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A Novel Electrical Configuration for Three Wire Piezoelectric Bimorph Micro-Positioners

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***Abstract*— This paper describes a new method for driving bimorph and multimorph piezoelectric benders. The 'Biased Bipolar Configuration' uses a bias voltage applied to the top electrode, a control voltage applied to the centre electrode, and a grounded bottom electrode. Using this technique the predicted deflection and force for a given piezoelectric bender is approximately 2.2 and 1.3 times greater than traditional methods. Experimental results demonstrate that the biased bipolar configuration provides an approximate 2.4 and 1.4 times improvement in the maximum deflection and force which correlates well with the predicted improvement.**

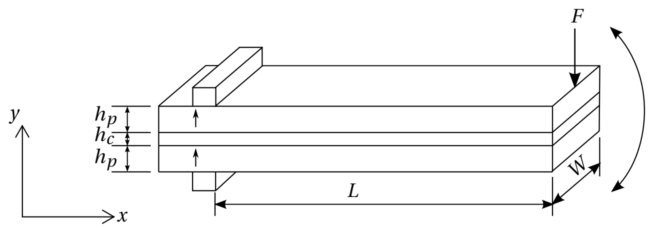

Fig. 1. Typical Piezoelectric Bimorph Bender

I. INTRODUCTION

Piezoelectric actuators utilise 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 response compared to other common actuators. The most common type of piezoelectric actuators 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 and will alternately contract and expand about the neutral axis.

This paper explores existing electrical configurations and compare 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 still achieving the same deflection as a larger bender driven with an existing electrical configuration.

Section II will give a brief history of the piezoelectric bimorph bender. Section III will derive the constituent equations describing the deflection and blocking force for a cantilever bender and the existing control methods will be described. The paper will then describe the new configuration and present experimental results.

II. 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 pickups [6]. In 1936 Sawyer patented the series and parallel configurations for driving a bimorph bender (US patent 1995257-A) [7].

US patent 4625137-A describes an electrical configuration for driving a bimorph bender using a single constant voltage source and a polarity switching circuit [8].

These configurations remained the only available methods for driving a bimorph or multi-morph bender until 1993 when Hayashi et al. produced US patent 5,233,256 outlining a new method for driving parallel and series configuration benders [9].

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

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Hahiro et al. describe a piezoelectric element driving circuit that uses a transformer with a centre tap, diodes and a capacitor to control a piezoelectric pump by sending a series of voltage pulses to the device in their 2011 US patent 0223044-A1 [11].

A method for driving a piezoelectric actuator in a way to suppress higher-order resonant modes is described in US patent 8508104-B2 by Kamitani et al. in 2012 This method uses a feedback circuit to drive the piezoelectric actuator.

In 1991 Smits et al. developed a set of constituent equations to describe the behaviour of piezoelectric bimorphs in the static case, mounted as a cantilever 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. in 1999 Wang and cross [5] use similar techniques to develop the constituent equations in the case of symmetrical triple layer bimorph bender where the outer two layers are piezoelectric and the inner layer is a non-piezoelectric elastic layer.

Due to the properties of piezoelectric benders, they have recently found use in the field of miniature robotics. Campolo et al. (2003) developed a unimorph actuator with an embedded piezoelectric sensor for use in a micro-mechanical flying insect [13]. A model for the sensor was developed and verified by experimentation.

Piezoelectric benders have been used in various fields to develop walking hexapod robots and amphibious robots [14], [4], [15].

Piezoelectric benders are also used in industrial applications such as textile machines, fluid control devices and beam steering [16], [17], [18].

III. Bimorph Model

A piezoelectric bender consists of two piezoelectric plates glued together, usually with a centre shim laminated between the plates and mounted as a cantilever beam. The piezoelectric plates can either be polarised 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.

Fig. 1 shows a typical Bi-morph bender with a centre shim and a positive polarisation 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, E_p and E_c respectively,

$$V_{max} = E_p h,$$
$$V_{min} = E_c h.$$

The poling field is defined as the point at which an increase in electric field has little or no effect to the stress

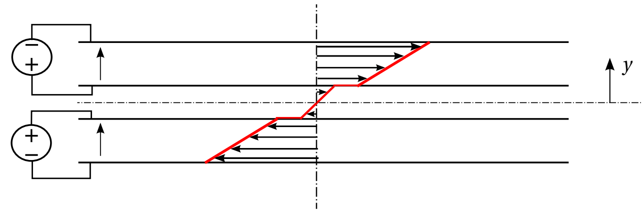

Fig. 2. Internal stress section of a piezoelectric bimorph beam

in the layer, usually around 1 to 2 kV/mm. The coercive field is the point at which the piezoelectric layer will start to de-polarise, typically between -200 to -500 V/mm.

