Preisach Modeling of Hysteresis for Piezoceramic Actuator System*

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This paper discusses the adaptation of the Preisach model to describe the hysteresis behavior of piezoceramic actuator system and presents a modified geometric interpretation and numerical implementation method for the Preisach model especially for the hysteresis modeling of piezoceramic actuator system. The demagnetized state, which refers both input and output equal zero state, and the generalized demagnetized state are used as the basis of Preisach model rather the saturation states. Experiments on the hysteresis behavior of a piezoceramic actuator were carried out and the experimental measurements are compared with the hysteresis predictions. The comparison results verify the application of the modified Preisach model to piezoceramic material system.

Key Words: Hysteresis, Preisach Model, Preisach Function, Hysteresis Operator, Piezoceramic Actuator

1. Introduction

Common for various branches of science and technology, hysteresis is associated with many physical phenomena such as ferromagnetism, ferroelectricity, plasticity and superconduct. Ferromagnetic hysteresis in particular has long been studied. Hysteresis appears when the output of a system is not uniquely determined by the input of the system, but depends on the evolution (or history) of the input. Generally speaking, hysteresis is a form of non-linearity, which contains memory. In order to simplify the representation, hysteresis is often defined as having rate independence property; Visintin (1990) defined the hysteresis as rate independent memory effect.

Piezoceramic materials with their high stiffness, fast frequency response, and high resolution have been extensively used over the years in many applications. In smart structures, piezoceramic materials can be used as actuators and as sensors for various purposes. Although the linear theory of piezoelectricity is well developed, the non-linear nature of electromechanical coupling remains a fundamental issue. Among non-linearity present in piezoceramic material systems, hysteresis has been particularly identified to be sensitive to the varying field conditions. Currently, a major limitation of piezoceramic actuators is their lack of accuracy due to hysteresis and drift. Since piezoceramic materials are ferroelectric, they are fundamentally nonlinear in their response to an applied electric field, exhibiting a hysteresis effect between the electric field and the displacement or force. Without modeling and incorporating hysteresis in the controller design, the hysteresis will act as an unmodeled phase lag presence and will cause instability in a closed loop control system. Hence, reliable modeling and predictions of hysteresis would be a valuable tool when these piezoelectric actuators are employed as part of closed loop system for purposes of motion control such as active control and micro-positioning. If hysteresis effects of these material systems could be predicted, then actuator controllers could be designed to correct these effects and the whole controller system could be made to appear as a device with a single valued output function and possibly even a linear device.

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The Preisach model is one of most widely used model that had been proposed by physicist Preisach in 1935 (Preisach 1935). The Preisach model of hysteresis has received considerable attention for many years, because it encompasses the basic feature of the hysteresis phenomena in a conceptually simple and mathematically elegant way.

It has been shown that the classical Preisach model can be represented in the following mathematical form:

\[
predictions \ f(t) = I_u(t) = \int_{\beta} \nu(\alpha, \beta) \tilde{y}_{\text{est}}(t) d\alpha d\beta
\]  

where \( u(t) \) is the input, \( f(t) \) is the output of a system and \( \tilde{y}_{\text{est}} \) is the elemental hysteresis operator. The output of each elemental hysteresis operator traces a rectangular loop on the input-output diagram switching from \(-1\) to \(+1\) when the input increases above the threshold \( a \). The output switches from \(+1\) to \(-1\) when the input decreases below the value of \( \beta \) as shown in Fig. 1. \( \nu(\alpha, \beta) \) is the distribution function, which is also called the Preisach function. The integral takes the past history values of \( u(t) \) to determine the current output \( f(t) \).

The past history values are accumulated in the \( a, \beta \) domain by storing the maximum and minimum values of the input variation. If the Preisach function \( \nu(\alpha, \beta) \) is known, the model (1) can be solved directly by integration. If the function \( \nu(\alpha, \beta) \) is not known explicitly, then experimental data is needed to estimate the Preisach function through the geometric interpretation and numerical implementation.

