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Study on Sensitivity and Accuracy of Piezoelectric Stack Actuators for Charge Self-Sensing

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Summary:
The charge response of a force applied to piezoelectric stack actuators was characterized in the range of 0 N – 20 N for application in piezoelectric self-sensing. Results show linear behavior between applied force and collected charge for both actuators tested in this study. One actuator exhibits a 3.55 times higher sensitivity slope than the other related to its larger capacitance. An error analysis reveals a reduction of relative error in charge measurement with rising forces applied to the actuators.

Keywords: Piezoelectricity, linear stack actuator, self-sensing, charge measurement, miniaturization

Introduction

Piezoelectric self-sensing has shown to be of great potential when it comes to miniaturization of actuator systems [1]. Information about the displacement and force acting on the actuator can be gained without additional sensors. This information can further be used in a control loop or be collected to display the information about the state of the environment. Piezoelectric self-sensing has already been used in various research fields, for example vibration suppression [2] or force control [3].
The presented work focuses on the analysis of two linear piezoelectric actuators (PEA) under the influence of applied force by measuring the direct piezoelectric effect. A better understanding of the self-sensing response of each of the actuators should be achieved. We compare the differences of the sensing response of two actuators to investigate sensitivity and signal to noise ratio differences.

Methods

The two chosen PEAs for this study comprise the PA2JEW (Thorlabs, Inc.) and the PK2JA2P2 (Thorlabs, Inc.) stack actuator. The latter is composed of 4 PA2JEW actuators bonded together to form a longer stack and provide 4x larger stroke and capacitance. To measure the direct piezoelectric effect on the PEA, the actuator is inserted in a previously designed mechanical setup [4]. The force is applied by a screw pressing down on the actuator. A force sensor (adafruit, 4540) is placed below the PEA to determine the applied force.

The direct piezoelectric effect is sensed using an electrical circuit (Fig. 1). Electric current is measured flowing through an ammeter (Keysight B2981A) and integrated over time, giving information about the charge on the electrode surface of the PEA.

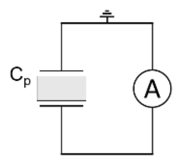

Fig. 1: Schematic of the electrical circuit to detect charge from the actuator surface. C_p: PEA

The charge resulting from applied force is detected for two PEAs, which both can be used in miniaturized inchworm actuators. Experiments are carried out with force of 5 N - 20 N, fitting to force occurring in the application of mandibular distractors [5]. The measurement at each force was repeated ten times. All experiments are done while the PEA is prestressed with a force of 0,3 N. The capacitance C of the PEAs can be calculated from Eq. (1) using the permittivity ε, the base area A, the distance d, and the number n of piezoelectric layers in each stack. The number of layers is obtained from Eq. (2) with the nominal stroke ΔL at an applied potential U and the dielectric constant d_{33}.

$$C = \frac{\varepsilon_0 * \varepsilon_r * A}{d} * n \quad (1)$$

$$n = \frac{\Delta L(U)}{d_{33} * U} \quad (2)$$

Results and Discussion

For PA2JEW, a capacitance of 185.48 nF is calculated, while the PK2JA2P2 has a capacitance of 741.9 nF. The calculated stack layers are 38 and 150, respectively. The capacitances deviate by more than 25 % from the manufacturer's specified capacitance. This can be explained by the uncertainties in layer thickness. The entire stack is assumed to contribute to the PEA, isolation layers are not considered. The results of the charge measurement at applied forces for both PEAs can be seen in Fig 2.

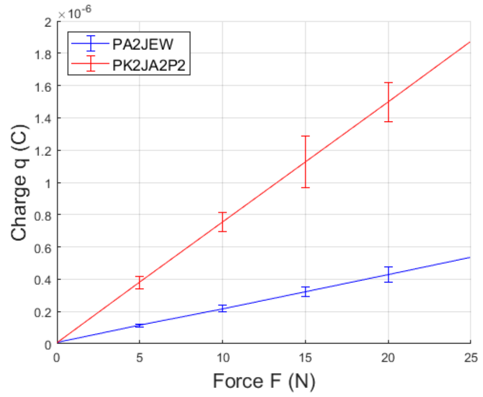

Fig. 2: Relationship between applied force and measured charge from the PEAs.

The results show that both measured piezoelectric stacks feature linear behavior between applied force and measured charge. The PK2JA2P2 has a slope 3.55 times higher than the slope from PA2JEW. Because the PK2JA2P2 is built of four blocks of the PA2JEW and shows a capacitance 4 times higher, the slope was expected to be four times higher.
This difference can have several reasons. The bonding layers between will be compressed by the acting force, thus reducing the total force acting on the piezoceramic layers. The PEAs both have an additional ceramic coating covering the sides of the PEAs, which might influence the force transmission. In addition, the PK2JA2K2 has a plastic wrapping, which might transfer some amount of force directly to the ground, bypassing the PEA.

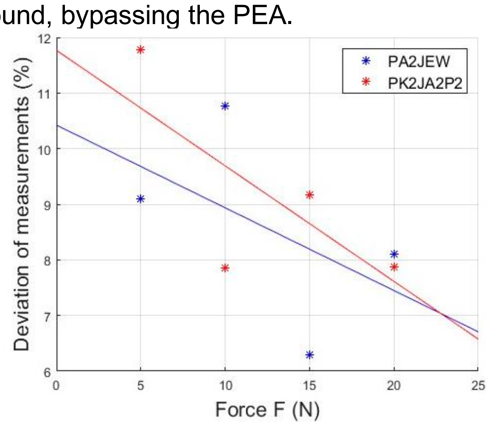

Fig. 3: Measurement error for charge measurement in percent with trend line

The relative error for each measured point is displayed in Fig. 3. It can be seen that with rising forces, the relative error gets smaller. This is due to noise in the system, which represents a smaller influence with larger measurement values. Additionally, the PA2JEW shows a better S/N ratio at low forces whereas at 20 N, the performance of both actuators is similar.

Conclusions

Different forces were applied to two PEAs and the resulting charge was measured to gather information about the number of accumulated charges at applied forces. Forces were applied in range that is expected to be observed in a medical application of piezoelectric self-sensing. Both PEAs show a linear behavior between applied force and collected charge. The range of error measurement is high but can be reduced with higher applied force due to noise reduction relative to the measurement.
The error in force measurement is lower for the PA2JEW at low forces up to 20 N and, therefore, more suitable for accurate force measurements.
In future work, the issue of errors in measuring charge at applied force needs to be addressed and reduced to make the stacks more feasible and measurements more accurate to use in any force sensing application. The measuring method can then be also adapted to work with actuation voltages on the PEA. The sensing circuit will need to be adapted accordingly.

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