Quasi-static displacement self-sensing measurement for a 2-DOF piezoelectric cantilevered actuator

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***Abstract*— This paper proposes a self-sensing measurement technique to perform the precise estimation of the displacements along two axes in a two-degrees of freedom (2-DOF) piezoelectric actuator. For that, a new electrical circuit scheme which permits charge amplification is first proposed to match the different electrodes combination of the 2-DOF actuator. Then a new bivariable observer that precisely estimates the displacements is calculated and implemented experimentally in cascade with the electrical circuit to complete the self-sensing. The experimental tests and results verification with external sensors revealed that the measured displacements given by the developed self-sensing measurement technique derive better than a micron of precision which well fits to micromanipulation applications. Discussion about the features and the performances improvement perspectives of the suggested approach are presented at the end of the paper.**

***Index Terms*— Piezoelectric self-sensing, 2-degrees of freedom, measurement, actuator.**

I. INTRODUCTION

Piezoelectric actuators are widely used in many micro/nano positioning applications. This is thanks to their high resolution, high bandwith, high force density and ease of integration. In many of these applications however, installing feedback sensors represents a challenging task. As an example, installing feedback sensors to position a small object that is manipulated using piezoelectric cantilevered beams (gripper) is difficult when the small object location changes, which requires relocating feedback sensors within acceptable range of measurement [1]. As another example, installing feedback sensors in smart fuel injecting systems that employ smart actuators like piezoelectric type is complicated due to the presence of the fluids at the nozzle of injector. However, designing displacement estimators such as the proposed self-sensing can facilitate estimating the amount of fluid for effective injection or the displacement during a micromanipulation task.

Piezoelectric sensors are based on the direct effect of piezoelectricity whilst piezoelectric actuators are based on the converse effect. In piezoelectric self-sensing, the direct effect, the converse effect and the dielectric effect are simultaneously brought into play in order to allow a piezoelectric actuator as its own sensor at the same time. Consequently, on the one hand, self-sensing suggests a very high integration feature relative to actuators with exteroceptive measurements [2]. On the other hand, relative to piezoelectric sensors [3]–[5], it is directly embedded in the system to be measured.

Piezoelectric self-sensing, initially pioneered by Dosch et. al. (1992) in [6], is widely used to work at medium or high frequency driving voltages in various applications such as: vibrations damping in flexible structures [7]–[9], surface scanning with atomic force microscopes [10]–[12] or high-speed inkjet printing based measurement [13], [14]. The principle incorporates employing the charge on the actuator's electrodes that appears during its deformation (actuation) to perform a measurement (sensing). Due to the charge leakage in many piezoelectric actuators, self-sensing techniques used in medium or high frequency applications will lose performances when the signals invovled are low frequency or constant. This limitation impedes the utilization of self-sensing in many applications such as micromanipulation and microassembly where it is important to maintain the displacements or the forces constant during several tens of seconds [16], [17]. In [18], a self-sensing technique was proposed to measure precisely the free displacement (without force) of a piezoelectric cantilevered actuator when the displacement is constant or at low frequency. The technique was afterwards extended to incorpotate the measurement of the force [19]. In both the principle consisted in modeling the charge leakage in the piezoelectric transducer as well as additional imperfection in the electrical circuit (capacitance dielectric absorption, operational amplifier bias current) and in introducing their compensation in an algorithm that treats the signal from the electrical circuit and that is called observer. The technique was therefore able to measure the displacement with micrometric precision and the force with hundreds of microNewton of precision which are very convenient for micromanipulation tasks. Further on, a dynamic model was introduced in the observer to estimate the displacement signal both at low and high frequency and a H_∞ robust feedback controller was successfully established from the self-sensing measurement

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[20]. Another self-sensing observer was studied in [21] which permitted to successfully estimate both the displacement, the force and the state of the piezoelectric actuator at low and at high frequency. In [15], a self-sensing technique capable of estimating both the force and the displacement was presented. The technique is used in piezoelectric actuators for MRI medical applications and shows an average of 12% of error between the self-sensed and the true values. All these techniques deal however with single degree of freedom (1-DOF) piezoelectric actuator and cannot be employed when the actuator has several axes of movement.

This paper proposes a self-sensing measurement technique devoted to estimate the free displacements in a 2-DOF piezoelectric actuator. Unlike the self-sensing techniques in the literature, the technique proposed is capable of estimating the two displacements of the actuator in its two directions. The actuator studied in the paper is used as basis of dexterous microgripper devoted to complex micromanipulation and microassembly tasks [24]. A main interest of introducing self-sensing measurement to the 2-DOF actuator is that it will be possible to perform feedback control with a high integration sensing, contrary to the employed feedback control from external sensors which was often difficult to settle due to the sizes of the sensors [17], [23]–[25]. For that, a precise modeling of the 2-DOF actuator and of the suggested electrical circuit is first carried out. Then on the basis of this model, the observer algorithm that permits to estimate the displacement precisely is derived. Experiments were carried out and proved the suggested concept.

