Design of a Charge Drive for Reducing Hysteresis in a Piezoelectric Bimorph Actuator

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***Abstract*—This paper describes the design of a charge drive for reducing the hysteresis exhibited by a piezoelectric bimorph bender. Existing charge drive circuits cannot be directly applied to bimorph benders since they share a common electrode. In this paper, a new charge drive circuit and electrical configuration are implemented that allows commonly available piezoelectric bimorphs to be linearized. This circuit consists of four major components, including, a high voltage amplifier, a differential amplifier, a piezoelectric load, and a PI feedback controller. An isolation amplifier was used to achieve a differential amplifier with a high common-mode rejection ratio. The charge drive was tested by driving a series poled three layer bimorph bender. The experiment showed a significant improvement to the hysteresis of the bender when compared to a typical voltage drive. This paper has identified an alternative Feedback method to improve the ac hysteresis performance of a piezoelectric bender by using a charge drive.**

I. Introduction

Piezoelectric actuators utilize 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 beam steering [1] and miniature robotics [2]. 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, shown in Fig 1.

Like all piezoelectric actuators, benders exhibit a significant hysteresis effect. Due to the hysteresis effect, 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 by using a charge source instead of a voltage source. It is well known that piezoelectric devices respond more linearly to charge [3]–[5]. It has been shown that by controlling the current or charge the hysteresis nonlinearity can be reduced by up to 90% [6]. Since the charge drive was first proposed, there have been several variations and improvements, including resistive feedback to compensate for drift [7] and grounded loads [8].

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

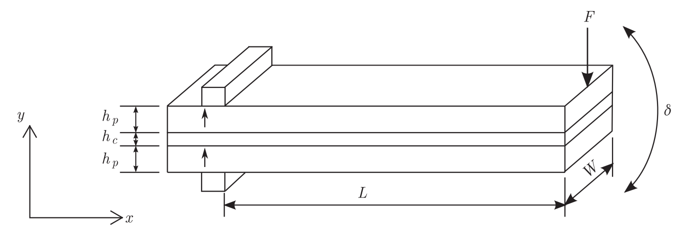

Fig. 1. Typical piezoelectric bimorph bender.

II. Existing Bender Control Methods

Piezoelectric benders are traditionally driven with voltage using one of several driving configurations. These configurations include the series, parallel, biased unipolar, biased bipolar, and dual bipolar configurations [9]. Each configuration trades complexity of design and driving voltage for deflection and force. These driving configurations are the basis for any method of controlling a piezoelectric bender. By using one of these configurations in conjunction with either a feedback or feedforward control loop, the hysteresis of the bender can be mitigated.

Sensor-based feedback control has been widely applied in the control of piezoelectric actuators [10]. However, these methods generally have a lower bandwidth than open-loop methods and add to the cost and complexity.

One example of a feedback controller used to control a piezoelectric actuator can be seen in [11]. In this implementation, the displacement and force of a unimorph piezoelectric actuator are measured using a self-sensing technique and one of these signals is utilized as feedback for a H_∞ feedback controller.

Feedforward control has also proven useful for linearizing piezoelectric actuators in applications where the dynamics are well known and do not significantly vary during service. Feedforward or inversion-based control is commonly applied to both open- and closed-loop nanopositioning systems that require improved performance [12].

A drawback to feedforward control techniques is the lack of robustness. This can be improved by integrating a feedforward controller into a traditional feedback controller to account for nonlinearities such as hysteresis. This combination also eliminates the need for modeling and inverting of nonlinear behaviors which can be difficult and computationally demanding [12].

