MATEC Web of Conferences **252**, 05009 (2019) https://doi.org/10.1051/matecconf/201925205009
CMES'18

Hysteresis modeling and investigations of a piezoelectric ring bender using Bouc-Wen model

Roman Regulski[1,*]

[1]Poznan University of Technology, Faculty of Mechanical Engineering and Management, Institute of Mechanical Technology, Piotrowo 3, 60-965 Poznan, Poland

Abstract. The paper describes theoretical and experimental investigation of applying Bouc-Wen model in displacement modeling of piezelectric ring benders. Under the increasing demand for more accurate position control systems, various hysteresis models appropriate for control purpose of mechanical systems have been proposed. Most of these models are based on phenomenological approach, for example: Prandtl–Ishlinskii or Krasnosel'skii-Pokrovskii and other, friction based like Maxwell-slip model. This paper presents a model described in analytical form, called the Bouc-Wen model, appropriate for position control purpose. Paper presents histeresis investigation results of Noliac CMBR05 ring bender under different voltages. Furthermore, article depicts how model was numerically implemented and investigated on dSpace Control System with Matlab Simulink Software for future research on real time position control with inverted hysteresis model.

1 Introduction

Piezoelectric actuators are widely used in many applications that require high resolution, fast response, and high positioning accuracy. One of them are piezoelectric bending actuators, also known as bimorphs. They are characterized by very good dynamic properties and by displacements in a range of a few millimetres. From many years there can be found a lot of examples with application of bender beams, such as hydraulic servovalves [1]–[4], micro robotics [5]–[7], energy harvesting [8]. Other types of transducers like piezoelectric tubes, stacks are predominantly the interest in micro and nano-positioners [9], [10] , atomic force microscopy [11] or vibration control [12].

Piezoelectric ring benders, as a modification of disc benders, are owing some advantages, comparing them to cantilever one. They have centred hole, which gives opportunity to mount eg. bushing and bolt through it. Another one benefit, is a much more larger blocking force at the same displacement value. The stroke ranges from 20 to 200 µm at a force of around 50 N, leading to a stiffness in the range of 1·106 N/m. Despite this, they may be only found in few exigent applications. For example in haptic interface [13] using modal frequencies to provide touch feeling. Next, in a precise control of fluid flow by a micro-valve [14]. In hydraulic servovalve to actuate a spool [15], [16] . Past, those transducers was also called circular and were used in physics optics to position laser mirror [17].

However, this actuators, like other piezoelectric materials suffer from two major problems, which are hysteresis and creep. Hysteresis possess strong nonlinearity around 20%, thus it considerably degrades position and tracking control, which becomes main challenge in this area. Hysteresis in the piezoelectric actuator is a memory-based nonlinearity between the input signal – voltage, and output, the mechanical displacement of the actuator. To reduce the impact of this unwanted drawback, many efforts and solutions of compensating hysteresis have been described in the literature. This topic in research area is named Hysteresis modellng.

Generally, hysteresis models can be divided into Physics-based models and phenomenological models. Mathematical equations as a part of this area, must describe this phenomena sufficiently accurate, efficient and amenable to use in real-time applications. Physics-based models tries to introduce and explain hysteretic behaviour with principles of physics effects. One of them is the Jiles-Artheon model, originally developed for ferromagnetic hysteresis [18]. Second one is the Domain wall model which have a possibility to be implemented as inverse compensator [19]. Phenomenological models are much more popular and has wider area of applications. One of the reason is that they don't provide unnecessarily physical background into the modelling problems. We can distinguish among them Operator-based models like: Preisach [20], Krasnosel'skii-Pokrovkii [21], Prandtl–Ishlinskii[22] have a common principle, that output is a sum of integral generalized elementary hysteresis operators, but each of them, use different kind of operator. Similar to those solutions is the Maxwell-slip model, originally designed for friction modeling, but after translating it to electrical domain it can adapted for a smart actuators modelling.[23]. Separate branch are models based on differential equations. Popular models that use this idea are Duhem approach [24], Backlash-like [25] and finally the Bouc-Wen model which is a subject

---

[*] Corresponding author: roman.regulski@put.poznan.pl

of the research described in this article, containing its analysis, parameter estimation and validation.

