Piezoelectic Self-Sensing Technique for Tweezer Style End-Effector

Timothy McPherson and Jun Ueda

***Abstract*— This paper presents the application of a piezoelectric self-sensing technique based on current integration to robotic tweezers incorporating a rhombus strain amplification mechanism driven by serially connected piezoelectric stack actuators. Connecting a shunt resistor in series with a piezoelectric element and measuring the voltage though the resistor allows the element to be used simultaneously as an actuator and a sensor by integrating the current to get the charge generated by the piezoelectric element. This allows the displacement to be measured without extra sensors or the loss of actuation capability. Applying an inverse model of the nested structure allows the force and displacement at the tip of the tweezers to be determined. The accuracy of this method is then examined by experiment for the case of free displacment.**

I. Introduction

Piezoelectric materials generate an electric field when mechanically deformed, or alternately will deform in the presence of an electric field. These effects are known as the direct and converse piezoelectric effects respectively [1], and they make piezoelectric materials useful as both actuators and sensors. Piezoelectric materials exhibit high bandwidth and high force but relatively small displacement. Prior work has developed strain amplification mechanisms to create useful amounts of displacement [2]. By nesting rhombus mechanisms within each other exponential strain amplification is achieved while reducing the force. The method is well suited to piezoelectric actuators because of their relatively high force but low displacement characteristics.

Based on this idea a piezoelectric tweezer-style end effector was developed with force and displacement characteristics suitable for use in robotic assisted surgery [3]. Robotic assisted surgery has many benefits including being minimally invasive. The surgeon can also be guided by imaging technologies such as MRI. Force and displacement sensing in this application is critical to provide haptic feedback to the surgeon as well as avoiding injuring the patient. This sensing capability was achieved by using five actuators in series with one being used passively as a sensor and four being used as actuators. An inverse model for the force and displacement at the tips was developed, allowing those values to be calculated based on the induced voltage in the sensor unit and knowledge of the tip conditions as fixed or free.

In this paper a simple self-sensing technique based on current integration will be presented that allows a piezoelectric unit to be used as a sensor and an actuator simultaneously.

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This eliminates the need to use one unit as a pure sensor which wastes its actuation capability. The piezoelectric self-sensing bridge circuit developed by Dosch et. al. is well known but has several drawbacks [4]. The circuit requires exact capacitive matching of the piezoelectric actuator, which can prove difficult in practice due to variations in capacitance caused by change in temperature. Attempts at improving this aspect of the circuit by placing capacitances in series or parallel with the piezoelectric actuator have met with some success [5], but the circuit is not well suited to static measurements due to the fact that all measuring devices contain an inherent resistance. The output of the circuit depends in part on the voltage generated by the piezoelectric actuator due to strain. It should be noted however that a piezoelectric material is not an ideal voltage source but rather generates a dipole moment when strained. Indeed, the induced voltage will decay over time even if a high resistance such as a measuring device or op amp is connected between the electrodes of a piezoelectric device. As such, a piezoelectric material can be thought of as generating some amount of energy when deformed but no power. The self-sensing technique proposed in this paper takes this property into account when modeling the system, giving it the ability to take static measurements. Static measurements are important for a surgical application, where the device could conceivably be required to maintain a force or displacement for an extended period of time while holding an object or body part.

Another technique has been proposed by Cui et. al. using current integration [6]. However, this method still relies on a matching element in the circuit which must be manually tuned. Further, the method is only applicable to displacement sensing since the authors assume no external stress at the start of the derivation of their equations. The method presented in this paper is simpler, requiring no matching element, and easily extendable to simultaneous force and displacement sensing. Another attempt at observing induced charge was made by Ohta et. al. [7] but the method relies on charge amps to sense induced charge and is therefore poorly suited to static measurements. The method proposed in [8] uses a modified charge amp as a current integrator and is similar to the one proposed in this paper. However, the method in [8] is reliant on high quality components and is sensitive to changes in ambient temperature. The method proposed in this paper uses numerical integration to find the charge generated by the actuator, reducing the components required for the self-sensing circuit to a single resistor. This increases the robustness of the method as well as decreasing the cost. While the numerical integration was done in post-processing