Although the Preisach model has enjoyed an extensive application in various areas, it has been gradually recognized that the Classical Preisach Model (referred as CPM) has some intrinsic limitations. Several generalizations of the original CPM have been proposed in order to improve its ability to reproduce the complex experimental results in ferromagnetic materials, including relaxation of congruent minor loops and wiping out properties requirements (Mayorgoyz 1989, 1992, Vajda and Torre 1991), the rate-dependent properties (Mayorgoyz 1988, Bertotti 1992) and the vector nature of hysteresis (Mayorgoyz 1987, Charp 1993).

Recently, the Preisach technique has been applied to piezoceramic material systems. Sreeram and Naganathan (1993, 1994) carried out the first application of the CPM to a piezoceramic material system. In their work, Mayorgoyz’s identification and numerical simulation procedures were used to model the hysteresis exhibited by a piezoceramic bimorph. The minor loop patterns and enclosed areas from simulation and experimental data matched well for the symmetrical minor hysteresis loop. Hughes and Wen (1995) discussed and verified the applicability of Preisach model to piezoceramic and shape memory alloy systems. The parameter identification based on the input/output data and hysteresis compensation via direct inversion of the identified model was also demonstrated. Freeman (1995) extended the CPM to a two-input model to handle the both the applied electric field and the mechanical stress effect on output strain. Ge (1996) used both the classic and generalized Preisach model to handle the hysteresis of the piezoceramic actuator and as a results, developed a tracking control approach by incorporating the hysteresis model in the feed forward loop to increase the tracking control precision. Ge (1996) also found that the input dependent Preisach model had a better modeling result in his case.

The previous efforts in the hysteresis modeling for Piezoceramic material systems show that due to the similarity between the primary hysteresis mechanisms in both ferromagnetic and ferroelectric materials, the successfully applied Preisach model in ferromagnetic materials can also be used for representing piezoceramic hysteresis. However, since most applications are in the magnetic area, the developed identification and numerical implementation methods for the Preisach model are based on the magnetic material properties. There are some differences in the hysteresis behavior of magnetic and piezoceramic materials especially in some specific applications. For example, as Ge (1996) pointed out for a preloaded actuator, the hysteresis loop is distorted and asymmetric due to the mechanical bias. In some cases, hysteresis is only defined in the positive quadrant of the input-output plane and has no saturation condition.

The specific issues that need to be addressed here concern the geometric interpretation and numerical implementation of Preisach models. For ferromagnetic materials, the geometric interpretation and numerical implementation of Preisach models are
based on the negative or positive saturation positions that are the only defined positions for the magnetic material (Mayergoz 1991). This saturation-based technique limits the system initial-input value to only saturation states.

For the piezoceramic material, the applied field is limited by the maximum strength at which the material can be operated without being damaged by voltage. Therefore, the applied field of piezoceramic material is prevented from attaining the saturation position. It is often supposed that the maximum allowable input value forms the limiting triangle for the Preisach model in a piezoceramic actuator system. But in applications, the system input value often does not reach that fixed maximum value and sometimes the system initial-input value may just be zero. In such cases, the hysteresis loop that needs to be modeled or predicted may be only a minor symmetric or minor asymmetric loop. The saturation-based geometric interpretation and numerical implementation for the Preisach model cannot account for such conditions. This paper presents a modified geometric interpretation and numerical implementation method for the Preisach model that is based on the demagnetized state. The demagnetized state is a ferromagnetic term referring to the both input and output equal to zero condition. For the piezoceramic actuator system, this state can be defined as the output force or strain equal to zero when the system input field value equals to zero. So the demagnetized state is a common condition for the piezoceramic actuator system.

The modified approach will allow the system-input starts from the saturation condition as well as the zero input and zero output conditions. Experiments are carried out to study the hysteresis behaviors of a piezoceramic actuator system and used to provide the necessary initial data for the hysteresis modeling.