Using Euler-Bernoulli beam theory and sandwich beam theory a model of the bimorph bender seen in Fig. 1 can be created. By re-arranging the constituent equations for the inverse piezoelectric effect [19] and only looking at the effect of the voltage across the thickness along the length of the plate, the stress (T) in the piezoelectric layer is,

$$T = d_{31} Y E + Y S_0, \tag{1}$$

where d_{31} is the piezoelectric constant, Y is the Young's modulus, E is the electric field, and S_0 is the net strain. Fig. 2 shows the stress distribution within a beam subject to bending caused by the piezoelectric effect. By taking the integral of the stress times the distance from the neutral axis, y over the cross-sectional area, $A = Wy$, the moment is,

$$M(x) = \int y T \, \mathrm{d}A = W \int y d_{31} Y E + y Y S_0 \, \mathrm{d}y. \tag{2}$$

As stress is a force per unit area, by taking the integral of stress over the area we are determining the internal forces within the beam. By then multiplying this force by distance we get the moment about the centroid of the beam. From Euler-Bernoulli Beam theory for relatively small deflections the strain can be simplified to be $S_0 = y\frac{\mathrm{d}^2\delta}{\mathrm{d}x^2}$. Then integrating by parts, the moment M is given by

$$M(x) = W h_m d_{31} Y_p (V_A - V_B) - W\mathscr{D}\frac{\mathrm{d}^2\delta}{\mathrm{d}x^2}, \tag{3}$$

where h_m is the distance between the centroid of the piezoelectric layer and the neutral axis, V_A and V_B are the layer voltages and $\mathscr{D}$ is the effective stiffness of the laminated beam given by,

$$\mathscr{D} = \int y^2 Y \, \mathrm{d}y,$$
$$\mathscr{D} = \frac{Y_p}{3}\left[h_A^3 + h_B^3\right] + \frac{Y_c h_c^3}{12} + \frac{Y_p h_c}{2}\left[h_A^2 + h_B^2 + \frac{h_c}{2}(h_A + h_B)\right], \tag{4}$$

where Y_p is the piezoelectric layer Young's modulus and Y_c is the centre shim Young's modulus.

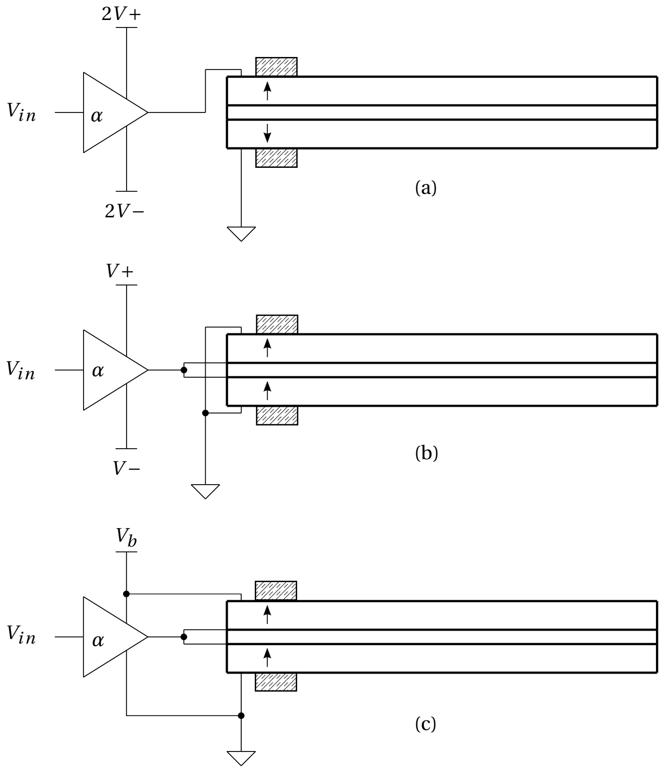

Fig. 3. Electrical Configurations; a) Series, b) Parallel, c) Biased Unipolar

Re-arranging (3) and solving for deflection (δ),

$$\delta(x) = \frac{d_{31} Y_p h_m (V_A - V_B) x^2}{2\mathscr{D}} - \frac{M x^2}{2\mathscr{D} W}. \quad (5)$$

Which is the same result achieved by Wan and Cross in 1999[5].