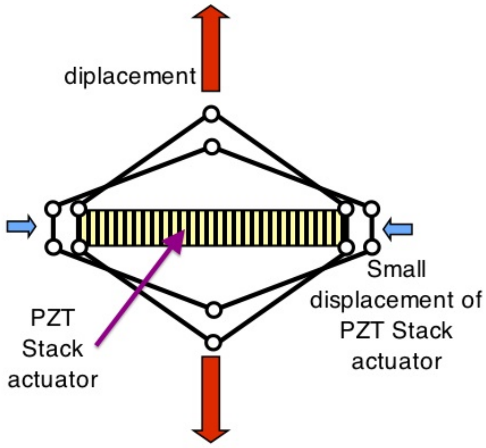

Fig. 1. Rhombus strain amplification principle

Fig. 2. Cedrat APA35XS Piezoelectric Actuator Module [9]

for this paper, it could be implemented on a microprocessor for applications where real time sensor output is required.

II. Piezoelectric Tweezer-style end effector based on nested rhombus strain amplification technique

A. Rhombus Strain Amplification Mechanism

While piezoceramics generate high force they generate extremely small strain. To amplify this strain to a usable level the rhombus strain amplification mechanism is used [2], shown in Fig. 1. Using this mechanism a tweezer-type end-effector was developed with three levels of strain amplification [3]. Five Cedrat APA35XS piezoelectric actuators in series, each consisting of a Lead Zirconate Titantate (PZT) stack actuator and an amplification mechanism, constitute the first layer of amplification, seen in Fig. 2. This layer is surrounded by another rhombus strain amplification mechanism, shown in Fig. 3. Finally, the arms of the tweezers provide another layer of amplification. The entire tweezer assembly is shown in Fig. 4. The tweezers produce 1.1 N of static piniching force in the blocked case or 9 mm of displacement in the free case between the tips when 150V is supplied to all five actuators.

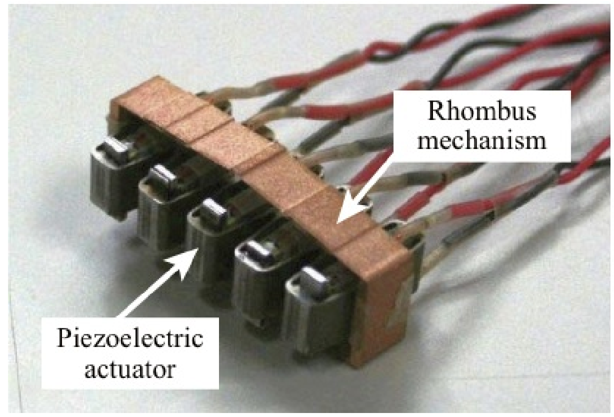

Fig. 3. Five Cedrat Actuators within second strain amplification layer [3]

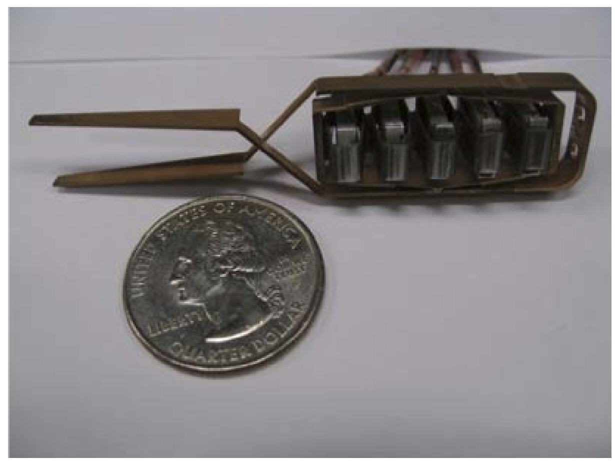

Fig. 4. Piezoelectric Tweezers [3]

A Rhombus strain amplification mechanism can be modeled by a lumped parameter model, shown in Fig. 5 [2]. Based on this model we obtain the following equations [3],

$$f_{pzt} + k_{BI}(\Delta x_c - \Delta x_{pzt}) - k_{pzt}\Delta x_{pzt} \tag{1}$$

$$ak_{BO}(a\Delta x_c - \Delta x_1) + k_J\Delta x_c + k_{BI}(\Delta x_c - \Delta x_{pzt}) \tag{2}$$

$$f_1 = k_{load}\Delta x_1 = k_{BO}(a\Delta x_c - \Delta x_1) \tag{3}$$

where a is the amplification leverage; f_{pzt} and Δx_{pzt} are the force and displacement applied from a internal PZT stack actuator; k_{BI}, k_J, and k_{BO} are spring constants from the lumped parameter model; k_{load} is the compliance of the load; Δx_1 is the amplified displacement; f_1 is the force applied to the load; and Δx_c is the displacement between the springs and the leverage. Note that Δx_c has no physical meaning and is simply a mathematical construct necessitated by the model. Solving (1) for Δx_c we obtain

$$\Delta x_c = \left(\frac{-f_{pzt}}{k_{BI}} + \Delta x_{pzt}\left(1 + \frac{k_{pzt}}{k_{BI}}\right)\right) \tag{4}$$

