Control of Piezoelectric Benders Using a Charge Drive

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Abstract:
This article describes the use of a charge amplifier to improve the linearity of a piezoelectric bender. Existing charge drive circuits can not be directly applied to bimorph piezoelectric benders since they share a common electrode. In this article a new charge drive circuit and electrical configuration is described that allows piezoelectric bimorphs to be linearised with charge. Experimental results demonstrate that the use of a charge source reduces hysteresis from 16.56% to 0.26%.

Keywords: Piezoelectric Actuators, Charge Drive, Bender, Bimorph

Introduction

Piezoelectric actuators utilise the inverse piezoelectric effect, where an applied electric field can induce an internal stress. These actuators are 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 time compared to other common actuators. The most common type of piezoelectric actuator in industrial applications is the bimorph bender.

Benders can be of the unimorph or bimorph type. Unimorph actuators consist of one piezoelectric plate bonded to a non-piezoelectric elastic shim. A typical bimorph actuator, shown in Fig. 1 consists of two piezoelectric plates joined together with possibly a third elastic layer sandwiched between the two piezoelectric layers to increase the mechanical reliability [5]. The beam or plate is typically mounted in a cantilever arrangement, however it can also be simply supported or fixed on both ends. Bimorph and unimorph actuators produce a deflection and force when the piezoelectric layers contract and expand. Multi-layer benders are a form of bimorph bender where the top and bottom piezoelectric layers are comprised of many thinner piezoelectric layers. This allows for a lower operating voltage to achieve the same results.

Like all piezoelectric actuators, benders exhibit a significant hysteresis effect, therefore precise positioning of the actuator cannot be achieved without position feedback or additional knowledge of the plant dynamics to implement a control loop.

This paper will explore an alternative method for driving piezoelectric benders, using a charge source instead of a voltage source. It is well known that piezoelectric devices respond more linearly to charge [6], [7]. By controlling the current or charge the hysteresis non-linearity can be reduced by up to 90% [8]. Since the charge drive was first proposed there have been several variations and improvements, including resistive feedback to compensate for drift [9], grounded loads [10]–[12], switched capacitor implementation [13] and dynamic compensation [8].

The following section will provide a brief overview of existing methods for controlling a bender and reducing the hysteresis non-linearity, following that, the general circuit topology and operating principles for a traditional charge drive will be explained. The paper will then describe the method for driving a piezoelectric bimorph actuator using charge and present the experimental results.

Existing Bender Control Methods

Piezoelectric benders are traditionally driven with voltage using one of several driving configurations. These configurations include series, parallel, biased unipolar, biased bi-polar [14] and dual bipolar, some of which are shown in Fig. 2. Each configuration trades complexity of design and driving voltage for deflection and force. For example the series and parallel configurations have the lowest maximum deflection but require only a single amplifier.

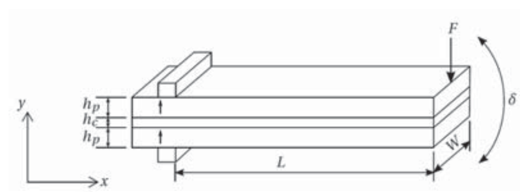

Fig. 1: *Typical Bimorph Bender*

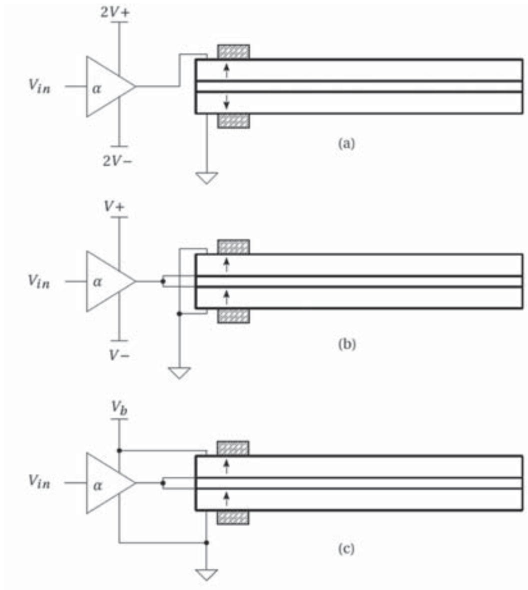

Fig. 2: *Common Bender Electrical Configurations*

The driving configurations seen in Fig. 2 are the basis for any method of controlling a piezoelectric bender. By using one of these configurations in conjunction with either a feedback or feed forward control loop, the hysteresis of the bender can be mitigated.

