Improvement of the Performance of Hysteresis Compensation in SMA Actuators by Using Inverse Preisach Model in Closed — Loop Control System

Kyoung Kwan Ahn*
School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2dong, Nam-gu, Ulsan 680-764, Korea
Nguyen Bao Kha
Graduate School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2dong, Nam-gu, Ulsan 680-764, Korea

The aim of this paper is to increase the performance of hysteresis compensation for Shape Memory Alloy (SMA) actuators by using inverse Preisach model in closed — loop control system. This is used to reduce hysteresis effects and improve accuracy for the displacement of SMA actuators. Firstly, hysteresis is identified by numerical Preisach model implementation. The geometrical interpretation from first order transition curves is used for hysteresis modeling. Secondly, the inverse Preisach model is formulated and incorporated in closed-loop PID control system in order to obtain desired current-to-displacement relationship with hysteresis reducing. The experimental results for hysteresis compensation by using this method are also shown in this paper.

Key Words : Preisach Model, Hysteresis, SMA Actuator, Compensation

1. Introduction

SMA is metal, which exhibits the shape memory effect property. This occurs through a solid-state phase change, that is a molecular rearrangement. The two phases, which occur in shape memory alloys, are martensite and austenite. As higher temperatures, the material is in the austenite phase. As the temperature is lowered, material changes to martensite phase and grows until at sufficiently low temperatures. The appropriate current intensity can be used for this purpose. This unusual property is being applied to a wide variety of applications in a number of different fields, such as : aeronautics, surgical tools, muscle wires, and so on.

One of the problems in designing the controller for SMA actuators is hysteresis phenomenon. This is encountered in many applications that involve SMA, magnetic materials or piezoelectric actuators. Hysteresis in SMA actuators is a complex nonlinearity phenomenon with properties of branching and nonlocal memory. These phenomena lead to inaccuracy and reduce the performance of the control systems.

The model of hysteresis in electromagnetics (Samir and Menq 2000), magnetostrictive (Tan and Baras 2002), ferroelectric (Smith and Massad 2001), and piezoceramics actuators (Hughes and Wen 1997) has been addressed in many reports but only a few in slow response system, like SMA. Two distinct types of models have been proposed to capture the hysteretic characteristics. The first type of models is derived from the physics of hysteresis and combined with empirical factors to

* Corresponding Author,
E-mail : kkahn@ulsan.ac.kr
TEL : +82-52-222-1404; **FAX** : +82-52-259-1680
School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2dong, Nam-gu, Ulsan 680-764, Korea. (Manuscript **Received** September 13, 2005; **Revised** February 22, 2006)

describe the models (Nakmahachalasint, Ngo and Quoc 2002), (Nealis and Smith 2002). However, these models are not easy to be used in control systems. The second type of models are based on phenomenological nature and described phenomena mathematically (Hughes and Wen 1997; Samir Menq 2000; Mayergoyz 2003; Choi et al., 2004). Among these, Preisach model is a well — known approach to model the hysteresis functions. This is just a geometrical model and a convenient tool to analyze the hysteresis phenomena. Therefore, it is suitable for control applications. In (Cruz-Hernandez and Hayward, 1997), hysteresis model is interpreted in terms of phase shift, and a linear controller is used for hysteresis compensation. This cannot be used for a nonlinear system with saturation like SMA actuator. In (Hasegawa et al., 1998), hysteresis model identification in SMA is based on the definition of Preisach model and the physics of the system. The model in this paper is described as a combination of N pieces of unit cells which has individual transformation at each specific temperature. As the physical basis of the hysteresis characterestic is not completely understood, it is too complex to capture accurately the hysteresis phenomena.

In this paper, the numerical Preisach model based on geometrical interpretation is used for hysteresis modeling. The model is inverted and then incorporated in closed — loop PID control system to compensate the hysteresis effect of SMA actuators. This control scheme can be used to reduce the error due to the limited of switching points in Preisach plane.

