Quasistatic displacement self-sensing method for cantilevered piezoelectric actuators

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Piezoelectric meso- and microactuator systems required for manipulation or assembly of microscale objects demand reliable force and/or displacement information. Available sensors are prone to dimension restrictions or precision limitation. Self-sensing method, based on the electric charge measurement, may represent a solution in terms of cost-effectiveness and integration, the actuator performing simultaneously as its own sensor. This paper presents a self-sensing method dedicated to free uni- and bimorph piezocantilevers but can also be adapted to other piezoactuator types. The integrated electric current, used to convert the charge, can be compensated against piezoelectric material nonlinearities to provide accurate displacement information. The advantages relative to existing self-sensing methods consist in the ability to keep this displacement information for long-term periods (more than a thousand seconds) and in the reduction in signal noise. After represent...
TABLE I. Displacement sensors for the microworld.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Triangulation lasers</td>
<td>High precision and resolution; fair band pass; and spot measurement</td>
<td>Quite expensive, large sizes, and limited measurement range</td>
</tr>
<tr>
<td>Interferometers</td>
<td>Very high precision resolution and range; increased band pass; and spot(s) measurement</td>
<td>Very expensive and large sizes Large sizes, require attaching target, and expensive Fragile, noisy output signal, and temperature influence</td>
</tr>
<tr>
<td>Diffraction grating target</td>
<td>High precision and multidimensional measurement</td>
<td>Require linearization, from fair to quite large dimensions, and close vicinity requirements</td>
</tr>
<tr>
<td>Strain gages</td>
<td>Less expensive and millimeter size</td>
<td>Expensive and limited resolution and response time</td>
</tr>
<tr>
<td>Capacitive or inductive</td>
<td>High sensibility, high precision, and fair price</td>
<td>Expensive and limited resolution and response time</td>
</tr>
<tr>
<td>Magnetic Hall effect, magnetoresisitive, and magnetostrictive</td>
<td>Good precision, band pass, and fair price</td>
<td></td>
</tr>
<tr>
<td>Using image processing</td>
<td>Large measurement range and in-plane displacement</td>
<td>Double functionality, high band pass, high resolution, and lowest price</td>
</tr>
<tr>
<td>Piezoelectric self-sensing</td>
<td></td>
<td>Require nonlinear compensation and long-term charge leaking</td>
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</table>

80 vantage was a linear voltage-to-displacement characteristic. However, the conventional HV supplier needs to be replaced by more complex charge driven circuits. In our paper we propose two simple schematics of current integrators (modi- fied charge amplifiers) that can also be easily implemented onto existing systems, avoiding requiring the redesign of actuator or HV supply. The developed self-sensing systems can be divided into three main parts, as in Fig. 1: the piezoelectric actuator, the electronic circuit, and the data processing system. The latter is the proposed self-sensing estimator. The estimate displacement could be used for further feedback or closed-loop control systems.

83 Piezoelectric actuators are submitted to \( V_{in} \) external voltages in a range of up to several hundred volts, depending on actuators. Resulted charge \( Q \) (in fact integrated current) is converted by the electronic amplifier to a measurable voltage \( V_{out} \). This signal will be converted for further numerical processing. Data is further processed on a computer or is deployed into a real-time processor or microcontroller. External signals can be provided to improve the self-sensing accuracy, for instance temperature variation may be compensated with a small thermistor. As the charge cannot be kept indefinitely, external resetting before each measurement prevents saturation and offsets large parts of the static error.

88 Among the contributions of this paper include: the intro- duction of an antiparallel reference capacitance, numerical compensations of amplifier bias currents and of piezoelectric leaking resistance, and dielectric absorption. A step by step approach of the identification of the self-sensing parameters is presented as well as experimental results.

90 The paper is organized as follows. First, we present the principle and related equations of the self-sensing estimator. Afterwards, we detail the parameter identification. Hence, we present the experimental results. Finally, we relate some is- sues to be taken into account when deploying self-sensing systems.