The remainder of this paper is organized as follows. The 2-DOF piezoelectric actuator and the experimental setup are first presented in section-II. Then, the new precise self-sensing measurement devoted to 2-DOF actuators are detailed in section-III. The section includes the principle, the modeling and the observer derivation of the self-sensing. Finally, section-IV provides the parameters identification, the experimental results and validation.

II. Presentation of the 2-DOF Piezoactuator and of the Experimental Setup

A. The 2-DOF piezoactuator

The 2-DOF piezoelectric actuator (piezoactuator) is a cantilever structure with a rectangular cross section, as described in Figure 1-a and was developed in previous work as a basis of a 4-DOF microprehensile microrobot on chip [22]. It is composed of two piezoelectric layers and has two electrodes on the top surface, for electrical potentials V_1 and V_2, and two other electrodes on the bottom surface, for electrical potentials V_3 and V_4, as described in Figure 1-b. An electrode that serves as ground GND is placed between the two layers. The two layers are initially poled with poling direction P as indicated in Figure 1-b. Since the objective is to obtain displacement y or displacement z, the system can be seen as a two-input-two-output block in which the outputs are y and z and the inputs are driving voltages V_y and V_z. In the next subsection, the functionining of the actuator is explained with details on how the driving voltages V_y and V_z are linked with the electrodes potentials V_i $(i = \{1, \cdots, 4\}$.

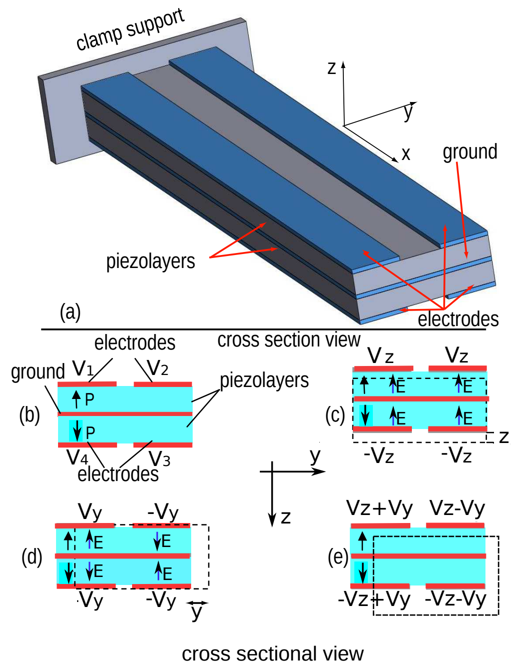

Fig. 1: (a): a simple 3D view which illustrates the location of the electrodes on the piezolayers. (b): default state of the cross-section of the actuator under zero input voltage. (c): deflection along z-axis. (d): deflection along y-axis. (e): simultaneous deflection along both y and z axes.

B. The functionining principle of the 2-DOF piezoelectric actuator

To obtain the bending along z axis, the four potentials are set as follows: $V_1 = V_z$, $V_2 = V_z$, $V_3 = -V_z$ and $V_4 = -V_z$. With this configuration, the upper layer undergoes an electrical field E in the same direction than the internal poling P and thus expands, and the lower layer undergoes an electrical field in the opposite direction and consequently contracts. This expansion/contraction yields a global deflection of the cantilever along z as shown in Figure 1-c. The deflection along y axis is obtained when the following configuration is set: $V_1 = V_y$, $V_2 = -V_y$, $V_3 = -V_y$ and $V_4 = V_y$. This second configuration creates an electrical field that is in the same direction of the poling in the left sector of the upper and lower layers, and an electrical field that is in the opposite direction in the right sector. Thus, the left sector expands whilst the right one contracts, which yields a global deflection of the actuator along y axis as shown in Figure 1-d. Finally, a combination of the two displacements y and z can be got when both V_y and V_z are applied to the different electrodes and potentials V_i, as schemated in Figure 1-e.

From these possible configurations, we can quickly see that we always have: $V_1 = -V_3$ and $V_2 = -V_4$. This makes easier the management and the affectation of the driving voltages V_y and V_z to the potentials V_i. In a control point of view, the use of V_y and V_z has more meaning whilst for the electronic and circuitry point of view, the potentials V_i are used. Since the self-sensing developed in this paper will use individual electronic circuit for each electrodes, we will use V_i in the different modeling and synthesis.

