A Charge-Amplifier Based Self-Sensing Method for Measurement of Piezoelectric Displacement*

Zhangming Du, Tianlu Zhang
*State Key Laboratory of Management
and Control for Complex Systems
Institute of Automation
Chinese Academy of Sciences
University of Chinese Academy of Sciences
Beijing, China*

Lu Deng
*School of Statistics
and Mathematics
Central University
of Finance and Economics
Beijing, China*
denglu521@sina.com

Chao Zhou, Zhiqiang Cao and Shuo Wang
*State Key Laboratory of Management
and Control for Complex Systems
Institute of Automation
Chinese Academy of Sciences
Beijing, China*

Abstract—**Manipulation in nano-scale is important to the development of Nano-technology, while position sensing is the base of nano-manipulation. Self-sensing is a method providing true sensor-actuator collocation and especially suitable for room-limited workspace. This paper introduced a self-sensing method for displacement measurement, based on charge amplifier. The principle of self-sensing was derived from piezoelectric constitutive equations, and a charge amplifier circuit was developed to obtain the displacement of piezoelectric stack. A series of experiments were conducted to evaluate the characteristics of our method. The results of the experiments and some characteristics of charge-amplifier based self-sensing method were presented.**

Index Terms—**Nano manipulation, self-sensing, position measure, sensor characteristics**

I. INTRODUCTION

As research keeps deep-going into extremely small scale, nano-technology is playing a rather important role in fields of material, bio-medicine, and semi-conductor, with huge applicable potentiality emerging. In the U.S. National Nanotechnology Initiative Strategic Plan, nano-technology was defined as the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications [1]. According to the definition, positioning and manipulation in nano-scale are bases of applicable nano-technology. As applications are getting further complicated, demands for automation and refinement appear, giving birth to nano manipulator.

Macro-sized manipulators that can operate nano scale objects, are widely used in nanotech. They usually have multiple macro-sized multi-DOF arms integrated in one platform [2], which can perform manipulation and positioning precisely in nano scale. The arms are often driven by piezoelectric actuators, taking advantage of converse-piezoelectric-effect. Several kinds of sensors are designed to precisely obtain positions of the nano-tools fixed in the arms' end and corresponding control methods are developed [3], [4]. A number of this kind of nano-manipulation systems have been developed by commercial companies and academia. Some state-of-the-art examples like Zyvex S100, Kleindiek MM3A, SmarAct SLC and TNI LifeForce can perform positioning with precision on the order of nanometers or sub-nanometers [5]–[7]. Nano manipulators usually co-operate with High-resolution imaging devices such as scanning electron microscope (SEM) or atomic force microscope (AFM), to perform manipulation based on feedbacks [2], [7]–[9].

Precise measurements of position is the base of precise control of nano manipulators. A variety of methods and sensors are developed for position measurements. Position of nano-tool's end is usually obtained by measuring displacement of piezoelectric actuator [10]. Mostly-used sensors for this purpose include capacitive sensors [11], optical encoder-based sensors [12] and strain gauge-based sensors [13], [14]. Despite of their maturity, these sensors have difficulties in integration with nano manipulators, of which the workspace is usually room-limited for external sensors to fit in. Besides, capacitive sensors are limited in range of measurements and are very difficult to be accurately fixed in actuator, and strain-gauge based sensors and optical sensors are usually not vacuum-compatible for their heat emission causes thermal drift problem, making them unsuitable to be employed inside a SEM. Meanwhile, all measuring methods based on sensors have the problem of mismatch between sensors and actuators, which means that the displacement measured by sensors also includes unavoidable assembly errors and any disturbance that influence the relative position of sensor-actuator pair. Then self-sensing method was proposed, combining piezoelectric actuators with the ability of sensing, saving the room occupied by extra sensors and wiping out the heat emission that could cause heavy thermal drift inside SEM's vacuum room. Most importantly, self-sensing method provides a truly collocated sensor-actuator pair [15], which improves the stability of measurement.

