ORIGINAL ARTICLE

Frequency Domain Effect of a Hysteresis Suppression System with Inverse Preisach Model Based Control

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Abstract: The extended Preisach model is used extensively in precision control for its ability to model and thus can be used to suppress the hysteresis phenomenon. Although an inverse model based on the classical Preisach model entails a very high level of computational complexity, recent advances in computer technology has enabled real-time implementation of such models. The extended Preisach model calculates the hysteresis action by fitting the α-β table in the Preisach model to a surface. One can then calculate the amount of extension and retraction simply by searching for the parameters on the surface. This paper proposes a real-time high speed implementation of a model-based hysteresis elimination control. The experimental results show that the proposed method produces a smaller tracking error with a smooth system output.

Keywords: Hysteresis, extended Preisach model, frequency contents

Introduction

Recent advancements in the semiconductor and precision manufacturing industry have pushed positioning demands to nanometer accuracy, raising the need to explore driving technologies that can achieve this degree of accuracy. Piezoelectric (PZT) stages, characterized by high resolution, high rigidity, and clean operations, have thus become very popular in the precision engineering arena [1].

The PZT stages are actuated by piezoelectric materials whose dimensions change with the applied voltages across their terminals. The PZT stages can deliver displacements at a nanometer resolution while maintaining relatively high stiffness [1] [2]. Their maneuvers are based upon the applied voltages, thus are also vacuum-compatible. However, PZT stages suffer from several shortcomings. They often require flexible hinges and displacement magnifying mechanisms that introduce undesirable compliances and vibrations. Moreover, PZT actuators suffer from the hysteresis problem making them very hard to control. Achieving highly accurate servo control requires an efficient way to eliminate the hysteresis. A high-performance controller can then be easily designed to suppress the vibration along with the remaining stability and performance issues.

The literature provides many mathematical models that can be used for hysteresis elimination. Table 1 lists their various advantages and disadvantages.

Hysteresis is a highly nonlinear phenomenon that precludes any linear model from obtaining very good performance. The Duhem model and Bouc-Wen model both suffer from difficulties that limit their use. Although the Duhem model is very powerful in handling electrical behavior, it does not address the mechanical properties very well. The Bouc-Wen model represents the hysteresis loop well, but requires very precise initial information. As

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a result, the Preisach model is recommended as the most suitable way to eliminate hysteresis.

The landmark "Preisach model" was first proposed by F. Preisach in 1935 [2] to describe the physical mechanisms exhibited in the magnetic after-effect. Preisach stated that the hysteresis can be modeled as a circuit with parallel connection of capacitors and resistance as shown in Fig. 1.

The statement implied that a complex hysteresis effect can be decomposed into a series of simple hysteresis entities known as "hysterons", as expressed in Fig. 2.

The Preisach model was first introduced to describe the magnetization behavior. The model was later popularized by Everett and Whitton [5] who suggested that the Preisach model could be used in areas other than magnetics such as chemical reactions, mechanical motion, and ferroelectric properties. However, it was not until Krasnosel'skii [6] that anyone offered a systematic mathematical treatment to the model. Krasnosel'skii examined the model's physical meanings and constructed for it a mathematical framework which eventually become the basis for the modern mathematical description of hysteresis. Kransnosel'skii's framework was based on some axioms and assumptions, and could thus be easily applied to the related physical problems.

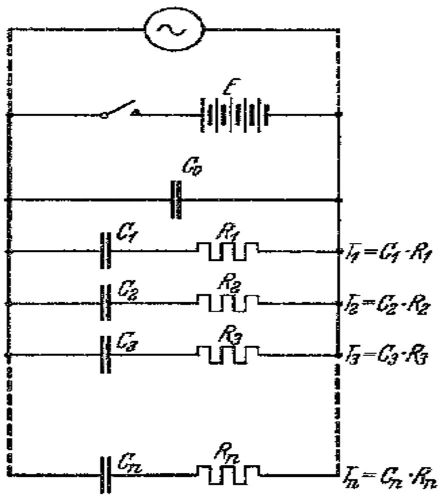

Figure 1. Hysteresis model by F. Preisach [4]