It is worthy to notice that the same principle than this actuator is found in piezotube scanners to obtain the displacements along two directions. Therefore the self-sensing measurement presented here is also applicable to them. The driving voltages V_y and V_z are limited to $\pm 10V$ for this actuator. By increasing the number of piezoelectric layers in the cantilever, the applied voltages can be reduced [23]. In the sequel, we use a cantilever with 36 layers which permits to use a maximal range of voltage of $\pm 10V$. It has $22mm$ of active length out of 27 mm total length, $1mm$ of width and $0.91mm$ of thickness. Figure 2 depicts the actuator.

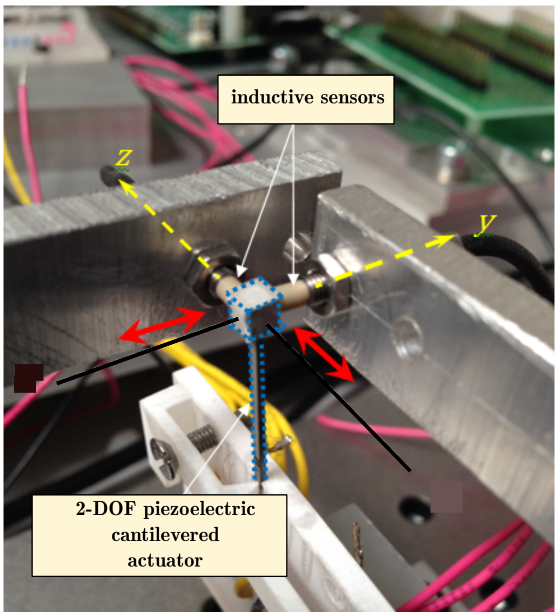

Fig. 2: The 2-DOF piezoactuator.

C. Presentation of the experimental setup

The experimental setup in the study includes:
- the 2-DOF piezoelectric actuator cantilever,
- two external inductive sensors which are used only for the characterization and identification of the parameters of the model and for the verification of the effectiveness of the proposed self-sensing measurement technique in each axis y and z. Notice that the objective is to use the self-sensing technique as the sole measurement of the displacements y and z of the 2-DOF actuator. Hence, the inductive sensors can be removed when the effectiveness of the self-sensing is validated. The sensors are tuned to have a bandwith of $2kHz$ and a resolution of tens of nanometers,
- the developed electrical circuit for the self-sensing and which will be presented in the next section,
- and a dSPACE acquisition board with a computer for data acquisition. This acquisition system is used to generate the voltages signals, to acquire all measurement signals and to implement the observer algorithm of the self-sensing. Matlab-Simulink environment is used for that.

III. Novel quasi-static displacement self-sensing for 2-DOF actuators

A. Principle scheme

A self-sensing technique used for precise measurement necessitates an electrical circuit and an observer [20], [21]. The electrical circuit serves to amplify and to transform the charge Q appearing on the electrodes during the deformation into an exploitable voltage V_o, and the observer serves to yield an estimate of the real displacement of the actuator based on the available signals, i.e. based on V_o and on the driving voltage V. For a 2-DOF piezoactuator, we propose the principle scheme in Figure 3. In the figure, V_i and Q_i are the (driving) electrical potentials and the charge appearing on the four electrodes respectively, y and z are the real displacements, $\hat{y}$ and $\hat{z}$ are the estimates from the self-sensing, and V_{o_i} are the four exploitable voltages at the output of the electrical circuit.

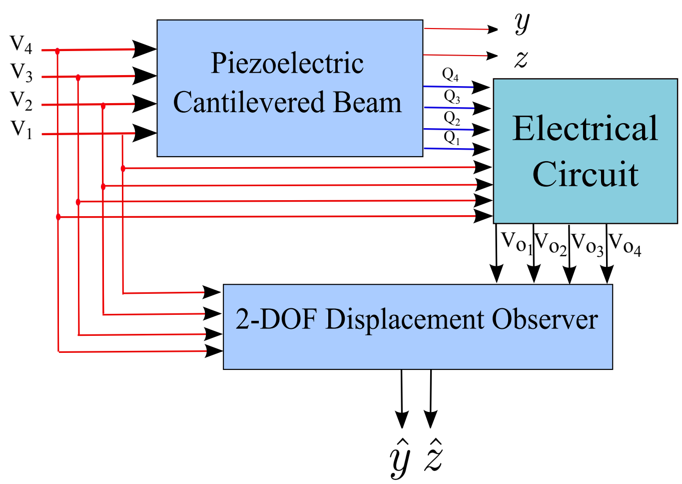

Fig. 3: Self-sensing principle for 2-DOF piezoactuators.