**Notation**

- $f(t)$: output of system
- $f(t)$: static component of hysteresis
- $f(t)$: dynamic output
- $f_{a}$: output value at first order curve when the increasing input is equal to $a$
- $f_{a,b}$: output value when the input increase to $a$, and then decrease to $b$
- $a$: sub-trapzoid
- $Q$: trapezoid
- $t$: time variable
- $T$: limited triangle
- $n(t)$: input of system
- $\alpha$: Preisach function (distribution weight function)
- $\gamma_{ab}$: elemental hysteresis operator

2. Experimental Study on the Hysteresis Behavior of Piezoceramic Actuator

The purpose of this study is to find out the hysteresis behavior of a bimorph piezoceramic actuator at different input conditions, so that it is possible to decide how to model the hysteresis by the Preisach technique. A piezoceramic actuator setup was used to conduct the experiments. The actuator is a commercial PZT bimorph with 0.019" thickness, 0.5" width, rigidly clamped by using a fixture at one end like a cantilever beam. The voltage input initiated by a signal generator is sent to the actuator through a high voltage amplifier. The output signal is measured by using a MTI Photonic Sensor. The sensor probe is mounted on a fixture over the free end of the bimorph actuator. The measured displacement signal is converted into an electric signal and sent to the PC. The graphical program language LabVIEW by National Instruments, which is a software emulation of the physical instrument, is used as the data acquisition system.

Figures 2 and 3 show some of the measured hysteresis loop for the piezoceramic bimorph actuator at different initial input values. In Fig.2, the extreme input values are the same as limited maximum input value (100 volts), while in Fig.3, the extreme input values are just half the limited maximum value. From the figures, it is easy to see that when the system initial input value is equal to zero, the system output value may have different values. In most cases, the initial output value is not equal to zero. The zero initial output value is caused by the residual electric charge since the piezoceramic can be considered as electric capacitor. The residual electric charge is the result of previous input value and history. The following output values obviously depend on the initial output values. The problem is that the previous input is not known. Can the Preisach technique handle such situations?

3. Modifications of the Geometric Interpretation and Numerical Implementation

3.1 Geometric interpretation based on the demagnetized-state

For the piezoceramic material, the applied field cannot reach the saturation condition. Usually in the Preisach modeling process, the largest possible applied field is considered to form the limiting triangular. In the limiting triangular, if the line $a = -\beta$ is the interface between the positive and negative sets $S^{+}(t)$
and $S(t)$ as shown in Fig. 4, then according to the symmetric properties of the Preisach function, the output is equal to zero. This state is called the demagnetized state in magnetics. For the piezoceramic actuator system, this state can be defined as the output force or strain equal to zero when the system input value equal to zero. This demagnetized state is assumed to be the new basis for the Preisach model rather than the saturation position. In this new basis, both the system initial input and output are equal to zero. Under such assumption, the symmetric and asymmetric minor loops can be modeled. The geometric interpretation for modeling of symmetric minor loop based on this demagnetized state can be explained as follows.

The input starting from the zero value monotonically increases until it reaches a maximum value $u$. The positive and negative sets $S^{+}$ and $S^{-}$ in

Fig. 2 Hysteresis loop when the initial output values are different and the maximum input values are equal to limiting value (100 volts)

Fig. 3 Hysteresis loop when the initial output values are different and the maximum input values less than the limiting input value
the limiting triangle are defined by the line $a = -\beta$ and $a = u_1$ as shown in Fig. 5. Next the input is assumed to be monotonically decreased and at some time reaches a value $-u_1$. This changes the previous subdivision of the limiting triangular into new positive and negative sets defined by $a = -\beta$, and $\beta = -u_1$ as shown in Fig. 5. If the input increases again to $u_1$, the output at these two extreme states can be shown to have the relationship as $f(u_1) = f(-u_1)$. This means that the hysteresis loop formed by such an input variation process should be symmetric. The symmetric loop formation process is shown in Fig. 6. The limiting triangle forms the outside limiting hysteresis loop with extreme values $A$ and $B$. The above input increasing and decreasing process forms a minor symmetric loop with two extreme points $E$ and $F$. If the increasing and decreasing extreme values are different, it will form an asymmetrical minor loop. If the input reaches the limiting value (both positive and negative), the $a = -\beta$ line will be eliminated by the limiting input value and have no effect on the positive and negative sets.