Self-sensing method takes advantage of piezoelectric material's unique property that it can sense the deformation of itself without disturbing the motion. Methods based on bridge circuit [15], [16] and on observer [17] are mostly-used two types. While the former has difficulties in parameter configuration,

the latter tries to build an equivalent model of the bridge. These two methods are usually applied in vibration suppression. And another type of self-sensing method based on charge amplifier was proposed [18]–[20], with simple structure, relatively easier to configure parameters.

In this paper, a self-sensing method for measurements of piezoelectric stack's displacement based on charge amplifier is presented. The method obtains displacement by measuring the charge in one of the electrodes, reducing the influence on workspace to the least. A simple circuit was used to measure the displacements of a piezoelectric stack, and results has been achieved in experiment.

Principle of self-sensing based on charge measurement is introduced in section II. And section III presents the circuit design. Self-sensing experiment measuring displacement of piezoelectric ceramic stack and its results are reported in section IV. Finally, section V concludes this paper.

II. PRINCIPLE OF SELF-SENSING

With a known constant preload applied to, piezoelectric ceramics can be regarded as external short-circuited and unbound. According to piezoelectric constitutive equations [21], [22], which present the relationships among strain S, electric displacement D, stress T and electric field intensity E, we have:

$$\begin{cases} S_m = \sum_i s_{im} T_i + \sum_j d_{jm} E_j \\ D_n = \sum_i d_{ni} T_i + \sum_j \epsilon_{nj} E_j \end{cases} \quad (1)$$

In (1), elastic compliance constant $s_{im} = \frac{\partial S_m}{\partial T_i}$, dielectric constant $\epsilon_{nj} = \frac{\partial D_n}{\partial E_j}$, piezoelectric coefficient $d_{jm} = \frac{\partial S_m}{\partial E_j}, d_{ni} = \frac{\partial D_n}{\partial T_i}$.

m,n,i,j=1,2,3 indicate the x,y,z directions of coordinate system established in piezoelectric stack, as shown in Fig 1, where z(designated as 3) is the polarization direction of piezoelectric stack, and x(designated as 1) is the main direction of displacement.
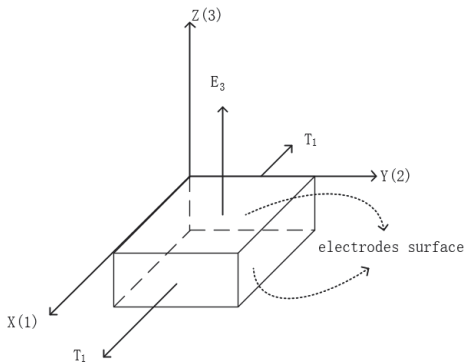

Fig. 1. Direction Definition of Piezoelectric Stack

Equations (1) can also be rewritten in form of matrix:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{21} & s_{31} & d_{11} & d_{21} & d_{31} \\ s_{12} & s_{22} & s_{32} & d_{12} & d_{22} & d_{32} \\ s_{13} & s_{23} & s_{33} & d_{13} & d_{23} & d_{33} \\ d_{11} & d_{12} & d_{13} & \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ d_{21} & d_{22} & d_{23} & \epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\ d_{31} & d_{32} & d_{33} & \epsilon_{31} & \epsilon_{32} & \epsilon_{33} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (2)$$

As driving voltage is only applied to the electrodes, in polarization direction(3) of piezoelectric stack, and only displacement in direction(1) is playing the role of actuator, only S_1 and D_3 are taken into consideration. And interactions among other secondary directions can be ignored. Piezoelectric stack is stress-free in direction(2)(3) and bears no external voltage in direction(1)(2), thus T_2, T_3, E_1 and E_2 are zero. Then equations can be simplified as:

$$\begin{cases} S_1 = s_{11} T_1 + d_{31} E_3 \\ D_3 = d_{31} T_1 + \epsilon_{33} E_3 \end{cases} \quad (3)$$