2 Test stand

For research purposes and experimental investigation, appropriate test stand was designed. Main part of the research stand, which diagram and picture are shown in the Fig. 1, is the dSpace Control System 2201 with a PC and Matlab Simulink software. Other key elements shown on the diagram are: optoNCDT 1700 laser displacement sensor with a resolution of 0.5µm and a measuring range of 2 mm, mounting of the transducer, two-channel high-voltage voltage amplifier, signal cables intended for controlling the output voltage from amplifier. Test stand has been mounted in rigid, non-conductive fixing, attached to a steel base. Data acquisition and processing control signals were performed using the dSPACE system via 16-bit ADC input module for laser sensor and 12-bit control output DAC to control the voltage. The sampling frequency of the measuring system was 1000 Hz.

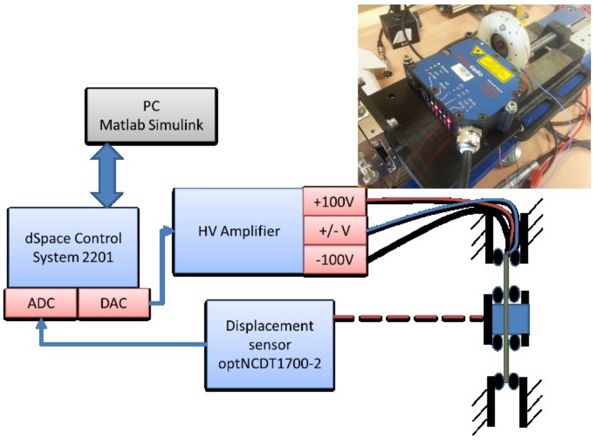

Fig. 1. Research stand for piezoelectric ring bender.

The test stand for piezoelectric transducer requires use of a power supply system that would provide an independent electrical voltage to each of the supplied electrodes. Two electrodes (positive, negative) are connected to constant DC voltage, while one control electrode is connected to the output of the amplifier. In the tests described here, transducer is deflecting in one axis, which requires only one variable voltage channel. Due to high price of commercial power systems, (order of thousands of euros), for this particular work purposes a two-channel high-voltage voltage amplifier made in our laboratory was used. The main part of amplifier's element is a high-voltage operational amplifier P91 from APEX. The gain of the control signal has been set to constant value of kV = 20 V/V with a maximum output voltage equal to $U_z = \pm 100$ V per channel. The current limit Imax was set to 65 mA. More information about amplifier can be found in [26], [27].

The system was controlled in real time by the dSpace system and the computer PC with a control system model prepared in the Matlab-Simulink program. The base of the station was mounted on the table reducing vibrations in order to reduce influence of the environmental impact on measurement results. The DAC output signal from dSpace control card is in the range of ±10V. Consequently, the control signal in Simulink with a range of ± 0,5 V corresponds to the supply voltage U_z.

The piezoelectric ring bender used in this study was Noliac CMBR05 made of NCE57 material. The actuator dimensions are 30x6x1.25mm (outer diameter, inner diameter, height) while Stiffness provided in datasheet is 0.41 *N/µm.* The actuator is able to generate ±70µm of a free stroke and 29N of a blocking force. It is worth to mention that it is a multilayer bender manufactured with ceramic layer thickness down to 20µm and capacitance of one electrode is only equal 940 nF.

Bending ring actuator can be mounted either by a mechanical clamping or gluing with an epoxy glue. It is very important to choose appropriate method according to a specific purpose. A mechanical clamping should be considered to be done with as low as possible moderate compressive force, as even small amount of the external force can reduce the maximum stroke of actuator. Therefore, this value should be taken into account when actuator is designed. Furthermore, mounting of an actuator at the outer diameter need some flexibility and contact gap to avoid unwanted additional clamping.

In this paper the mechanical clamping idea of piezoelectric ring bender is shown on the Fig. 2. Concept drawing shows the principle, in which, fixing force is provided by two rubber o-rings in the inner and outer edge. Clamping force on outer edge is regulated by three bolts with pushing springs, which holds and centralizes the polyamide body. Output displacement is transferred with 3D printed bushing with ABS material. It is hold by a single bolt with nut and washer. Washer transfers the clamping force by two o-rings on inner edge. In this case the clamping force is determined only by elasticity of rubber o-rings. The picture of bottom and top side of prototyped actuator is also shown on Fig. 2. High voltage wires of piezoelectric ring bender are connected to the electrodes on the side edge, thus it doesn't affect the movement of bimorph. The method of connecting the wires to the electrodes can be agreed with the manufacturer and two solutions are provided by the datasheet [28].

