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DEVELOPMENT OF A NONLINEAR MODEL FOR A HIGH PRECISION PIEZOELECTRIC POSITIONING SYSTEM WITH APPLICATIONS IN MODEL-BASED DESIGN

Ciprian LAPUSAN, Calin RUSU, Simona NOVEANU

Abstract: *The paper proposes a new approach for developing the nonlinear model for a piezo actuated precision positioning system. In the model development the System Identification Toolbox from Matlab is used. The model that defines the systems dynamics is a nonlinear ARX model that considers the specific nonlinearities of piezo actuators. In the paper a set of models are identified, and the performance of the method is evaluated. The best obtained model is then used to develop new experiments in a simulated environment.*
Key words: *piezoelectric actuator, nonlinear model, precision positioning system, model identification*

1. INTRODUCTION

In the last decades more and more applications that use high precision positioning system were developed in different fields of activities [1]. This type of applications needs precisions that vary from micrometer to nanometer scale. Examples of such systems could be found in biomedicine [2][3], precision manufacturing [4][5] aerospace [6], optical lens systems [7] or robotics [8].

The actuation of such systems is in many cases implemented using piezoelectric actuators. This type of actuators offers several advantages like high resolution, large blocking force, fast response, and compact structure. These advantages make them ideal for implementing in high precision positioning systems [9].

Despite all the advantages mentioned above, there are still some drawbacks in using piezoelectric actuators. Perhaps the biggest challenge is the nonlinearity due to hysteresis [10]. Several approaches based on physical and phenomenological models have been developed to model the hysteresis phenomenon for these actuators. Physical models aim to describe the hysteresis model, mainly using the characteristics of the piezoelectric material. Phenomenological models try to describe hysteresis using a mathematical model based on experimental data [11]. The most used phenomenological models are Preisach, Parndtl-Ishlinskii, Duhem and the Bouc-Wen models [12]. These models have a rigid structure and involve a large volume of calculations, so they are relatively difficult to implement [13].

In this paper an alternative method that uses system identification techniques is proposed. In this approach the dynamic model is obtained from the experimental data (inputs and outputs) from the modeled system.

2. SYSTEM DESCRIPTION

In order to test the proposed method, a three-axis positioning system shown in Figure 1 is used.

The linear displacement along Ox is ensured by a NFL5DP20S/M - NanoFlex™ 5 mm Travel Translation Stage from Thorlabs. This module (1) consists of a linear flexure stage driven by a differential micrometer and a piezoelectric actuator. A displacement of max 5 mm is ensured by the differential micrometer (2) with a resolution of 0.5 µm. At any point, a supplementary displacement of 20 µm can be added by means of the piezoelectric actuator.

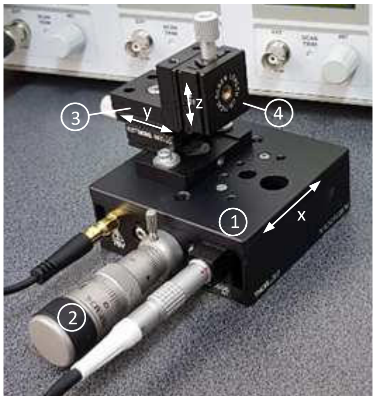

Fig. 1. The three-axis positioning system

Linear displacements along Oy and Oz axis are ensured by a DT12XZ/M - 12.7 mm XZ Dovetail Translation Stage (3), (4) also from Thorlabs. They have a stroke of 12.7 mm and can only be operated manually with the help of two precision M3 x 0.35 adjusters.

In order to acquire the experimental data needed in the identification process and experimental stand was developed. The setup consists of the three-axis positioning system (3), MDT693B Open-Loop Piezo Controller (2), power supply (4) and dSpace platform (1 (Fig. 2). The controller accepts external signals in the range of 0...10V. Proportional to these signals, it will provide the piezo actuator with a control voltage between 0 and 75V.

The external command signals for the piezo controller are provided by dSpace platform using a 16 bit DAC port.