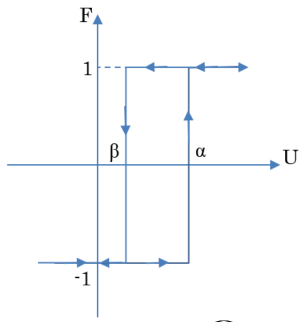

Figure 2. Elementary hysteresis operators $\hat{\gamma}_{\alpha\beta}$

In 1991, I.D. Mayergoyz [7] [8] integrated studies by Preisach, [5], [6] and other authors to establish a more complete mathematical form for the Preisach model. His model could be represented as:

$$f(t) = \hat{H}u(t) = \iint_{\alpha \ge \beta} \mu(\alpha, \beta)\hat{\gamma}_{\alpha\beta}u(t)d\alpha d\beta \qquad (1)$$

Mayergoyz further provided a discrete representation of Eq. (1) for computer implementation, as shown in Eqs. (2) and (3).

$$f(t) = -f^{+} + \sum_{i=1}^{n-1}(f_{\alpha_i\beta_i} - f_{\alpha_i\beta_{i-1}}) + f_{u(t)} - f_{u(t)\beta_{n-1}} \qquad (2)$$

$$f(t) = -f^{+} + \sum_{i=1}^{n-1}(f_{\alpha_i\beta_i} - f_{\alpha_i\beta_{i-1}}) + f_{\alpha_n u(t)} - f_{\alpha_n\beta_{n-1}} \qquad (3)$$

Hsin-Fang Tsai received both her BS and MS degree from the Department of Mechanical Engineering, National Taiwan University in 2012. She then went to Osaka University, Japan for a one year exchange study. Her research interests include precision control, modeling of hysteresis phenomena.

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Lien-Sheng Chen received her BS, MS, and PhD degrees from National Taiwan University in 2006, 2008, and 2013, respectively, all in Mechanical Engineering. He joined the Syntec Inc. after graduation and has been a senior research engineer at Syntec ever since. Lien-Sheng specializes in precision control and had been working on semi-conductor scanner related technology and machine tool controller related researches.

Hung-Cheng Chang was born in Changhua city, Taiwan (R.O.C). He received the B.S. degree in civil engineering from Chung Yuan Christian University, Taiwan (R.O.C) in 2003, and the M.S. degree in mechanical engineering from National Tsing Hua University, Taiwan in 2006. He received his Ph.D degree from National Taiwan University in 2013. He now works as a senior research engineer in HTC Corporation Taiwan.

Jack J.H. Chen received his BS and PhD degrees in Physics in National Taiwan University. He then joined the Taiwan Semiconductor Manufacturing Co., and had been a senior researcher since then. Dr. Chen was the TSMC/ASML representative in Nederland and had been the leader for the Nanopatterning Technology Infrastructure Division. He now heads the TSMC research department on extreme ultra-violet lithography technology.

Fu-Cheng Wang was born in Taipei, Taiwan, in 1968. He received the B.S. and M.Sc. degrees in mechanical engineering from National Taiwan University, Taipei, Taiwan, in 1990 and 1992, respectively, and the Ph.D. degree in control engineering from Cambridge University, Cambridge, U.K., in 2002. From 2001 to 2003 he worked as a Research Associate in the Control Group of the Engineering Department, University of Cambridge, U.K. Since 2003 he has been with the Control Group of Mechanical Engineering Department at National Taiwan University, in which he is now a Professor. His research interests include inerter research, fuel-cell systems, vibration suppression, robust control, suspension systems, medical engineering, and embedded systems.

Wen-Pin Weng was born in 1972. He received the BS and MS degrees in Power Mechanical Engineering from National Tsing Hua Uinversity, Hsinchu, Taiwan, in 1995 and 1997, respectively. He is currently working towards his Ph.D. degree in the Department of Mechanical Engineering at National Taiwan University, Taipei, Taiwan. His research interests focus on applications of piezoelectric actuator.

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	Approximated polynomial model	Maxwell slip model	Duhem model	Bouc-Wen model	Preisach model	TF model
Complexity	Easy	Not complex	Complex	Not complex	Complex	Easy
Parameters	Numerous	Numerous	Three	Several	Numerous	Three
ID	Required	Required	Required	Required	Required	Required
Linearity	Linear	Linear	Nonlinear	Nonlinear	Nonlinear	Linear
Limitation	Works for specific situation	Works for system without preloading	No limit (needs special charge amplifier)	No limit (requires initial values)	Needs a more efficient way to determine data table	Works for specific frequencies
Popularity	Rare	Rare	Rare	Common	Common	Rare
Memory	Medium	Medium	Small	Small	Large	Small

Table 1 Methods of hysteresis elimination [3]