Substitute E_3 in (3), then we have:

$$S_1 = (s_{11} - \frac{(d_{31})^2}{\epsilon_{33}}) T_1 + \frac{d_{31}}{\epsilon_{33}} D_3 \quad (4)$$

Here D_3 is in proportion to the quantity of free charges on electrodes of piezoelectric ceramics, according to Maxwell's equations:

$$Q_0 = \oiint_s D_3 ds = S D_3 \quad (5)$$

S is the surface area of an electrode of piezoelectric stack. Then (4) can be rewritten as

$$S_1 = A T_1 + B Q_0 \quad (6)$$

Here $A = (s_{11} - \frac{(d_{21})^2}{\epsilon_{33}})$, $B = \frac{d_{31}}{S \epsilon_{33}}$ are constants. From (6) we can get that deformation in direction(1) can be described as a linear polynomial of quantity of free charges Q_0 on electrode and stress T_1 in direction(1). When T_1 is fixed (or is known), Q_0 measured on an electrode can represent the deformation caused by inverse piezoelectric effect in direction(1). In actual applications, flexure hinges are used, performing a preload force T_1 in direction(1) and transforming deformation S_1 to the displacement in a direction vertical to direction(1). The displacement resulted from transformation is in proportion to S_1. Therefore the final outputted displacement is also linear to both stress T_1 and the quantity of free charges Q_0:

$$S = \alpha S_1 = A' T_1 + B' Q_0 \quad (7)$$

III. CIRCUIT DESIGN

According to the principle presented in section II, the quantity of induced charges in electrodes of piezoelectric ceramics can be described as a linear polynomial of stress and deformation displacement. In condition of fixed preload, deformation displacement can be acquired by measuring induced charges.
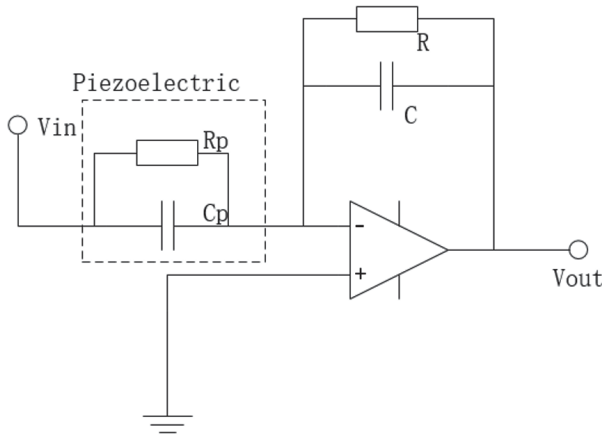
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Fig. 2.   Simplified schematic of charge amplifier

Fig. 3.   Experiment configuration

A charge amplifier shown as Fig 2 is adopted to measure the charges induced on an electrode of piezoelectric ceramics.

Ideally, piezoelectric ceramics can be taken as a capacitor Cp when working as an actuator. The charge on its electrodes induces equal quantity of inverse charges on feedback capacitor C, whose capacitance can be pre-measured. Because $Q = CU$, the output voltage U is linear with quantity of induced charges on C, and is suitable to denote deformation displacement of piezoelectric stacks. However, piezoelectric ceramic stack is not an ideal capacitor. A tiny current will leak through if a voltage is performed over it, making it actually a parallel connection of an equivalent capacitor and an equivalent resistor Rp with large resistance. Although the leakage of current is extremely small, it still unignorably causes drift to results of measurement, as the capacitor C is continuously charged by leaking current. To solve the problem, a resistor is parallel connected to C, designated as R in Fig 2, establishing a passage for leaking current. The drift will be effectively slowed down if the resistance value of R is properly set. And a precise operation amplifier with low bias current is also employed to improve the balance between currents through Rp and R.