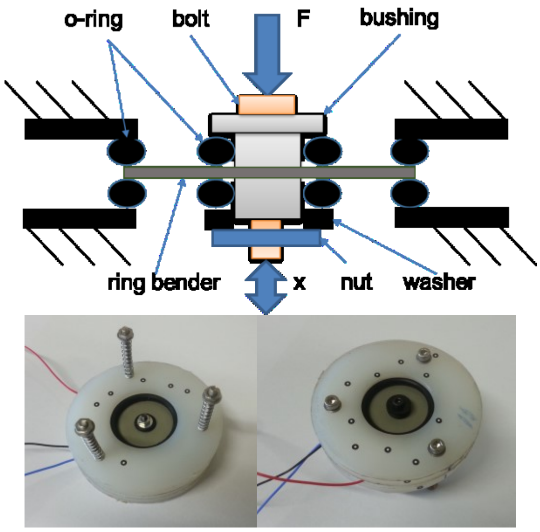

Fig. 2. The prototype actuator with piezoelectric ring bender.

3 Experimental research

In order to evaluate and to study the basic properties of the piezoelectric material, an open control positioning study was performed. The study was conducted on the above-described test stand. Electrical connection of the electrodes was done for differential voltage control. In this mode the bending can be controlled upwards and downwards. In this option positive electrode is connected to +100VDC, negative electrode is connected to -100VDC, and voltage applied to the middle electrode is controlled by the output of the high voltage amplifier. The range of operating voltage is ±100 VDC. The piezoelectric charge constants for the actuator d_{31} = -170e-12 C/N made of NCE57 material. If this voltage is positive the bender bends to one direction, and if it is negative it bends to opposite direction.

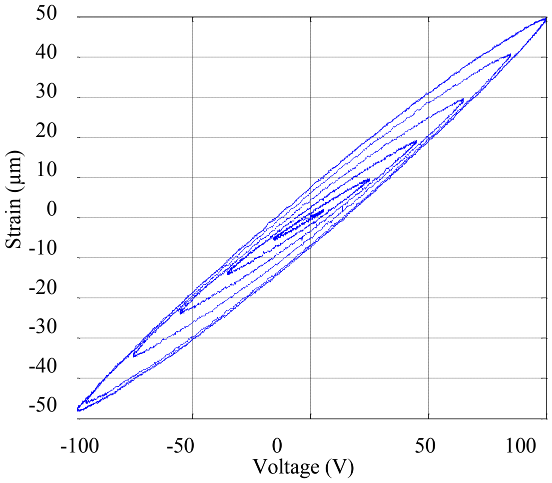

Fig. 3. Hysteresis measurement results.

Figure 3 shows experimental results of measuring strain hysteresis. The displacement of the bushing attached to inner edge of piezoelectric ring bender was measured in response to voltage change. Figure shows that the relationship between voltage and displacement is not linear. The test material also exhibits a hysteresis of approximately up to 20%, which is typical to piezoelectric materials. Maximum displacement for designed and manufactured prototype actuator is around ±50 µm. This value is quite smaller for data provided by the datasheet of the bender which is ±70 µm. Difference in this case can be explained by compressive forces made by mechanical clamping. However, the tolerance of this parameter is also given in range of ±15%.

Aforementioned and described measurement was performed for decreasing voltage to achieve hysteresis in whole range of actuator, for major and minor loops . As an input signal sine wave was used, which is described by function (1).

$$v(t) = A\sin(f \cdot t + k\pi) + b \qquad (1)$$

where *A* is amplitude, *f* is frequency, *b* is function bias. Values of each parameter are presented in equation (2).

$$v(t) = \begin{cases} 0 & for\ t\ \in \langle 0; 0.5) \\ 100\ (2\pi \cdot t - 0) + 0 & for\ t\ \in \langle 0; 16\rangle \end{cases} \qquad (2)$$

Decreasing of the amplitude for input signal is achieved by additional function q(t). Asymptotically amplitude decrease to 0 starts at 4 second (3)(4).