The remainder of the paper is organized as follows. Section 2 provides an introduction to the Preisach model and its geometrical interpretation. Numerical Preisach model is presented in section 3 along with the experimental results for the identification of hysteresis model. In section 4, the inverse model is incorporated in closed loop control schemes to investigate the effect of hysteresis compensation in SMA actuators. Concluding rearmarks are provided in section 5.

2. Hysteresis identification by Preisach model

2.1 Preisach model

As documented in (Mayergoyz, 2003), the main assumption made in the Preisach model is that the system consists of a parallel su mmation of a continuum of weighted hysteresis operators $\gamma_{\alpha\beta}$. This is illustrated in Fig. 1.

As the input varies with time, each relays adjusts its output according to the current input value, and the weighted sum of these output provides the system output:

$$y(t)=\iint_{\alpha\geq\beta}\mu(\alpha,\beta)[\gamma_{\alpha\beta}u(t)]d\alpha d\beta \qquad (1)$$

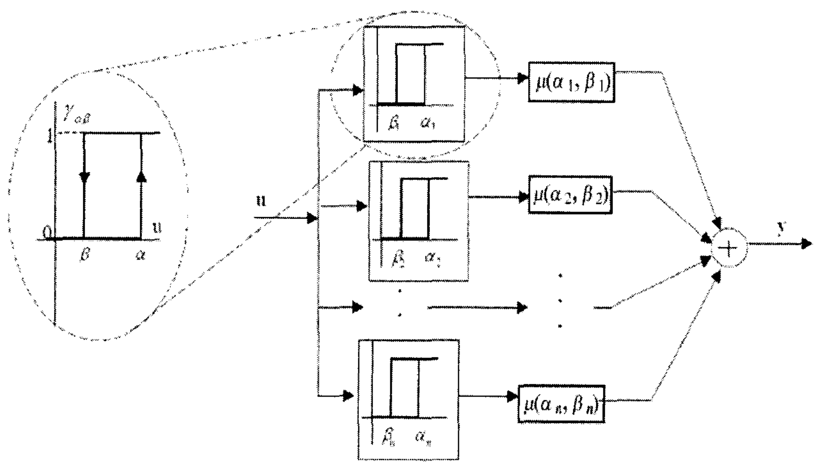

Fig. 1 Preisach model schematic

The collection of weights $\mu(\alpha, \beta)$ describes the relative contribution of each relays in overall hysteresis.

2.2 Geometrical interpretation of Preisach model

It is assumed that there is a one-to-one corresponding between operator $\gamma_{\alpha\beta}$ and point (α, β) on the half plane $\alpha \geq \beta$. This is also called the Preisach plane. The function $\mu(\alpha, \beta)$ is assumed to be zero outside the triangle **T** in Fig. 2.

To start the discussion, consider the case of hysteresis formation in SMA actuator when the driving input $u(t)$ is current, and the resulting output is displacement $y(t)$. When the current to the SMA actuator is zero, the output of all operators is zero.

Now, we assume that the input is monotonically increased to a value α_1 as shown in Fig. 3, the outputs of all hysteresis operators withswitching value less than α_1 become equal to +1. Geometrically, it leads to the subdivision of the triangle **T** into two sets : $S^+(t)$ consisting of point (α, β) where the output is +1, and $S^0(t)$ where the output is zero. This subdivision is made by the line $\alpha = u(t)$ that moves upwards as the input is being increased.

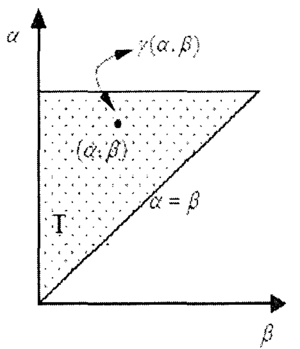

Fig. 2 Preisach plane

Next, the input is monotonically decreased from α_1 to a value β_1. As the input is being decreased, the outputs of all hysteresis operators in the set $S^+(t)$ with β switching values greater than β_1 become equal to zero. This changes the previous subdivision of **T** into two sets again. The interface between $S^+(t)$ and $S^0(t)$ has now two links, the horizontal and vertical ones. As illustrated by Fig. 4, vertical link moves from right to left as the current is monotonically decreased from α_1 to β_1. The vertical line is $\beta = u(t)$.

