Modelling of Piezoelectric Actuator (PEA) for Advanced Process Control in Chemical Mechanical Polishing (CMP)

Jing-Hang Liu, William J. O'Connor, Eamonn Ahearne, and Gerald Byrne

***Abstract*—Lead zirconate titanate (PZT) stacks are commonly used for submicron resolution actuation, fast response times and high sensitivity. They are usually modeled as expansion generators without external load. This paper proposes an electromechanical model for a commercially available micro-piezoelectric actuator (PEA) which comprises pre-stressed PZT stacks and external amplifier flexure frame for closed loop force control. The proposed model avoids the need to measure the piezoelectric charge which is usually required in conventional electromechanical models. The mechanical part of the PEA was modeled as a linear, lumped, double mass-spring-damper system and the related parameters were experimentally identified. The PEA system was characterised under load-free and load-applied conditions, and the electromechanical coupling ratios which describe the energy transfer from the electrical domain (voltage) to the mechanical domain (endpoint displacement/force) were experimentally determined.**

***Index Terms*—Electromechanical modeling, micro-piezoelectric actuator, parameter identification, force control.**

NOMENCLATURE

v_{in} total input voltage of the PEA system, V
v_e effective voltage of the PEA system, V
v_z voltage on amplifier resistance, V
f_{ext} external applied force to the PEA, N
f_{pzt} exerted force by the PZT stacks, N
n_{em} electromechanical coupling factor, NV^{-1}
t_{em} electromechanical coupling factor, mV^{-1}
z resistance of the PEA amplifier, Ω
c constant capacitance of the PEA,F
k_{pzt} stiffness of the PZT stacks, Nm^{-1}
k_s stiffness of PEA preload springs, Nm^{-1}
m_1, m_2 equivalent mass of the PEA, kg
k_1, k_2 equivalent stiffness of the PEA, Nm^{-1}
b_1, b_2 equivalent damper value of the PEA, Nsm^{-1}
x_1 endpoint displacement of the PEA, m
x_2 modelling displacement of the PEA, m
δ total electric transformed displacement, m
h nonlinear hysteresis displacement, m
S strain tensor
T stress tensor, Nm^{-2}
E electric field vector, Vm^{-1}
X output displacement, m
V exerted voltage to the PZT stacks, V
$\hat{s}_{33}$ elastic compliance, m^2N^{-1}
d_{33} material constants, mV^{-1} or CN^{-1}
A cross-section of the PZT cylinder, mm^2
l length of the PZT cylinder, m
k stiffness of the PEA, Nm^{-1}
ω_i the i^{th} resonance frequency in Bode plot (i=1,2), $rads^{-1}$

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I. INTRODUCTION

Chemical mechanical polishing (CMP) is described as "the process of smoothing and planarising synergistically aided by combined chemical and mechanical effects" [1] which is widely used for planarisation in semiconductor manufacturing. The Advanced Manufacturing Science (AMS) Research Centre at UCD is pioneering a new concept for advanced process control, called multifunctional intelligent tooling (MIT), with the potential to provide a major improvement in the interfacial pressure control between the silicon wafer and polishing pad [2]–[3]. In the proposed system, a long range micro-piezoelectric actuator is used as a force generator rather than its more common use in motion control. Models for relating voltage to displacement in PZT stacks can be divided into two major types: models based on or partly derived from PZT linear constitutive equations [4], and electromechanical models describing the electrical and mechanical energy transformations considering the nonlinear hysteresis between voltage and charge [5]–[9]. Constitutive equation based models treat the stacks as a linear component by ignoring the nonlinear behaviour of PZT, to which hysteresis is the most significant contributor. By contrast, electromechanical models adopt hysteresis operators to describe the nonlinear relationship between voltage and charge. Accordingly, charge measurement is essential since charge is the only index to indicate the accuracy of the hysteresis model. However, charge measurement is not recommended or not possible for some applications, for example where the disassembly for identification would have negative consequences for the whole system. This arises when the PZT stacks are pre-stressed and housed by the flexure amplifier mechanism, as in the PEA used in this project. In addition, the charge measurement is usually costly and has limited sensitivity.

