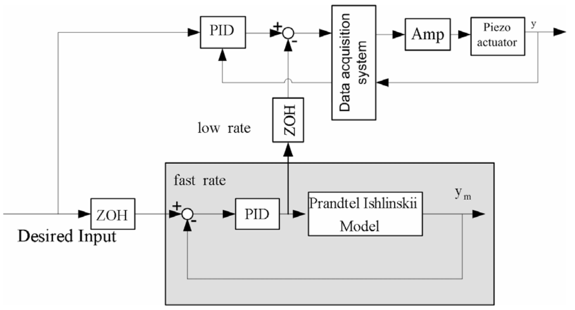

Fig. 1 Block diagram of adaptive control strategy for PEA

After setting the threshold parameters r and d as described in the previous section the weight parameters W_h and W_s are estimated by performing a least squares fit of equation (8).

The identification input signals were chosen as a waveform signal with amplitude of 100V and rising rate that can be seen in Fig 2. The proposed multirate control structure has been combined with PID feedback so improve the aggravating effect such as external loading on tracking control.

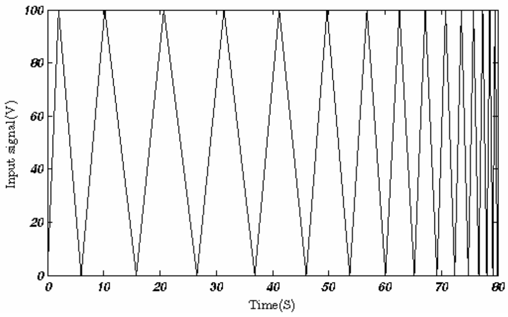

Fig. 2 waveform input voltage with amplitude of 100V and rising rate

4. EXPERIMENTAL RESULTS

In this section, multirate feedforward control is applied to The PI P-611.1s Piezo actuator stage. The nonlinear behavior of P-611.s1 Stage is depicted in fig 3 which depicts voltage-to-displacement hysteresis in a PEA when the input voltage is sinusoidal.

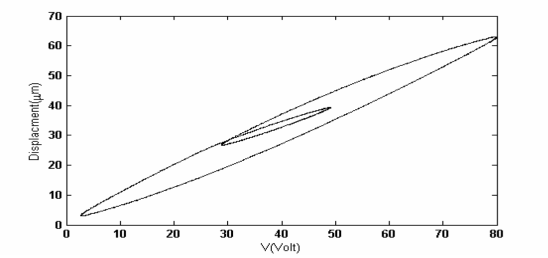

Fig. 3 Voltage-to-displacement hysteresis curves for P-611.s1 stage.

The control structure designed in simulink and then compiled and loaded into acquisition board to produce desired control input for P-611.s1 Stage. The displacement of P-611.s1 is Measured and feed backed via a strain gage sensor. To close the loop, we use PID as sampled-data controller in parallel with the hysteresis compensation operator as shown in Figure 1. The error signals of different tracing control can be seen in Figure 4 and Figures 5 - 8 compare the response of a single-rate PID-controller with a constant sampling period of $0.001s$ against the response of the multirate controller where the period of fast rate was $T_f = 0.0001s$ and the period of low rate was $T_l = 0.001s$. As can be clearly seen from figures, the multirate controller, with the more accurate Hysteresis estimation, was able to achieve more accurate tracking. Figure 6 shows input tracking result and tracking error for feedforward multirate control without PID feedback. The tracking errors of fig. 5 and 7 depict that the feedforward multirate controller perform more accurate than low gain PID controller. Although the performance of PID controller can be improved by increasing their gains but high PID gains produces rugged and noisy control input as can be seen in figure 6. Furthermore high gains PID may result in instability in system when reference input persistent excitation increases. Also the rugged and noisy control input lead to decrease of PEA durability. Figure 8 shows that the multirates control structure accompanying PID-controller with low gains can achieve the lowest tracking error with smooth control input which is suitable for system. Table 1 shows measured performance of PID and multirate controllers in tracking of sinusoidal input.