One application of feedforward control uses system identification to approximate the transfer function model for a piezoelectric actuator. The transfer function and its inverse are

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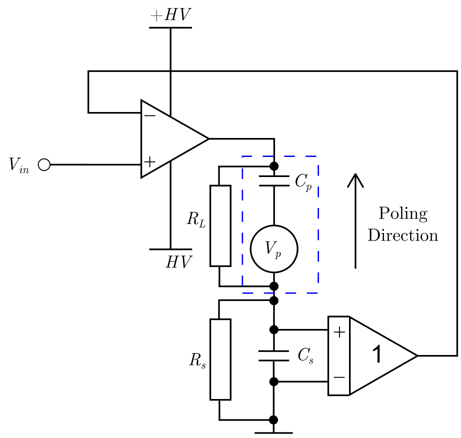

Fig. 2. Typical charge drive circuit.

successfully incorporated into a PID controller with active force feedback to suppress unwanted vibrations [13].

Rakotondrabe *et al.*, used a combination of feedforward techniques to compensate for a range of nonlinear effects in piezoelectric actuators [14]. 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. Finally, the vibration of a system is compensated for using ZV input shaping.

A charge drive is a type of feedback controller where the sensing element is a capacitor connected in series with the piezoelectric actuator. A charge drive is ideal where the additional weight or complexity of external sensing devices would negatively impact the performance of the piezoelectric device. A charge drive is simpler to implement when compared to a feedforward controller since the only required prior knowledge of the system is the impedance of the actuator.

III. Charge Drive Circuit Topology

A simplified charge drive circuit can be seen in Fig. 2. 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,

$$A = \frac{C_s}{C_p}. \quad (1)$$

Despite the potential reductions in hysteresis there are some fundamental drawbacks when using charge drives, including: stray currents, finite output impedance, and dielectric leakage [12]. 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

$$\frac{R_L}{R_s} = \frac{C_s}{C_p}$$

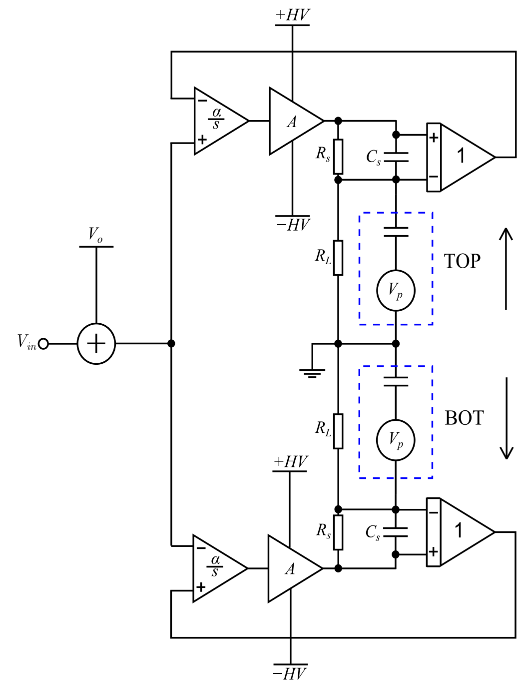

Fig. 3. Bimorph charge drive topology.

where R_s is the sense resistor used for low frequency or dc operation and R_L is the load resistance. The resistor ratio determines the dc gain of the amplifier when below the transition frequency

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

At frequencies below f_T, the amplifier acts as a voltage drive. The transition frequency can be set arbitrarily low by increasing the resistance R_L, 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 stabilization [15]. By using this method, 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.

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. A new type of charge drive must be designed that is capable of driving grounded loads.

Fig. 3 shows the simplified 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, such as an isolation amplifier, in order to detect the voltage across the sense capacitor C_s. Another approach to this problem is to use an integrator circuit connected between the dc and ac bridges as seen in the work by Ivan *et al.* [16].

Previous work on this topic analyzed driving a custom made four layer piezoelectric bender [17]. Since both piezoelectric elements were isolated, a traditional nongrounded charge drive was used to independently drive the top and bottom piezoelectric layer. This paper achieved a reduction in the hysteresis of 98%. In practice this approach is not feasible for driving standard bimorph actuators because the central electrode is shared.