By generating this analysis with the case of increasing or decreasing of the input, the following conclusion can be reached. At any instant of time, the triangle **T** is subdivided into two sets : $S^+(t)$ and $S^0(t)$ corresponding the output of hysteresis operators is +1 or zero. The interface between $S^+(t)$ and $S^0(t)$ is the staircase line whose vertices have α and β coordinates respectively with local maxima and minima of input at previous instant of time.

Thus, at any instant of time the integral in (1) can be expressed as

$$y(t) = \iint_{S^+(t)} \mu(\alpha, \beta)\, \gamma_{\alpha\beta} u(t)\, d\alpha d\beta - \iint_{S^0(t)} \mu(\alpha, \beta)\, \gamma_{\alpha\beta} u(t)\, d\alpha d\beta \tag{2}$$

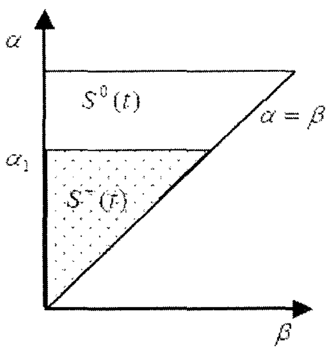

Fig. 3 Division of the triangle due to a increasing input α_1

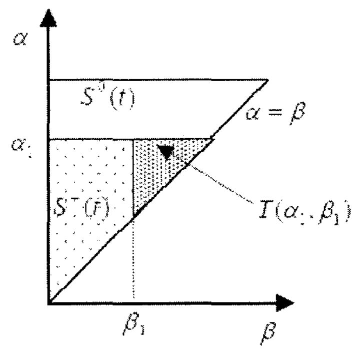

Fig. 4 Division of the triangle due to a decreasing input β_1

where $\gamma_{\alpha\beta}u(t)=0, \forall(\alpha, \beta)\in S^0(t)$, and $\gamma_{\alpha\beta}u(t)=1$, $\forall(\alpha, \beta)\in S^+(t)$, then this expression becomes:

$$y(t)=\iint_{S^+(t)} \mu(\alpha, \beta)\, d\alpha d\beta \tag{3}$$

From the above expression, the output of Preisach model depends on the subdivision of triangle **T**. This subdivision is determined by an interface which depends on the past extremum values of input. This means that the Preisach model describes hysteresis nonlinearity with nonlocal memory.

3. Numerical Preisach Model for Hysteresis of Smart Acuators

3.1 Numerical Preisach model

To apply classical Preisach model of hysteresis for SMA actuators, it encounters many difficulties. It requires the evaluation of double integrals in (1). This is a time consuming procedure that makes the use of Preisach model difficulties in practical applications. In (Choi and Lee, 2004) the model of an SMA actuator is divided into a heat dynamic transfer model and a Preisach static hysteresis model. Although it can increase the speed of computation, it is not easy to be applied in a control system. In this paper, the numerical Preisach model implementation is based on the geometrical interpretation method, which avoids double integrals in Preisach model formula. To do this, we define a new function:

$$F(\alpha_1, \beta_1)=\frac{1}{2}(y_{\alpha_1}-y_{\alpha_1\beta_1}) \tag{4}$$

where y_{α_1} is the output at current value of α_1, and $y_{\alpha_1\beta_1}$ is the output after current has been decreased to β_1 from its maximum value of α_1.

From Fig. 4, we can find the fact that the integral over the area $T(\alpha_1, \beta_1)$ equals the difference in hysteresis outputs of current values of α_1 and β_1

$$\iint_{T(\alpha_1\beta_1)} \mu(\alpha, \beta)\, d\alpha d\beta=F(\alpha_1, \beta_1) \tag{5}$$

The set $S^+(t)$ can be subdivided into $n(t)$ trapezoids Q_k. As a result, we have

$$\iint_{S^+(t)} \mu(\alpha, \beta)\, d\alpha d\beta=\sum_{k=1}^{n(t)} \iint_{Q_k(t)} \mu(\alpha, \beta)\, d\alpha d\beta \tag{6}$$

where n trapezoids Q_k may change with time.

