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Simultaneous quasi-static displacement and force self-sensing of piezoelectric actuators by detecting impedance

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ABSTRACT

This article extends the conventional permittivity change based displacement self-sensing technique for piezoelectric actuators to an impedance change based displacement–force self-sensing technique. The presented methodology evaluates changes in capacitance and resistance at an electrical resonance frequency and uses a third order polynomial fit to estimate displacement and force. Experimental validations show a mean error of 1.8%, and an error standard deviation of 1.9% for displacement and a mean error of 1.7%, and an error standard deviation of 1.8% for force.

1. Introduction

Self-sensing is a technique that employs an actuator simultaneously as a sensor. In the past decades, self-sensing has gained attention in micro-engineering applications by enabling the design of compact devices with lower costs and simpler configurations [1]. Piezoelectric materials with direct and inverse effect, have been widely used in self-sensing techniques [2–6]. These techniques can be divided into charge based, voltage based, and permittivity change based groups.

Charge based self-sensing techniques rely on the linear relationship between charge and displacement of piezoelectric actuators [7]. However, they require sophisticated charge drive amplifiers [8]. Also, their performance is relatively poor at quasi-static frequencies [9].

Voltage based self-sensing techniques cope with the hysteresis nonlinearity between the driving voltage and the displacement of a piezoelectric actuator. They use mathematical hysteresis operators to map the displacement to the driving voltage [8]. Most of these operators include computationally expensive numerical approaches [10].

Permittivity change based self-sensing techniques are based on a non-hysteretic relationship between the displacement of a piezoelectric actuator and its permittivity change [11]. They have been utilized in displacement self-sensing of piezoelectric benders [11–13] and stack actuators [2].

The listed self-sensing techniques have only been used for constant force operating conditions. However, applications such as micro-grippers [14,15] exhibit both varying displacement and force. Using both charge and voltage measurements, simultaneous displacement–force self-sensing techniques are constructed in [16–18]. The presented techniques require computationally expensive hysteresis models.

This study proposes a novel displacement–force self-sensing technique at quasi-static frequencies. The proposed technique extends conventional permittivity change based self-sensing to impedance change based self-sensing by adding a resistance measurement. In contrast to [16–18], the presented technique is hysteresis free and performs well at low frequencies [19].

In the remainder of the article, the effect of external forces on impedance of piezoelectric actuators is studied in Section 2. The proposed technique is constructed in Section 3. Experimental validation results are provided in Section 4. Finally a conclusion is provided in Section 5.

2. The effect of external force on impedance

To construct the proposed technique, the effect of external loads on the impedance of a piezoelectric actuator needs to be investigated. In this regard, a push–pull test setup consisting of two piezoelectric stack actuators is employed. Fig. 1(a) shows the setup. An Agilent-E4980A LCR meter performs a frequency sweep

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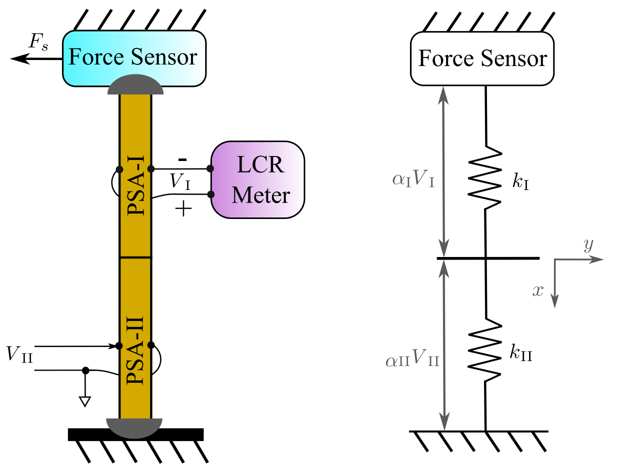

(a) The setup (b) Quasi-static electromechanical model

Fig. 1. The setup used for studying the effect of external loads on the impedance of a piezoelectric actuator.

Table 1
Reference values for PSA-I and PSA-II characteristic parameters [20].

Operating range	−20 to 120 V
Max. no load displacement	32 μm @ 100 V
Max. clamped force	950 N @ 120 V
α (force factor)	7.9 (N/V)[a]
k (stiffness)	25 (10^6 N/m)
C_P (capacitance)	3.1 ± 20% (μF) @ 1 kHz

[a] Data sheet value for α is determined by $\alpha = \frac{F_{\max}}{V_{\max}}$.

impedance measurement for piezoelectric actuator PSA-I, while the other actuator PSA-II varies the external load on PSA-I.

Both actuators are PI-885.90 from Physik Instrumente. Their dimensions are 5 mm × 5 mm × 36 mm. The remaining characteristics are summarized in Table 1.