Substituting (4) into (2) then yields an expression for Δx_1

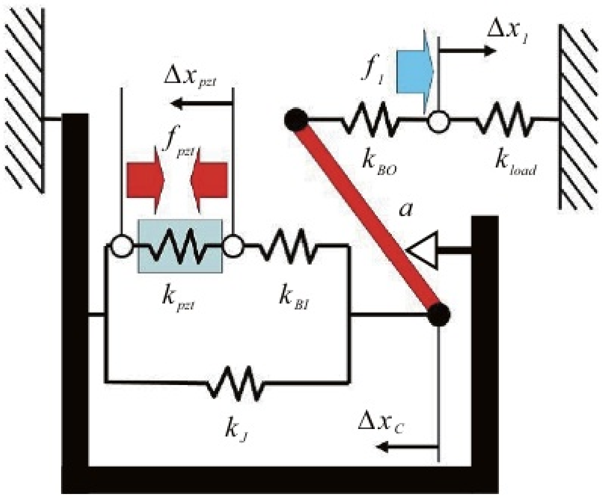

Fig. 5. Lumped parameter model of strain amplification mechanism [3]

in terms of Δx_{pzt}, f_{pzt}, and constants.

$$\Delta x_1 = \left(a + \frac{k_J + k_{BI}}{ak_{BO}}\right)\left(\frac{-f_{pzt}}{k_{BI}} + \Delta x_{pzt}\left(1 + \frac{k_{pzt}}{k_{BI}}\right)\right) - \frac{k_{BI}\Delta x_{pzt}}{ak_{BO}} \tag{5}$$

It can now be seen that f_1 is a function of Δx_{pzt} and f_{pzt} as well since it is a linear combination of (4) and (5).

The second layer of strain amplification can also be modeled by the lumped parameter model and is therefore described by equations of the same form. Let a_2, k_{BI2}, k_{BO2}, k_{J2}, k_{load2} and k_{pzt2} be the constants describing the second amplification layer, while Δx_2 and f_2 are the force and displacement of that layer. Note that k_{pzt2} is the stiffness of the five APA35XS actuator modules in series while k_{pzt} is the stiffness of the interior PZT stack actuator itself. The following equations give the force and displacement after the second amplification.

$$\Delta x_{c2} = \left(\frac{-f_1}{k_{BI2}} + 5\Delta x_1\left(1 + \frac{k_{pzt2}}{k_{BI2}}\right)\right) \tag{6}$$

$$\Delta x_2 = \left(a_2 + \frac{k_{J2} + k_{BI2}}{a_2 k_{BO2}}\right)\left(\frac{-f_1}{k_{BI2}} + 5\Delta x_1\left(1 + \frac{k_{pzt2}}{k_{BI2}}\right)\right) - \frac{5k_{BI2}\Delta x_1}{a_2 k_{BO2}} \tag{7}$$

$$f_2 = k_{load2}\Delta x_2 = k_{BO2}(a\Delta x_{c2} - 5\Delta x_1) \tag{8}$$

A multiplier of five is included with Δx_1 to account for the five actuators in series at the previous level.