One method of linearising the response of an actuator is to include the inverse of the actuator model in the control loop. Maslan and Darus [15] used system identification to approximate the transfer function model for a piezoelectric actuator. The transfer function and its inverse were successfully incorporated into a PID controller and a PID with active force feedback to suppress unwanted vibrations.

Rakotondrabe et al used a combination of feedforward techniques to compensate for a range of non-linear effects in piezoelectric actuators [16]. The inverse Prandtl-Ishlinskii static hysteresis model was used to compensate for the hysteresis. The creep compensator was implemented in cascade with the hysteresis compensator using a new method that did not require inversion. Lastly the vibration of a system is compensated for using ZV input shaping.

Charge Drive Circuit Topology

A simplified charge drive circuit can be seen in Fig. 3. The piezoelectric element is represented by a capacitor (C_p) in series with a voltage source (V_p) highlighted in the box. A sense capacitor (C_s) is connected between the piezoelectric layer and ground. The voltage across the sense capacitor is the feedback for the high voltage amplifier. The ratio of the capacitors is the AC gain of the system,

$$A = \frac{C_s}{C_p}.$$

Despite the potential reductions in hysteresis there are some fundamental drawbacks when using charge drives, including: stray currents, finite output impedance and dielectric leakage, represented by R_l[17]. These effects can cause the output voltage to drift at low frequencies. This can be avoided by setting the ratio of resistances equal to the ratio of capacitances such that;

$$\frac{R_l}{R_s} = \frac{C_s}{C_l}.$$

This determines the DC gain of the amplifier when below the transition frequency, given by,

$$f_T = \frac{1}{2\pi R_L C_p}.$$

At frequencies below f_T the amplifier acts as a voltage source. The transition frequency can be set arbitrarily low, however as the transition frequency is reduced, the settling time of the system increases.

An alternative method of controlling the DC gain of the amplifier is to use a controlled current source instead of the resistors R_L and R_s, this is referred to as active DC stabilisation [18]. Using this method means that the low-frequency voltage gain is fixed and does not depend on load capacitance. Furthermore the transition frequency can be extremely low because long transient responses are eliminated.