Fig. 1(a) shows that the actuators are in a series configuration. Ball seats are used at the fixed ends. This configuration guarantees that the tip displacement x and the external force F_s are the same for both actuators at low frequencies, where inertial forces can be neglected. Force is being measured using a PCB-208C2 force sensor with a resolution of 4 mN. A small sinusoidal voltage of V_I = 1 V is fed to PSA-I from the LCR meter for measurement purposes. A driving voltage V_{II} in the range of 0–100 V is fed to PSA-II to vary the external forces. Fig. 1(b) illustrates the quasi-static electromechanical model of the mechanism. Since the two actuators are equivalent, $\alpha_I = \alpha_{II} = \alpha$ and $k_I = k_{II} = k$. Force equilibrium in the x direction leads to

$$kx = F_s + \alpha V_I, \tag{1}$$

$$2kx = \alpha(V_I - V_{II}), \tag{2}$$

where αV_I and αV_{II} are the generated piezoelectric forces, assuming that there is no hysteresis nonlinearity [21]. Neglecting V_I in (1) and (2), ($V_I \ll V_{II}$), a linear approximation of the external force as a function of applied V_{II} can be derived as

$$F_s = -\frac{\alpha V_{II}}{2}. \tag{3}$$

Using the setup described, the impedance of PSA-I is measured at three different loading conditions of F_s = 0 N, −166 N, and −361 N by exiting PSA-II with V_{II} = 0 V, 50 V, and 100 V respectively. An attentive reader would notice that, the theoretical force value using (3) and the corresponding measured values at 50 V and 100 V, have 19% and 9% discrepancy respectively. This is due to hysteresis which is neglected in (3).

The Agilent-E4980A LCR meter performs a frequency sweep impedance measurement at each loading condition. In order to compensate for the creep effect, each frequency sweep is carried out approximately one minute after applying the preload voltage to PSA-II. The frequency range for the sweep is 60–180 kHz, which is well above the first mechanical resonance frequency of 4 kHz of the test setup. Thus, the displacement of PSA-I is not influenced by the impedance measurement [12].

Magnitude and phase of zero force condition impedance are depicted in blue in Fig. 2(a) and (b) respectively. The corresponding capacitance and resistance values are depicted in Figs. 2(c) and (d) respectively. Four major resonance peaks at frequencies of 60 kHz, 95 kHz, 125 kHz, and 135 kHz are detected in zero force condition. The red and yellow profiles depict the results of F_s = −166 N and F_s = −361 N external forces respectively.

No noticeable change in the impedance is observed outside the resonance frequencies for the three levels of applied external load. Thus, a permittivity measurement between resonance peaks is not a good indicator of applied force.

However, a clear shift in the location of the resonance peaks in Fig. 2 is detected as a result of external forces. The reason for the observed behavior of the impedance at the resonance frequencies is yet to be studied. Clearly, the domain structure of piezoelectric materials change under external forces. On the other hand, the domain structure change affects the impedance of the material [13]. This study shows that, the effect is magnified at the electrical resonance frequencies. Therefore, in contrast to conventional permittivity change based displacement self-sensing technique that uses frequencies far from the electrical resonance frequencies, the proposed technique suggests measuring impedance at electrical resonance frequencies to detect changes in external forces.

Two measurements are required to simultaneously predict displacement and force. The proposed self-sensing technique measures capacitance and resistance of a piezoelectric actuator at a specific electrical resonance frequency, where both are affected by the external forces and the actuator displacement.

3. The proposed self-sensing technique

3.1. Impedance measurement method

Similar to permittivity detection methods in the literature, a ripple voltage V_r is added to the driving voltage V_d of PSA-I in order to carry out a real-time impedance measurement [11]. The magnitude of V_r needs to be small (0.1 V pp) in order to limit the resulting ripple current. Section 2 suggested that, the frequency of the impedance measurement voltage needs to be: (1) far from the first mechanical resonance frequency of the setup (4 kHz). (2) Close to an electrical resonance frequency to detect any impedance change as a result of applied external loads. In this study V_r has a frequency of 100 kHz which meets both criteria.

Fig. 3 illustrates the setup used for framing the impedance measurement technique. It is a modified version of the setup described in Section 2. A thin metal sheet is sandwiched between the tips of the actuators for displacement measurement, using a Polytec-HSV2002 differential high-speed laser vibrometer with a resolution of 0.3 μm. Displacement and force sensors are not parts of the proposed self-sensing technique and have been employed for two reasons: (1) construction and calibration of the relationship between the actuator's impedance, displacement, and force. (2) Validating the performance of the proposed technique.

While PSA-II is still being used to vary the external force, the ripple voltage V_r is added to the desired driving voltage V_d via