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Impacts on multi-layer piezoelectric actuator when coupled with mechanical elements☆

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ABSTRACT

Multi-layer piezoelectric actuators (MPA) have been widely used as linear actuators for various applications including micro/nano-positioning. When MPA is employed to drive a positioning mechanism, the arrangement normally involves one of its ends being fixed to the ground/base and the other end being joined with other mechanical part(s) of the device to be driven. Based on the IEEE standards on piezoelectricity and the verified assumptions, the vibration characteristics of a MPA, which has one end fixed and the other end coupled with mechanical elements, namely the equivalent mass, spring and damper is mathematically modelled. The derived equations are coded in Matlab and various values of the coupled mass, spring and/or damper are implemented to investigate the resulted impacts including changes of the vibration magnitudes at off-resonance frequencies and the shifts of resonant frequencies and phases.

1. Introduction

Multi-layer piezoelectric actuators (MPA) have been widely used as actuators for various applications including micro/nano-positioning, for example in compliant micro/nano-motion stages [7,9], which normally operate at lower frequencies (off-resonance), and in Smooth Impact Drive Mechanisms (SIDMs) [6,8], which normally operate at higher but still at off-resonant frequencies. Later in literature, in order to generate faster moving speed and higher output power than conventional SIDMs, resonant-type SIDM (R-SIDM) principle was proposed and successfully realised using hard-type piezoelectric transducers [3]. The resonant-type SIDM uses longitudinal vibration modes with a frequency ratio of 1:2 to form quasi-saw shaped vibration for stick-slip motion.

When MPA is employed as actuator to drive a positioning mechanism, the arrangement normally involves one of its ends being fixed to the ground/base and the other end being coupled with other mechanical part(s). In the case of a compliant micro-motion stage, for example, the one shown in Fig. 1 [7], the coupling end is connected to flexure hinge linkage to mechanically amplify the displacements generated by MPA which is eventually connected to the end-effector together in parallel with the other two flexure hinge linkages.

In the case of a R-SIDM [3], for example, the one shown in Fig. 2 [10], the coupling end of the MPA is connected to a metal rod and then a friction rod on which a slider sits to generate stick-slip motions through friction contact. The other end of MPA in this special case is sitting and touching on a sponge. The arrangement is therefore a free-free MPA configuration with one of the free end coupled with mechanical elements consisting of a metal rod, a friction rod, and a slider through friction contact.

To produce the required longitudinal vibration modes with a frequency ratio of 1:2 to form quasi-saw shaped vibration for stick-slip motion, great attentions and efforts are required on how the overall device including size and shape is designed and what materials are used. The use of metal plate with symmetric step design and Langevin transducers reported in [11] is a good example.

When MPA is used to drive a positioning mechanism, the combined dynamics is complex but can be and normally is approximated empirically by a second-order system; nevertheless, the rationale for such an approximation is lacking in literature [2]. Through employing assumed mode method to solve the governing equation, the rationale for such approximation was investigated and reported with a method to quantify the error associated with the approximation [2]. In the study, the free end of the fixed-free MPA is coupled with a mass. Such second-order system approximation could be effective for many applications including predicting the 1st mode frequency, but it is not sufficient for the estimation of

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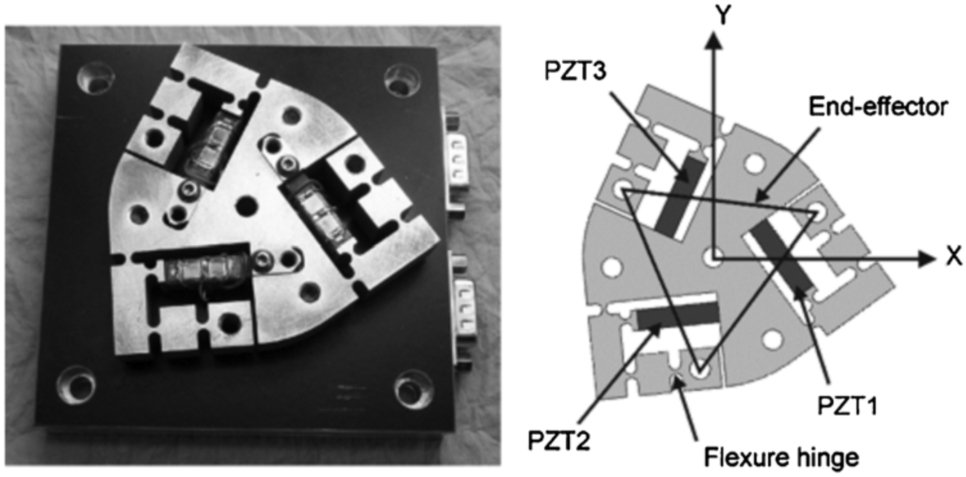

Fig. 1. 3RRR compliant micromanipulation device (Lu et al., 2004) [7].