In Eqs. (2) and (3), f^+ is the positive saturation value and $f_{\alpha_i\beta_i}$ is the change in the piezo output when input $u(t)$ changes from $\alpha = \alpha_i$ to $\beta = \beta_i$, where α and β are the turning each time the signal switches. To obtain the $f_{\alpha_i\beta_i}$, experimental data had to be collected for repeated descending curves originating from various points on the primary ascending curve to construct an "α-β" table. A first order bilinear spline interpolation function was then suggested to calculate the output value. The procedure yields a very good match with the test results. An inverse model, termed the "Classical INverse Preisach model (CINP)," could be derived from this formula and could then be used to cancel the hysteresis effect. The CIPM has been used in many applications; however, the interpolation could provide only discrete solutions and the procedure involved a large amount of data. A more recent approach used a modified kernel that depends not only on the α, β but also on the input value to represent the loading effect [9]. Some other researchers also used neural networks to represent the hysteresis behavior [10].

The extended Preisach model is used to obtain easier access to the estimated PZT elongation. Using a 3-parameter equation, it is possible to describe the α-β table, which then serves as the basis for the construction of an effective inverse Preisach model. The matched surface provides an easy access to calculate the piezo displacements which can then be used for the suppression of hysteresis effects. Although the α-β table represents only the behavior of the "first order reversal curve", experimental implementation of the proposed model yields highly satisfactory results, especially when used in conjunction with effective feedback controls.

The Experimental Apparatus

The experiment setup is based on a self-made piezoelectric-actuated stage (PZT stage) equipped with a PZT-ceramic stack (Pst 150/5x5/20 from Piezomachanilk). The amplifier of the PZT-ceramic stack is a PI E-663 three-channel piezo driver. The final specification of the PZT-stage system is shown in Table 2.

A laser interferometer system is used to measure the PZT stage position. The interferometer system consists of an HP 5517D laser head and an Agilent 10705A single beam interferometer. The system resolution is set to 1.2nm according to the suggested value. To raise the resolution, plane mirrors are used in our measurement system to achieve 2 times the resolution. The final measurement system is represented in Fig. 3, with 0.6nm resolution. The measurement sampling rate is set to at 1 KHz.

PZT Stage Specification	
Voltage Gain	10±0.1V
Output Voltage	-20V to 120V
Bandwidth	63Hz (resonance)
Travel Distance	-7μm to 7μm

Table 2. Specification of PI E-663

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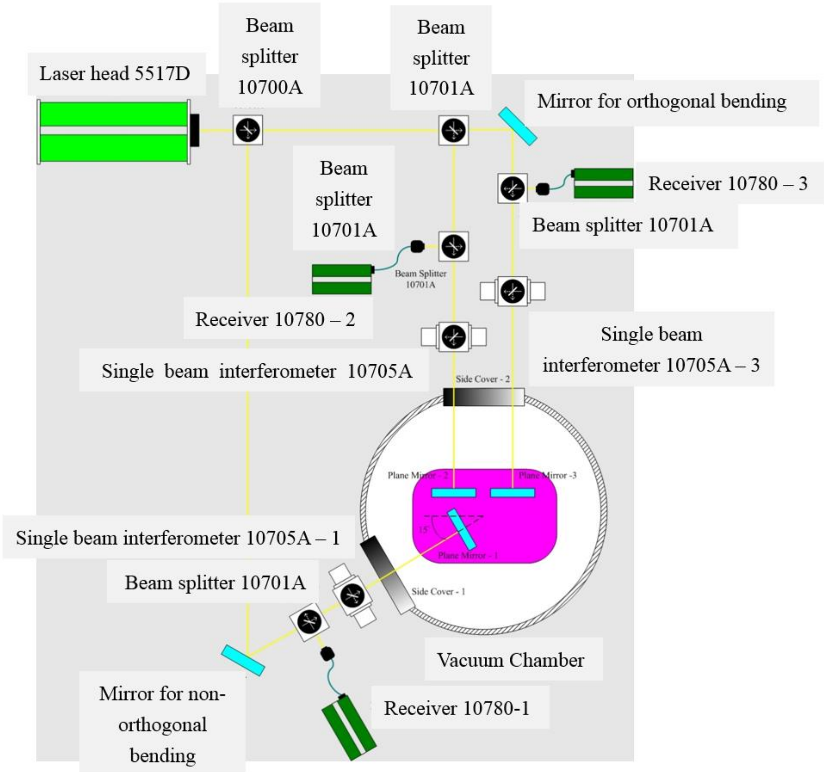

Figure 3. Laser interferometer system for position measurement

Methodology

To build the extended Preisach model, an α-β table is necessary. Following the suggestions in [8] and [9], the piezo stage is subject to a combination of the sinusoidal signal riding over a decreasing slope to achieve a "First Order Reversal Curve" response. The excitation profile and the response hysteresis curves are shown in Fig. 4, and Fig. 5 shows the resulting first order reversal curve subject to this excitation. The data shows the relationship of α, β and output $f(t)$, meaning fab, and was used in classical and surface-fitting inverse Preisach models. Notice that, for easy of control, the signals are offset to a null position before all the experiments.