93 A. Charge output of piezoelectric cantilever

Consider a bimorph cantilevered beam piezactuator subjected to an electrical excitation \( V_{in} \) (Fig. 2). The beam is characterized by its length \( L \), its width \( w \), and its half-thickness \( h \).

96 In the absence of external force, we have a theoretically linear relation between displacement and applied voltage:

\[
\delta = - \frac{3d_{31} E_{33}^2}{4 L^2 S_{11}} V_{in},
\]

where \( S_{11} \) is the compliance coefficient along the beam (X direction), \( E_{33} \) and \( d_{31} \) are dielectric and piezoelectric material coefficients.

98 Using the relation between the applied voltage and the capacitance for bimorph piezoelectric cantilever beam

\[
Q = \frac{4wL E_{33}^2}{h} V_{in},
\]

charge directly results and, as stated previously, is quasipro- portional to free displacement \( \delta \)

FIG. 1. (Color online) Displacement self-sensing system.

FIG. 2. A bimorph piezoelectric cantilever beam.
\[ Q = \frac{4\omega e S}{3d_31 L} \left( 1 + \frac{d_31^2}{4S_31^2} \right) \delta = \alpha \delta, \]  

where \( \alpha \) is denoted as an actuator charge-displacement coefficient. In the sequel, this charge will be converted into a measurable voltage \( V_{out} \) from which the deflection \( \delta \) will be estimated, as described in Fig. 1.

B. Experimental setup

A schematic overview of the setup is depicted in Fig. 3. Several unimorph and bimorph rectangular actuators (PZT on Cu or Ni substrate) were tested, of length between 10–15 mm, width between 1–2 mm, and total thickness of 0.27–0.45 mm. A Keyence LC-2420 optical displacement reader was only used for intermediate tests on actuators displacement; for some measurements requiring better precision a SIOS SP-120 miniature plane-mirror interferometer was employed. However displacement readings served only for referencing and evaluating purposes of the self-sensing method.

The high voltage (HV) amplifier allowed applying a voltage up to \( \pm 150 \) V. A current integrator amplifier circuit (modified charge amplifier) was discussed next chapter provided \( V_{out} \) output signal. The Matlab Simulink detection model was deployed on a high speed DSpace DS1103 real-time controller board. A PC-based CONTROLDESK interface served for model parameterization and data acquisition/presentation.

C. Integrator amplifier

The static electrical equivalent schematic of piezoelectric bender is a charge generator in parallel with a capacitor and a leaking resistance, as seen in Fig. 5, and its electromechanical model is shown in Ref. 2. \( C_p \) capacitance is in the order of nanofarads depending on the shape and dimensions of the microactuator’s structure while \( R_{FP} \) is the insulating resistance, whose order of magnitude is between \( 10^7 \ldots 10^{12} \) \( \Omega \).

If we ignore nonlinear effects, charge is proportional to the applied voltage and the external force. To measure charge, we propose a precise integrator circuit scheme, as pictured in Fig. 6 and described below.

The input signal \( V_{in} \) is inverted and applied to a “reference capacitor” \( C_R \) whose the value is close to \( C_p \) value; it will “absorb” a significant part of the charge due to the applied voltage, according to the second Kirchhoff law. Although \( C_R \) and HV inverter may miss from the circuit, their use is recommended. Indeed, the output will saturate at a 175 higher \( V_{in} \) input voltage value (up to several hundred volts) while preserving the same sensitivity. Feedback capacitor \( C \) will integrate the current due to external force variation and applied voltage (depending on \( C_R / C_p \) fraction). An electro-mechanical relay-switch \( k \) (in series with several kilo ohms resistor) allows resetting \( V_{out} \) voltage from DSpace environment in order to avoid the saturation. Electronic switches are not suitable because of their “off” source/drain leakage currents. Further details and propositions are discussed in Sec. V.