$$V(t) = \begin{cases} 0 & for\ t\ \in \langle 0; 0.5) \\ v(t) \cdot (1 - 0.1 \cdot q(t)) & for\ t\ \in \langle 0.5; 16\rangle \end{cases} \qquad (3)$$

$$q(t) = t - 4 \qquad for\ t\ \in \langle 4; 16\rangle \qquad (4)$$

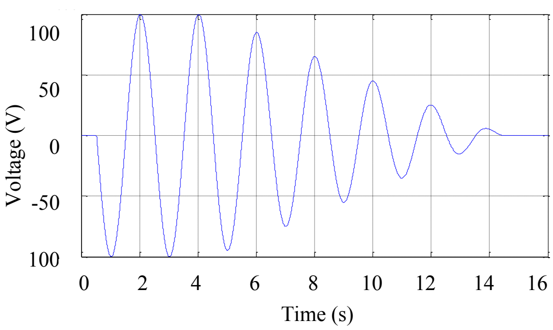

Fig. 4. Voltage input signal for hysteresis measurement.

Input signal is plotted in figure 4. This signal was generated using Matlab Simulink blocks and dSpace system. Values of the signal parameters was obtained experimentally and was tested many times to get repeatability. Before every measurement piezoelectric transducer must be slowly extinguished to zero position using this method to obtain the same zero position in the displacement. This is necessary to obtain initial curve of hysteresis, otherwise it will start in different position and it will be different every time, due to this phenomena. In other words the internal memory of displacement in material must be erased to zero.

To determine other parameters of piezoelectric actuator such us creep and mechanical damping the step response measurement was performed. Figure 5 shows results for three different step input signals 10V, 50V, 100V (blue, green, red - respectively). Each signal was triggered at 1s from 0V. The creep can be observed to be much stronger for higher voltage. This experiment was performed only for positive voltage and will be investigated deeper in future work related to creep modelling.

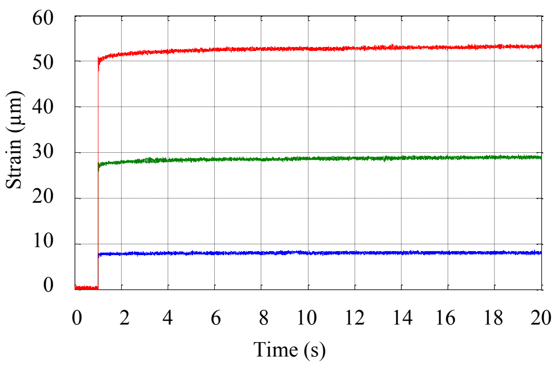

Fig. 5. Step response and creep results.

4 Modeling

4.1 Bouc-Wen model

The classical Bouc-Wen model was originally designed and used in the field of nonlinear vibrational mechanics. It took the name from two persons – Bouc who introduce the idea [29] and Wen who has later extend this formula [30]. It has found a large popularity due an interesting simplicity, which may represent a large class of hysteresis. The main factor of this model is a state variable h, also called the hysteretic variable or parameter. Using this variable it is possible to obtain hysteresis relationship to mechanical excitation F, which is given by the following non-linear differential equation (5):

$$\frac{dh}{dt} = A_{BW}\frac{dF}{dt} - B_{BW}\left|\frac{dF}{dt}\right| h|h|^{n-1} - \Gamma_{BW}\frac{dF}{dt}|h|^{n} \quad (5)$$

where A_{BW} parameter controls the restoring force amplitude, B_{BW} and Γ_{BW} parameters are responsible by the shape of hysteresis loop and n denotes the smoothness of the transition from elastic to plastic response. By obtaining a proper set of these parameters, it is possible to model the output of the model to real hysteresis loops. Thus, the tuning of the parameters for the specific application and material is an important aspect of the control system design.

According to universal structure of Bouc-Wen model formula, Low and Guo [31] have verified that this model can be adapted to describe piezoelectric hysteresis formula for three-later bimorph beam, and consequently to any piezoelectric actuator which exhibits this phenomena. Jouaneh [32] demonstrated that due to the elasticity of several piezoelectric and especially for cantilevered structure actuators parameter n =1. Thus, it makes model simpler to be adapted for this purpose. Making changes in equation (5) by replacing the mechanical input F with the applied electrical voltage U, the BW model adapted to piezo transducers is described by (6).

$$\begin{cases} y(t) = d_p U(t) - h(t),\ y(t_0) = y_0 \\ \frac{dh}{dt} = A_{BW}\frac{dU}{dt} - B_{BW}\left|\frac{dU}{dt}\right| h - \Gamma_{BW}\frac{dU}{dt}|h|, h(t_0) = h_0 \end{cases} \quad (6)$$

where y is the displacement output and U becomes the input control. Parameter d_p is the piezoelectric coefficient.