B. Tweezer Structure

Fig. 6 shows a schematic diagram of the tweezer structure. The force and displacement after the second layer rhombus are f_2 and Δx_2, and the force and displacement at the tip can be written as [3]

$$f_{tip} = \frac{\Delta x_2 - Q_1 f_2}{Q_2} \tag{9}$$

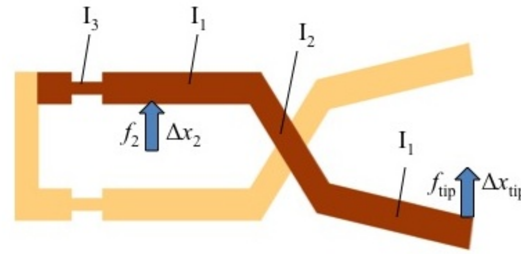

Fig. 6. Schematic of tweezer structure

$$\Delta x_{tip} = Q_3 f_2 + Q_4 f_{tip} \tag{10}$$

Where

$$Q_1 = \left(\frac{C_{A2}}{2EI_1} + \frac{C_{A4}}{2EI_3}\right) \tag{11}$$

$$Q_2 = \left(\frac{C_{A1}}{2EI_1} + \frac{C_{A3}}{2EI_3}\right) \tag{12}$$

$$Q_3 = \left(\frac{C_{B2}}{2EI_1} + \frac{C_{B5}}{2EI_3}\right) \tag{13}$$

$$Q_4 = \left(\frac{C_{B1}}{2EI_1} + \frac{C_{B3}}{2EI_2} + \frac{C_{B4}}{2EI_3}\right) \tag{14}$$

E is the Young's Modulus of phosphor bronze, and I_1, I_2, and I_3 are the second moment of area. $C_{A1} \rightarrow C_{A4}$ and $C_{B1} \rightarrow C_{B5}$ are coefficients obtained using Castigliano's Theorem and modeling the tweezer structure as Bernoulli-Euler beam [3].

Based on (4) through (10) it is seen that f_{tip} and Δx_{tip} are linear combinations of f_{pzt} and x_{pzt}. Theoretically, one could predict f_{tip} and Δx_{tip} by choosing the right constants for the lumped parameter model. While this is technically possible, in practice it proves easier to use a multiple regression to determine an appropriate combination of f_{pzt} and Δx_{pzt}.

III. Piezoelectric Self-Sensing

A. Piezoelectric Constitutive Equations

It has been shown that f_{tip} and Δx_{tip} can be determined if f_{pzt} and Δx_{pzt} are known. Now, a self-sensing technique to measure those values will be described. Let us begin by examining the piezoelectric constitutive equations. Piezoelectric materials are characterized by the direct and converse piezoelectric effects, described in tensor notation by equations (15) and (16) [1]

$$D_i = \epsilon_{ij}^T E_j + d_{ijk} T_{jk} \tag{15}$$

$$S_{ij} = \underline{d}_{ijk} E_k + s_{ijkl}^E T_{kl} \tag{16}$$

where D_i is electric displacement, ϵ is permittivity, E is electric field, T is stress, S is strain, s is compliance, and d_{ijk} and $\underline{d}_{ijk}$ are the piezoelectric constants. Superscripts E and T indicate that the relevant value is measured at a constant electric field or stress respectively. In this case, it

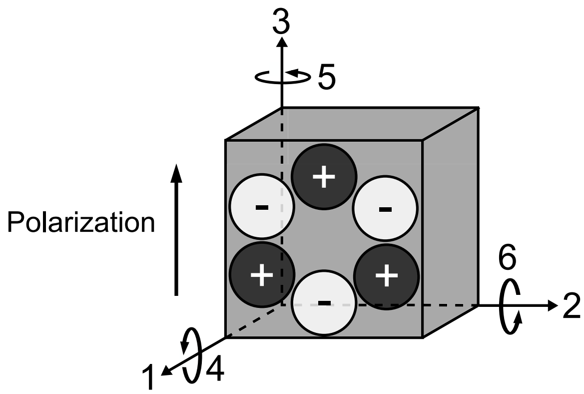

Fig. 7. Schematic diagram of piezoelectric crystal with conventional direction numbering

can be assumed that stress and electric field only occur along the poling direction, since this is the actuation direction of the PZT stack. The constitutive relations then reduce to two scalar equations,

$$D_3 = d_{33}T_3 + \epsilon_3^T E_3 \tag{17}$$

$$S_3 = \frac{1}{y_{pzt}}T_3 + d_{33}E_3 \tag{18}$$

As is common when dealing with piezoelectric materials, the subscript is now written in the compact Voigt notation. The subscript 3 indicates that the quantity is measured along the 3 axis, which by convention is parallel to the polling direction, shown in Fig. 7. The piezoelectric constant d_{33} describes the coupling of electric phenomena in the 3 direction to mechanical phenomena in the 3 direction. y_{pzt} is the Young's modulus of the PZT stack. Now (17) and (18) are multiplied by the length of the PZT stack in the 3 direction, l. Realizing that

