Parameter Determination for an Electromechanical Model of a Displacement-Amplified Piezoelectric Actuator

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Abstract

The "long range displacement" piezoelectric actuator (PEA) investigated in this paper comprises pre-stressed piezoceramic lead zirconate titanate (PZT) stacks in a flexure-constrained multi-component frame. This paper proposes a PZT electromechanical model which relates the stacks' electrical and mechanical domains. This paper introduces an identification approach to the determination of the model parameters without disassembling the embedded piezoceramic stacks. The electromechanical couplings of the PZT stacks, which describe the energy transfer between the electrical and mechanical domains, were experimentally identified.

1 Introduction

Our research group is pioneering the use of long range PEAs for closed loop control of the applied force in a number of manufacturing processes including chemical mechanical planarisation (CMP), with the potential to provide a major improvement in the control of the local interfacial pressure between the silicon wafer and polishing pad [1]–[2]. The PEA is a commercial product, "Flextensional Piezoelectric Actuator™" (Dynamic Structures and Materials, LLC, Franklin, USA) which is composed of PZT stacks and a flexure-hinged amplification mechanism (FAM). The PZT layers are electrically connected in parallel generating strain when charged which is magnified by the flexible mechanism so as to realise a relatively large output displacement, as showin in Fig. 1 (a).

2 Methodology

In the PEA model, the whole actuator was divided into the PZT stacks, the mechanical parallel pre-stress springs, and the external FAM. In this approach the electromechanical model of the pre-stressed multi-layer PZT stacks is supplemented with a kinematic model of the FAM.

2.1 Electromechanical model of PZT stacks

The electromechanical model of the PZT stacks is shown in Fig. 1 (b). The input to this model is voltage, and the output is the PZT displacement. The total input voltage (v_{in}) was divided into the voltage that induces hysteresis (v_h) and the voltage linearly proportional to the piezoelectric force (v_p). H represents the hysteresis operator, x is the stack displacement, f_p is the transduced force from the electrical domain. The electrical and mechanical domains are related by the electromechanical coupling factors. T is the electromechanical coupling between piezoelectrical charge and displacement, and N is the factor between voltage and displacement. In the PZT model a linear relationship is assumed between the mechanical and electrical domains:

$$q_p=T\times x \tag*{Eq. 1}$$

$$v_p=N\times x \tag*{Eq. 2}$$

The total current is the sum of the current through the capacitor, resistor and the current introduced by the piezoelectric effect. So the charge can be defined by:

$$q=c\times v_p+ q_p + q_r^{*} \tag*{Eq. 3}$$

* dynamic part only.

The mechanical part was modelled as a linear, lumped mass-spring-damper system. The equivalent capacitance c, equivalent resistance r, the equivalent mass m_p, damping ratio b_p, the stiffness of PZT stacks k_p, and the stiffness of preload springs k_s are parameters that need to be identified.

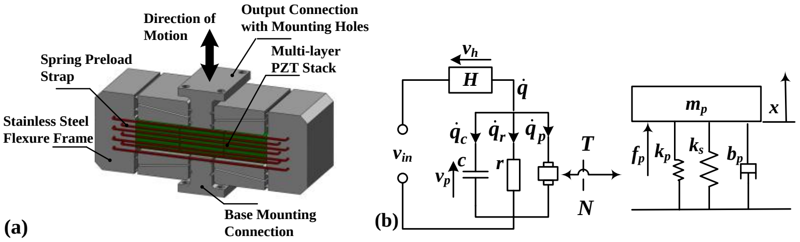


Fig. 1: (a) DSM PEA; (b) Electromechanical model of the PZT stacks

2.2 Parameters identification

During identification two PEAs were fixed in series in a closed structural loop in a Hounsfield testing machine, as shown in Fig. 2. The preload force exerted on the PEAs is adjustable. In the experiments, the actuator #2 was investigated in short and open circuit conditions. Under both conditions, tensile and compressive forces were applied by actuator #1. The induced displacements in horizontal directions were measured while the vertical force was measured by an inline force sensor.

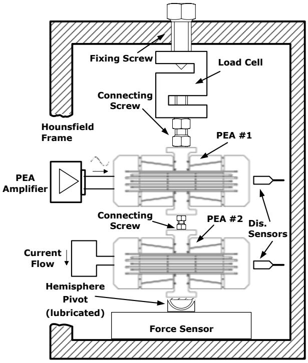


Fig. 2: Experimental setup: actuator #2 in short circuit condition

The principle of this experiment is that, when the actuator was tested in short circuit, the coupling between the charge and the PZT stack displacement can be identified, and when the actuator was tested in open circuit, the coupling between the voltage and PZT stack displacement (or force) can be determined.

3 Results and discussion

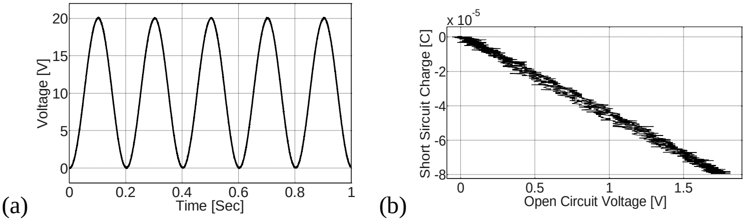
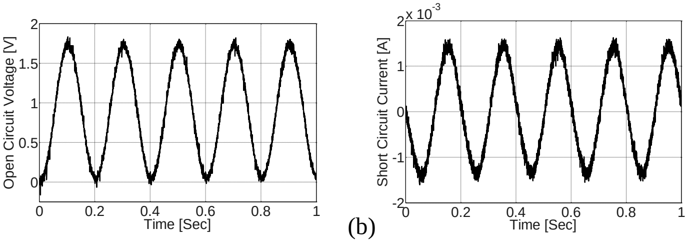


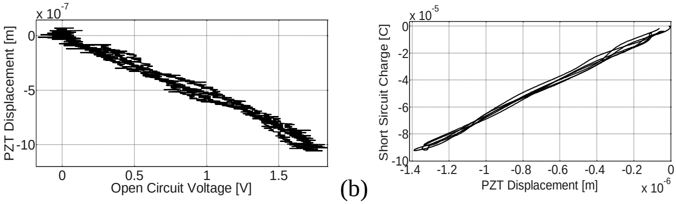
Fig. 3: (a) Signal to PEA #1; (b) Short circuit charge versus open circuit voltage

The driving signal to PEA #1 is shown in Fig. 3 (a). The relationship between the short circuit charge and the open circuit voltage is shown in Fig. 3 (b) indicating that hysteresis is not relevant for this situation. The open circuit voltage and short circuit current is shown in Fig. 4 (a) and (b). The slope of Fig. 5 (a) represents the coupling ratio between PZT displacement and the linear voltage. The slope of Fig. 5 (b) represents the coupling ratio between short circuit charge and the PZT displacement. The identified parameters are listed in Table1.



(a) (b)

Fig. 4: (a) Open circuit voltage of PEA #2; (b) Short circuit current of PEA #2



(a) (b)

Fig. 5: (a) PZT displacement vs. open circuit voltage; (b) Short circuit charge vs. displacement

Table1: Identified electromechanical coupling coefficients

Parameters	*N*	Units	*T*	Units
Value	-1.76×10^6	[V/m]	67.62	[C/m]

In summary, in this paper the values of the coupling ratios between electrical and mechanical domains in the PZT model were experimentally determined and these values will be used in future modelling work.

References:

[1] 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, 2011, pp.311-314.

[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.*, 2011, Dublin , pp.1-8.