The displacement of the positioning system on Ox axis, caused by the piezo actuator, is measured using a full bridge strain gauge sensor. The sensor is connected to the AMP2-Strain Bridge Instrumentation amplifier (5) from Thorlabs. The analog signal from the instrumentation amplifier output is transmitted to an ADC input port on dSpace board.

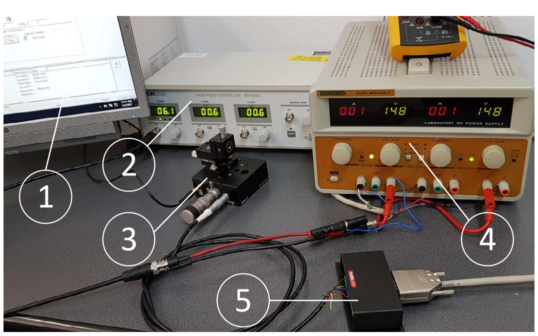

Fig. 2. Experimental setup

3. MODEL IDENTIFICATION AND VALIDATION

The dynamic model is developed using an experimental identification approach. For this a set of input/output data were measured on the experimental stand. The Simulink model that was developed for the dSpace board and used for signal generation and acquisition is presented in figure 3. In the model the DAC01 port is used to generate de command signal and ADC05 is used to measure the sensor voltage. The sampling time used for the experiment is 0.001 [s].

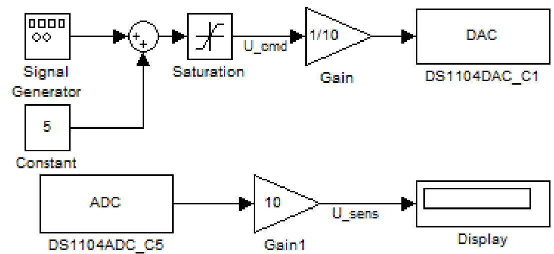

Fig. 3. Simulink model used for data measurement

First step was to evaluate the system hysteresis curves of the piezoelectric actuator. For this a triangular control signal with a decreasing amplitude and a constant frequency was used. The obtained hysteresis curves are presented in figure 4.

Next a set of rectangular signals with variable amplitude and frequency was used as input for the system (fig. 5). The input and the output of the system was measured and saved. The data were imported in System Identification Toolbox from Matlab. The rectangular signal is used for model identification and the triangular signal is used for model validation.

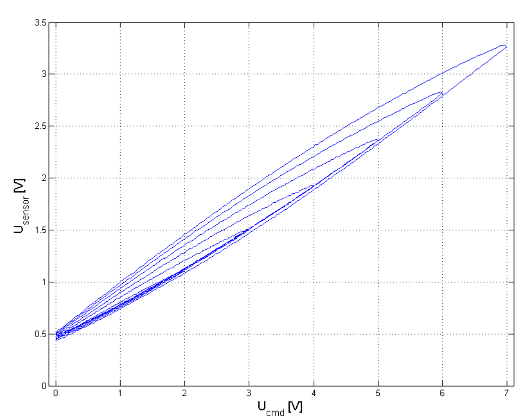

Fig.4. Piezoelectric actuator hysteresis curve

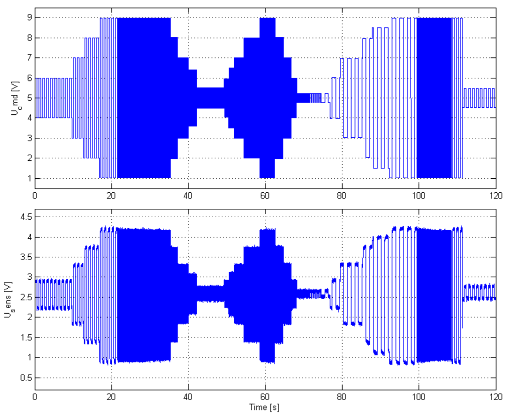

Fig. 5. Measured experimental data

For the identification process, a SISO nonlinear ARX candidate model is used. The general structure of such a model is presented in eq. 1.

$$y_p(t) = F(y(t-1), y(t-2), \dots y(t-na), u(t-nk-1), u(t-nk-2) \dots u(t-nk-nb)) \qquad (1)$$

In the model the *y* and *u* terms represent the input and outputs of the system. The current value of output y_p is obtained based on a flexible nonlinear mapping function *F*, that has as parameters the model regressors. The structure of such model integrates boots the model regressors and a nonlinear estimator. In defining such model one should give the *na* (no. of past output values), *nb* (no. of past input values) and *nk* (delay between input and output related with the sample rate) parameters.