To find the inverse model, it the easiest to use the reverse equations. Rearranging Eqs. (2) and (3) so that the terms involving the input $u(t)$ are on the left and the terms involving the output $f(t)$ are on the right. The reverse equations for the inverse Preisach model can thus be written as:

$$f_{u(t)} - f_{u(t)\beta_{n=1}} =$$

$$f(t) + f^{+} - \sum_{i=1}^{n-1}(f_{\alpha_i\beta_i} - f_{\alpha_i\beta_{i-1}}) \quad (4)$$

$$f_{\alpha_n u(t)} =$$

$$f(t) + f^{+} - \sum_{i=1}^{n-1}(f_{\alpha_i\beta_i} - f_{\alpha_i\beta_{i-1}}) + f_{\alpha_n\beta_{n-1}} \quad (5)$$

The reverse equations (4) and (5) form the basic operations of the inverse Preisach model. When the input $u(t)$ is injected into the system, depending on whether the actuator is ascending in the α-β plot (extending) or descending in the α-β plot (contracting), one can calculate the differences in the hysteresis output from the α-β Table using Eqs. (4) or (5). Note that the α-β Table is recorded experimentally from discrete data, and the classical inverse Preisach model relies on interpolation to obtain the $f_{\alpha_i\beta_i}$ values. This can be a very time-consuming process and requires a large amount memory.

Taking a closer look at the measured α-β Table, one observes a continuous change in the f value with respect to the changes in α and β. The assumption is practical because we do not expect any abrupt change in the hysteresis output anyway. Also, note that this is based upon the first order reversal curve. From this observation, the authors propose adopting a 3-parameter surface matching approach. The variation in the f value can be represented by a bilinear map. The fitting result using a 4th order bilinear map of the hysteresis surface is shown in Fig. 6.

The fitted surface describes the nonlinear relationship of the f variation against the α, β range of interest. This surface can be used to find the $f_{\alpha_n\beta_n}$ and $f_{\alpha_n\beta_{n-1}}$ values in Eqs. (4) and (5) for the input $u(t)$. To illustrate how the surface matches the data, a 2-D curve fitting result is also shown to ensure the correct value for

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$f_{u(t)}$ (Fig. 7). The application of the hysteresis estimation and suppression is then presented in the next section.