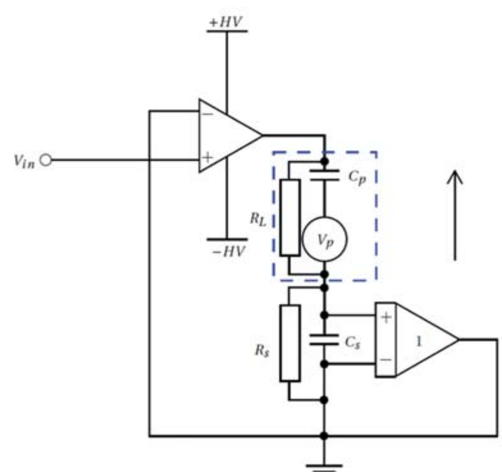

Fig. 3: *Typical Charge Drive Circuit*

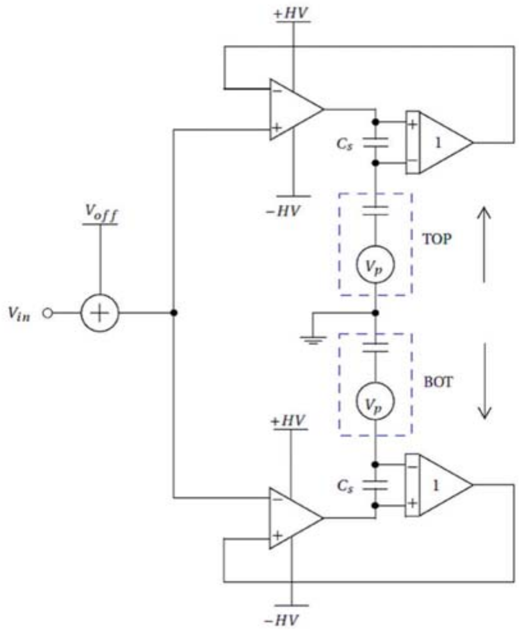

Fig. 4: *Bimorph Charge Drive Circuit*

Traditional charge drives are compatible with floating piezoelectric actuators; however, bimorph benders have two piezoelectric layers with a shared electrode that are driven with complementary voltages, therefore they are not directly compatible. If the central electrode is electrically grounded, the two layers can be driven independently by two amplifiers which is compatible with charge drives designed for a grounded load.

Fig. 4 shows the electrical configuration of a charge drive for a triple layer bimorph bender. This circuit requires a differential amplifier with a high common mode rejection ratio in order to detect the voltage across the sense capacitor.

Another option for driving a piezoelectric bender using a charge amplifier is to separate the two central electrodes, effectively creating a four electrode bender. In this arrangement each piezoceramic layer is floating and a traditional charge drive can be used for each piezo layer. Driving the two layers 180° out of phase will cause the beam to bend.

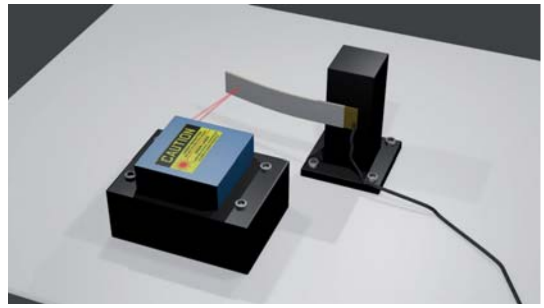

Fig. 5: *Experimental Setup*

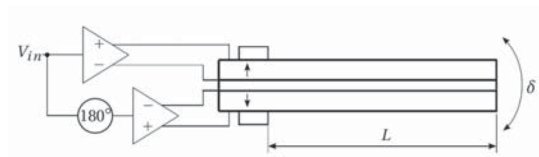

Fig. 6: *Circuit Diagram*

Experimental Results

An experiment was conducted to determine the effect of using a charge source instead of a voltage source when driving a bimorph bender and to observe any improvement in the hysteresis of the system. In order to test the charge drive we created a four layer bender approximately 72 mm x 18 mm using 0.2-mm thick PZT-5A5E from Piezo Systems INC. [19] with 0.8-mm thick fibreglass double sided PCB for the central shim. The bender was mounted such that the free length was approximately 66 mm. The four layer electrical configuration allows the piezoelectric layers to be driven independently or connected in series or parallel so that any traditional voltage control method can also be evaluated.

The maximum and minimum driving voltages were calculated by multiplying the polling (E_p) and coercive (E_c) electric field strengths by the thickness of the piezoelectric layer,

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

Using these equations the maximum driving voltage was determined to be approximately 400 V/mm and the minimum was -100 V/mm. Early experiments at these voltages caused several of the four layer benders to fail, therefore the driving voltage was limited to 50% of the maximum.

Each piezoelectric layer was independently controlled using an Agilent 33521A signal generator and PDQ charge drive [20] with a gain of 40. A LAT61 laser distance sensor was used to measure the displacement of the tip. The displacement sensor provides a 0-10-V output signal with a resolution of

Table 1: Hysteresis of Piezoelectric Bender

Drive	Voltage		Charge	
	Hysteresis (%)	Hysteresis (mm)	Hysteresis (%)	Hysteresis (mm)
Parallel	9.31%	0.0389	2.65%	0.0111
Unipolar	13.76%	0.0607	1.09%	0.0047
Bi-polar	16.56%	0.1910	0.26%	0.0029

0.5 µm. The equipment was arranged as per Fig. 5 and Fig. 6.