Each trapezoid Q_k can be represented as a difference of two triangles $T(M_k, m_{k-1})$ and $T(M_k, m_k)$. Therefore, we can obtain the following expression

$$y(t)=2\sum_{k=1}^{n(t)} [F(M_k, m_{k-1})-F(M_k, m_k)] \tag{7}$$

In the case the input is monotonically decreasing, shown in Fig. 5, the final link of the interface is a vertical one, thus: $m_n=u(t)$. Consequently, the equation (7) can be written as

$$\begin{aligned} y(t)=2\sum_{k=1}^{n(t)-1} [F(M_k, m_{k-1})-F(M_k, m_k)] \\ +2[F(M_n, m_{n-1})-F(M_n, u(t))] \end{aligned} \tag{8}$$

If the input is monotonically increasing, as shown in Fig. 6, the final link of the interface is

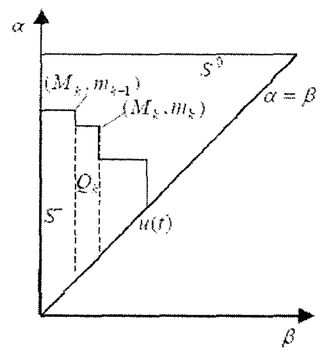

Fig. 5 Triangle **T** for numerical implementation of Preisach model corresponding to a decreasing input current signal

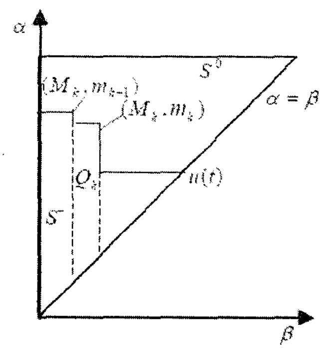

Fig. 6 Triangle **T** for numerical implementation of Preisach model corresponding to an increasing input current signal

a horizontal one, $m_n = M_n(t) = u(t)$, and equation (7) becomes

$$y(t) = 2\sum_{k=1}^{n(t)-1} [F(M_k, m_{k-1}) - F(M_k, m_k)] + 2F[u(t), m_{n-1}] \quad (9)$$

Using the above expressions, the output of the Preisach model can be calculated from an input, a set of first-order transition curves, and an input history that are all specified by the user.

To implement this algorithm, there are two main steps for hysteresis modeling. First, a square mesh covering the triangle **T** is created. The number of switching points in the Preisach plane, as shown in Fig. 2, can be selected by the user. During this stage, a discrete set of first — oder transition curves is entered. This set consists of mesh values of the function $F(\alpha, \beta)$ obtained from experimental data.

At the second stage, an input history and current values of input are entered. Using these dàta, the alternating series of dominant input extrema (M_k, m_k), (M_k, m_{k-1}) must be determined and updated at each instant of time. All terms in the formula (8), (9) are computed from these values: M_k, m_k, m_{k-1} and the mesh value $F_{\alpha\beta}$. This is done first of all by determining particular square (or triangle) cells to which points (M_k, m_k), (M_k, m_{k-1}), and $(M_n, u(t))$ belong, and then by computing the value of $F(\alpha, \beta)$ at these points by means of interpolation of mesh values of $F(\alpha, \beta)$ at the vertices of these cells. After computing all values of $F(\alpha, \beta)$, the output value can be calculated in (8) or (9) for the case of decreasing (or increasing) of the input.

3.2. Experimental result

Figure 7 shows the experimental apparatus for SMA positioning system. In this experimental setup for hysteresis modeling and compensation, a small tensile SMA actuator is used with some main specifications: heat current: ca.2V/0.85A, gen. force: 8N, displacement: ca.5 mm. The displacement is measured by a potentiometer with high precision. This system is controlled in real-time by using Advantech PCI-1711 Card with Realtime Windows Target Toolbox of Matlab.