$$S_3 l = \Delta x_{pzt} \tag{19}$$

$$v_{pzt} = E_3 l \tag{20}$$

$$C_{pzt} = \frac{\epsilon_3^T A}{l} \tag{21}$$

and

$$D_3 = \frac{q}{A} \tag{22}$$

where v_{pzt} is the voltage across the PZT stack, q is the free charge on PZT stack, C_{pzt} is the equivalent capacitance of the PZT stack, and A is the cross sectional area perpendicular to the 3 axis, (17) and (18) become

$$\Delta x_{pzt} = \frac{T_3 l}{y_{pzt}} + d_{33}v_{pzt} \tag{23}$$

$$\frac{q}{C_{pzt}} = \frac{d_{33}T_3 A}{C_{pzt}} + v_{pzt} \tag{24}$$

It will be seen that these forms of the equations are in terms of useful quantities for self-sensing.

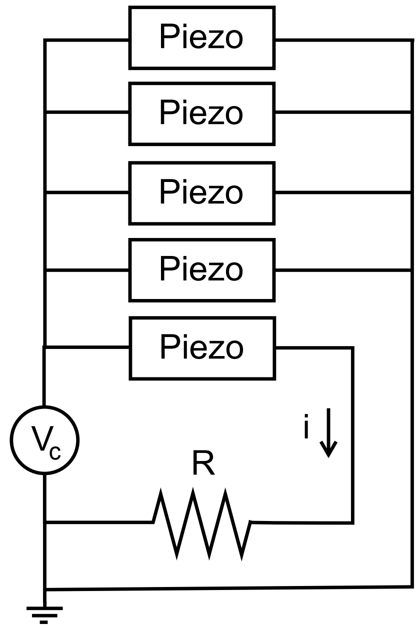

Fig. 8. Piezoelectric self-sensing circuit

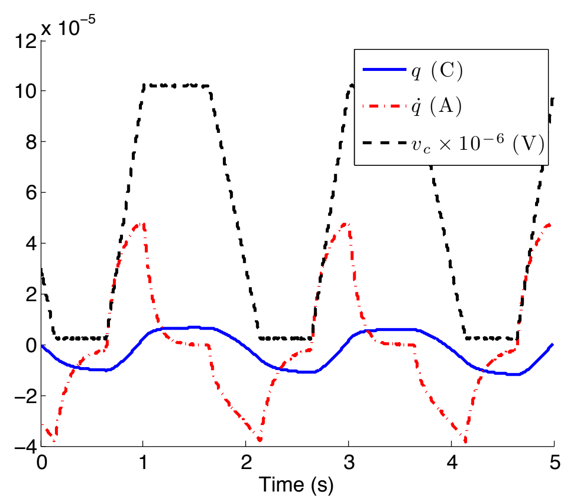

Fig. 9. Response of induced charge and current to a trapezoidal input. v_c is scaled by 10^{-6} to show its shape in relation to charge and current

B. Self-sensing Technique Based on Current Integration

Consider the circuit shown in Fig. 8 with five PZT actuators. Four actuators are connected in parallel with the driving voltage souce. One actuator is connected in series with a shunt resistance to the voltage source for current sensing. By Kirchoff's loop law we have the following

$$v_{pzt} = iR - v_c \tag{25}$$

where i is the current in the loop, R is the resistance, and v_c is the command voltage that drives the PZT actuator. Since the current is the same through all elements of the loop, integrating the current will yield the charge flowing through the PZT actuator. When the piezoelectric material