IV. EXPERIMENTS

A. Experiment Configuration

A piezoelectric stack is fixed inside a flexure hinge, which applies a preload force to the stack and convert its displacement proportionally into the vertical direction of original displacement. The stack is driven by a voltage varying in range of 0∼60V, with peak-to-peak ripples less than 10mV. The self-sensing circuit is serially connected to the piezoelectric stack. And an eddy-current sensor is used to simultaneously measure the displacement of the stack, as a comparison to the measurements of self-sensing method.
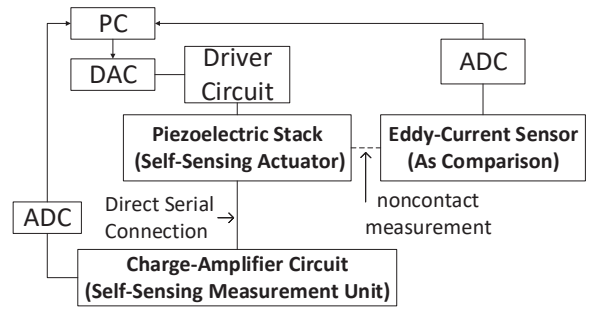
B. Results

1) Displacement Measurement: Fig 4 presents the normalized outputs of the two methods. Two sets of results are rescaled into same scale, according to the slope and intercept calculated by least square method in linearity evaluation. Red curves map the outputs of eddy-current sensor to the voltage applied to piezoelectric stack, and blue ones indicate the measurements of self-sensing method.
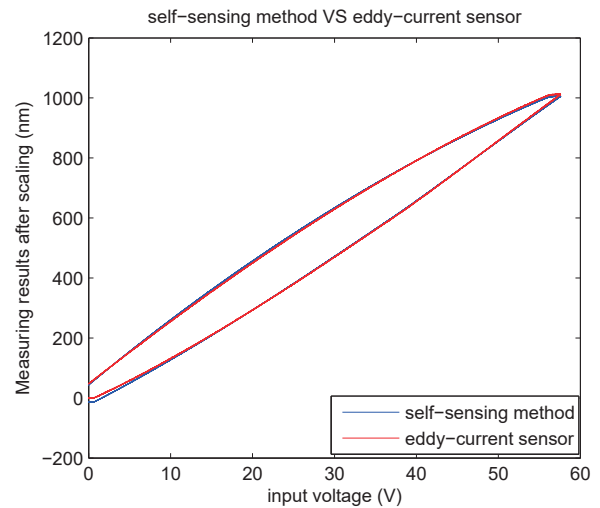

Fig. 4.   Displacement measurements of a piezoelectric stack driven by a changing voltage. The lower two curves demonstrate outputs of the two methods during the ascent of voltage, while the upper ones present the outputs during the descent of voltage. A hysteresis curve of piezoelectric ceramics was presented.

Fig 5 presents outputs of the two methods along time, giving another angle of view.

The voltage applied to piezoelectric stack increased to 60V in a constant rate for 30s and then decreased in a same rate back to 0V. As shown in Fig 4 and Fig 5, the comparison demonstrates that self-sensing method and eddy-current sensor have similar measurements of the stack's displacement, although there are small offsets between the two results (with an average difference of 3.6nm), especially when the piezoelectric stack is driven at low voltage (maximal difference is 14.8 nm). One reason for this is that the output of self-sensing method is
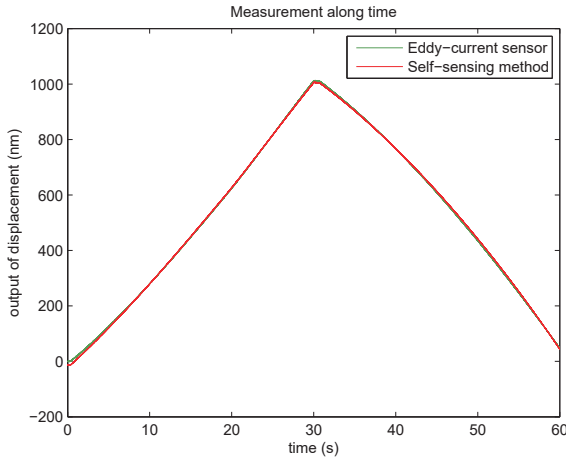
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Fig. 5. Same measurements as fig 4 but outputs of two measurements were displayed along time

also coupled with preloaded force, which is induced by flexure hinge.