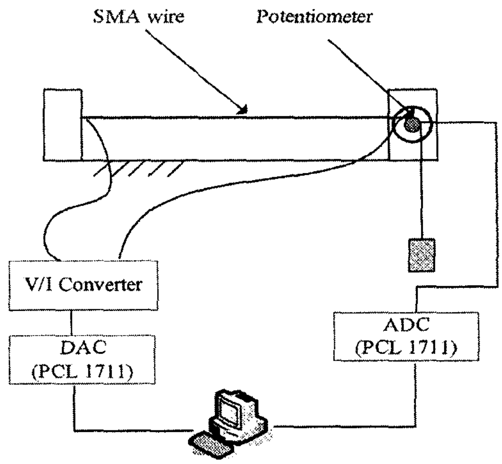

Fig. 7 Experimental apparatus

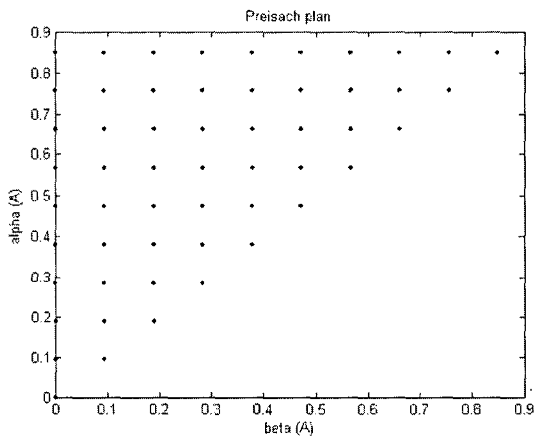

Fig. 8 Number of switching points is used in the experiment

The switching points used in this program are shown in Fig. 8. The more switching points we use, the more accuracy of model we can obtain. For each switching (α, β) points, the mesh values of the function $F(\alpha, \beta)$ in (4) are calculated by measuring the output displacement as the input current is increased to $\alpha(f_\alpha)$ and then decreased to $(f_{\alpha\beta})$.

The input current applied to SMA actuator is decaying sinusoidal signal, shown in Fig. 9. During the experiment, the dominant input maxima and minima are determined and updated at each instant of time. The maximum and minimum points are updated by comparing any new dominant extrema with previous extrema. During this

