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Modelling and Inverse of Hysteresis of Piezoelectric Actuator Based on Prandtl-Ishlinskii Model

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Abstract

Piezo actuators are used in positioning and control applications widely. Hysteresis nonlinearity in piezo actuators contributes to the error in positioning systems. In order to compensate the hysteresis nonlinearity of piezo actuators, in one of the methods, the hysteresis is modelled, and its inverse is used in controller design. In this paper, Prandtl-Ishlinskii model is used for modelling and compensation of hysteresis nonlinearity of piezo actuator. Experimentation is carried out on system using electro pneumatic positioner which has piezo valve. As the hysteresis under study has zero slope region at saturation because of which analytical inverse cannot be found. To avoid this problem and to find analytical inverse a positive slope is added at the region where the slope is zero. By mapping output values at zero slope region to the new values of output with positive slope, analytical inverse can be obtained. The paper demonstrates how adding positive slope in place of zero slope region can facilitate calculating analytical inverse without losing accuracy. MATLAB is used to find model and inverse of hysteresis. The results are verified using simulations.

Key Words:piezo actuator, hysteresis, Prandtl-Ishlinskii model, MATLAB.

1 Introduction

Piezoelectric actuator converts an electric signal into a physical displacement. They are used in precision positioning and tracking control applications such as finely adjusting machining tools, lenses, mirrors etc. However, one of the major obstacle in using piezo actuators in positioning applications is that they have hysteresis nonlinearities. These hysteresis nonlinearities can give rise to undesirable inaccuracies in positioning and control applications. Therefore, number of methods have been proposed to model and compensate the hysteresis of piezo actuators. A feedforward method of compensating hysteresis involves modelling the hysteresis which is similar to the actual hysteresis and then designing a feedforward controller using inverse of the hysteresis model to linearize the response of the actuator.

In order to design feedforward controller, getting accurate model of the hysteresis is important. So many methods like Maxwell model, support vector machine model, Duhem model [2], Bouc-Wen model [1], Prandtl-Ishlinskii (PI) model [3], Preisach model [5] and so on.

PrandtlIshlinskii (PI) model proposed by Kuhnen is a phenomenology-based model. Advantage of using PI model for hysteresis modelling is its simplicity in modelling hysteresis with few PI operators and its inverse can be found out analytically. Primary aim of the work is to find out hysteresis model using PI model and find a solution to obtain analytical inverse for ill formed hysteresis with zero slope region [4] without decreasing the accuracy.

2 LITERATURE SURVEY

S.F. Alem,I.Izadi,F.Sheikholeslam discuss the adaptive sliding mode control with proportional-derivative (PD) using a Bouc-Wen model of hysteresis. In their work, uncertainty in the actual behavior and the model is compensated with online parameter estimator. [1]

GengWang ,GuoqiangChen, reveal Duhem model used to construct a neural network for hysteresis description and parameter identification can precisely model and identify the actuator response. [2]

Xie, Shenglong, Mei, Jiangping, Liu, Haitao, Wang, Yu show the effectiveness of a modified PrandtlIshlinskii (MPI) model for modelling asymmetric hysteresis and compensation of the pneumatic muscle actuator (PMA) using fast switching valves. [3]

U. X. Tan, T. L. Win, W. T. Ang showed that using PI operator, modelling of the hysteresis of a piezoelectric actuator is possible but has inadequacy that the inverse of the operator does not exist when the slope of the hysteretic curve is not positive definite. This paper proposes a way to obtain inverse of PI model by mapping the hysteresis data through a linear transformation onto another domain. [4]

Adwait A. Borwankar, Shilpa Y. Sondkar, Neville C. Fernandes show the system usingpiezoelectric actuator and effect of different methods of finding adaptive model for the system. Kalman Filter, Recursive Least Square, Least Mean Square and Normalized Least Mean Square methods for adaptive inversion control are discussed and compared. They found that RLS adaptive model is most suitable of all above discussed methods. [5]

3 PROCESS SETUP

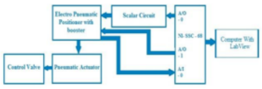

Fig. 1 System Block Diagram

Fig. 1 shows block diagram of physical system. Pneumatic actuator is placed on the control valve. The electro pneumatic positioner with booster is the final control element for controlling stroke of the pneumatic actuator. Input signal to scalar circuit is given from analog output port zero of NI-SSC-68 block. The input signal is generated from LabVIEW.