B. The electrical circuit

The basis of the electrical circuit is a charge amplifier [18]. To adapt this for 2-DOF piezoactuators, we propose to repeat the same scheme for the four electrodes. Consequently the charge Q_i appearing on the electrode i due to displacement (y and z) and due to the driving voltage V_i will be transformed into the exploitable voltage V_{o_i}. Figure 4-a shows the suggested electrical circuit for the electrode i, in which the equivalent electrical circuit of the piezoactuator at the sector i has also been schemated. This piezoelectric equivalent scheme is composed of a charge generator Q_i, a capacitance C_{p_i} and an internal resistor R_{fp_i}. In fact this resistor is the cause of the charge leakage in a piezoelectric element as the capacitance tends to discharge accross this. The capacitance C_{r_i} is chosen to be $C_{r_i} \approx C_{p_i}$ in order to improve the self-sensing sensitivity, as we will show in the next subsection. The capacitance C_i is utilized for the charge amplification. The commutator k_i is only employed to manually reset the circuit by discharging the capacitance C_i's content through R_i if there is a saturation of the operational amplifier (op-amp). A photography of the four-stage electrical circuit is depicted in Figure 4-b. If the actuator requires high voltages (such as piezotube scanners), a floating point is added [26] to avoid the destruction of the electrical components.

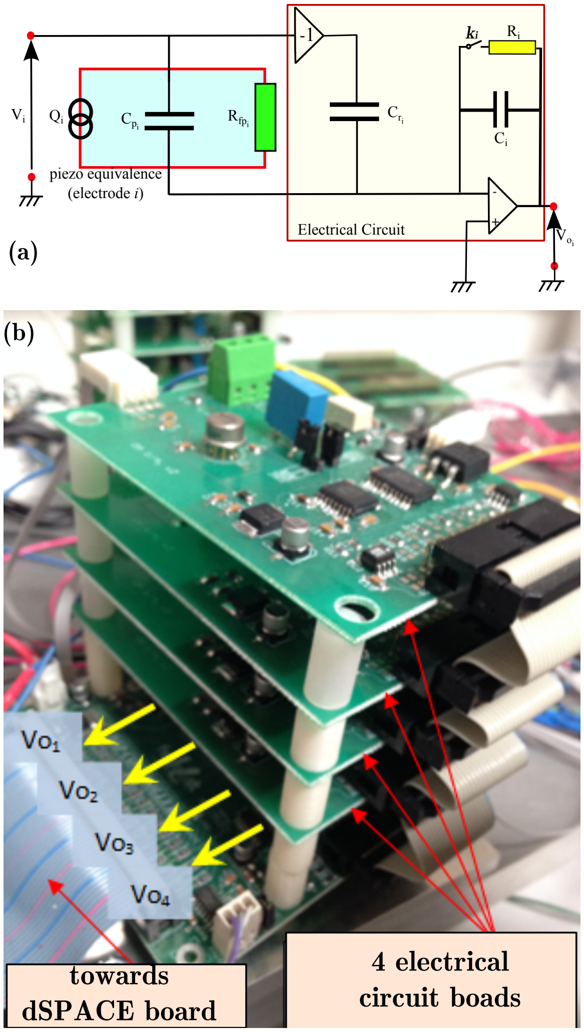

Fig. 4: (a): Electrical circuit for the electrode i, and (b): photo of the four-stage electrical circuit.

C. Modeling

In order to calculate an observer that will provide the estimate displacements $\hat{y}$ and $\hat{z}$, we first develop the model of the piezoactuator and the electrical circuit combined. When an input voltage V is applied to a piezoelectric cantilever actuator, it bends with deflection δ. If this displacement (bending) is free, i.e. no external force applied to the actuator, the charge Q which appears on the electrode of the actuator is expressed as: $Q = \gamma\delta$ [27], where γ is the charge-displacement coefficient. This model is valuable if the input voltage is applied in an unidirection manner and thus if the actuator is 1-DOF.