Above described equation can be adapted to prototyped actuator with piezoelectric ring bender using a second-order linear model modified by hysteresis non-nonlinearity. To make it simpler to present a different mathematic notation is used and it becomes as follows:

$$m\ddot{x} + b\dot{x} + kx = k(du - h) \quad (7)$$

$$\dot{h} = \alpha d\dot{u} - \beta|\dot{u}|h - \gamma u|\dot{h}| \quad (8)$$

where, as similar to (5) and (6) α, β, and γ are BW model parameters, m is the effective mass (kg), b is the effective damping (Ns/m), k is the mechanical stiffness (N/m), and d is the effective piezoelectric coefficient (m/V) of the piezo actuator. In this form, equations (7) and (8) are very simple for implementation in an automatic point of view. This makes the model easy to transcribe into Simulink block diagram solution, which part represents the calculation of state variable h (8),is shown on figure 6. It worth notice that the model use only basic blocks from the library.

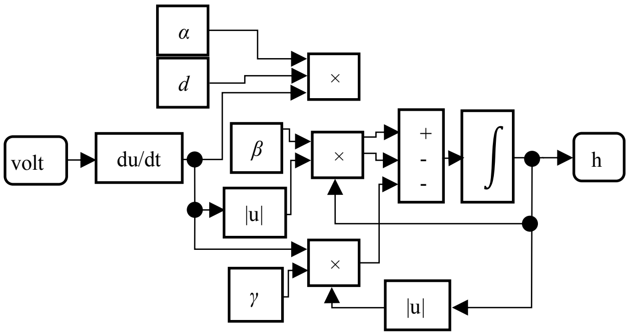

Fig. 6. Simulink block diagram of Bouc-Wen model.

The Matlab Simulink model expanded by the dynamic part (7) expose the hysteresis relationship between input control voltage and strain output. This model, experimental data (Fig. 3) and voltage input signal (Fig. 4) were applied to identify the parameters prototyped transducer. For this purpose the Parameter Estimation toolbox was used for estimate values of α, β, and γ. Effective mass m as sum of all moving elements was measured by the precision weight, in this case it is total weigh of bushing, bolt, nut, washer and two o-rings mounted inside piezoelectric bender. Damping coefficient b was obtained with step response test. Stiffness value k and piezoelectric coefficient d were provided by the manufacturer in datasheet of CMBR05 bender and NCE57 material [33]. All these parameters are listed in the table 1. Due to only three parameters which require to be tuned and due that this model is based on a set of equations, this approach is useful to be easily adapted in a control system. Next subheading describes verification of the model and its comparison with experimental data.

Table 1. Bouc Wen model parameters.

Parameter	**Value**	**Unit**
m	0.00134	kg
b	1.58*E3	Ns/m
k	4.10*E5	N/m
d	7*10^-E7	m/V
α	0.3575	-
β	0.0272	-
γ	0.0172	-

4.2 Verification and model test

In order to verify the model and parameters mentioned previously an additional experiment was conducted. It is necessary to get an answer how suitable is this approach in the case of future planned research with position control. Implementation of the model was also done in Matlab Simulink, model was compiled and programmed on dSpace. Input signal was prepared similar to signal used to model parameters identification. It is a sine wave damped asymptotically, but with different parameters. Signal was set to 0.1 Hz, triggered at 5 second and started damping at 25 second. On figure 7 it is plotted as red line, it was standardized to make it comparable. The value of the voltage signal at electrode was ±100 V.

Results are also presented on figure 7. Displacement response of the model is plotted as a green line and experimental data as a blue line. It can be noticed that the output of the Bouc-Wen model and experimental data are quite fitted to the input signal, which means, that the model was prepared correctly and has a potential to be used in control or positioning system, for example with PID regulator, which can feed forwarded by model. Value of the error between signals can be seen on figure 8. It shows magnified part of the chart, where difference is around 5 μm. This value could be smaller but it is need to make more experiments and some improvement on the test bench. Although, it is a first approach of the author to modeling piezoelectric ring bender, this results were regarded as satisfactory.