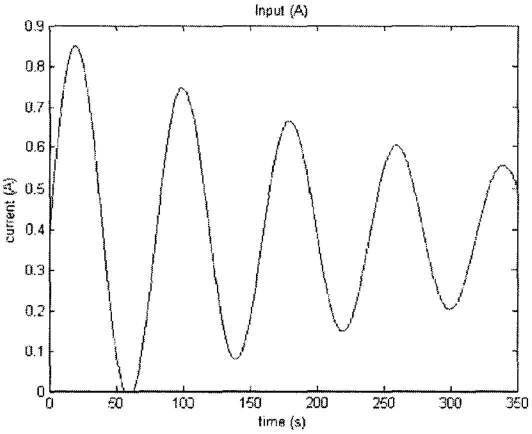

Fig. 9 Input current signal

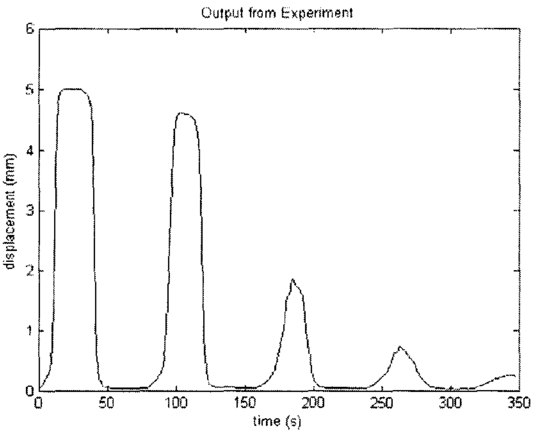

Fig. 10 Output displacement from experiment

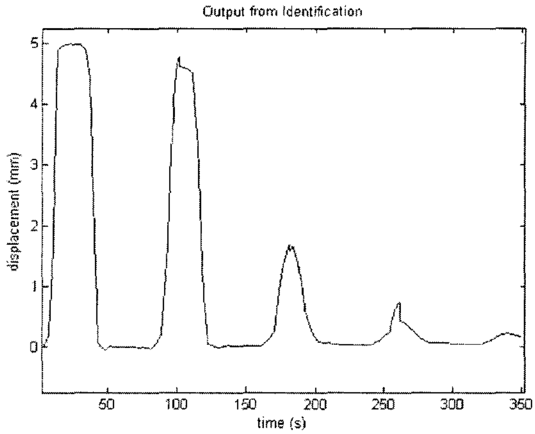

Fig. 11 Output displacement from Preisach hysteresis modeling

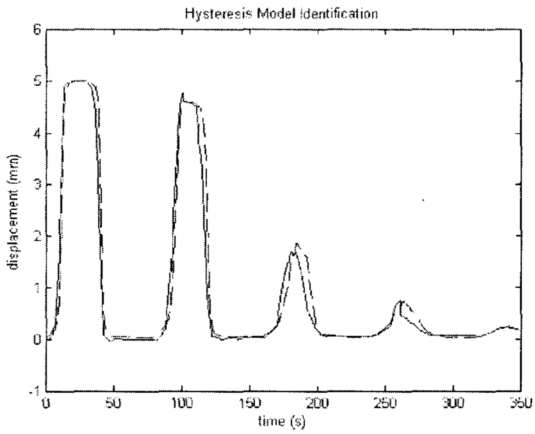

Fig. 12 Comparison of the output displacement through experiment and prediction of Preisach hysteresis modeling

work, the previous extrema can be deleted none, one or more point and added the new dominant extrema.

The induced output displacement from experiment is shown in Fig. 10. The output of hysteresis model computed from (8) and (9) is shown in Fig. 11. In Fig. 12, the experimental results are in good agreement with those of Preisach model prediction.

The discrepancy between experiment and model is due to the limited of switching points available in the corresponding region of the Preisach triangle. This error can be eliminated by increasing the number of points in Preisach plane, Fig. 8. In Fig. 12, the output displacement through experiment and prediction of preisach hysteresis modeling were compared and verified to be very effective the Preisach hysteresis modeling.

4. Hysteresis Compensation by Inverse Preisach Model

The inverse Preisach model is developed to correct the hysteresis effect of SMA actuators. In this section, the implementation of the inverse Preisach model is described first, and then its application in hysteresis compensation for control is proposed.

4.1 Inversion of Preisach model

The inverse Preisach model determines the current that will result the desired output displacement. In the formulation of the inverse Preisach model, there are two different cases corresponding to the decreasing and increasing of the current input. To find the current input values $u(t)$ for the desired output $y_d(t)$, the expressions in (8) and (9) are rewritten as follows

Case of decreasing desired displacement output

$$y_d(t)=\sum_{k=1}^{n-1}(y_{M_k m_k}-y_{M_k m_{k-1}})+y_{M_n u(t)}-y_{M_n m_{n-1}} \quad (10)$$

Inverting above expression, the solution to the inverse model for this case is derived to be:

$$\begin{aligned} u(t)&=\beta=G^{-1}(y_{M_n u(t)}) \\ &=G^{-1}\left[y_d(t)+y_{M_n m_{n-1}}-\sum_{k=1}^{n-1}(y_{M_k m_k}-y_{M_k m_{k-1}})\right] \end{aligned} \quad (11)$$

Case of increasing desired displacement output

$$y_d(t)=\sum_{k=1}^{n-1}(y_{M_k m_k}-y_{M_k m_{k-1}})+y_{u(t)}-y_{u(t)m_{n-1}} \quad (12)$$

and the input current value for the desired output

$$\begin{aligned} u(t)&=\alpha=G^{-1}(y_{u(t)}-y_{u(t)m_{n-1}}) \\ &=G^{-1}\left[y_d(t)-\sum_{k=1}^{n-1}(y_{M_k m_k}-y_{M_k m_{k-1}})\right] \end{aligned} \quad (13)$$