II. ELECTROMECHANICAL MODEL OF THE PEA

The actuator used here is a commercial product, "Flextensional Piezoelectric Actuator™" (Dynamic Structures and Materials (DSM) LLC, Franklin, USA) which is composed of PZT stacks and flexure-hinged displacement amplifier frame, as shown in Fig. 1 and Fig. 2. The PZT layers were stacked in parallel acting as the strain generator and the generated deformation will be magnified by the flexible mechanism so as to exert a relatively larger output displacement. The gain of amplification is determined by the geometric dimensions of links, and the direction of motion is changed from horizontal to vertical.

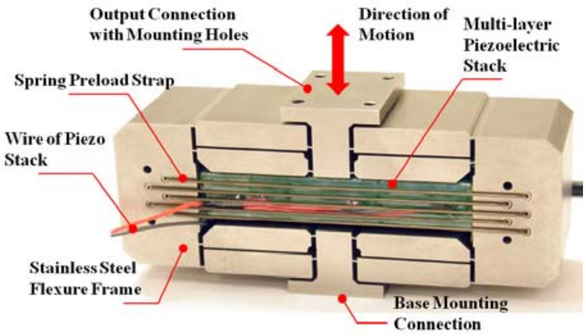

Fig. 1. The flextensional piezoelectric actuator™ fabricated by DSM

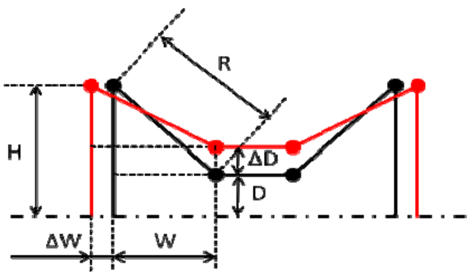

Fig. 2. Simplified structure of the flexure-hinged frame in PEA

The improved electromechanical mathematical model is represented in Fig. 3. This model moved the hysteresis operator from the electrical domain to the mechanical domain to avoid charge measurement. The hysteresis operator should be capable of providing resistance to the complex static or dynamic external loads. The PEA mechanical part was viewed as a linear, lumped double mass-spring-damper system governed by both piezoelectric equations and Newton's Law. The electric and mechanical domains are connected by the electromechanical coupling factors which can be experimentally determined.

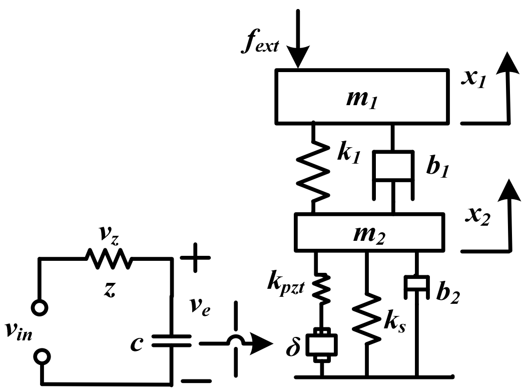

Fig. 3. Improved electromechanical model of the PEA

The mathematical description of the model can be expressed by (1) to (6).

$$v_{in} = zc\dot{v}_e + v_e \tag{1}$$

$$f_{pzt}(t) = k_{pzt} \times \delta \tag{2}$$

$$\delta = t_{em} v_e + h \tag{3}$$

$$k_2 = k_{pzt} + k_s \tag{4}$$

$$k \approx \frac{k_1 \times k_2}{k_1 + k_2} \tag{5}$$

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{bmatrix} + \begin{bmatrix} b_1 & -b_1 \\ -b_1 & b_1 + b_2 \end{bmatrix} \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} f_{ext}(t) \\ f_{pzt}(t) \end{bmatrix} \tag{6}$$

where δ represents the total transformed expansion of the PZT material which is composed of linear displacement and nonlinear hysteresis displacement. The electromechanical coupling factor t_{em}, stiffness of the PEA k, equivalent masses m_1, m_2, equivalent damper values b_1, b_2 and equivalent stiffnesse k_1, k_2 are the parameters that need to be identified.