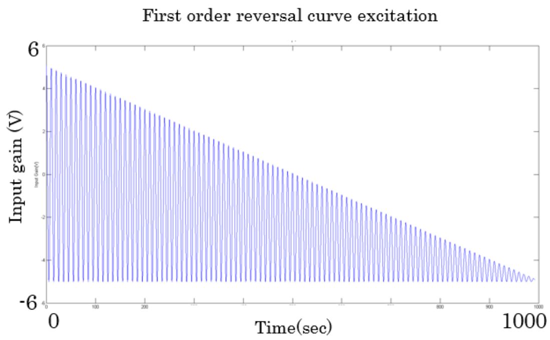

Figure 4. Semi-sinusoidal input to excite a First Order Reversal Curve

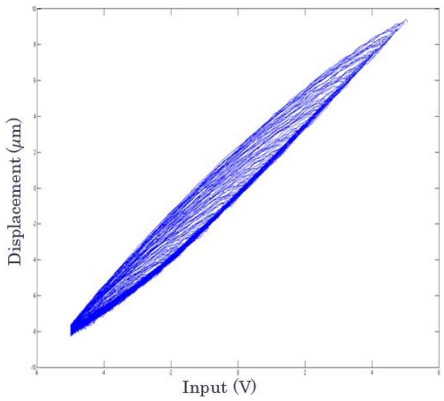

Figure 5. First Order Reversal Curve excitation

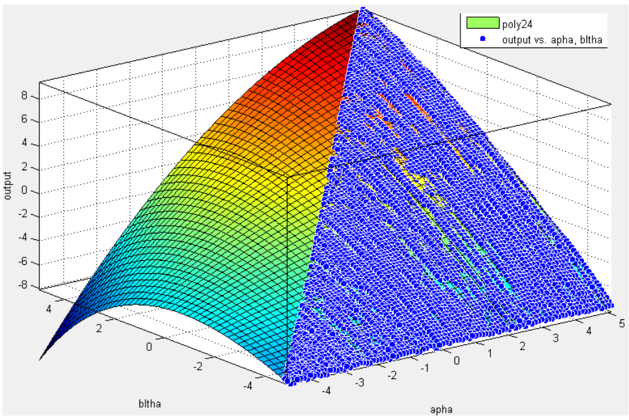

Figure 6. The fitting of the f surface using bilinear map

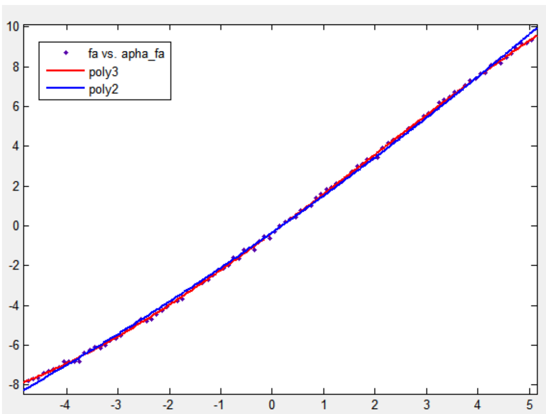

Figure 7. Curve fitting for the $f_{u(t)}$ curve

Simulation and Experimental Results

This section describes the simulation results and the experimental results.

Simulation results of the CINP and the inverse extended Preisach model

We first present simulation results to demonstrate the differences between the Classical Inverse Preisach (CINP) model and the extended inverse Preisach model. A 1Hz sinusoidal signal is used for the desired reference signal for the closed-loop control system. Figure 8a shows that, with the resulting tracking performance without the inverse hysteresis models, the actual output lags behind the desired signal and leaves an error magnitude of 2m (lower part in figure 8a) for a reference signal of 5m. Figure 8b shows the hysteresis effect from this reference signal. For comparison, Fig. 9a shows the control result using the classical inverse Preisach model. The output of the control system (lower part of Fig. 9a) now follows the reference with the same magnitude without apparent phase lag. Figure 9b shows that the control based on the inverse Preisach model can suppress the hysteresis effect but the cancelation produces small disturbances due to the numerical interpolation process.

Figures 10a and f show the control results using the proposed surfaced matched inverse Preisach model. It is clear that the proposed method produces a smaller tracking error (lower part of Fig. 10a) with a smooth system output. Figure 10b shows that the proposed inverse extended Preisach model is more effective in suppressing the hysteresis effect.

	2000 points	1 point
CINP	145.3305 (sec)	72.66525 (ms)
inverse extended Preisach model	0.375090(sec)	0.187545 (ms)

Table 3. Comparison of computational efforts for classical inverse Preisach model and surface fitted inverse Preisach model

A more important observation is that the proposed method is computationally less expensive. Table 3 compares the computing efforts required by the classical and the surface fitted inverse Preisach model. The proposed inverse extended Preisach model requires 0.188 ms for each control point whereas the classical inverse Preisach model used up 72.7 ms on a common Intel processor based computer. Notice that the time required for the inverse extended Preisach model is now less than 1 ms which is short enough for practical real time control.