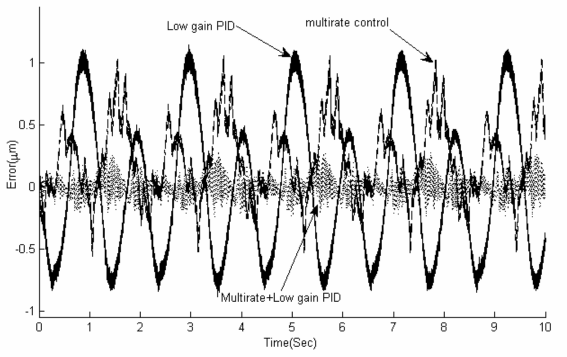

Fig. 4 Error signals

Table 1 measured performance of PID and multirate controllers in tracking 58-μm P-P sinusoidal input

Control method	RMS (μm)	$e_{\max}$ (μm)	e_{mean} (μm)
Open loop multirate control	0.376	1.1	0.293
Low gain PID control	0.574	1.142	0.501
High gain PID control	0.129	0.302	0.112
Low gain PID +multirate	0.071	0.285	0.0573

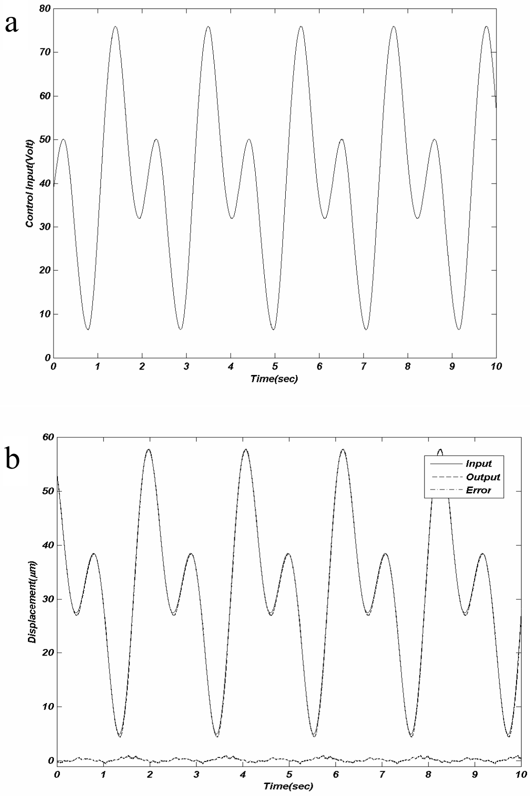

Fig. 5 Tracking control with multirate controller. (a) Control Input (b) Reference tracking and tracking error.

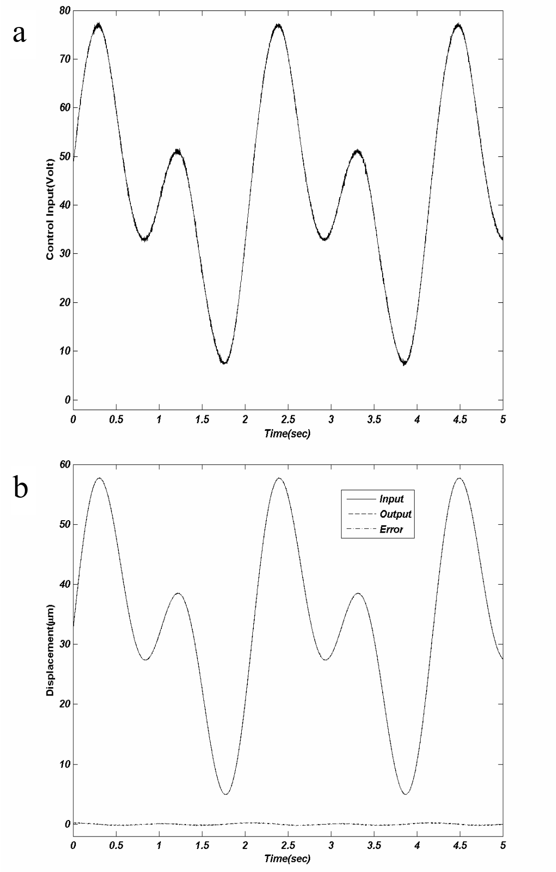

Fig. 6 Tracking control with High gain PID.(a) Control Input generated. (b) Reference tracking and tracking error.