IV. Grounded Charge Drive Circuit

The grounded charge drive circuit consists of four major components; a high voltage amplifier, the piezoelectric load, a differential amplifier, and a feedback controller. The most challenging part of this circuit is the design of the differential amplifier stage. The differential amplifier must be able to detect a small voltage with a high-common-mode rejection ratio. As the dynamics of the piezoelectric bender actuators are relatively slow, an isolation amplifier was chosen to perform the function of a differential amplifier. The AD202JN isolation amplifier can provide up to 2000 V of galvanic isolation with a differential voltage of ± 5 V and a bandwidth of up to 2 kHz.

The dc gain of the charge drive is determined by the ratio of the resistors, R_s and R_l and similarly the ac gain is determined by the ratio of the capacitors C_p and C_s. The two ratios should be made equivalent such that

$$\frac{R_s}{R_l} = \frac{C_p}{C_s} = \frac{V_{\max}}{V_s} \tag{2}$$

where $V_{\max}$ is the maximum voltage across the piezoelectric load and V_s is the maximum input voltage to the isolation amplifier. In order to achieve a reasonable system gain, the maximum piezoelectric voltage was limited to $V_{\max} = 200$ V, giving a system gain of approximately 40 V/V.

Resistor values of $R_L = 16$ MΩ and $R_s = 400$ kΩ variable potentiometer were chosen to match the system gain of 40. The inclusion of the variable resistor allows the dc gain to be tuned to more accurately match the ac gain which is highly dependent on the capacitance of the particular bender being used. Given a bender capacitance of approximately 143 nF, the sense capacitor was chosen to be $0.143\ \mu\text{F} \times 40 \approx 6.2\ \mu\text{F}$.

The output of the isolation amplifier is connected to a PI feedback controller with a transfer function of $\frac{\alpha}{s}$, where α is the integral gain of the feedback controller and is primarily used to set the bandwidth of the system. The controller attempts to equate the voltage across the sense capacitor to the input signal V_{in}. The output of the controller is connected to a high voltage amplifier with a gain of 40 V/V and power supply rails of $+\text{HV} = 230$ V and $-\text{HV} = -80$ V.

V. System Dynamics

Fig. 4 shows the frequency response of the system from dc to 10 kHz. To perform the frequency response, the bender was replaced with a 150 μF capacitive load to remove the effects of the bender resonances and to protect the actuator. The cutoff point of the system is approximately 5 kHz and is primarily due to the low bandwidth of the isolation amplifier.

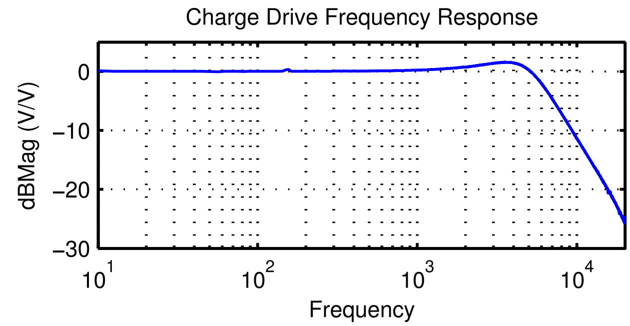

Fig. 4. Charge drive frequency response.

Since the voltage amplifier has a significantly higher bandwidth than the other system components, it can be approximated by a static gain of 40. The transfer function of the charge amplifier from the applied reference voltage to the measured charge is then

$$H(s) = \frac{40\frac{\alpha}{s}\frac{C_p}{C_s}F(s)}{1 + 40\frac{\alpha}{s}\frac{C_p}{C_s}F(s)} \tag{3}$$

where $F(s)$ is the transfer function of the instrumentation amplifier.

If the instrumentation amplifier bandwidth is significantly higher than the closed-loop bandwidth, $F(s) \approx 1$, and the transfer function can be simplified to

$$H(s) = \frac{40\alpha\frac{C_p}{C_s}}{s + 40\alpha\frac{C_p}{C_s}} \tag{4}$$

which is a unity gain first-order low-pass filter with a cutoff frequency of $f = \frac{40\alpha C_p}{2\pi C_s}$.