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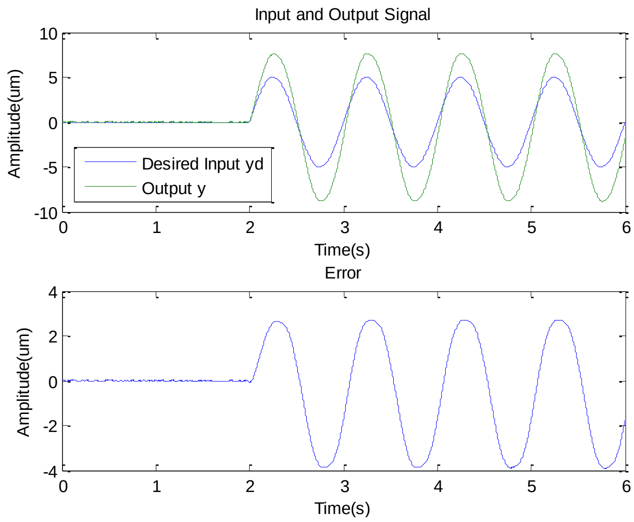
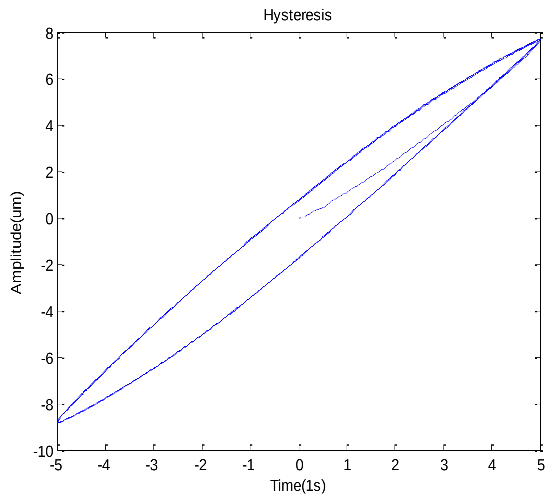
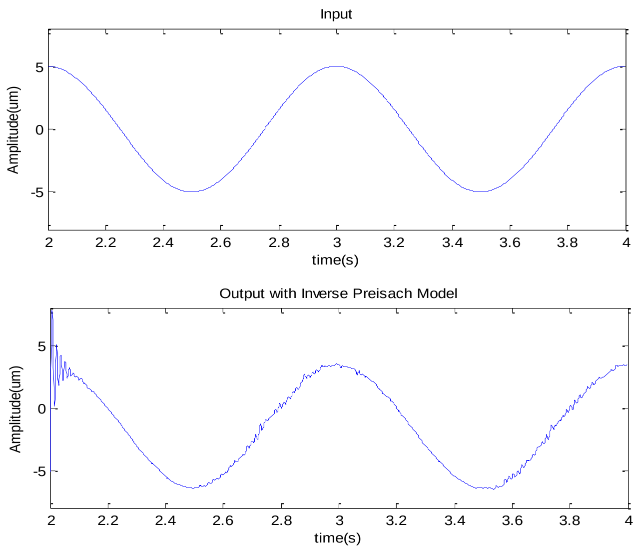


(a)

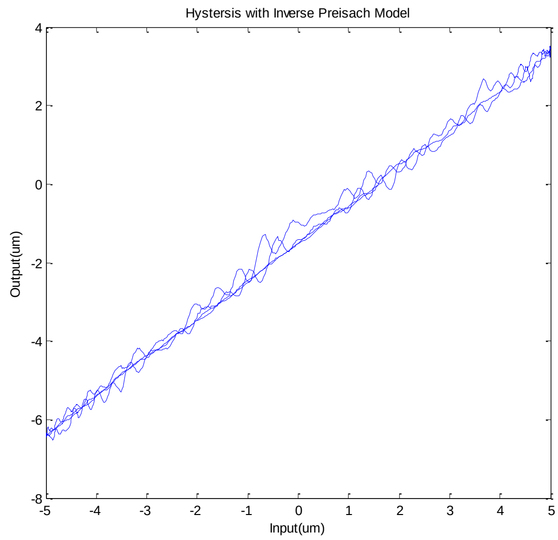


(b)

Figure 8. (a) Input/output and error responses, and (b) Hysteresis response of the original system

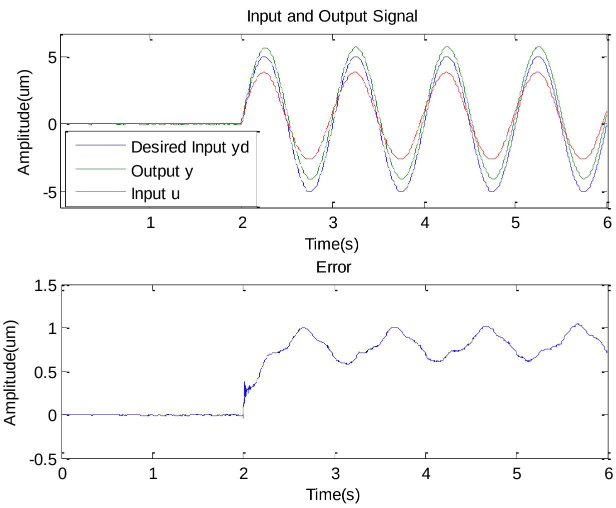


(a)