By then setting $M = 0$ the tip deflection becomes,

$$\delta(x) = \frac{h_m d_{31} Y_p (V_A - V_B) x^2}{2\mathscr{D}}. \quad (6)$$

Similarly when $\delta = 0$ and $M = Fx$ the blocking force becomes,

$$F_{blk}(x) = \frac{W d_{31} Y_p (V_A - V_B) h_m}{x}. \quad (7)$$

The blocking force is the force required at a point x along the length of the beam, so that the $\delta = 0$ at point x.

In the case of a simple bimorph with no centre shim the tip displacement and blocking force can be found by setting $h_c = 0$ to be,

$$\delta(x) = \frac{3 d_{31} (V_A - V_B) x^2}{8 h_p^2}, \quad (8)$$

$$F_{blk}(x) = \frac{W d_{31} Y_p (V_A - V_B) h_p}{x}. \quad (9)$$

IV. Existing control methods

The three most common methods for driving a piezoelectric bender are series, parallel and biased unipolar, shown in Fig. 3. Another less common method is the bridged bi-polar configuration. This section will identify and compare the main features of each electrical configuration.

By using the series and parallel configuration as a baseline, such that $\delta_0 = \delta_{series} = \delta_{parallel}$ and $F_0 = F_{series} = F_{parallel}$. The deflection and blocking force of each configuration can be defined relative to this by the factor $\gamma = \frac{\delta}{\delta_0} = \frac{F}{F_0}$

To further simplify the comparison another factor, β, is defined to relate the maximum and minimum voltage, $V_{max} = \beta |V_{min}|$.

For all of the following cases V_{in} is varied between [-1,1] and maximum deflection and force occur at ±1 V input to the amplifier.

A. Series Configuration

The series type bender uses only two wires and the polling direction of the two layers are opposite. This method requires $V_{pp} = |4V_{min}|$ where V_{pp} is the peak to peak voltage and can be controlled with a single amplifier. For the series bender seen in Fig. 3 the gain (α), extension (ϵ_x), tip deflection (δ), blocking force (F_{blk}) and capacitance (C) are

$$\begin{aligned}
\alpha &= |2V_{min}|, \\
\gamma &= 1, \\
\epsilon_x &= 0, \\
\delta(L) &= d_{31} Y_p h_m (2|V_{min}| V_{in}) \frac{L^2}{2\mathscr{D}}, \\
F_{blk}(L) &= d_{31} Y_p h_m (2|V_{min}| V_{in}) \frac{W}{L}, \\
C &= \frac{K \epsilon_0 L W}{2 h_p}.
\end{aligned}$$

B. Parallel Configuration

The parallel configuration uses only two wires for control and the polling direction of the two layers are aligned. One wire is connected to the centre electrode and the other wire is connected to the two outer electrodes. Only one amplifier is required with a peak to peak voltage of $V_{pp} = 2V_{min}$. For the parallel bender seen in Fig. 3 the gain (α), extension (ϵ_x), tip deflection (δ), blocking force