Using the System identification tool several models were obtained. Several candidate models were used with different values for *na, nb* and *nk* parameters. The obtained results are presented in figure 6. The fit value varies from 73% to 95%.

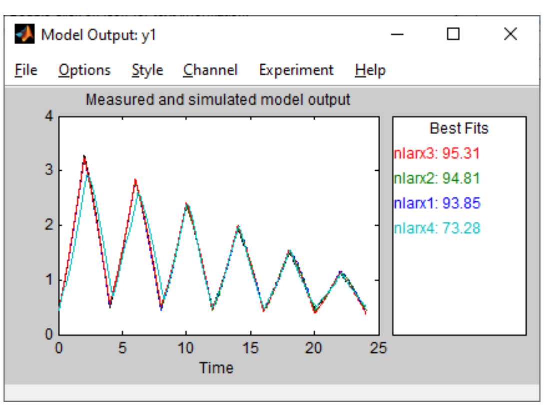

Fig. 6. Identification results

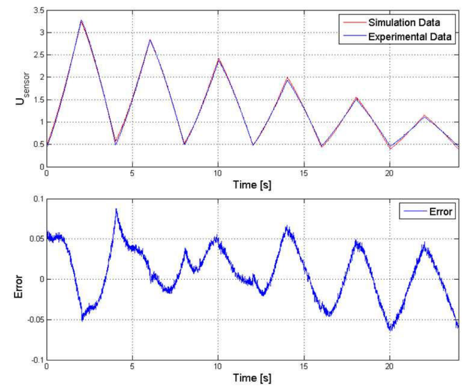

Fig. 7. Simulation results

The model chosen for further use is *nlarx3*, which has the parameters *na=15* and *nb=15*. The fit values is 95.31 %.

The obtain model is imported in Simulink using the *Nonlinear ARX Model* block from *System identification toolbox* library. Using this model, a set of simulation were developed. In figure 7 the values obtained from the model are compared with the experimental values. The errors vary from -0.06 to 0.08 (fig. 7).

The model was also used to evaluate the system hysteresis. The obtained results were compared with the experimental data. As shown in figure 8 the model was able to reproduce the hysteresis effect of the actuator with good results.

Further the model is intended to be used for creating simulations where a set of control algorithms are developed, optimized and tested.

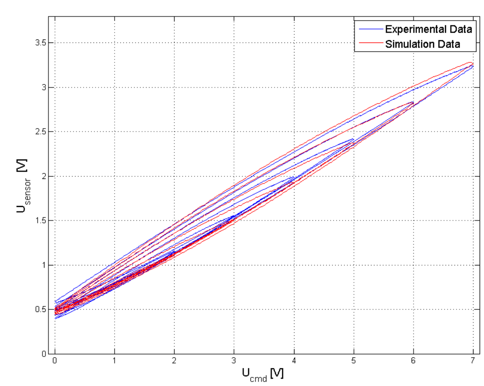

Fig. 8. Hysteresis curve evaluation

4. CONCLUSION

In this paper an experimental approach for modeling a piezoelectric actuator using system identification is presented. The obtained results showed that the method can be used with success for obtaining the nonlinear model of such system. The model is then imported in Simulink and a set of experiment were developed.

6. REFERENCES

[1] Liu, Y., Deng, J., Su, Q., *Review on multi-degree-of-freedom piezoelectric motion stage*, Journal IEEE Access, Vol. 6, 2018.