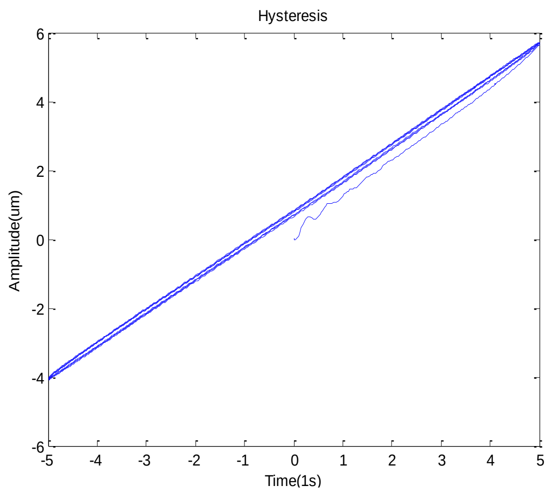


(b)

Figure 9. (a) Input/output responses, (b) Hysteresis response of the system with classical inverse Preisach model (CINP)



(a)



(b)

Figure 10. Simulation results (a) system responses, (b) hysteresis response for system with extended Preisach model

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4.2 System Identification with the extended Preisach model

To implement good servo control, a suitable system identification is necessary to achieve an accurate system model for the control design. The idea behind the servo system is to use the inverse model to eliminate the hysteresis effect and then superimpose the compound system with high-performance linear controls. Similarly, the hysteresis effect must first be eliminated with the inverse model, followed by rigorous linear system identification on the remaining system.

Figure 11 shows the identification result using the original system. The fitting rate was 76.5 for model orders smaller than 8. When used in conjunction with the inverse extended Preisach model (Fig. 12), the fitting rate rose as high as 88.69 using models with orders not higher than the 8th order. It is also worth noting that unstable zeros resulted from the plain system identification, possibly as a result of the significant output delay due to hysteresis. On the other hand, the identification process incorporating the inverse extended Preisach model, was able to avoid these unstable zeros while still achieving better fitting.

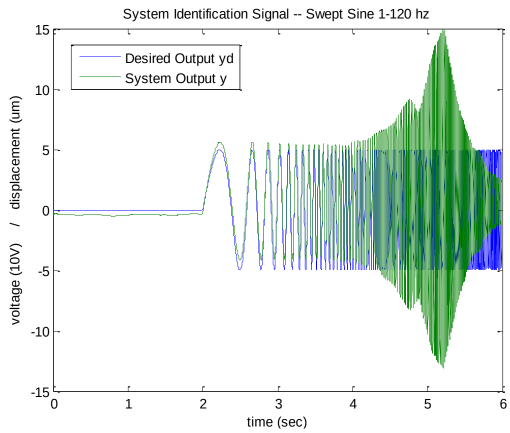

Figure 11. System identification w/o inverse hysteresis model

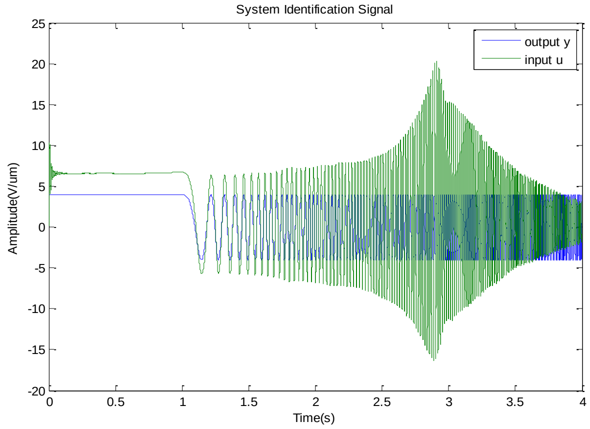

Figure 12. System identification with Surface Fitted Inverse Preisach model

4.3 Controller with inverse extended Preisach model

As stated in the previous section, the reduced computation time enables the extended Preisach model to compute the inverse hysteresis effect in real time, allowing for practical control with the embedded inverse extended Preisach model in the controller. The inverse extended Preisach model eliminates the hysteresis effects, allowing one to conduct high performance linear control design on the remaining system. The linear part of the proposed controller is a robust controller shown in Eq. (6) resulting from the MATLAB loop-shaping control toolbox for signal tracking.

$$C(z) = \frac{1.2665z(z-0.7285)(z+1)(z^2-1.767z+0.9154)}{z(z-1)(z+0.05665)(z^2-1.265z+0.4779)}$$

The experimental responses from the system without the inverse hysteresis model are shown in Fig. 13, with the lower plot showing the tracking error. Figure 14 compares the control of the original system and the control of the system with the embedded Surface Fitted Inverse Preisach model. The result is somewhat unexpected. The control with the inverse model is clearly does a better job of eliminating the output delay introduced by the hysteresis effect, but it produces a vibration at a higher frequency, resulting in an error signal composed of multiple components. Checking the power spectra from the error signals, the inverse extended Preisach model control clearly suppresses undesirable low frequency errors but was not as effective at suppressing higher frequency errors.