Experimental data from figure 3 and 7 gives the good point to go further with the design of prototype. Materials used for body construction must reconsidered and tested instead of polyamide, as well as the material of the o-rings which seems to be too much stiff. This stiffness in combination with compressive force can be a reason of limitation the maximum displacement of bimorph, thus it can also reduce the maximum blocking force, hence, it may limit the possible application of this actuator. Therefore future research will be conducted in this area along with model improvements.

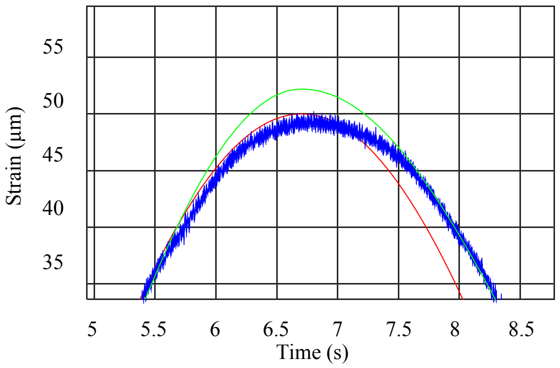

Fig. 8. Magnified chart part of the results from figure 7.

5 Conclusion

The presented paper focus on the problem of modeling hysteresis nonlinearity in the prototyped piezoelectric actuator. Through conducted experiments it was proved that the Bouc-Wen approach is a very efficient model for modeling the hysteresis in the piezoelectric ring bender. Its main advantage relative to existing approaches is the simplicity of computation and implementation. Basic knowledge of the model, its parameter estimation method and its validation were described. It was implemented in Simulink software and tested on real time dSpace control system. The developed research stand allowed the registration of the displacement with high accuracy. Achieved results are good output for future research and to develop inverse BW model, which will be the part of the control system dedicated to position control. It will be compared with other methods of hysteresis compensation and will be enlarged for example with creep model.

The presented research was executed under the 02/22/DSPB/1434 and funded with grants for education allocated by the Ministry of Science and Higher Education in Poland.

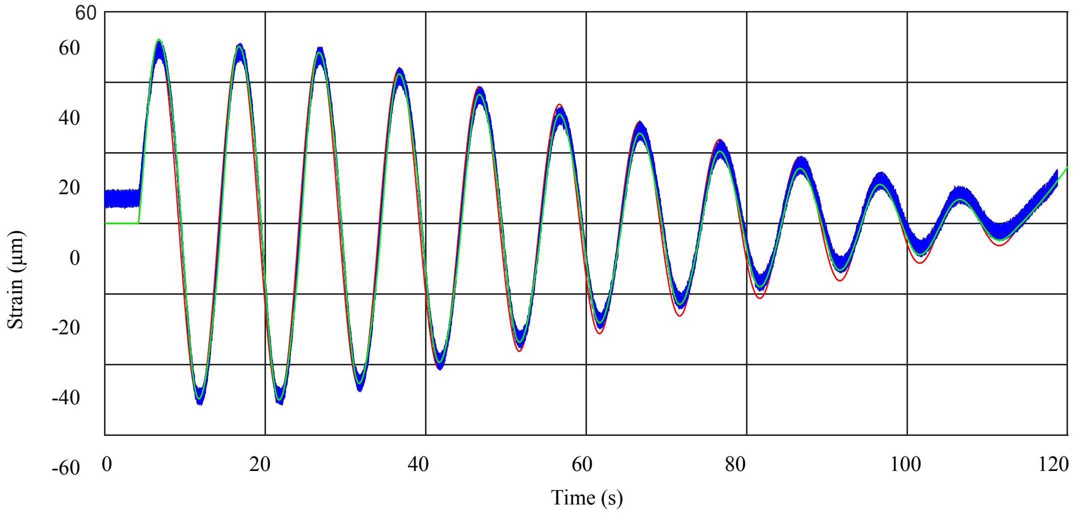

Fig. 7. Results comparison of Bouc-Wen model output and displacement experimental data.