The piezoelectric layers were driven at 5 Hz, 180 degrees out of phase and at three different voltage ranges; ±50 V, 0 V to 100 V and -50 V to 200 V. The hysteresis curve for each of the driving voltages can be seen in Figures Fig. 7, Fig. 8 and Fig. 9 respectively. These voltage ranges were chosen as they are a good representation of common driving methods, e.g. parallel and unipolar, as well as a full range method.

Hysteresis was measured as the ratio of the error at the driving voltage mid-point compared to the full range span of the bender. The hysteresis, shown in Table 1, improves dramatically when driven with charge. Interestingly an increase in maximum driving voltage significantly reduced the hysteresis. This is due in part to an increase in total deflection but is mostly due to the decrease in mid-point error.

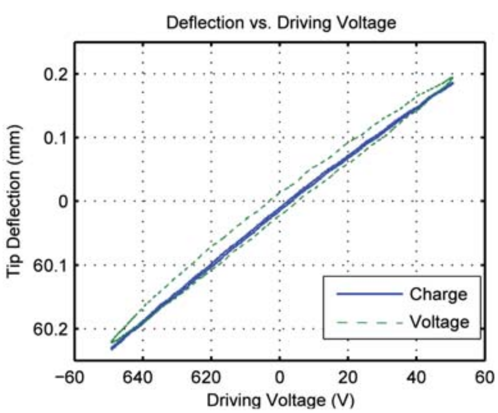

Fig. 7: Voltage and Charge Drive Hysteresis for the Parallel Electrical Configuration

Conclusion

This paper outlines the use of a charge amplifier to drive a four layer piezoelectric bender in order to reduce the piezoelectric hysteresis effect. When driving the bender with charge the hysteresis was reduced from 16.56% to 0.26% which is a 98% improvement.

As well as the improvement to the hysteresis, the experiment also showed that when using a charge source and increasing the driving voltage, the mid-point error is reduced. Meaning that higher driving voltages produce less hysteresis.

Currently a charge amplifier can only be used when the piezoelectric element is floating. Future work will design a charge drive that is capable of controlling the more common three electrode configuration.

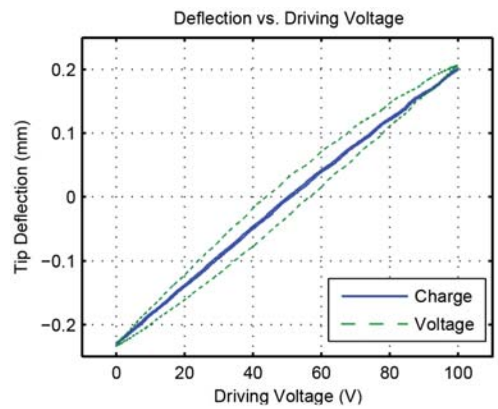

Fig. 8: Voltage and Charge Drive Hysteresis for the Unipolar Electrical Configuration

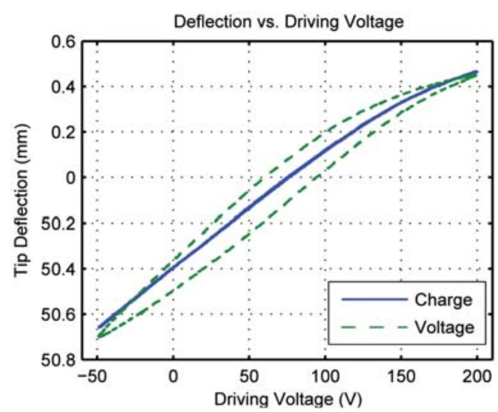

Fig. 9: Voltage and Charge Drive Hysteresis for the Bipolar Electrical Configuration

References

[1] S. Dong, S. P. Lim, K. H. Lee, J. Zhang, L. C. Lim, and K. Uchino, “Piezoelectric ultrasonic micromotor with 1.5 mm diameter.,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 50, no. 4, pp. 361–7, Apr. 2003.