Furthermore, the input current can be computed from the inverting of expression (9) for this case

$$\begin{aligned} u(t)&=\alpha=G^{-1}(F(u(t),m_{n-1})) \\ &=G^{-1}\left[\frac{y_d(t)}{2}-\sum_{k=1}^{n(t)-1}(F(M_k,m_{k-1})-F(M_k,m_k))\right] \end{aligned} \quad (14)$$

The input current value used in the inverse model is the desired displacement. This computation in (11), (13), or (14) consists of the following procedure: updating dominant input extrema (M_k, m_k) and (M_k, m_{k-1}) at each instant of time, calculation $F(\alpha, \beta)$ or $y_{\alpha\beta}$ corresponding to the desired output displacement, and determination of the square or triangle in Preisach plane which the inverse solution may lie. The input current, the α or β value, is computed from the expression (11), (13), or (14) by mean of interpolation at each instant of time.

4.2 Closed — loop hysteresis compensation with inverse Preisach model

In order to obtain high performance of the control systems, hysteresis phenomena must be reduced. Due to the inverse Preisach model can predict the input value that would achieve the desired output, consequently, it is possible to use inverse model to compensate the hysteresis nonlinearity effect. In (Samir and Menq 2000), this inverse Preisach model is used in open — loop control scheme to compensate the hysteresis phenomenon of electromagnetic actuators. In this paper, the inverse Preisach model is incoporated in closed — loop PID controller to increase the performance of hysteresis compensation for the slow response systems like SMA actuators. This control strategy is shown in Fig. 13.

The desired output displacement is used as input of hysteresis inverse model. The error between the desired displacement and the output of the system is the input of PID controller. The output of inverse model and PID controller is the current which is applied to SMA actuator. By choosing the appropriate PID parameters, the performance of the compensation strategy is experimentally

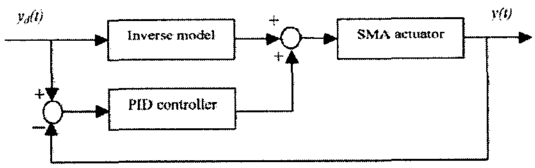

Fig. 13 Closed — loop compensation of hysteresis in SMA actuator

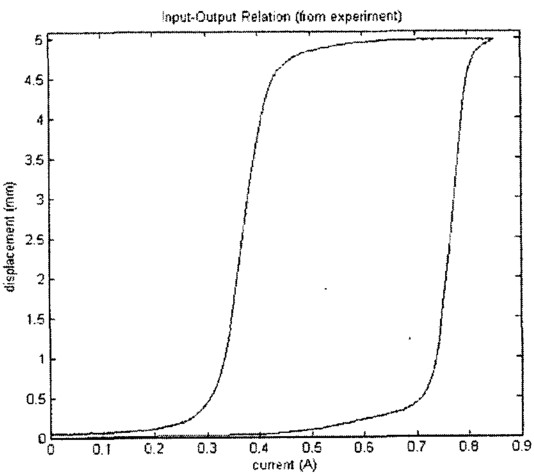

Fig. 14 Input — Output relation obtained from experiment before compensation

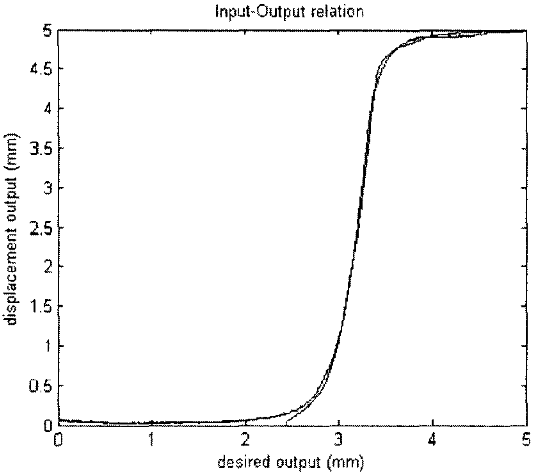

Fig. 15 Hysteresis curve obtained from experiment after using hysteresis compensation strategy

investigated and the result is shown in Fig. 15.