VI. Experimental Results

An experiment was conducted to test the performance of the grounded load charge drive circuit. An outwardly poled piezoelectric bimorph bender from Piezo Systems, Inc., measuring 31.8 mm wide by 63.5 mm in length with an overall thickness of 0.51 mm was used as the piezoelectric element. The bender was mounted such that the free length was approximately 53.5 mm and was driven using the bridged bipolar series electrical configuration [9].

The driving voltages for the bender were $V_{\max} = 400$ V and $V_{\min} = -100$ V. For the experiment the driving voltages were limited to 50% of these to improve the reliability of the actuator and simplify the design of the differential amplifier.

Each piezoelectric layer was controlled using an Agilent 33500B dual channel signal generator and two of the newly designed grounded load charge drives. An 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 0.5 μm.

The bender was driven over a range of voltages and frequencies, the results of which can be seen in Table I. The hysteresis

TABLE I
HYSTERESIS OF PIEZOELECTRIC BENDER

Voltage Range	Drive	5 Hz	10 Hz	15 Hz
±50 V	Voltage	13.7%	15.0%	16.2%
	Charge	1.4%	4.2%	5.6%
−50 to 200 V	Voltage	23.0%	24.6%	26.8%
	Charge	6.1%	4.9%	2.1%

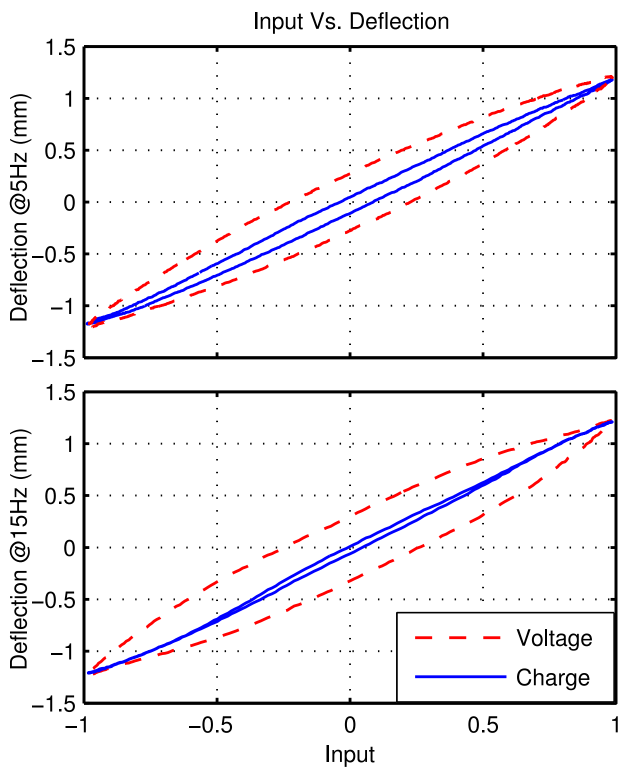

Fig. 5. Voltage and charge drive hysteresis at 5 and 15 Hz.

was calculated as the ratio of the error at the driving voltage mid-point compared to the full range span of the bender.

The hysteresis of the bender when driven with charge and voltage at the full span voltage of −50 V to +200 V is shown in Fig. 5 for 5 and 15 Hz, respectively. These results show that as the driving frequency increases, the hysteresis decreases. This is expected as the fidelity of the charge source improves at frequencies above the transition frequency at 0.05 Hz.

VII. Conclusion

This paper outlines the design, construction, and testing of a charge drive circuit designed to control piezoelectric bimorph actuators and thus reduce hysteresis. When driving a bender with charge as opposed to voltage the hysteresis was shown to be reduced from 26.8% to 2.1% which is a 92% improvement when driven at 15 Hz. Additionally, the results demonstrate improved performance when driven with higher frequency asymmetric driving voltages compared to a symmetric driving voltage. Conversely, at lower frequencies the actuator performed 17% better under symmetric driving voltages compared to an asymmetric signal. One possible explanation for this is the dc offset of the asymmetric drive introducing a significant creep effect at lower frequencies.