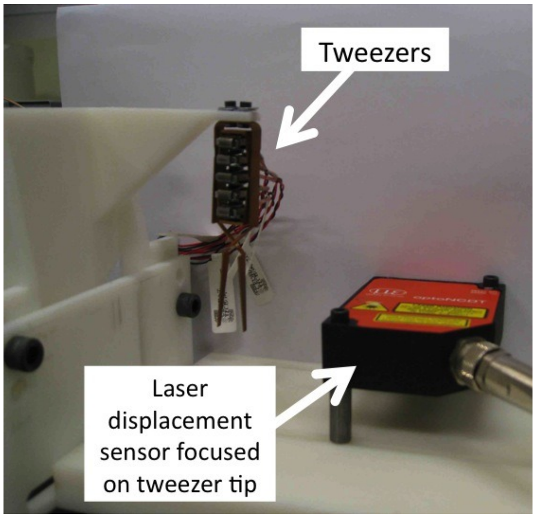

Fig. 10. Experimental Setup

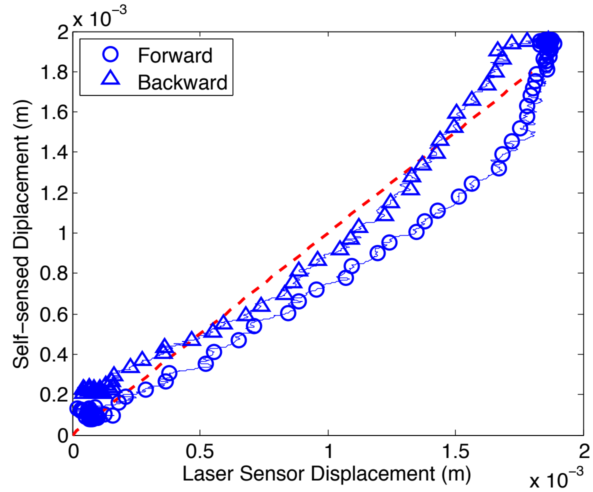

Fig. 12. Calibrated self-sensed displacement vs. laser sensor data

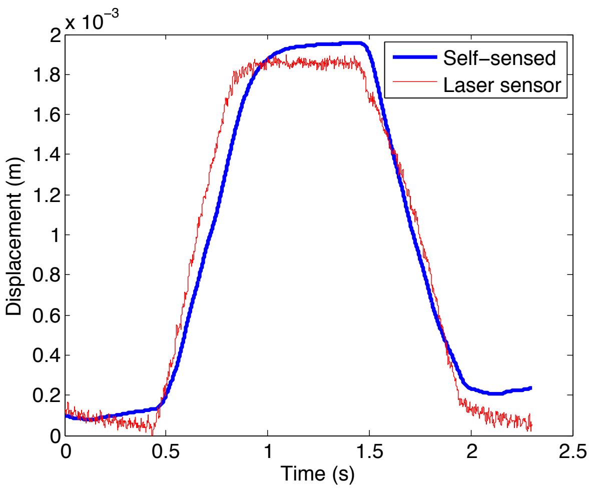

Fig. 11. Calibrated self-sensed displacement with laser sensor data for a trapezoidal input

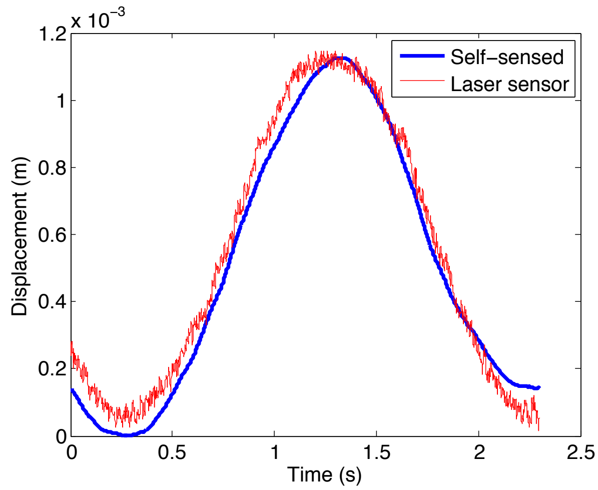

Fig. 13. Same calibration applied to a lower amplitude sine input

is deformed, the extra charge produced by strain will be immediately discharged through the resistor and will appear as a transient increase in current through the loop. By substituting (25) into (24) and realizing that $i = \dot{q}$, a differential equation for T_3 in terms of q is obtained as follows

$$T_3 = \frac{-\dot{q}RC_{pzt} + q + v_c C_{pzt}}{Ad_{33}} \tag{26}$$

Multiplying (26) by A gives an expression for the force generated by the actuator

$$f_{pzt} = \frac{-\dot{q}RC_{pzt} + q + v_c C_{pzt}}{d_{33}} \tag{27}$$

Equation (26) can be substituted into (23) yielding

$$\Delta x_{pzt} = \frac{l}{y_{pzt}Ad_{33}}(-\dot{q}RC_{pzt} + q + v_c C_{pzt}) + d_{33}(\dot{q}R - v_c) \tag{28}$$

Now Δx_{pzt} and f_{pzt} are known in terms of v_c, q, and $\dot{q}$, or i. i is easily found by measuring the voltage across the resistor and dividing by R per Ohm's law. Integrating i then gives q. Fig. 9 illustrates the response of the charge and current to a trapezoidal input.