The hysteresis curve between input and output relation before compensation is shown in Fig. 14. The experimental result for the displacement actuator after using hysteresis compensation strategy is shown in Fig. 15. The hysteresis curve in Fig. 15 is narrower than in Fig. 14. Consequently, the closed-loop PID compensation strategy based on the inverse Preisach model provides the effective for reducing the hysteresis phenomena of SMA actuators.

5. Conclusion

In this paper, the Preisach model for hysteresis in SMA current — displacement response has been presented. The experiments show that the model is suitable for predicting the hystersis phenomenon in SMA actuators. The numerical inverse Preisach model is successfully applied for hysteresis compensation and the hysteresis effect of SMA actuators is reduced by using it in closed — loop control strategy. This method is not only useful for SMA actuators but also other actuators with hysteresis phenomena.

Acknowledgments

This work was supported (in part) by Ministry of Co mmerce, Industry and Energy (MOCIE) of Republic of Korea, through the Research Center for Machine Parts and Materials Processing (ReMM) at University of Ulsan.

References

Choi, B. J., Lee, Y. J. and Choi, B. Y., 2004, "Fast Preisach Modeling Method for Shape Memory Alloy Actuators Using Major Hysteresis Loop," *Smart Material Structures*, Vol. 13, pp. 1069~1080.

Choi, J. J., Kim, J. S. and Han, S. I., 2004, "Pre-sliding Friction Control Using the Sliding Mode Controller with Hysteresis Friction Compensator," *KSME International Journal*, Vol. 18, pp. 1755~1762.

Cruz-Hernandez, J. M. and Hayward, V., 1997, "On the Linear Compensation of hYsteresis," *Proceedings of IEEE Conference on Decision and Control*, Vol. 2, pp. 1956~1957.

Cruz-Hernandez, J. M. and Hayward, V., 2001, "Phase Control Approach to Hysteresis Reducing," *IEEE Transactions on Control Systems Te chnology*, Vol. 9, No. 1, pp. 17~26.

Hasegawa, Tadahiro, Majima and Sumiko, 1998, "Control System to Compensate the Hysteresis by Preisach Model on SMA Actuator," *Proceedings of the International Symposium on Micromechatronics and Human Science*, pp. 171~176.

Hughes, D. and Wen, J. T., 1997, "Preisach Modeling of Piezoceramic and Shape Memory Alloys Hysteresis," *Smart Material Structures*, Vol. 3, pp. 287~300.

Mayergoyz, I. D., 2003, "Mathematical Models of Hysteresis and Their Applications," *Elsevier Science Inc.*

Nakmahachalasint, Ngo, D. T. K. and Quoc, L. V., 2002, "A Static Hysteresis Model for Power Ferrites," IEEE Transactions on Power Electronics, Vol. 17, No. 4, pp. 453~460.

Nealis, J. M. and Smith, R. C., 2002, "Nonlinear Adaptive Parameter Estimation Algorithms for Hysteresis Model of Magnetostrictive Actuators," *Proceedings of SPIE — the International Society for Optical Engineering* 4693, pp. 25~36.

Samir, Mittal, Menq and Chia-Hsiang, 2000, "Hysteresis Compensation in Electromagnetic

Actuators Through Preisach Model Inversion," *IEEE/ASME Transactions on Mechatronics*, Vol. 5, No. 4, pp. 394~409.

Smith, R. C. and Massad, J. E., 2001, "A Unified Methodology for Modeling Hysteresis in Ferroelectric, Ferromagnetic and Ferroelastic Materials," *Proceeding of the ASME Design Engineering Technical Conference*, Vol. 6 B, pp. 1389~1398.

Tan, X. and Baras, J. S., 2002, "Modeling and Control of a Magnetostrictive Actuators," *Automatica*, Vol. 40, pp. 1469~1480.