Fig. 2 Process Setup

Fig. 2 shows actual system consisting electro pneumatic positioner with piezo valve, booster which is coupled with piezo valve and the scalar circuit. The pneumatic booster boosts pressure up to 5 bar. This boosted pressure is applied to diaphragm of the pneumatic actuator. Range of piezo valve is -21 to +21 volts. A scalar circuit scales voltage from 0 to 3 volts to -21 volts to +21 volts to operate piezo valve. A scalar circuit acts as interface between data acquisition card (NI-SSC-68) and piezo valve in electro pneumatic positioner. Rotary type potentiometer, coupled with gear arrangement serves as a feedback signal mechanism. This gear arrangement converts linear displacement of stroke of cylinder in rotary motion which is then used to identify the position of the pneumatic valve. Rotary type potentiometer requires reference signal of 10 volts. So, to obtain the variable stroke position. Reference signal is generated on analog output port 1 in. Variable stroke position is obtained in voltage because of rotary type potentiometer and gear arrangement.

4 Prandtl-ISHLINSKII (PI) MODEL

Prandtl-Ishlinskii Model

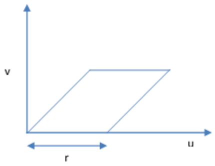

Fig. 3 Unilateral Play Operator

PI model is summation of weighted play operators.The unilateral play operator shown in fig. 3 can be expressed as

$$y(k) = max\{u(k) - r, min[u(k), y(k-1)]\}$$

Where kis the input time, ris the threshold of the unilateral play operator, u(k) is the input of the operator and y(k) is the operator output. Operator initial value is defined as

$$y(0) = max\{u(0) - r, min[u(0), h0]\}$$

Hysteresis is modelled using number of play operators with each having different weight. Hysteresis is summation of these weighted play operators. The mathematical expression of the hysteresis is given as

$$Y(k) = \sum_{i=1}^{n} w_i * y_i(k) = max\{u(k) - r_i, min[u(k), y(k-1)]\}$$

Where w_i is the weight of the play operator, nis the number of operators, y(k) is the output of the model at time kand $r_i$is the threshold of the ithoperator. In the vector form the equation can be written as

$$Y(k) = w^T * y(k)$$

Where threshold vector is W=$(w_1, \cdots, w_i, \cdots, w_n)^T$ the operator state vector at the moment kis y(k)=$(y_1(k), \cdots, y_i(k), \cdots, y_n(k))^T$and state vector of operator at initial time is y(0)=$(y_1(0), \cdots, y_i(0), \cdots, y_n(0))^T$.

Inverse PI model

The inverse of the PI model is another PI model. The thresholds and the weights of the inverse model can be calculated as,

$$r_i^{'} = \sum_{j=1}^{i} w_j(r_i - r_j), i = 1, \cdots, n$$

$$w_1^{'} = \frac{1}{w_1}$$

$$w_1^{'} = \frac{-w_i}{[(\sum_{j=1}^{i} w_j)(\sum_{j=1}^{i=1} w_j)]}, i = 2, \cdots, n$$

$$u_i[0] = \sum_{j=1}^{i=1} w_j y_i[0] + \sum_{j=1}^{n} w_j y_j[0], i = 2, \cdots, n$$

Output of the inverse is given as,

$$U(k) = \sum_{i=1}^{n} w_i^{'} * u_i(k)$$

$$= \sum_{i=1}^{n} w_i^{'} * max\{y(k) - r_i^{'}, min[y(k), u(k-1)]\}$$

Linearization of system using inverse model

Fig. 4 shows linearization of the system having hysteresis using inverse model.