It is surmised that this effect is a controller effecting power redistribution. The energy in the middle frequency range has been redistributed to the high frequency range, magnifying the error spectrum at a higher frequency range. The authors are currently pursuing further investigation of this phenomenon. Notice that the experiments do not include the traditional inverse model because the computation effort involved was too great for precision high speed servo implementation.

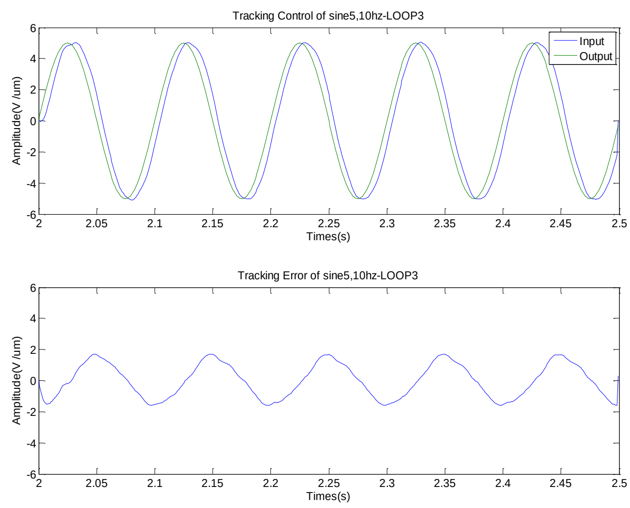

Figure 13. Experimental responses of the original system

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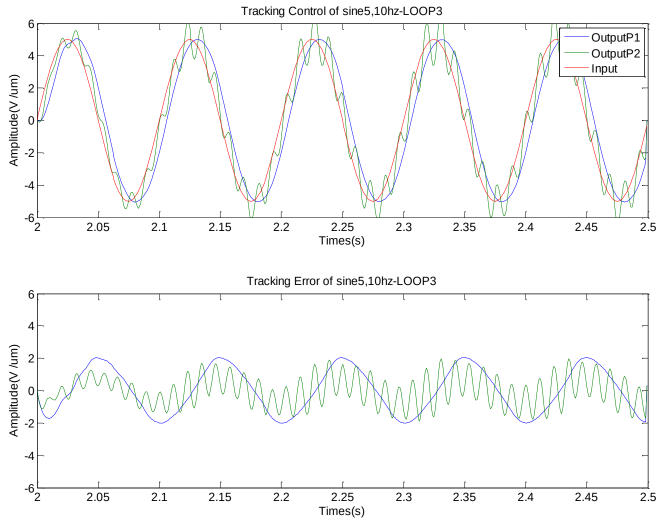

Figure 14. Comparison between the original system and the control with embedded inverse extended Preisach model model

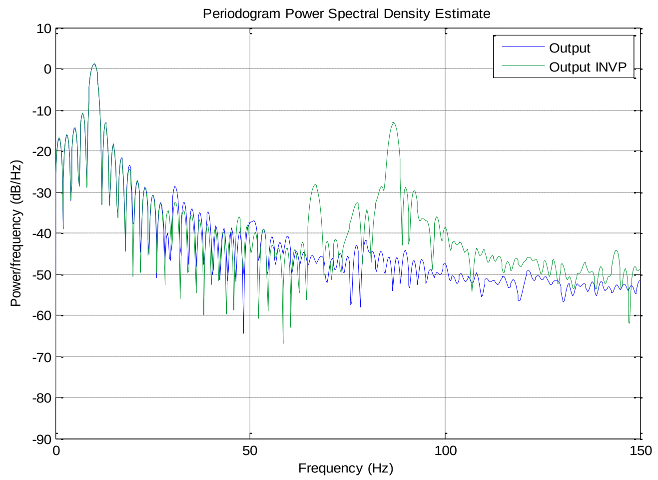

Figure 15. Comparison of the power spectrums from the control errors

Conclusions

A surface fitting approach to derive the extended Preisach model is proposed. This model is less stringent in tracing the hysteresis response curve but is very easy to compute. As a result, the model allows for real time implementation of a control with the model embedded for inverse calculation. Both simulation results and experimental results are presented to illustrate the effectiveness of the inverse model based control. The experimental results show that the extended Preisach model based control can better suppress low frequency errors while allowing more high frequency error to go through.

Acknowledgements

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