In Fig 4, we can also find that same driving voltage results in different displacement output during voltage-increase phase and voltage-decrease phase. This phenomena shows the hysteresis characteristic of piezoelectric ceramics.

2) Linearity: Fig 6 presents the linearity of self-sensing measurements, using the output of eddy-current sensor as standard. Original output voltage of the self-sensing methods in subsection 1) are used to plot, without rescaling.
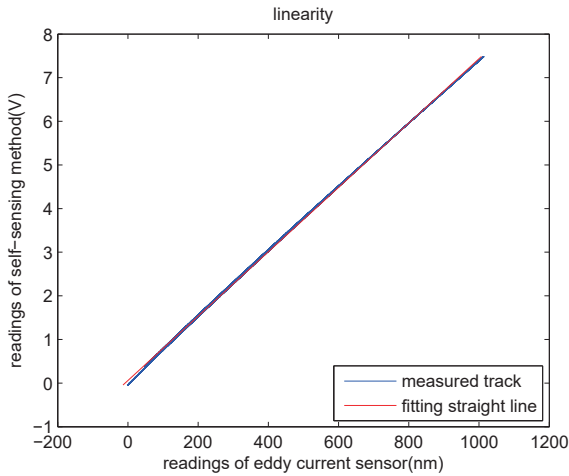

Fig. 6. Linearity of self-sensing method. Mapping outputs of Self-Sensing method to the outputs of eddy-current sensor, results in an almost straight curve

Two blue lines indicate experimental results (one with increased voltage and the other with decreased voltage) and the red line is a fitted straight line. The three lines are nearly coincident, showing good linearity of self-sensing method. As calculated, the coefficient of determination R^2 of the fit is 0.9998, meaning that self-sensing output is almost proportional

to the output of eddy-current sensor,which we regard as true displacement of piezoelectric stack.

3) Resolution: The resolution can be explained as minimum distance between two adjacent but unique locations. This distance must be larger than the uncertainty introduced by noise, to avoid mistaking one point for the other [23]. Fig 7 presents the resolution of self-sensing method, also compared with eddy-current sensor.
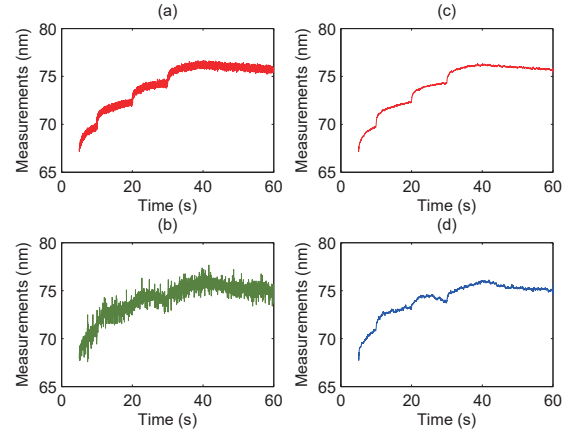

Fig. 7. Resolution comparison between self-sensing method and eddy-current sensor: (a)resolution of self-sensing method (b)resolution of eddy-current sensor (c)filtered output of self-sensing method (d)filtered output of eddy-current sensor