When the actuator works with a vector of voltages containing V_y and V_z (and thus with the electrodes potentials V_i), as in our case, two different output displacements of y and z will be contributed. The displacement in each direction contributes a total electrical charge on the total surface of all the four electrodes: $\sum Q_i = Q_y + Q_z = \gamma_y y + \gamma_z z$, with γ_y and γ_z the charge-displacement coefficient for each axis. This charge can be employed after amplification to estimate the output displacements of the actuator in each axis. However, for each electrode i, the individual charge Q_i is composed of piezoelectric effect (due to the deformation) which is denoted by Q_{s_i}, and a dielectric effect due to the potential V_i and which is denoted by $C_{p_i}V_i$, that is: $Q_i = Q_{s_i} + C_{p_i}V_i$. Since the charge due to piezoelectric effect is relatively small, the reference capacitance C_{r_i} will be chosen as close as possible to C_{p_i} ($C_{r_i} \approx C_{p_i}$) in order to cancel the charge due to dielectric effect, and thus to increase the self-sensing sensitivity. This yields:

$$Q_{s_i} + C_{p_i}V_i - C_{r_i}V_i \approx Q_{s_i}, \tag{1}$$

By doing this, only charge Q_{s_i} will be amplified by the capacitance C_i.

In the sequel, we consider the following hypothesis:
- the op-amp is nonideal and has therefore a biased current i_{B_i},
- the piezoactuator is nonperfect and therefore contains a dielectric absorption Q_{DA_i} additionally to its leakage resistor R_{fp_i}.

Consequently, the exploitable output voltage V_{o_i} after amplifying the charge Q_{s_i} can be expressed as:

$$V_{o_i} = -\frac{1}{C_i}(\gamma_y y + \gamma_z z - (C_{p_i} - C_{r_i})V_i \\ -\frac{1}{R_{fp_i}}\int_0^t V_i dt - Q_{DA_i}(t, V_i) + \int_0^t i_{B_i} dt), \tag{2}$$

where t is the time.

By employing a first order system to model the dielectric absorption [20], we have for each electrode:

$$Q_{DA_i}(s, V_i(s)) = \frac{g_{DA_i}}{1 + \tau_{DA_i}s}V_i(s) \tag{3}$$

where g_{DA_i} is the static gain, τ_{DA_i} is the time constant, and s is the Laplace variable.

In the sequel, we use the same capacitance value for all C_i, i.e. $C_1 = C_2 = C_3 = C_4 = C$.

D. Derivation of the observer

In previous studies [18], [20], [21], a monovariable observer was designed for a 1-DOF piezoelectric actuator. In this paper, a multivariable observer should be developed for the 2-DOF piezoelectric actuator which should consider the cross-couplings between the electrodes potentials of the four electrodes. Notice that Eq. (2) describes the output voltage for each of the four electrodes, with $i = \{1, 2, 3, 4\}$. The corresponding total output voltages when the actuator is excited in y-axis are $+V_{o_1}$,$-V_{o_2}$,$-V_{o_3}$ and $+V_{o_4}$. When the excitation is in z-axis, they are V_{o_1},$+V_{o_2}$,$-V_{o_3}$ and $-V_{o_4}$.

Manipulating the summation of the output voltages and considering Eq. (2) for each electrode yield an estimation $\hat{y}$ for the output displacement along y-axis, which can be expressed as:

$$
\begin{aligned}
\hat{y} &= \frac{C}{4\gamma_y}[(V_{o_1} - V_{o_2} - V_{o_3} + V_{o_4}) \\
&+ \frac{1}{C}\int_0^t (i_{B_1} - i_{B_2} - i_{B_3} + i_{B_4})dt - \frac{1}{C}(-(C_{p_1} - C_{r_1})V_1 \\
&+ (C_{p_2} - C_{r_2})V_2 + (C_{p_3} - C_{r_3})V_3 - (C_{p_4} - C_{r_4})V_4)) \\
&+ \frac{1}{C}(-Q_{DA_1}(t, V_1) + Q_{DA_2}(t, V_2) + Q_{DA_3}(t, V_3) \\
&- Q_{DA_4}(t, V_4)) - \frac{1}{C}(-\frac{1}{R_{fp_1}}\int_0^t V_1 dt + \frac{1}{R_{fp_2}}\int_0^t V_2 dt \\
&+ \frac{1}{R_{fp_3}}\int_0^t V_3 dt - \frac{1}{R_{fp_4}}\int_0^t V_4 dt)]
\end{aligned}
\quad (4)
$$

while the estimate $\hat{z}$ is:

$$
\begin{aligned}
\hat{z} &= \frac{C}{4\gamma_z}[(V_{o_1} + V_{o_2} - V_{o_3} - V_{o_4}) \\
&+ \frac{1}{C}\int_0^t (i_{B_1} + i_{B_2} - i_{B_3} - i_{B_4})dt - \frac{1}{C}(-(C_{p_1} - C_{r_1})V_1 \\
&- (C_{p_2} - C_{r_2})V_2 + (C_{p_3} - C_{r_3})V_3 + (C_{p_4} - C_{r_4})V_4) \\
&+ \frac{1}{C}(-Q_{DA_1}(t, V_1) - Q_{DA_2}(t, V_2) + Q_{DA_3}(t, V_3) \\
&+ Q_{DA_4}(t, V_4)) - \frac{1}{C}(-\frac{1}{R_{fp_1}}\int_0^t V_1 dt - \frac{1}{R_{fp_2}}\int_0^t V_2 dt \\
&+ \frac{1}{R_{fp_3}}\int_0^t V_3 dt + \frac{1}{R_{fp_4}}\int_0^t V_4 dt)]
\end{aligned}
\quad (5)
$$