III. Identification of the System

The actuator was characterised under two different working conditions: load-free and load-exerted. In the load-free condition, one side of the PEA was fixed to a rigid support and the other side was free (under no load); in the load-exerted condition, the PEA was fixed in a closed structural loop in a Hounsfield universal materials testing machine (Tinius Olsen, Inc., Horsham, PA, USA) such that the preload force exerted on the PEA can be adjusted by the Hounsfield machine, as shown in Fig. 4. The force sensor is a piezoelectric force sensor with a measurement range of ± 5KN and resolution of 1 mVN^{-1} (Kistler Instrument GmbH, Ostfildern, Germany) while the displacement sensor is a non-contact capacitive displacement sensor (Micro-Epsilon, GmbH & Co. KG, Ortenburg, Germany) with nanometre resolution. A National Instruments compact controller (model cRIO-9022, National Instruments (NI) Co., Austin, TX, USA) was used. The analog input and output modules combined with the NI controller are capable of simultaneous data acquisition and arbitrary signal generation.

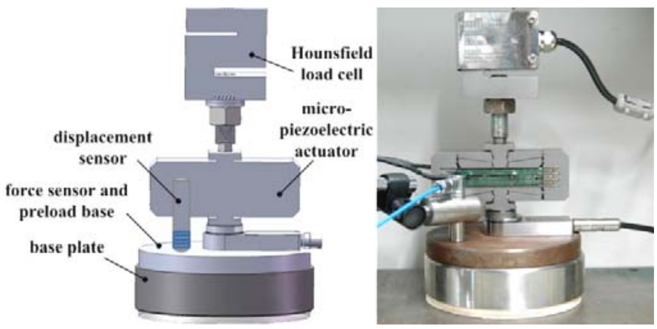

Fig. 4. The load-exerted experimental setup

The test programme described below was designed in NI

LabVIEW™ to accomplish the PEA characterisation and modelling parameters identification, as shown in Fig. 5. The programme involves generating control signals to the PEA and monitoring/recording the response. The responses of PEA were experimentally investigated based on different types of driving signals: sinusoidal or triangle waveforms with controllable parameters (amplitude, offset, phase, update rate, etc).

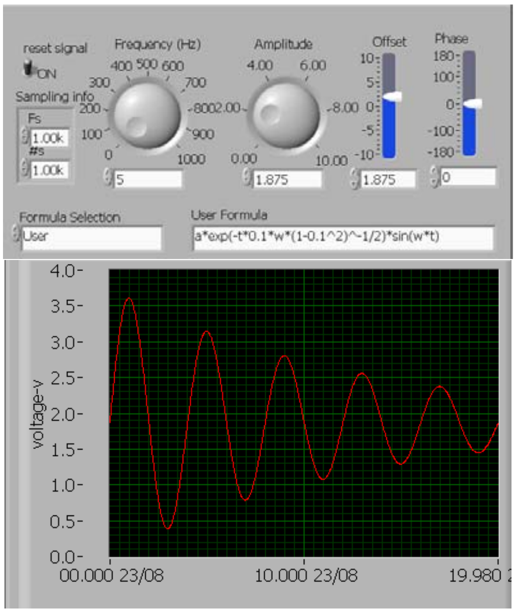

Fig. 5. The front panel of the programme in NI lab VIEW™

A. Coupling Factors Identification

Assuming the PZT component is a cylindrical disk of cross section A and length l, the relationship between external force, input voltage and the output displacement can be derived by the PEA constitutive equation (7).

$$S = \hat{s}_{33}T + d_{33}E \tag{7}$$

$$\begin{aligned} f_{ext} &= \begin{bmatrix} \dfrac{A}{l\hat{s}_{33}} & -\dfrac{Ad_{33}}{l\hat{s}_{33}} \end{bmatrix} \begin{bmatrix} X \\ V \end{bmatrix} = \begin{bmatrix} k & -k_l \end{bmatrix} \begin{bmatrix} X \\ V \end{bmatrix} \\ &= k\begin{bmatrix} 1 & -d_{33} \end{bmatrix} \begin{bmatrix} X \\ V \end{bmatrix} \end{aligned} \tag{8}$$