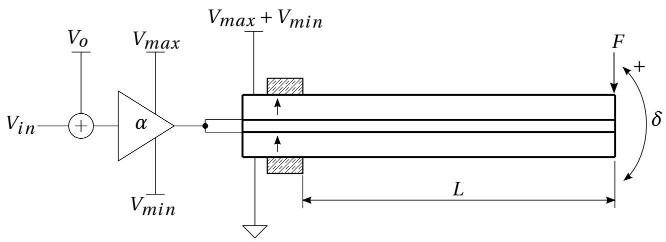

Fig. 4. 'Biased Bi-polar' Bender configuration

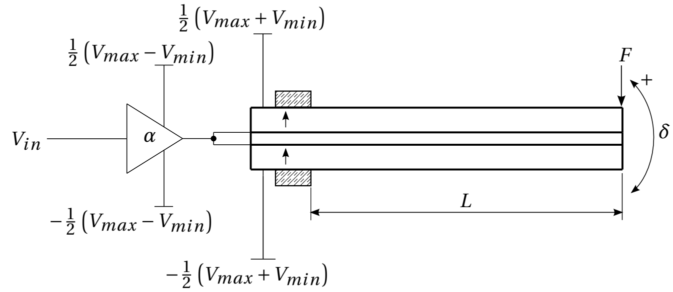

Fig. 5. 'Biased Bi-polar' symmetric power supply rails configuration

(F_{blk}) and capacitance (C) are

$$\begin{aligned}\alpha &= |V_{min}|,\\ \gamma &= 1,\\ \epsilon_x &= 0,\\ \delta(L) &= d_{31} Y_p h_m (2|V_{min}| V_{in}) \frac{L^2}{2\mathscr{D}},\\ F_{blk}(L) &= d_{31} Y_p h_m (2|V_{min}| V_{in}) \frac{W}{L},\\ C &= \frac{2K\epsilon_0 LW}{h_p}.\end{aligned}$$

C. Biased Unipolar Configuration

The biased unipolar configuration requires three wires and three electrodes to operate. Additionally two power supplies are required, one bias supply, $V_b = V_{max}$, and the other controlled supply between 0V to V_{max}. For the unipolar bender seen in Fig. 3 the gain (α), extension (ϵ_x), input offset voltage (V_o), tip deflection (δ), blocking force (F_{blk}) and capacitance (C) are

$$\begin{aligned}\alpha &= \frac{V_{max}}{2},\\ \gamma &= \frac{\beta}{2},\\ V_o &= 1\ V,\\ \epsilon_x &= \frac{d_{31} Y_p (V_{max})}{(2h_p + h_c) Y_c},\\ \delta(L) &= d_{31} Y_p h_m (V_{max} V_{in}) \frac{L^2}{2\mathscr{D}},\\ F_{blk}(L) &= d_{31} Y_p h_m (V_{max} V_{in}) \frac{W}{L},\\ C &= \frac{2K\epsilon_0 LW}{h_p}\end{aligned}$$

V. Biased Bi-polar Control Method

The biased bipolar piezoelectric bender control method is a new technique for driving three electrode, three wire, parallel poled benders, including bimorphs and multimorphs. This technique uses the full range of available positive and negative electric field.

Fig. 4 shows the electrical connection of the biased bipolar arrangement. The voltage V_{in} in this example varies between ±1 V, however any input voltage could be used as long as the gain (α) and offset (V_o) are set accordingly.

For the bender seen in Fig. 4 the gain (α), offset voltage (V_o), extension (ϵ_x), tip deflection (δ), blocking force (F_{blk}) and capacitance (C) are,

$$\begin{aligned}\alpha &= \frac{V_{max} - V_{min}}{2},\\ \gamma &= \frac{(\beta + 1)}{2},\\ V_o &= \frac{V_{max} + V_{min}}{V_{max} - V_{min}},\\ \epsilon_x &= \frac{d_{31} Y_p (V_{max} + V_{min})}{(2h_p + h_c) Y_c},\\ \delta(L) &= d_{31} Y_p h_m (V_{max} - V_{min}) V_{in} \frac{L^2}{2\mathscr{D}},\\ F_{blk}(L) &= d_{31} Y_p h_m (V_{max} - V_{min}) V_{in} \frac{W}{L},\\ C &= \frac{2K\epsilon_0 LW}{h_p}.\end{aligned}$$

By Shifting the supply and bias voltages the biased bipolar bender can be controlled using a symmetric power supply. An example of this is seen in Fig. 5. This configuration is electrically identical to the one in Fig. 4.

Compared to the biased unipolar configuration, no additional power supplies are needed, and only a modest increase in peak to peak voltage is required. Also, similar to the biased unipolar configuration a voltage of $\frac{1}{2}(V_{max} + V_{min})$ is required to be present on the middle layer for 0mm deflection, which is less than that required by the biased unipolar configuration.