[2] Konno, K. I., Kosawada, T., Yamazaki, H., Hozumi, Y., & Goto, K., *Development of three-dimensional micro vibration stage and its application to control device for cell culture,* Journal of Biomechanical Science and Engineering, Vol. 3, pp. 38-49, 2008.

[3] Qian, J. Y., Hou, C. W., Li, X. J., Jin, Z. J., *Actuation Mechanism of Microvalves: A Review,* Journal of Micromachines, Vol 11, No. 2, 172, 2020.

[4] Li, J., Huang, H., & Morita, T., *Stepping piezoelectric actuators with large working stroke for nano-positioning systems: a review*, Sensors and Actuators A: Physical, Vol 292, pp. 39-51, 2019.

[5] Noveanu, S., Ivan, I. A., Noveanu, D. C., Rusu, C., Lates, D., *SiMFlex Micromanipulation Cell with Modular Structure*, Journal of Applied Sciences, Vol. 10, No. 8, 2861, 2020.

[6] Li, M., Yuan, J., Guan, D., Chen, W., *Application of piezoelectric fiber composite actuator to aircraft wing for aerodynamic performance improvement,* Science China technological sciences, Vol. 54, No. 2, pp. 395-402, 2011.

[7] Rouvinen, J., Kauhaniemi, I., Ahlgren, P., Johansson, S., Mattsson, C., *U.S. Patent No. 6,710,950*. Washington, DC: U.S. Patent and Trademark Office, 2004.

[8] Lupea, I., Ciascai, I., *Finding vibration modes for a piezo driven robot structure*, Journal Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, and Engineering, Vol. 60, No. 3, pp. 351-356, 2017.

[9] Aggogeri, F., Borboni, A., Faglia, R., Merlo, A., de Cristofaro, S., *Precision Positioning Systems: An overview of the state of art*, Journal Applied Mechanics and Materials Vol. 336, pp. 1170-1173, 2013.

[10] Tzen, J. J., Jeng, S. L., Chieng, W. H., *Modeling of piezoelectric actuator for compensation and controller design*, Journal Precision Engineering, Vol. 27, no.1, 70-86, 2003.

[11] Xiong, R., Liu, X., Lai, Z., *Modeling of Hysteresis in Piezoelectric Actuator Based on Segment Similarity*, Journal Micromachines, Vol. 6, No. 11, pp. 1805-1824, 2015.

[12] Rebai, A., Guesmi, K., Hemici, B., *Modeling of the hysteresis property in piezoelectric actuators a survey*, International Conference on Electrical Engineering and Automatic Control, pp. 24-26, 2013.

[13] Saraygord Afshari, S., Nobahari, H., Kordkheili, S. A. H., *Experimental parametric identification of a flexible beam using piezoelectric sensors and actuators*, Journal Shock and Vibration, 2014.

Dezvoltarea unui model neliniar pentru un sistem de poziționare piezolectric de înalta precizie cu aplicații in proiectarea bazata pe model

Rezumat: Lucrarea propune o noua abordare pentru dezvoltarea modelului neliniar pentru un sistem de poziționare de precizie cu acționare piezo. Pentru dezvoltarea modelului se utilizează modulul System Identification Toolbox din Matlab. Modelul ce definește dinamica sistemului este un model ARX neliniar ce ia in considerare neliniaritățile specific actuatorilor piezo. In lucrare sunt identificate un set de modele la care sunt evaluate performantele. Cel mai bun model obținut este ulterior utilizat pentru a dezvolta noi experimente într-un mediu simulat.

Ciprian LAPUSAN, PhD.Eng., Assoc.Prof, Technical University of Cluj-Napoca, Department of Mechatronics and Machine Dynamics

Calin RUSU, PhD.Eng., Lecturer, Technical University of Cluj-Napoca, Department of Mechatronics and Machine Dynamics calin.rusu@mdm.utcluj.ro (corresponding author)

Simona NOVEANU, PhD.Eng., Assoc.Prof, Technical University of Cluj-Napoca, Department of Mechatronics and Machine Dynamics