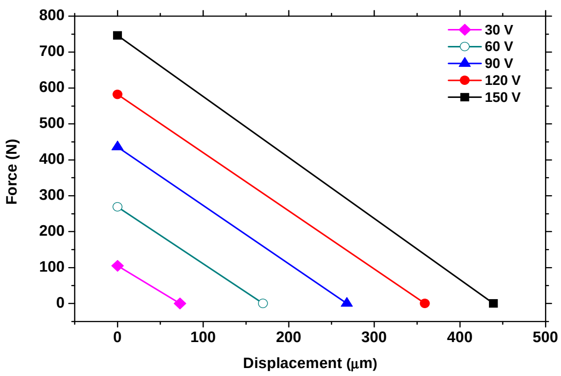

Fig. 6. The PEA characterisation under different voltages

Equation (8) indicates that the induced displacement is directly proportional to input voltage when the external load remains constant, and similarly, the external force is proportional to the voltage when the displacement remains constant. Five control voltages (30, 60, 90, 120 and 150V) were selected in the identification process, as shown in Fig. 6. The average identified value of coupling factors are listed in Table I. N_{em} and T_{em} slightly varied with voltage, as shown in Fig. 7. This is due to the inherent nonlinearity of coupling factors when the piezoelectric materials are subject to high control voltages [8]–[10].

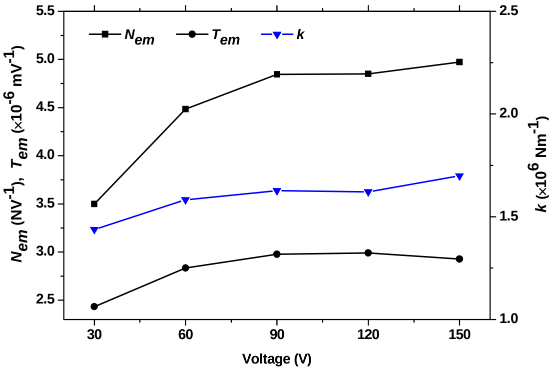

Fig. 7. The identified coupling factors

TABLE I: AVERAGE IDENTIFIED ELECTROMECHANICAL COUPLING FACTORS AND STIFFNESS OF THE PEA

Parameters	Description	Identified value	Units
T_{em}	electromechanical coupling from input voltage to endpoint (amplified) displacement	2.8	$\times 10^{-6}$ mV^{-1}
N_{em}	electromechanical coupling from input voltage to endpoint force	4.5	NV^{-1}
k	stiffness of the PEA	1.6	$\times 10^{6}$ Nm^{-1}

B. Dynamic Parameters Identification

To identify the parameters m_1, m_2, b_1, b_2 and k_1, k_2, the dynamic property of the PEA was investigated under load-free condition. The magnitude of the measured Bode curve in Fig. 8 represents endpoint displacement divided by the external force exerted on the actuator as the input is swept over the frequency range of 0 to 500 Hz. The amplitude of the input was 80 V and the sampling rate was up to 10^5 Hz.

The values of the first resonance frequency, ω_1, and the frequency of the zero of the response, ω_0, were experimentally determined from the measured Bode curve. The relationship between equivalent masses m_1, m_2 and equivalent stiffnesse k_1, k_2 were expressed as in (9), (10), under the assumption that the damper values b_1, b_2 and external force f_{pzt} were temporarily assumed to be zero. With the values of m_1, m_2, k_1 and k_2 identified from (5) and (9), (10), the damper values b_1, b_2 were chosen to obtain a good match between model and measured frequency responses, as shown in Table II.

$$\begin{aligned} \omega_{1,2}^2 &= \frac{k_1 m_2 + (k_1 + k_2)m_1}{2m_1 m_2} \\ &\mp \sqrt{\frac{1}{4}\left(\frac{k_1}{m_1} - \frac{(k_1+k_2)}{m_2}\right)^2 + \frac{(-k_1)^2}{m_1 m_2}} \end{aligned} \tag{9}$$

$$\omega_0^{\ 2} = \frac{k_1 + k_2}{m_2} \tag{10}$$

TABLE II: IDENTIFIED PARAMETERS OF THE PEA DYNAMIC MODEL

Parameters	Identified value	Units	Parameters	Identified value	Units
m_1	0.25	kg	m_2	5.62	kg
b_1	55.0	Nsm^{-1}	b_2	1.0	Nsm^{-1}
k_1	1.62	$\times 10^6$ Nm^{-1}	k_2	40	$\times 10^6$ Nm^{-1}

The simulated Bode plot based on the listed parameters is compared with the measured curve in Fig. 8. It shows good matching between the simulated and measured responses, especially in the useful frequency range below 10^3 rads^{-1}. the proposed model therefore can represent the actuator dynamics with sufficient accuracy.