5. CONCLUSION

For control of piezo material actuated systems a multirate sampled-data control was proposed using fast rate hysteresis estimation. Both closed-loop and open loop control based on hysteresis compensation have been considered.

Experimental results of a Piezo actuator demonstrate the multirate scheme performance in comparison with PID controller. In addition PID control in accompany with multirate hysteresis estimation can provide more accuracy with lower control effort than a single PID controller.

Furthermore Performance of the tracking control of PEA was improved by using a proposed new controller structure for compensation of the hysteresis nonlinearity. Quick and simple identification procedure of the proposed controller structure makes it convenient and valuable in PEA practical application. Moreover the proposed controller structure can be combined with additional control system especially classical control system such as PID or pole placement controller.

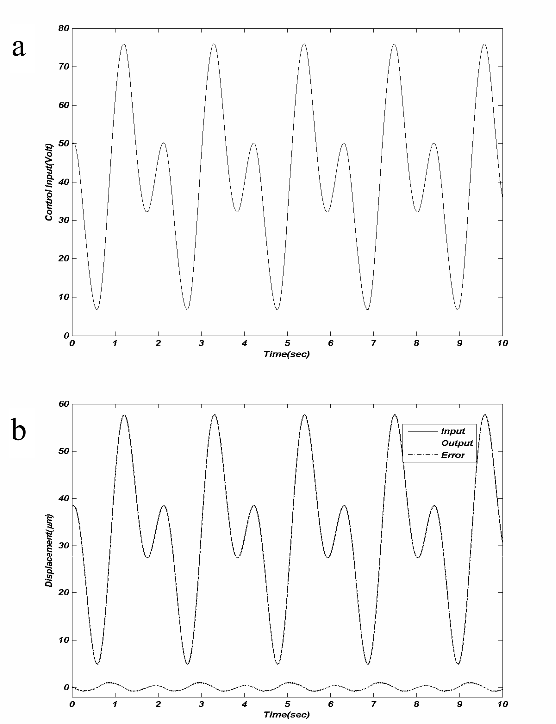

Fig. 7 Tracking control with low gain PID (a) Control Input (b) Reference tracking without and tracking error.

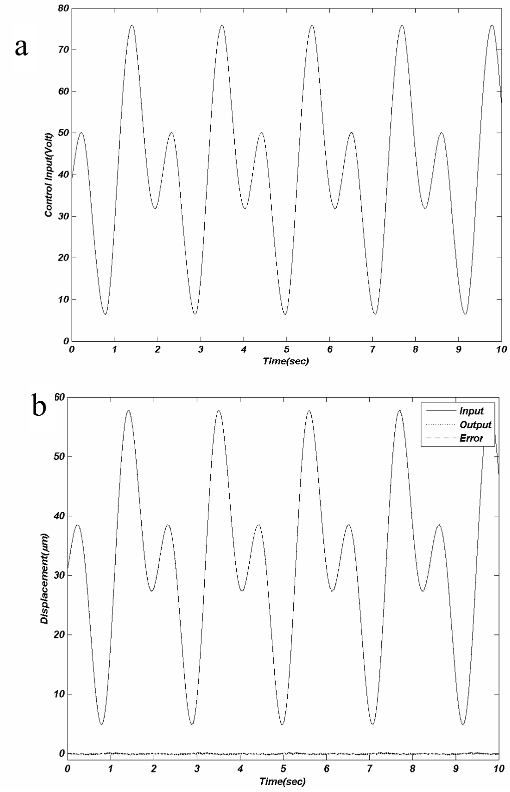

Fig. 8 Tracking control low gain PID controller along with open loop multirate controller.(a) Control Input generated. (b) Reference tracking and tracking error.

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