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A new electrical configuration for improving the range of piezoelectric bimorph benders

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ABSTRACT

This article describes a new electrical configuration for driving piezoelectric benders. The 'Biased Bipolar' configuration is compatible with parallel-polled, bimorph and multimorph benders. The new configuration is similar to the standard three-wire drive method where the top electrode is biased with a DC voltage and the bottom electrode is grounded. However, the new configuration uses an alternate DC bias voltage and adjusted range for the central electrode which allows the full range of positive and negative electric fields to be utilized. Using this technique, the predicted deflection and force can be increased by a factor of 2.2 compared to the standard two wire configuration and 1.3 times for the standard three wire configuration. These predictions were verified experimentally where the measured factor of improvement in displacement and force was of 2.4 and 1.3 compared to the standard two-wire and three-wire configurations.

1. Introduction

Piezoelectric actuators utilize the inverse piezoelectric effect, where an applied electric field can induce an internal stress. These actuators are already used in a wide range of applications such as ultrasonic motors [1], beam steering [2], vibration dampening [3] and miniature robotics [4]. Piezoelectric actuators have a high stiffness, resolution and fast response compared to other common actuators. The most common type of piezoelectric actuator in industrial applications is the bender.

Benders can be of the unimorph or bimorph type. Unimorph actuators have one piezoelectric plate bonded to a non-piezoelectric elastic plate. Bimorph actuators, shown in Fig. 1, have two piezoelectric plates joined together possibly with a third elastic layer sandwiched between the two piezoelectric layers to increase the mechanical reliability [5]. The beam or plate is usually mounted in a cantilever arrangement; however, it can also be simply supported or fixed on both ends. Bimorph and unimorph actuators develop deflection and force when one piezoelectric layer contracts while the other layer expands, or in the case of unimorphs only when the piezoelectric layer contracts or expands. An additional type of bender is the multi-layer bender. Multi-layer benders work in a similar fashion to bimorph benders except that each piezoelectric plate is comprised of many thinner piezoelectric layers co-fired together, thus reducing the maximum driving voltages required.

This paper explores existing electrical configurations and compares them to a proposed method for driving bimorph and multilayer piezoelectric benders. The new driving method allows a bender to be driven using the full range of electric field with only a single bias supply and a single variable power supply. By using this configuration, the size of a piezoelectric bender can be reduced while maintaining the same deflection as a larger bender driven with an existing electrical configuration.

In the following section, the history of piezoelectric bimorph benders is briefly discussed. Section 3 then describes the constituent equations for the deflection and blocking force. The new configuration is then presented, followed by experimental results.

2. History

The first piezoelectric benders were invented by Sawyer in 1931. These early benders used Rochelle salt bars cut at specific angles and cemented together to create bimorph benders. These benders were used primarily for audio applications such as microphones, speakers and pick-ups [6]. In 1936, Sawyer patented the series and parallel configurations for driving a bimorph bender [7]. These configurations remained the only available methods for driving a bimorph or multi-morph bender until 1993 when Hayashi et al.

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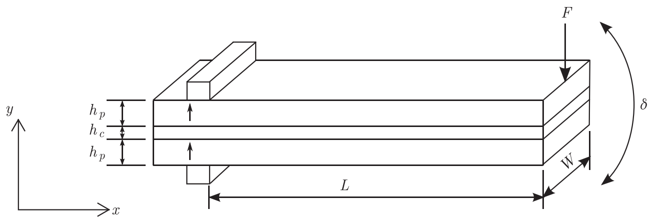

Fig. 1. Typical piezoelectric bimorph bender.

lodged US patent 5,233,256 outlining a new method for driving parallel and series configuration benders [8].

In 2005, Wood et al. proposed an electrical configuration for bimorphs that used one bias voltage and another unipolar voltage as part of their study on the optimal energy density of piezoelectric bending actuators [9]. This configuration was similar to US patent 5382864-A which switches the center electrode between the bias voltage and ground [10] and US patent 6888291-B2 which describes a method for driving an electrostrictive bimorph actuator by controlling the center voltage between the top and bottom electrode voltages [11].

In 1991, Smits et al. developed a set of constituent equations to describe the behavior of piezoelectric bimorphs for various mechanical boundary conditions including: a moment at the end of the beam, a force perpendicular to the beam applied at the tip and a uniformly distributed body load [12]. Following on from the work of Smits et al., Wang and Cross used similar techniques in 1999 to develop the constituent equations for symmetrical triple layer bimorph benders where the outer two layers are piezoelectric and the inner layer is a non-piezoelectric elastic layer [5].

Due to the advantageous properties of piezoelectric benders, they have recently found use in the field of miniature robotics [14,4,15]. Campolo et al. (2003) developed a unimorph actuator with an embedded piezoelectric sensor for use in a micromechanical flying insect [13]. A model for the sensor was developed and verified by experimentation. Piezoelectric benders are also used in industrial applications such as textile machines, fluid control devices and beam steering [16–18].