IV. Experimental Verification

A. Comments on Simultaneous Force and Displacement Measurement

The self-sensing method developed in the previous section is applicable to both force and displacement measurements in a piezoelectric actuator. However, due to the flexibility of the tweezer design the force and displacement cannot be simultaneously measured because there are multiple tip forces and positions for each f_{pzt} and Δx_{pzt} based on the conditions encountered by the tip, i.e. blocked, free, or compliant. To achieve simultaneous measurement for a tweezer device the structure must be approximately rigid, i.e. the flexure is negligible compared to the displacement of the tips, or the tip conditions must be known. As such, in this paper only the displacement in the free case will be verified experimentally.

B. Experiment

Fig. 10 shows the experimental setup used to measure displacement. A laser position sensor measured the displacement of the tip for comparison against the self-sensing circuit. As shown above, Δx_{tip} is a linear combination of f_{pzt} and Δx_{pzt}. The appropriate coefficients can be calibrated by performing a multiple linear regression against data from the laser displacement sensor. Fig. 11 shows the calibrated displacement output plotted with the sensor data in response to a trapezoidal input. The maximum error was 20% of the dynamic range. Fig. 12 shows the calibrated displacement output plotted against the sensor data.The nonlinearity of the PZT stack is evident, but for many applications a linear approximation may be sufficient.

For the sensing technique to be truly useful, the calibration from one set of data should still yield acceptable results when applied to a different data set. Fig. 13 shows the self sensed displacement using the same calibration and the sensor data when the tweezers were given a sinusoidal input with smaller amplitude. In this case the maximum error was 12% of the dynamic range. These errors arise from several places. As noted in [3], piezoelectric ceramics exhibit hysteresis. Here the charge generation was assumed to be linear with respect to displacement. Further, the equivalent capacitance was assumed to be invariant. In reality this value changes with deformation.

C. Discussion

This measurement technique can accomodate static measurements because it takes the discharge of the PZT actuator into account. However, the inclusion of a resistor in series decreases the efficiency of the actuator. Since a portion of the applied voltage is taken by the voltage drop across the resistor the actuator in series sees a smaller effective voltage. This causes the sensor information from the self-sensing PZT stack to be slightly different than the true force and displacement of the PZT stacks used purely for actuation as well. R can be decreased to minimize wasted power, but is practically limited by the fact that a smaller resistance will produce a smaller and eventually unmeasurable voltage change in response to the transient current changes. Therefore decreasing R improves the efficiency but decreases resolution. The technique is also limited by the fact that nonlinearities in the piezoelectric material can cause the current generated in the backwards and forwards directions to be different. If this occurs the sensed displacement will drift away from a zero minimum. Note the slight drift in the self-sensed data from Fig. 11 due to these nonlinearities. A compensation method for this problem would make the technique more robust. Also note that the shape of the response generally matches the data from the laser sensor, except for the rounded corner where the displacement approaches the top of the trapezoid. This is another source of error that will be investigated in future research.

V. Conclusion and Future Works

In this paper a piezoelectric self sensing technique has been presented that is well suited to static measurements. Based on the piezoelectric constitutive equations the force and displacement of the PZT actuator were written based on charge on the actuator, its first derivative in time, and the input command voltage. The technique is limited by the inherent nonlinearities of PZT which cause drift in the output signal. Further an increase in the shunt resistance will have negative effects on the efficiency of the self-sensing actuator. The method was applied to a set of piezoelectrically driven tweezers using strain amplification mechanisms. Based on a lumped parameter model of the strain amplification mechanism and a Euler-Bernoulli beam model of the tweezer structure, the force and displacement of the PZT stack can be extrapolated to the force and displacement at the tips.The self-sensed displacement of the tips was validated against measurements from a laser position sensor in the free case. For a rigid tweezer structure or known tip conditions simultaneous measurements would be possible. Future work will focus on validating force and displacement measurements when the condition at the tips is unknown, as well as minimizing causes of error. A further goal is to extend the applicability of the tweezers to the MRI environment so they can be used for MRI guided surgery.

VI. Acknowledgements

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