References

1. D. Sędziak, R. Regulski, Solid State Phenom. **220,** 520-525 (2015)
2. D. Sędziak, Arch. Technol. Masz. Autom., **26**, 185-190 (2006)
3. A. Milecki, Arch. Technol. Masz. Autom., **26**, 177-184, (2006)
4. A. Plummer, Proceedings of 10th International Fluid Power Conference, **2**, 405-424 (2016).
5. S. A. Rios, A. J. Fleming, Y. K. Yong, *International Conference on Advanced Intelligent Mechatronics*, (IEEE, 982-986, 2016)
6. S. A. Rios, A. J. Fleming, Y. K. Yong, IEEE/ASME Trans. Mechatron. **23,** 524-530 (2018)
7. R. J. Wood, IEEE Trans. Robot. **24**, 341–347 (2008)
8. S.J. Jeong, M.-S. Kim, J.-S. Song, H. Lee, Sens. Actuators Phys., **48**, 158-167 (2008)
9. Y. Shan, K. K. Leang, Automatica, **48**, 1751-1758 (2012)
10. G.-Y. Gu, L.-M. Zhu, C.-Y. Su, H. Ding, S. Atikow, IEEE Trans. Autom. Sci. Eng. **13**, 313–332 (2016)
11. Y. K. Yong, B. Ahmed, and S. O. R. Moheimani, Rev. Sci. Instrum. **81**, 033701 (2010)
12. S. O. R. Moheimani, A. Fleming, *Piezoelectric Transducers of Vibration Control and Damping*, (Springer, 2006)
13. C. Winter, Y. Perriard, *International Conference on Electrical Machines and Systems* (ICEMS), 1383–1387 (2013)
14. M. S. Groen, *Microvalves for precise dosing: proportional flow control on a chip* (Enschede, 2015)
15. M. J. F. Bertin, A. R. Plummer, C. R. Bowen, D. N. Johnston, Symposium on Fluid Power and Motion Control ASME/BATH, V001T01A034 (2014)
16. L. Persson, A. Plummer, C. Bowen, I. Brooks, Proc Recent Advances in Aerospace Actuation Systems and Components, 99-104 (2016)
17. J. H. McElroy, P. E. Thompson, H. E. Walker, E. H. Johnson, D. J. Radecki, R. S. Reynolds, Appl. Opt. **14,** 1297–1302 (1975)
18. D. C. Jiles, D. L. Atherton, J. Magn. Magn. Mater. **61**, 48–60 (1986)
19. R. C. Smith,Z. Ounaies, J. Intell. Mater. Syst. Struct. **11**, 62–79 (2000)
20. K. Kuhnen and P. Krejci, IEEE Trans. Autom. Control. **54**, 537–550 (2009)
21. M. A. Krasnosel'skiĭ, A. V. Pokrovskiĭ, *Systems with hysteresis* (Springer, 1989)
22. M. Al Janaideh, J. Mao, S. Rakheja, W. Xie, C.-Y. Su, *47th IEEE Conference on Decision and Control* (IEEE, 5182-5187, 2008)
23. Y. Liu, J. Shan, Y. Meng, D. Zhu, IEEE/ASME *Trans. Mechatronics*, **21** ,38–43 (2016)
24. C.J. Lin and P.T. Lin, Comput. Math. Appl. **64**, 766–787 (2012).
25. C.-Y. Su, Y. Stepanenko, J. Svoboda, T.P. Leung, IEEE Trans. Autom. Control. **45**, 2427–2432 (2000)
26. A. Milecki, R. Regulski, Mech. Syst. Signal Process. **78**, 43–54 (2016)
27. R. Regulski, A. Nowak, B. Minorowicz, F. Stefański, Prog. in Aut., Rob. and Meas. Tech. **350**, 207–213 (2015)
28. Noliac, *Piezoelectric ring bender CMBR05 datashee*t,"http://www.noliac.com/products/actuators/ring-benders/show/cmbr05/"
29. R. Bouc, *Proc Fourth Conf. Nonlinear Oscil.* 315-319 (1967)
30. Y. K. Wen, ASCE J Eng Mech Div. **102**, 249-263 (1976)
31. T. S. Low and W. Guo, J. Micro. Syst. **4**, 230–237 (1995)
32. M. Jouaneh, ASME Jpn. Symp. Flex. Autom. **1**, 631–637 (1992)
33. Noliac, *NCE57 material specification datasheet*, "http://www.noliac.com/products/materials/nce57/"