For a three wire multi-layer bender, with the centre electrode connected to the input signal, the top electrodes would alternate between the bias voltage and the control voltage, while the bottom half electrodes would alternate between the ground or negative bias voltage and the control voltage. By driving the bender using this method with $V_{max} = 300$ V and $V_{min} = -90$ V giving a β of $3\frac{1}{3}$, it will have a relative deflection and force of $\gamma = 2.167$ while the unipolar method has a relative factor of $\gamma = 1.667$, resulting in a 30% increase.

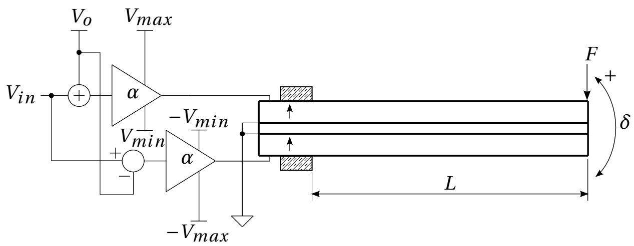

Fig. 6. Bridged Bipolar parallel polled bender

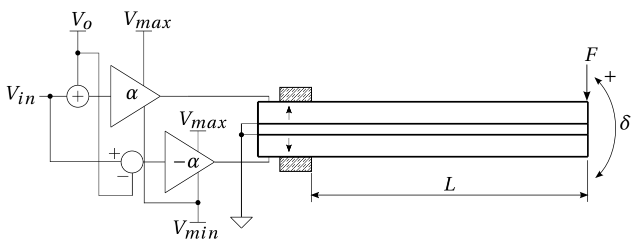

Fig. 7. Bridged Bipolar series polled bender

A. Bridged Bi-polar Configuration

The bridged bipolar configuration, seen in Fig. 6 and 7, is a more complicated configuration that requires two controlled power supplies. This method can be used on both aligned and opposite polled benders. For aligned polled benders $V_{pp} = 2V_{max}$. Similar to the biased bipolar configuration, the advantage of using the bridged bipolar configuration is the ability to use the full voltage range. An additional possibility of this configuration is the ability to use the beam as an extender by changing the phase difference or voltage offset of the two power supplies. For the bridged bipolar bender seen in Fig. 6, the gain (α), extension (ϵ_x), input offset voltage (V_o), tip deflection (δ), blocking force (F_{blk}) and capacitance (C) are the same as the biased bipolar configuration

VI. Experimental Results

An experiment was conducted to compare the bender control methods and assess the accuracy of the analytical model. The experiment was performed using a two layer, parallel polled piezoelectric plate from PIEZO SYSTEMS, INC. The plate measured 31.8 mm x 63.5 mm, was 0.51 mm thick and was constructed from PSI-5A4E type piezoceramic. The plate was mounted to a board using epoxy such that the free length was 57 mm. This ceramic has a V_{max} of 300 V and V_{min} of -90 V [20].

In order to accurately measure both the tip deflection and the blocking force, the experimental set up illustrated in Fig. 8 was used. This set up uses an di-soric LAT61 Laser distance sensor and a HONEYWELL FSS1500NS piezo-resistive force sensor. The distance sensor has a 0-10 V output signal and the force sensor gives a differential voltage output of 0-360 mV which is amplified to a 0-3 V signal. Both of these outputs can be connected to a micro controller for data logging or directly observed