3. Bimorph model

A piezoelectric bender consists of two piezoelectric plates glued together, usually with a center shim laminated between the plates and mounted as a cantilever beam. The piezoelectric plates can either be polarized in the same direction or in opposite directions, this is referred to as the polling direction. By controlling the voltage across the piezoelectric plates with respect to the polling direction, the beam can be made to bend up or down and extend or contract.

In Fig. 1, a typical bimorph bender is illustrated with a center shim and a positive polarization direction indicated by the arrows. A positive voltage would be one that is higher at the tip compared to the base of the arrow. The maximum and minimum voltage, $V_{\max}$ and $V_{\min}$ respectively, that can be applied across each plate is derived from the poling and coercive electric field strength, E_p and E_c respectively, that is

$$V_{\max} = E_p h,$$

$$V_{\min} = E_c h.$$

The poling field is defined as the point at which an increase in electric field has little or no effect to the stress in the layer, usually around 1–2 kV/mm. The coercive field is the point at which the piezoelectric layer will start to depolarize, typically between −200 to −500 V/mm.

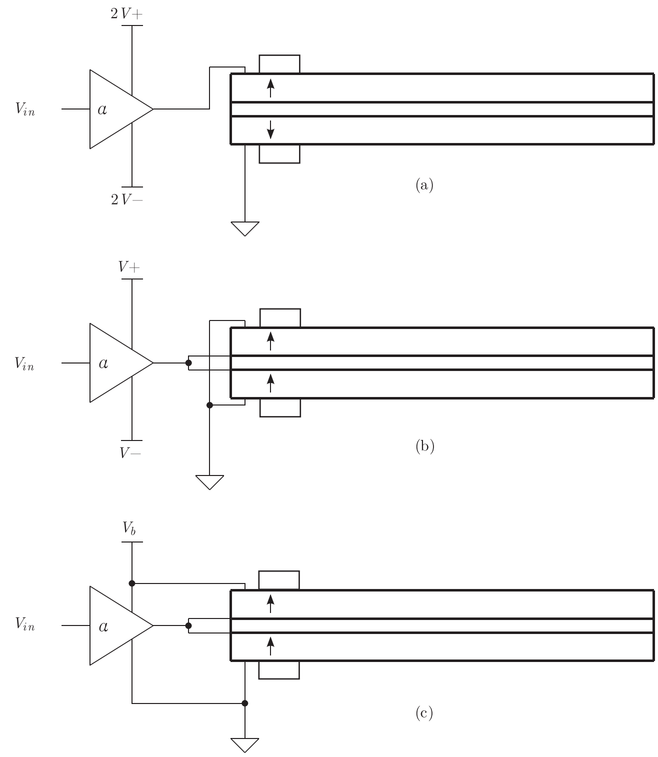

Fig. 2. Electrical configurations: (a) 'Series', (b) 'Parallel', (c) 'Biased Unipolar'.

The relationships between the tip deflection $\delta(x)$, blocking force $F_{blk}(x)$ and the applied voltages are,

$$\delta(x) = d_{31} Y_p h_m (V_A - V_B) \frac{x^2}{2D}, \qquad (1)$$

$$F_{blk}(x) = d_{31} Y_p h_m (V_A - V_B) \frac{W}{x}, \qquad (2)$$

where $\delta(x)$ is the tip deflection, d_{31} is the piezoelectric constant, Y_p is the Young's modulus of the piezoelectric material, h_m is the distance between the centroid of the piezoelectric layer and the neutral axis, V_A and V_B are the voltages applied across the top and bottom piezoelectric layers respectively, and D is the flexural stiffness of the beam. The derivation for these equations is reported in previous work [12,5,21].

4. Existing electrical configurations

The three most common electrical configurations for driving a piezoelectric bimorph bender are the 'Series', 'Parallel' and 'Biased Unipolar' configurations, which are illustrated in Fig. 2. This section will identify and compare the main features of each electrical configuration.

To more easily compare the performance of the different electrical configurations a baseline deflection and blocking force is defined such that δ_0 and F_0 is equal to the deflection and force produced by the parallel and series electrical configurations. Using this baseline a performance factor, γ can be defined as $\gamma = \delta/\delta_0 = F/F_0$. To further simplify the comparison, another factor, β, is defined to relate the maximum and minimum driving voltage, $V_{\max} = -\beta V_{\min}$. For example, if the specified maximum voltage is 200 V and the minimum voltage is −50 V, then $\beta = 4$.

For each of the following cases V_{in} is the control signal and is varied between [−1, 1]. The maximum deflection and force will occur at ±1 V input to the system.