Output voltage is

\[ V_{out} = -\frac{1}{C} \int_0^T i(t)dt = -\frac{1}{C} Q, \]  

where, for the free beam (\( F_{ext} = 0 \)), charge is
\[ Q = -C_R V_{in} + \alpha \delta, \]  
where \( \alpha \) was introduced in Eq. (3).

If we consider a nonlinear dielectric absorption effect of piezoelectric material, we propose the following slight modification:

\[ Q = -C_R V_{in} + (\alpha \delta + Q_{DA}), \]  
where \( Q_{DA} \) is an internal amount of charge depending on \( \varepsilon_{33} \) and \( \tau \) variation.

D. Detected displacement formula

Adding the influence of the nonzero bias current \( i_{BIAS} \) of the operational amplifier (op-amp) and finite leaking resistance \( R_{FP} \) of the piezoactuator, output voltage \( V_{out} \) of the free cantilever beam is given by

\[ V_{out} = C_R I_{in} - \frac{\alpha \delta + Q_{DA}}{C} - \frac{1}{C} \int \frac{V_{in}(t)}{R_{FP}} dt \]  

\[ - \frac{1}{C} \int i_{BIAS}(t) dt, \]  
(7)

Extracting the displacement \( \delta \), we obtain the estimate as

\[ \delta_{est} = -\frac{C}{\alpha} V_{out} - \frac{Q_{DA}(V_{in})}{\alpha} + \frac{C_R}{\alpha} V_{in} - \frac{1}{R_{FP} \alpha} \int V_{in}(t) dt \]  

\[ - \frac{1}{\alpha} \int i_{BIAS}(t) dt. \]  
(8)

We will consider a simple relaxation effect described by a first-order transfer function for the dielectric absorption term

\[ Q'_{DA}(s) = \frac{Q_{DA}(s)}{\alpha} = \frac{k'_s}{\tau s + 1}, \]  
(9)

where static gain \( k'_s = k_s / \alpha \). Based on the previous equations, Fig. 7 presents the detailed estimation bloc-scheme. Some parameters of the identification in Eq. (8) have to be identified. It will be presented in the next section.

III. SELF-SENSING PARAMETER IDENTIFICATION

Parameters identification of Eq. (8) can be performed under a manual or semiautomatic procedure. Capacitances are given (\( C=47 \) nF and \( C_R=8.2 \) nF in our case). The identification procedure for the rest of parameters \( \alpha, i_{BIAS}, R_{FP}, \) and \( Q_{DA} \) is based on Eq. (7), where the displacement \( \delta \) is provided by the displacement sensor (optical or interferometer). The following steps describe the identification procedure.

A. Bias current \( i_{BIAS} \) identification

Under \( F_{ext}=0, V_{in}=0, V_{out} \equiv 0, \) and zero temperature change, there is no electric current through the piezoelectric material; the \( V_{out} \) rate of change is measured for several dozens of seconds, deriving \( i_{BIAS} \).

B. Leaking resistance \( R_{FP} \) identification

Under \( F_{ext}=0, \) a constant voltage \( V_{in} \neq 0 \) is applied to the actuator. After several hundred seconds the creep influence becomes negligible, and the output voltage \( V_{out} \) shifts with a constant slope, depending on \( i_{BIAS} \) (identified before) and \( R_{FP} \) (to be identified).

The identification can be repeated for different \( V_{in} \) values and averaged. Each point in Fig. 8 was recorded after a 1000–2000 s delay, to eliminate residual creep influence. Linear regression was applied.

Quality piezocantilevers will exhibit \( R_{FP} \) values superior to 1010 \( \Omega \). For our actuator we identified \( R_{FP}=0.435 \) T\( \Omega \).