The charge drive described in this paper is suitable for driving a series poled triple layer bimorph from 1 Hz to 2 kHz. Below the lower frequency limit, the charge drive acts as a voltage source. The charge drive is a suitable replacement for a feedback controller in the situation when it is impractical to use external sensors for positional feedback.

References

[1] B. Potsaid, J. T. Wen, M. Unrath, D. Watt, and M. Alpay, "High performance motion tracking control for electronic manufacturing," *J. Dynam. Syst. Meas. Control*, vol. 129, pp. 767–776, Nov. 2007.
[2] A. T. Baisch, P. S. Sreetharan, and R. J. Wood, "Biologically-inspired locomotion of a 2g hexapod robot," in *Proc. Int. Conf. Intell. Robots Syst.*, 2010, pp. 5360–5365.
[3] R. H. Comstock and A. West, "Charge control of piezoelectric actuators to reduce hysteresis effects," U.S. Patent 4 263 527 A, Apr. 21, 1981.
[4] H. Kaizuka and B. Siu, "A simple way to reduce hysteresis and creep when using piezoelectric actuators," *Jpn. J. Appl. Phys.*, vol. 27, no. 5, pp. L773–L776, 1988.
[5] M. Goldfarb and N. Celanovic, "Modeling piezoelectric stack actuators for control of micromanipulation," *IEEE Control Syst.*, vol. 17, no. 3, pp. 69–79, Jun. 1997.
[6] G. Clayton, S. Tien, A. Fleming, S. Moheimani, and S. Devasia, "Inverse-feedforward of charge-controlled piezopositioners," *Mechatronics*, vol. 18, nos. 5–6, pp. 273–281, Jun. 2008.
[7] K. A. Yi and R. J. Veillette, "A charge controller for linear operation of a Piezoelectric stack actuator," *IEEE Trans. Control Syst. Technol.*, vol. 13, no. 4, pp. 517–526, Jul. 2005.
[8] 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.
[9] S. A. Rios and A. J. Fleming, "A new electrical configuration for improving the range of piezoelectric bimorph benders," *Sens. Actuators A, Phys.*, vol. 224, pp. 106–110, 2015.
[10] Y. K. Yong, A. J. Fleming, and S. O. R. Moheimani, "A novel piezoelectric strain sensor for simultaneous damping and tracking control of a high-speed nanopositioner," *IEEE/ASME Trans. Mechatron.*, vol. 18, no. 3, pp. 1113–1121, Jun. 2013.
[11] M. Rakotondrabe, I. A. Ivan, S. Khadraoui, P. Lutz, and N. Chaillet, "Simultaneous displacement/force self-sensing in piezoelectric actuators and applications to robust control," *IEEE/ASME Trans. Mechatron.*, vol. 20, no. 2, pp. 519–531, Apr. 2015.
[12] A. J. Fleming and K. K. Leang, *Design, Modeling and Control of Nanopositioning Systems*. London, U.K.: Springer, 2014.
[13] M. N. Maslan, M. Mailah, and I. Z. Mat Darus, "Identification and control of a piezoelectric bender actuator," in *Proc. 3rd Int. Conf. Intell. Syst. Modelling Simul.*, 2012, pp. 461–466.
[14] M. Rakotondrabe, C. Clévy, and P. Lutz, "Complete open loop control of hysteretic, creeped, and oscillating piezoelectric cantilevers," *IEEE Trans. Autom. Sci. Eng.*, vol. 7, no. 3, pp. 440–450, Jul. 2010.
[15] 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, Aug. 2013.
[16] I. A. Ivan, J. Agnus, and M. Rakotondrabe, (2015). Micropositioning device with multidegrees of freedom for piezoelectric actuators and associated method. [Online]. Available: https://www.google.com/patents/US20150054520
[17] S. Rios and A. J. Fleming, "Control of piezoelectric benders using a charge drive," presented at the 14th Int. Conf. New Actuator, Bremen, Germany, 2014.