Fig. 4 Geometric interpretation of demagnetized state

Fig. 5 Interfaces line for increasing input $u_1$ and decreasing input $u_1$ cases based on demagnetized state

Fig. 6 Formation of minor symmetric hysteresis loop based on demagnetized state

Fig. 7 The different possible initial output values when the initial input values equal to zero

Fig. 8 The geometric interpretation of different possible initial output values when the initial input values equal to zero

The demagnetized state based geometric interpretation method can be extend to handle more general cases such as the cases when the initial input is equal to zero, the initial output is not equal to zero as observed in experimental results shown in Figs. 2 and 3. This extension can be explained by using Figs. 7 and 8. Figure 7 presents the possible initiate output values when the initiate input values equal zero. Point O is in the demagnetized state condition and the geometric interpretation can represented by the interface line OO' (divide positive and negative sets $S^-(t)$ and $S^+(t)$) in Fig. 8, while point A, B is on up and down limiting triangle and can be represented by the
interface lines OA and OB in Fig. 7 respectively. Since points C (as well as point D) in Fig. 8 are in between points O and A, the geometric representation can be assumed by the interface line OC which is between OO' and OA in Fig. 8. The output value of point C determines the exact positions of line OC. In a similar way, OD (in Fig. 8) can be assumed as the interface of point D (in Fig. 7). The numerical implementation and verification of such geometric interpretation will be conducted in following.

3.2 Numerical implementation scheme

The CPM can be numerically implemented by using Eq. (1) for the computation of system output. The difficulty is that it requires the numerical evaluation of double integral to get the Preisach function \( \mu(\alpha, \beta) \). This is not only a time-consuming procedure, it may strongly amplify errors inherently present in any experimental data. Mayervozy (Mayervozy 1991) proposed a finite difference method to calculate the system output, which completely circumvents the above difficulties. The final expression for the numerical implementation is given by the following equations:

\[
f(t) = f^* + \sum_{k=1}^{n} \left[ f_{M_{k,n_k}} - f_{M_{k,n_k-1}} \right] + \left[ f_{M_{k,n_k-1}} - f_{M_{k,n_k}} \right]
\]

for \( u(t) \) increasing case (2)

\[
f(t) = f^* + \sum_{k=1}^{n} \left[ f_{M_{k,n_k}} - f_{M_{k,n_k+1}} \right] + \left[ f_{M_{k,n_k+1}} - f_{M_{k,n_k}} \right]
\]

for \( u(t) \) decreasing case (3)

where, \( f^* \) is the output value when input is at the negative saturation, \( f_{M_{k,n_k}} \) is the \( k \)th input dominant maxima and minima set. (Mayervozy 1991). This numerical implementation method is based on the initial input value in saturation conditions. For the numerical implementation of the demagnetized-state based method, we assume that there is a previous input process, which will establish the demagnetized-state. Figure 9 shows such an assumed previous input process by recording a series of dominant maxima and minima values which approximate the \( \alpha = -\beta \) line. The actual input history will add to such an assumed series. The extended zero-zero input condition can be handled in similar way. Under this assumption, Mayervozy’s numerical implementation method can then be used for such conditions.

4. Comparison Results

In order to compare the effectiveness of hysteresis modeling for piezoceramic actuator by using modified Preisach technique, experiments were carried out and the experimental results were compared with the predictions of Preisach model. Figures 10

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**Figure 9** Assumed previous input series to approximate the \( \alpha = -\beta \) line

**Figure 10** Comparison of measured and predicted symmetric and un-symmetric as well as high order hysteresis loop
and 11 show some of the comparison examples. In Fig. 10, the modeling is based on the demagnetized state that means the input electric field was increased from the zero. These examples show how the minor symmetric and minor asymmetric loops and high order transition curve are being modeled based on the demagnetized state. Figure 11 show the effectiveness of generalized demagnetized state method to handle the no zero initiate output cases. These examples demonstrated a good agreement between the experimental measurements and the predictions.

5. Conclusions

The Preisach model has been adapted to describe the hysteresis behavior of piezoceramic actuator system. A modified geometric interpretation and numerical implementation method for the Preisach model for the hysteresis modeling of piezoceramic actuator system is presented. Experimental measurements on the hysteresis behavior of a piezoceramic actuator are compared with the hysteresis predictions. The comparison of results verified the application of the modified Preisach model to piezoceramic material system.

References