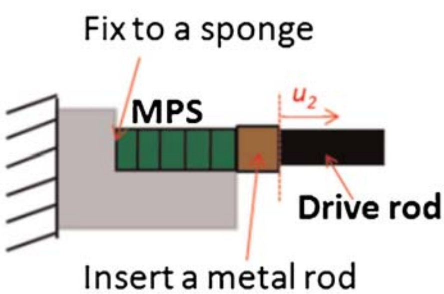

Fig. 2. R-SIDM and quasi-saw shaped waveform (Zhang et al., 2016) [10].

multiple mode frequencies for such as R-SIDM to find 1:2 ratio to form quasi-saw shaped vibration.

There are different methods in literature which could be further developed to potentially provide the general model with the combined dynamics for parametric studies, for being included in the control loop and to better understand the impacts of such couplings with mechanical elements. These methods include the distributed parameter method, the transfer matrix method, and the equivalent electric circuit based method. As revealed in [10,12,14], each method has its own advantages in such as incorporating the mechanical couplings or electric couplings into the model.

Even though all are capable of including mechanical couplings in the combined model, so far only mass has been included to couple with MPA in mathematical modelling [2,10]. There has no one method been employed to develop the general model in literature coupling the MPA with the combination of mass, damper and spring altogether, neither investigating thoroughly the resulted impacts including changes of vibration magnitudes and shifts of vibration modes and phases in literature. Therefore, by following the distributed parameter approach [12], this study firstly formulate the general mathematical model involving MPA, equivalent mass, equivalent damper and equivalent spring for fixed-free (but coupled) boundary condition to effectively represent the dynamic behaviours. Then the model is used in simulations to reveal the results and to understand the impacts. It should be noted that by changing the boundary conditions, new sets of equations can be easily derived for different coupling types (i.e. fixed-fixed, free-free, etc.) and different designs.

2. Model formulation

Generally speaking, mechanisms can be effectively simplified and dynamically modelled as their equivalent mass(es), damper(s) and spring(s). Depending on the needs, in many applications, mechanisms modelled as a second order mass-spring-damper system would be sufficient for the understanding of their dynamic behaviours and for control purposes. In this study, the coupled mechanical elements/mechanism is also modelled as effective mass, damper and spring. However, the MPA is modelled as a distributed system in order to estimate multiple vibration modes.

Based on the IEEE standards on piezoelectricity [4], the 3-D piezoelectric constitutive equations can be organized as:

$$\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 & 0 & 0 & d_{31} \\ s_{12}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 & 0 & 0 & d_{32} \\ s_{13}^E & s_{23}^E & s_{33}^E & 0 & 0 & 0 & 0 & 0 & d_{33} \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 & 0 & d_{24} & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 & d_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{15} & 0 & \varepsilon_{11}^T & 0 & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 & 0 & \varepsilon_{22}^T & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 & 0 & 0 & \varepsilon_{33}^T \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ E_1 \\ E_2 \\ E_3 \end{Bmatrix}, \quad (1)$$

Where S_i, T_i, E_i, and D_i are respectively the components of strain, stress, electrical field and electrical displacement vectors. s_{ij}^E are the components of compliance matrices measured at constant electrical fields. d_{ij} are the piezoelectric strain coefficients measured at constant stresses. ε_{ii}^T are dielectric coefficients measured at constant stresses. These piezoelectric material constants can be obtained from MPA manufacturer or by measuring and analysing electrical impedance [1,5].

Following the assumptions made and verified in [12] by:

- assuming MPA is at least three times longer in the longitudinal direction than its lateral dimension;
- considering that the thickness of each piezo layer is often far less than the overall length of MPA in the longitudinal direction, the distribution of the displacement across the thickness of each piezo layer is therefore assumed to be uniform (i.e. S_3 is a constant);
- assuming the distribution of the electrical field across the thickness direction of each piezo layer is uniform;
- assuming negligible thickness of electrode layers [13]; and