The observer is composed of Eq. (4) and Eq. (5). This observer has the exploitable voltages V_{o_i} from the four electrical circuits and from the applied voltages V_i to the electrodes as its inputs. The parameters required by the observer before its implementation are:

- the values of the capacitances C, C_{p_i} and C_{r_i},
- the values of the four leakage resistors R_{fp_i},
- the values of the four bias currents i_{B_i} (considered constant) of the operational amplifiers,
- and the four dielectric absorptions Q_{DA_i}.

Capacitance C is chosen to perform a charge amplification in a good condition. Capacitances C_{r_i} are chosen to be equal to C_{p_i}. The identification of the rest of the parameters are described in the next section. The implementation of the observer can be done by text programing Eq. (4) and Eq. (5), or by bringing them into the Laplace domain first and then implementing the related block-diagram in Matlab-Simulink. In our case, we used block-diagram implementation in Matlab-Simulink which was afterwards run in real-time with the dSPACE board. It is worthy noting that the whole acquisition system (computer and dSPACE board) is here practical because it permits to quickly verify the suggested self-sensing and to modify the parameters if required. For an end-use application, it is possible to implement the observer in a more integrated system such as FPGA or microcontroller, by using text programing version of Eq. (4) and Eq. (5).

IV. Identification and experiments

A. Identification procedure

In order to apply the suggested 2-DOF self-sensing experimentally on the actuator and to implement the related 2-DOF observer, several parameters have to be identified. They are: C_{p_i}, i_{B_i}, R_{fp_i}, γ_y and γ_z, g_{dDA_i} and τ_{DA_i}. For that, the identification procedure is similar to that of 1-DOF case in [18]. Unlike to this latter however, here we have four equations and each equation is described by Eq. (2) from which the identification is based.

a) Piezoelectric capacitance C_{p_i}: The equivalent capacitance of each subsector that links the electrode i with the ground electrode GND is measured with a multimeter. This value gives an approximate value of C_{p_i} for low frequency functionining condition, which is the objective of this paper. Notice that at high frequency, the capacitance value changes. Such high frequency condition is out of the scope of this paper.

b) Bias current i_{B_i}: The input potential V_i is set to zero, and thus no charge appears in the circuit. Under this condition, if the exploitable voltage V_{o_i} is a ramp signal with a slope S_o, therefore, the bias current is its only cause and can be calculated as: $i_{B_i} = -C_i S_o$. This current is generally very small and thus the ramp V_{o_i} behaves like a horizontal curve.

c) Leakage resistor R_{fp_i}: Here, the input voltage/potential V_i is set constant. In the meantime an ammeter is used to measure the current passing through the capacitance C_i of Figure 4, that we call i_{c_i}. When removing the identified i_{B_i} in step-b from this current, we have the current passing through the resistor approximately and from which we derive the value of R_{fp_i} as: $R_{fp_i} \approx \frac{V_i}{(i_{c_i} - i_{B_i})}$.

d) Charge-displacement coefficients γ_y and γ_z: When applying a step potential V_i to one electrode, we obtain displacements y and z as well as exploitable voltage V_{o_i} as described in Eq. (2). Immediately after the step potential is applied, i.e. before the slope S_o of V_{o_i} appears, from Eq. (2) and from the fact that C_{r_i} was chosen to be equal to C_{pi}, we have approximately the following relation: $V_{o_i} \approx \frac{-1}{C_i}(\gamma_y y + \gamma_z z)$. Doing this procedure for two electrodes (V_1 and V_2 for example), we have two equations with two unknown parameters γ_y and γ_z, the displacements y and z being measured with external sensors. Therefore, we can directly calculate the charge-displacements coefficients from these two equations.

e) Dielectric absorption Q_{DA_i}: The dielectric absorption has unknown parameters g_{DA_i} and τ_{DA_i}. To do their identification, a step potential V_i is applied. Then, knowing the other parameters of Eq. (2) from the identification of step-a to step-d, Q_{DA_i} and its parameters can be identified from the difference between the simulation of the already known parameters and the experimental response of V_{o_i}. Systems identification techniques such as ARMAX or ARX can be applied for that [28].