[2] B. Potsaid, J. T.-Y. Wen, M. Unrath, D. Watt, and M. Alpay, “High Performance Motion Tracking Control for Electronic Manufacturing,” *J. Dyn. Syst. Meas. Control*, vol. 129, no. 6, p. 767, 2007.

[3] S. S. Aphale, A. J. Fleming, and S. O. R. Moheimani, “Integral resonant control of collocated smart structures,” *Smart Mater. Struct.*, vol. 16, no. 2, pp. 439–446, Apr. 2007.

[4] A. T. Baisch, S. Member, P. S. Sreetharan, and R. J. Wood, “Biologically-Inspired Locomotion of a 2g Hexapod Robot,” pp. 5360–5365, 2010.

[5] Q. M. Wang and L. E. Cross, “Constitutive equations of symmetrical triple layer piezoelectric benders.,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 46, no. 6, pp. 1343–51, Jan. 1999.

[6] C. V. Newcomb and I. Flinn, “Improving the linearity of piezoelectric ceramic actuators,” *Electron. Lett.*, vol. 18, no. 11, p. 442, 1982.

[7] R. H.- Comstock and A. West, “Charge Control of Piezoelectric Actuators o reduce hysteresis effects,” 42635271981.

[8] G. M. Clayton, S. Tien, A. J. Fleming, S. O. R. Moheimani, and S. Devasia, “Inverse-feedforward of charge-controlled piezopositioners,” *Mechatronics*, vol. 18, no. 5–6, pp. 273–281, Jun. 2008.

[9] K. A. Yi, S. Member, and R. J. Veillette, “Piezoelectric Stack Actuator,” vol. 13, no. 4, pp. 517–526, 2005.

[10] A. J. Fleming and S. O. R. Moheimani, “A grounded-load charge amplifier for reducing hysteresis in piezoelectric tube scanners,” *Rev. Sci. Instrum.*, vol. 76, no. 7, p. 073707, 2005.

[11] A. J. Fleming and K. K. Leang, “Charge drives for scanning probe microscope positioning stages.,” *Ultramicroscopy*, vol. 108, no. 12, pp. 1551–7, Nov. 2008.

[12] A. J. Fleming, “Quantitative scanning probe microscope topographies by charge linearization of the vertical actuator.,” *Rev. Sci. Instrum.*, vol. 81, no. 10, p. 103701, Oct. 2010.

[13] L. Huang, Y. T. Ma, Z. H. Feng, and F. R. Kong, “Switched capacitor charge pump reduces hysteresis of piezoelectric actuators over a large frequency range.,” *Rev. Sci. Instrum.*, vol. 81, no. 9, p. 094701, Sep. 2010.

[14] S. A. Rios and A. J. Fleming, “A Novel Electrical Configuration for Three Wire Piezoelectric Bimorph,” 2014.

[15] M. N. Maslan, “Identification and Control of a Piezoelectric Bender Actuator,” pp. 461–466, 2012.

[16] M. Rakotondrabe, C. Clévy, and P. Lutz, “Complete open loop control of hysteretic, creeped, and oscillating piezoelectric cantilevers,” *Autom. Sci. …*, vol. 7, no. 3, pp. 440–450, 2010.

[17] A. J. Fleming and K. K. Leang, *Design, Modeling and Control of Nanopositioning Systems*. London, UK: Springer, 2014.

[18] A. J. Fleming, “Charge Drive with Active DC stabilization for Linearization of Piezoelectric Hysteresis,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 60, no. 8, pp. 1630–1637, 2013.

[19] “Piezo Systems.” [Online]. Available: http://www.piezo.com/index.html. [Accessed: 06-Feb-2014].

[20] “PiezoDrive.” [Online]. Available: http://www.piezodrive.com/products.html. [Accessed: 06-Feb-2014].