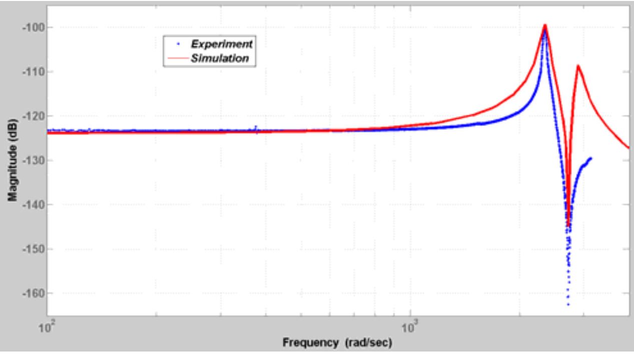

Fig. 8. Measured Bode curve (blue points) and the simulated Bode curve (red line)

IV. CONCLUSIONS

An improved electromechanical model is presented for a commercially available PEA composed of pre-stressed PZT stacks and an external amplifier flexure mechanism. Characterisations were accomplished when the PEA was working under load-free and load-exerted conditions and the voltage-displacement electromechanical coupling coefficient and voltage-force electromechanical coupling coefficient were experimentally identified. The mechanical part of the PEA was modeled as a linear, lumped double MSD system governed by both piezoelectric constitutive equations and Newton's Law. The equivalent parameters were experimentally identified and verified.

REFERENCES

[1] J. M. Steigerwald, S. P. Murarka, and R. J. Gutmann, *Chemical Mechanical Planarization of Microelectronic Materials*, New York: John Wiley & Sons, 1997.

[2] J. Liu, E. Ahearne, and G. Byrne, "Characterisation of the External Loading Conditions of an Advanced Process Control System Integrated with Piezoelectric Actuator (PEA) in Chemical Mechanical Polishing (CMP)," in *Proc. 2011 28th International Manufacturing Conf.*, Dublin, pp. 1-8, 2011.

[3] J. Liu, E. Ahearne, and G. Byrne, "Characterisation of the Transfer Function of an Advanced Process Control System for Chemical Mechanical Polishing (CMP)," in *Proc. 2011 11th International Conference of the European Society for Precision Engineering & Nanotechnology*, Como, vol. 1, pp. 311-314, 2011.

[4] S. B. Choi and Y. M. Han, *Piezoelectric Actuators Control Applications of Smart Materials*, New York: CRC Press Taylor & Francis, 2010, ch. 4, pp. 71-72.

[5] M. Goldfarb and N. Celanovic, "Modeling piezoelectric stack actuators for control of micromanipulation," *IEEE Control Systems*, pp. 69-79, June 1997.

[6] H. J. M. T. S. Adriaens, W. L. D. Koning, and R. Banning, "Modeling piezoelectric actuators," *IEEE/ASME Transactions on Mechatronics*, vol. 5, no. 4, pp. 331-341, 2000.

[7] H. M. S. Georgiou and R. B. Mrad, "Electromechanical Modeling of Piezoceramic Actuators for Dynamic Loading Applications," *Journal of Dynamic Systems, Measurement, and Control*, vol. 128, no. 3, pp. 558-567, 2006.

[8] M. Quant, H. Elizalde, A. Flores, R. Ramírez, P. Orta, and G. Song, "A comprehensive model for piezoceramic actuators: modelling, validation and application," *Smart Materials and Structures*, vol. 18, pp. 1-16, Dec. 2009.

[9] L. Juhász, J. Maas, and B. Borovac, "Parameter identification and hysteresis compensation of embedded piezoelectric stack actuators," *Mechatronics*, vol. 21, no. 1, pp. 329-338, Feb. 2011.

[10] H. L. H. Richter, E. A. Misawa, and D. A. Luccaa, "Modeling nonlinear behavior in a piezoelectric actuator," *Precision Engineering*, vol. 25, no. 2, pp. 128-137, Apr. 2001.

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