B. Experimental results

The first experimental test consists in applying a series of steps to the driving voltages V_y and V_z of the 2-DOF piezoactuator. These include applying independent step inputs

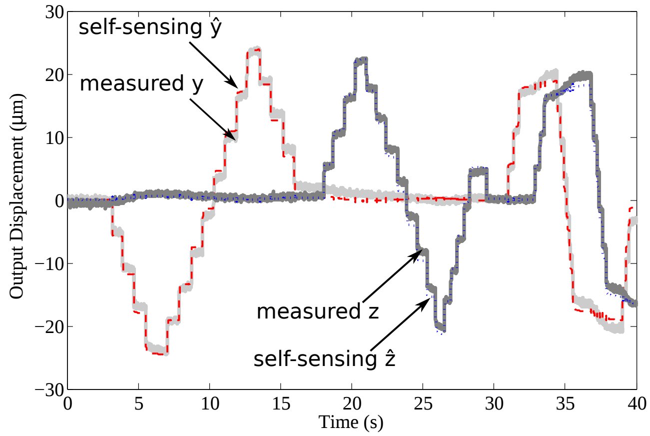

Fig. 5: A comparison between the time histories of the measured output displacement by the sensors and the estimated output displacement of the developed self-sensing.

up to $4V$ in each axis, as well as applying simultaneous step inputs of $3V$ in both directions. A comparison of the self-sensing results (the estimate displacements $\hat{y}$ and $\hat{z}$) with the real displacements y and z measured by the external inductive sensors is illustrated in Figure 5. As the figure shows, the observer can effectively track with less than a micron of error the output displacement of the actuator along each axis under independent input, as well as in both axes together under simultaneous inputs.

The aim of the second experiment is to verify the self-sensing precision devaluation when a constant voltage is maintained for several tens of seconds. This permits to evaluate the maximal error in real static condition. For that, a step input voltage V_y is applied for y: first $2V$ and then $3V$. The latter voltage is maintained for more than $150s$. The resulting output displacement measured by the external sensor and that estimated by the suggested self-sensing are pictured in Figure 6-a. In the meantime, the same voltage value is applied for z ($V_z = 2V$ and then $V_z = 3V$) but at a different time than that of y. The resulting displacements (measured and self-sensing estimate) are pictured in Figure 6-b. These results clearly show that the self-sensing shows better precision (maximal error much less than $1\mu m$) than with series of steps (Figure 5) when working with a long-term constant condition. This is thanks to the fact that the self-sensing is dedicated to static measurement and brusque variation of input voltages such as in the previous experiment may cause deviance between the estimation and the real displacements. Furthermore, the identified parameters were otained for low frequency condition. Thus, exciting high dynamics with a series of brusque voltages may also cause modification in the parameters.

In an attempt to investigate the effectiveness of the self-sensing to estimate inherent properties of the piezoactuator, in particular its hysteresis nonlinearity, we now use a sine input voltage of amplitude $3V$. The self-sensing being intended to work at low frequency, we choose a sine voltage of $1Hz$ frequency which permits to avoid phase-lag effect on the hysteresis curve and thus permits to see the real nonlinearity of the actuator [17]. Figure 7 illustrate the resulting input-output

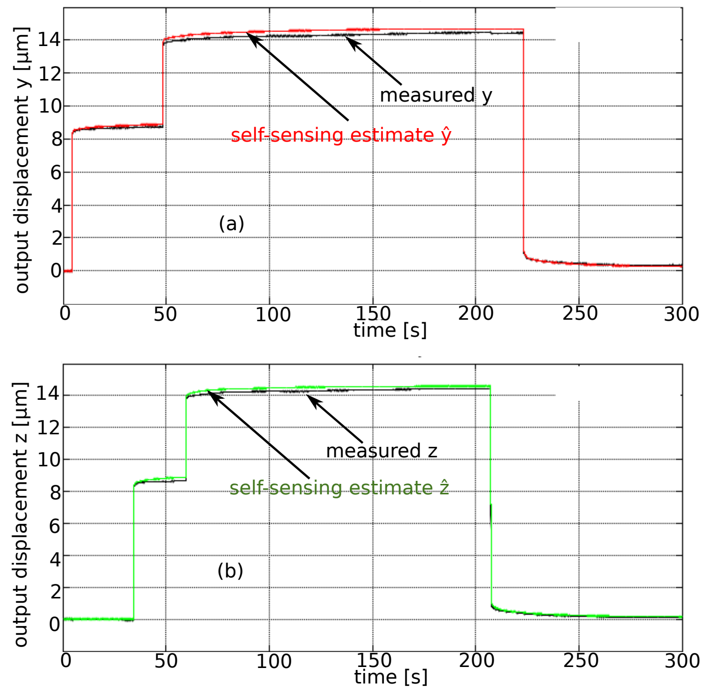

Fig. 6: Long-term duration experimental test. (a): displacement y. (b): displacement z.