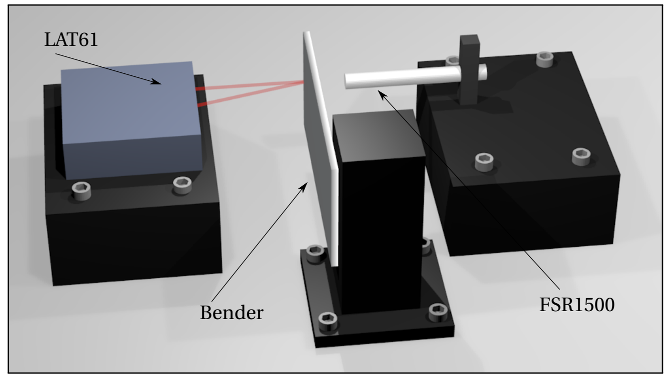

Fig. 8. Experimental setup

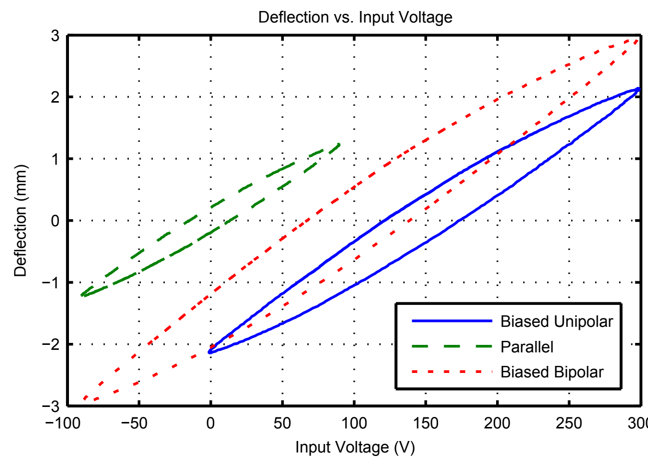

Fig. 9. Bender Hysteresis

using an oscilloscope. Hysteresis was measured using a 5Hz sine wave signal and expressed as a percentage of the full signal span.

The voltage across each piezo layer is controlled using signal generators wired to two PDm200 (±200 V) voltage amplifiers from PiezoDrive [21]. The 'Bridged Bi-polar' and 'Series' configurations were not tested as these control methods are electrically identical to the other methods tested.

Table I lists the static analytical and experimental results for both the maximum tip deflection (δ_{max}), maximum blocking force (F_{blk}), relative deflection/force factor (γ) and the hysteresis. The value for the deflection is half the difference of the minimum and maximum deflections when excited with a 5 Hz sine wave. The force was measured by moving a force sensor in contact with the beam and then applying a step response and waiting for the signal to settle. Hysteresis is measured as maximum variation between rise and fall over full span. Fig. 9 compares the hysteresis of each configuration tested. The difference between the analytical results and the experimental results is attributed to imperfect geometry and tolerances in the d_{31} constant of the bender used.

TABLE I
PIEZO BENDER PERFORMANCE

Control Type	Experimental					Analytical		
	Hysteresis(%)	δ_{max}(mm)	F_{blk}(N)	Relative δ (%)	Effective Gain (μm/V)	δ_{max}(mm)	F_{blk}(N)	Relative δ (%)
Parallel	16.06	1.235	0.382	100%	13.7	0.774	0.195	100%
Uni-polar	18.21	2.141	0.629	173%	14.3	1.290	0.325	167%
Bi-polar	19.31	2.947	0.826	239%	15.1	1.677	0.423	217%

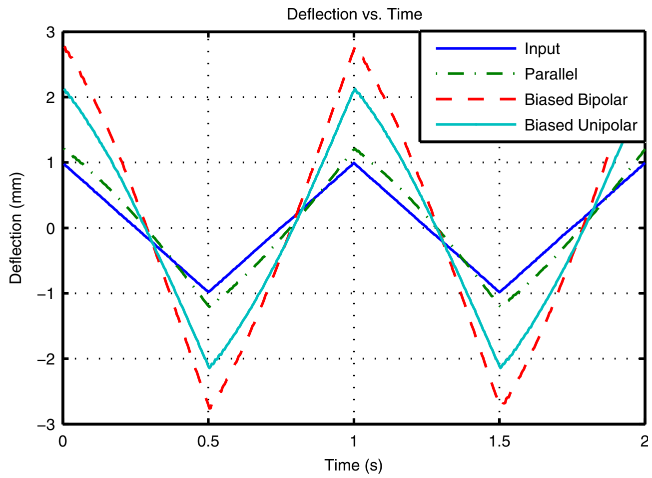

Fig. 10. Deflection and input vs time

Although the new control method requires a greater peak to peak voltage than the unipolar control method (in this case 30% more) there is approximately 38% more tip deflection and 31% more blocking force. The hysteresis is marginally worse than the unipolar control method, 19% compared to 18%, as shown in Table I. Fig. 10 also shows the deflection of the three tested methods, as well as the input signal vs time.

VII. CONCLUSION

This paper describes a new electrical configuration for bimorph and multimorph piezoelectric benders. The new method works by biasing the top electrode so that the full voltage range can be applied across all piezoelectric plates. An analytical analysis showed that the expected deflection is 117% greater than the parallel configuration and 30% greater than the biased unipolar arrangement. Experimental results demonstrate an improvement of 37% and 139% over the standard biased and parallel configurations respectively.

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