C. Displacement coefficient \( \alpha \) identification

A step signal is applied on the free actuator. To avoid dynamic oscillations of the actuator, the step signal is shaped with ramp of around 20 V/s (Fig. 9). Measured values of \( \delta \) and \( V_{out} \) immediately after \( V_{in} \) step signal will serve to compute \( \alpha \)

\[ \alpha = (C V_{out} + C_R V_{in}) / \delta. \]  
(10)

An alternate method for deriving \( \alpha \) is to apply one or several sinusoidal signals as in Fig. 10 and use amplitude values in Eq. (10).
The last part to be identified in displacement in Eq. (8) is the dielectric absorption $Q_{DA}(V_{in},t)$ of the piezoelectric material.

$$\Delta \delta_{est}(s) = Q_{DA}(s)V_{in}(s), \quad (11)$$

where $\Delta \delta_{est} = \delta_{est} - \delta$ is the difference between estimated (using already identified parameters) and measured tip displacement (Fig. 11). Identification of $k_s$ and $\tau$ is performed on a step response, calculating the static gain and response time to reach 63.2% of final value.

IV. SELF-SENSING RESULTS

Several tests have been performed to evaluate the accuracy of the proposed self-sensing technique. Known and identified parameters are entered into the real-time processor, we have

$$\begin{align*}
\alpha &= -10.05e^{-9} \text{ C/m}, \\
C &= 47e^{-9} \text{ F}, \\
C_P &= 1.74e^{-9} \text{ F}, \\
C_R &= 8.2e^{-9} \text{ F}, \\
R_{FP} &= 0.435e^{12} \text{ } \Omega, \\
I_{BIAS} &= -1.7e^{-12} \text{ A}, \\
\tau &= 57 \text{ s}, \\
k_s &= 3.02e^{8} \text{ m/V}.
\end{align*}$$

A. Displacement self-sensing results

In Fig. 12, an input signal $V_{in}$ was applied in several steps between +20 and -25 V, under null external force. Data was recorded for 1020 s—largely sufficient for most applications involving piezoelectric actuators. A very good agreement is found; measured and detected displacement curves almost superpose.

A comparative representation of displacement errors is made as follows. Three graphs are traced (Figs. 13–15) from uncompensated to fully compensated with respect to leaking resistance and dielectric absorption. Measurement with Keyence optical displacement reader provided a poorer linearity than self-sensing signal, making it impossible for accurate error evaluation; SIOS interferometer was eventually em-
ployed. Our constraint on the utilized interferometer is that data is only available offline. Vertical error lines in the figures can be neglected and are due to the linear interpolation and sampling period mismatch between the two data sets acquired at sampling rates of 10 and 16.11 Hz.

As seen in the Fig. 13, peak-to-peak error of uncompensated signal is 2.75 μm. Compensation of RFP leaking resistance allowed a reduction in maximum error to 1.05 μm (Fig. 14). Adding the compensation of dielectric absorption provided a 0.38 μm (0.55%) peak-to-peak error.

Unaveraged measured self-sensing signal noise in displacement is of only 1.6 nm rms, being 10 times less noisy than that of filtered Keyence LC-2420 sensor (16.7 nm rms noise on 4096 averaged samples). However, as expected, SIOS SP 120 interferometer showed best results: 0.5 nm rms noise (Fig. 16).

B. Temperature influence on displacement self-sensing accuracy

Temperature exhibits changes in dielectric and piezoelectric constants. Also, differences in thermal expansion of piezoelectric and passive material tend to bend the structure like a thermal bimetallic, conducting to parasitic displacement (and charges). In this case Eq. (2) between charge and displacement no longer applies \((Q \neq a\delta)\), leading to displacement errors. To analyze the thermal influence, we compared its effects on two types of piezoelectric beams: unimorph and bimorph cantilevers. As seen in figures and as expected, unimorphs (Fig. 17) are more affected by ambient temperature than bimorphs (Fig. 18). As bimorph cantilevers are intrinsically symmetric, charges from both sides sum up and self-compensate.

If we compare the above results, we see that unimorph cantilevers are five times more sensitive to temperature than bimorphs. Errors can be limited by a proper thermal isolation or compensated with a sensitive temperature sensor like a miniature thermistor. However, temperature sensor should be in contact with the actuator for more correlate readings.