(displacement *versus* voltage) properties of the actuator along y and z respectively. The figures show that the real hysteresis property of the actuator which are measured by the external sensors are also well estimated and thus well measured by the self-sensing. This is interesting since it is possible to further use the self-sensing measurement to control the actuators with consideration of its nonlinearity.

To summarize, the performances of the static self-sensing developed for the 2-DOF piezoelectric cantilever actuator has provided the performances described in Tab I. The duration corresponds to the time during which the constant input voltage is maintained and the accuracy corresponds to the maximal difference between the self-sensing estimate signal and the real displacement measured from external sensor.

TABLE I: *Performances of the 2-DOF self-sensing.*

	accuracy (nm)	duration (s)
along y	$259nm$	$100s$
along z	$189nm$	$100s$

C. Discussions

The identification procedure was carried out in a room where the ambiant temperature was maintained practically constant. The experiments were also carried out with the same conditions. It has been observed however that piezo-electric actuators could have their parameters very sensitive to the environments, the temperature being one of the most influenting causes. For example, the inherent parameters of the materials themselves depend on the temperature [29].

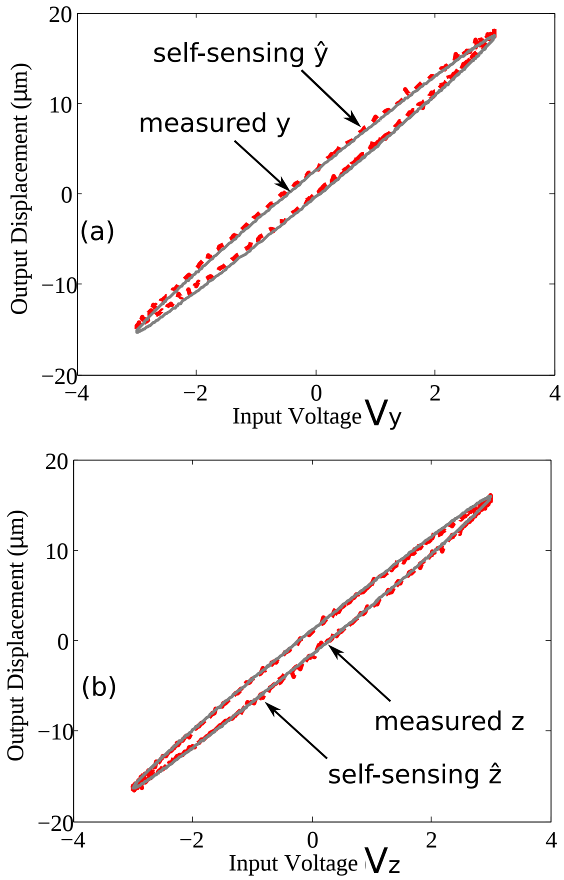

Fig. 7: Hysteresis nonlinearity of the actuator measured by an external sensor and by the self-sensing. (a): displacement y. (b): displacement z.

In addition to that, the thermal expansion properties of the materials that compose a piezoelectric actuator could strongly affect its global parameters according to its structure, for instance a cantilever piezoactuator wich is not symmetrical [30], [31]. As a consequence, when working under varying environment condition, in order to maintain a certain level of performances, an update of the identified parameters should be done. A possible way to tackle this is to update the parameters inside the observer algorithm given by Eq. (4) and Eq. (5) depending on the temperature measured in real-time with external thermocouple sensors for instance, which is outside the scope of this paper.

V. Conclusions

A new 2-DOF self-sensing measurement methodology is developed to estimate the quasi-static output displacement of 2-DOF piezoelectric cantilevered actuators. The methodology employs a 2-DOF observer along with an external electrical circuit to describe the output displacement of a 2-DOF cantilevered actuator without using external sensors. The comparison of the extimate displacements from the suggested self-sensing with those of measured from external sensors illustrates that the proposed method can follow the outputs of the actuator with precision already sufficient to perform micromanipulation and microassembly tasks. A main advantage of self-sensing is the high packageability of the measurement system since no external sensors are required. Future works deal with the extension of the self-sensing into dynamic self-sensing capable of measuring high-frequency deflection and which will be usable for feedback dynamic control.

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