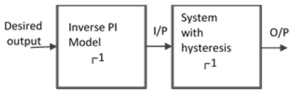

Fig. 3 System Control Using PI Inverse Model

In the inverse feedforward controller inverse hysteresis operator is cascaded with the plants hysteresis to achieve mapping between desired output and the actual output.

5 EXPERIMENTATION

During experimentation readings were taken with input step of 10 mV. It is observed that system has very small linear range of operation. So, to analyze the system, buffer to hold 5 second of data is kept using the LabVIEW measurement I/O toolkit. The sampling rate was kept suitably high for better results viz. 20000 samples/sec. Fig. shows the response of the system for 10 mV input step which is shifted to left to obtain model with PI model. Fig. 5 shows the experimental results.

6 MODEL AND INVERSE IDENTIFICATION

As the hysteresis has negative slope, mirror image is taken to convert it to positive slope and shifted in the first plane as shown in Fig. 6

As the hysteresis curve is asymmetric, weights used for increasing and decreasing input are different. To obtain the model, thresholds and weights identified are given in Table I.

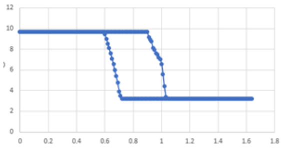

Fig. 5 Actual Response

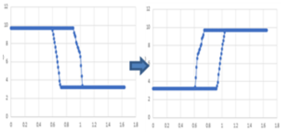

Fig. 6 Mirror Image of Hysteresis curve

TABLE. I Thresholds and Weights

Threshold(r_i)		Weight(w_i)	Input increasing	Input decreasing
r_0	0	w_0	3.5217	3.5217
r_1	0.57	w_1	0	0
r_2	0.92	w_2	44.4783	28.6783
r_3	1.02	w_3	0	41.8
r_4	1.08	w_4	-44.4783	-70.4783

As the hysteresis has zero slope region at saturation, analytical inverse cannot be obtained. To avoid this problem the zero slope is converted to positive slope as shown in Fig. 7

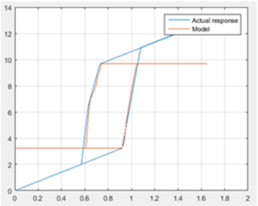

Fig. 7 Actual response Vs Model with zero slope converted to positive slope

As seen in the Fig. 7, at ymax and ymin, value of outputs are different from actual as the zero slope at saturation is converted to positive slope. So, while we calculate input required for set point from inverse PI model, set point value of ymax and ymin need to be mapped to new value. For the saturation ymax, new value obtained because of slope change can be calculated as,

$$y = y_{max} + w_1 * (y_1(0) - (r_{max} - r_2 - r_3))$$

where w1 is the weight of the first operator, y1(0) is the initial value of the first operator. Similarly, new value for the saturation ymin can be given as,

$$y = w_1 * y_1(0)$$

Analytical inverse can now be obtained as there are all positive slopes in the hysteresis curve. Fig. 8 shows analytical inverse of the model. So to get the input voltage for the desired output, first the desired output voltage is mapped to the output voltage which corresponds to the model with positive slopes. And then the input required for the desired set point is calculated using inverse PI model.

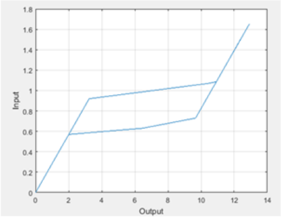

Fig. 8 Inverse

Analytical inverse can now be obtained as there are all positive slopes in the hysteresis curve. Fig. 8 shows analytical inverse of the model. So, to get the input voltage for the desired output, first the desired output voltage is mapped to the output voltage which corresponds to the model with positive slopes. And then the input required for the desired set point is calculated using inverse PI model.

7 CONCLUSION

Obtaining analytical inverse for hysteresis curve with zero slope is not possible. To get analytical inverse thus requires that slopes of the hysteresis curve is positive definite. So, PI model can be obtained by adding a positive slope at the saturation. This enables to calculate analytical inverse of the model. Altering zero slope region of the hysteresis curve does not decrease the model accuracy.

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