V. CURRENT INTEGRATION RELATED ISSUES

An improper choice of charge amplifier will significantly reduce sensing accuracy. The circuit should be protected against temperature changes, with a special care to PCB design (guard rings, sufficient space between routes, vias, and pads) otherwise unwanted leakage will easily exceed op-amp bias current.

Integrating capacitor must have primarily an extremely high insulation resistance, low dissipation factor, and good temperature stability. Polypropylene plastic film capacitors were employed in our case, with a measured leaking resistance of 24 TΩ for \(C=10 \text{nF}\), high enough to ignore its...
leaking influence in the circuit. Polystyrene or Teflon capacitors also showed better performance than ceramic or polyester film capacitors.

Precise operational amplifiers used in charge amplifiers must be unity-gain stable; otherwise they will tend to oscillate. Noise and bias currents have to be as small as possible. Several op-amp types were tested, OP A111BM Difet model was chosen for its very small bias current $1.7 \text{ pA}$, small offset voltage, small temperature drift, fair supply voltage, and on-chip guarding ring. OP A627 model is also suitable.

Attention has must be paid to supply and input voltages. The circuit is damaged if high input voltage is applied in the absence of supply voltage. Also, to prevent the output saturation, the $k$ switch allows resetting when necessary. Further increase in voltage over an already saturated op-amp will cause damage.

Cables should be shielded properly to avoid the electromagnetic interference. Further noise rejection can be achieved by modifying the electronic schematic presented in Fig. 19 where the current, proportional to the voltage drop across a series resistance or more likely across a voltage divider to avoid op-amp damage due to HV, is buffered or preamplified and then integrated. Indeed, this schematic allows noise reduction thanks to the grounded series resistance $R_z$ connected to the high impedance amplifier input.

$$V_{\text{out}} = -\frac{R_z}{RC(R_z + R_z)} \int_0^T i(t) dt, \quad (12)$$

For our actuator the best compromise between response time, sensitivity, and noise was a series resistance of $82 \text{ k}\Omega$ ($R_z$) and noise was reduced by a factor of five but on the other hand this schematic was much more sensitive to temperature offset drifts than that of Fig. 6. As $V_c$ voltage is in the $\mu \text{V}$ range or lower, op-amp offset voltage temperature drift $\pm 0.5 \text{ \mu V/°C}$ and supply rejection $\pm 3 \text{ \mu V/V}$ limited system accuracy. Usually op-amp offset is trimmed manually (with potentiometers); in our case this measure was not sufficient to compensate thermal drifts. We made an automatic compensation of the offset voltage with random temperature changes. This was performed by connecting DSpace DAC outputs (Fig. 20) to op-amp "trim" pins and by measuring and referencing the temperature to a miniature thermistor in close contact with op-amp chip. This way, we preserved a signal up to $100 \text{ s}$ similar in accuracy with that of Figs. 12–15, however rms noise was reduced from $1.6 \text{ nm}$ to only $0.4 \text{ nm}$, inferior to even that of SIOS SP120 interferometer.
Zero-drift chopper op-amps (typically ±0.03 μV/°C) will probably ameliorate temperature drifts but other effects such as thermal electro motive force (EMF) (Seebeck effect) in cable junctions will still perturbate the circuit.

To generally resume, charge integration is prone to nonlinearities (hysteresis and creep) and externally compensated to others (leaking resistivity and dielectric absorption).

In the case of detected or a priori—supposed absence of external forces, displacement is almost directly proportional to the charge. Further compensation of nonzero amplifier bias current, finite actuator leaking resistance, and dielectric absorption lead to a significant reduction in errors, up to 0.55% and an increase in measurement period to more than 1000 s, sufficient enough for most tasks. Signal noise was lower than that measured with expensive laser triangulation sensor. Two schematics were presented, the first one based on direct current integration showed its feasibility for long integration periods while the second integrating shunt voltage drop allowed a further reduction in signal noise with a cost of a more unstable long-term signal. Practical issues related to long-term charge preservation were presented, and temperature influence discussed.

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