Started at 6V, a voltage in form of tiny steps (0.12V) is applied to piezoelectric stack, causing an increase about 2nm of piezoelectric-stack-flexure-hinge deformation for each step. The lower curves map the output of eddy-current sensor to time while the upper ones indicate the output of self-sensing method. As the piezoelectric stack itself has creep effect, the curve at top of each step is not flat. But it is easy to notice that self-sensing method has smaller noise and better resolution than the eddy-current sensor we had use. Using filtered data as base value we figured out that the maximal noise is about 0.57nm for self-sensing method, while eddy-current sensors has a maximal noise of 2.52nm as contrast. So we can consider the resolution of self-sensing method as 0.6nm. This comparison shows the advantage of self-sensing method in sensor-actuator pair collocation, which improves the stability of measurements, as no relative movement exists between sensor and actuator.

4) Drift: Fig 8 compares the drift characteristics of self-sensing method and eddy-current sensor. Output of self-sensing method shows better stability. As eddy-current sensor is not stable enough to present real position of piezoelectric stack in this case, we assumed the piezoelectric stack has stopped creeping after 150s and used the data in last 30s to calculate the drifting rate of self-sensing method, which is about 2.23nm/h, as show in Fig 9.

The result means that the circuit we used in experiment are not suitable for long-period tasks, as the error of measurement accumulates along time. The main reason for this is the
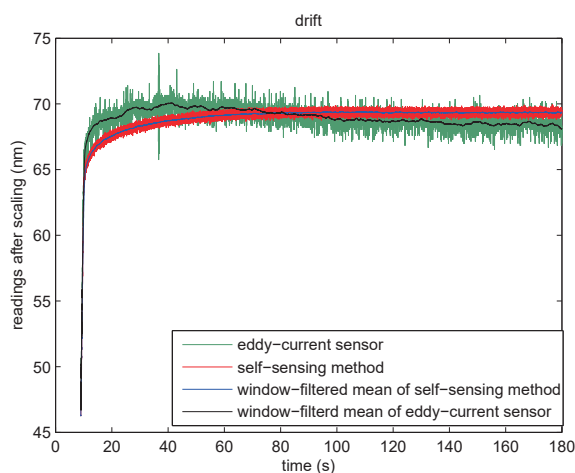
Fig. 8. Compared measurements of piezoelectric stack driven by a fixed voltage
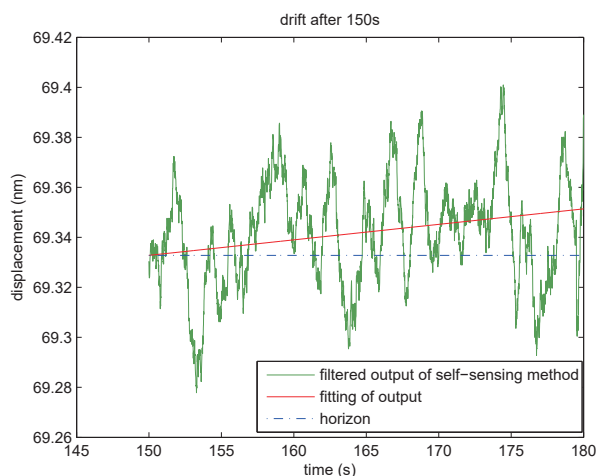

Fig. 9. Drift of a piezoelectric stack, assuming the stack has stopped creeping, then the slope of the fitting line is the drifting rate

unbalance between the current running through piezoelectric stack and the leakage through the passage established by resistor R. Thermal effects and other environmental facts also influence the balance to some extent. To solve the problem, a self-balancing design is in progress to improve the performance.

V. Conclusion

In this paper, a charge-amplifier-based self-sensing measurement for piezoelectric stacks was introduced. The principle of self-sensing was derived from piezoelectric constitutive equations, illustrating the relationship between displacement and quantity of surface charges. A charge amplifier circuit was developed to obtain the displacement of piezoelectric stack and achieved good performance in experiments. More improvements remains to be made, including solutions to EMI sensitivity and the drifting problem caused by electric leakage.

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