Lateral strain force sensitivity measurements for piezoelectric polyvinylidenefluoridene sensor array

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***Abstract*—An elastic polydimethylsiloxane (PDMS) membrane was used to transfer a lateral strain force on a piezoelectric polyvinylidenefluoridene (PVDF) sensor array, which was polarized perpendicular to the applied force. The stretching force was measured using a mechanical tester and the generated piezoelectric charge was measured using a charge amplifier. The measured lateral force sensitivity values varied from 200 to 700 pC/N and they were relatively independent of the applied strains in the range of 0.03 - 0.3 %.**

Keywords—polyvinylidenefluoridene, polydimethylsiloxane, lateral force, piezoelectric sensitivity, piezoelectric sensors

I. INTRODUCTION

Polyvinylidenefluoridene (PVDF) is a transparent and flexible commercial piezoelectric film-type sensor material [1, 2]. Recently, PVDF has be demonstrated to be suitable for various application such as physiological measurements [3, 4], an underwater touch panel [5] and energy harvesting [6]. PVDF is highly sensitive sensing material and thus, it is suitable for measuring small forces, for example for monitoring of patient's heart rate and breathing using a sensor placed under a pillow [3].

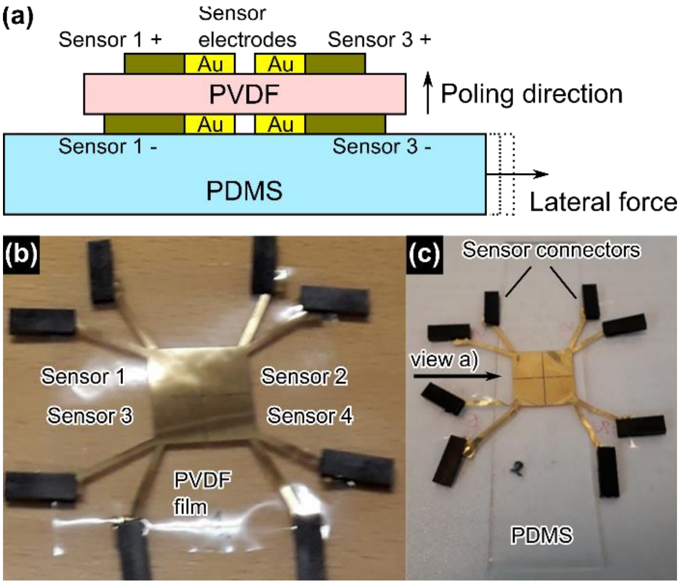

Fig. 1. Illustration of the sensor principle. (a) Schematic of the device, not drawn to scale. Layer thicknesses: PDMS 1 mm, Au 100 nm, PVDF 28 µm, Au 100 nm. (b) A photograph of PVDF sensor array (2 × 2 array of 10 mm × 10 mm square shaped electrodes) and (c) PVDF sensor array attached to PDMS film.

Several different type methodologies have been proposed for measuring small forces. The physical phenomena used for measuring small forces include elastic, electrostatic, electromagnetic, resonance, Van Der Waals and Casimir force, fluid flow and capillary, biochemical and radiation pressure methods [7]. Stretched and poled PVDF film is sensitive to both normal and lateral forces, referring to piezoelectric coefficients d_{33} and d_{31} [8]. Thus, PVDF film is an interesting piezoelectric material for detection of small lateral forces.

In this paper, we have measured normal and lateral force piezoelectric sensitivities for a 2 × 2 PVDF sensor array (Fig. 1). The sensor array was exposed to lateral forces by attaching an elastic polydimethylsiloxane (PDMS) film on one side of the sensor array and by sequentially applying an elongation on the PDMS film. Stretching and force measurements were performed using a mechanical tester, and generated piezoelectric charge was measured using a change amplifier during the sinusoidal elongation cycles. The developed measurement technique is an elegant way to determine lateral force sensitivities for thin film sensors.

II. MATERIALS AND METHODS

A. *Fabrication of piezoelectric sensor array*

A PVDF sensor array was fabricated by e-beam evaporation of four square shaped 100-nm-thick gold (Au) electrodes (see Fig. 1a) through a mechanical laser-cut shadow masks on both sides of a commercial 28-µm-thick PVDF film. Polarized PVDF film without electrodes was purchased from Measurement Specialties, Inc. [7]. Electrical connections to the sensors were obtained using crimp connectors (Nicomatic Crimpflex) which are well suitable for obtaining a reliable connections to flexible electrodes. Coaxial wires were used to connect the sensors with measurement system to decrease noise coupling from the environment.

B. *Fabrication of elastomer film for stretching*

Stretchable PDMS film was fabricated by mixing cross-linker and siloxane in ratio 1:10 (Sylgard 184, Dow Corning, USA). Then, air bubbles were removed from mixture by vacuum suction and solution was casted on a square shaped plastic petri dish. Finally, the PDMS film convection oven at 60 °C for 10 hours. The process resulted in about 1-mm-thick PDMS films, which was then cut with a scalpel into about 25-mm-wide and 10 cm long slices to be attached to the PVDF array (see Fig. 1b).

C. *Normal force sensitivity measurement system*

An in-house developed setup was used for measurement of normal force sensitivities for PVDF array sensors. It is important to notice that the normal force sensitivity measurements were conducted without the PDMS film being present. The measurement setup has been previously described in details [1]. Briefly, a Mini-Shaker (Brüel & Kjaer, Type 4810) was used to generate a dynamic excitation force for the sensor, while a sinusoidal input for the shaker was provided with a function generator (Tektronix AFG3101). A commercial high sensitivity dynamic force sensor (PCB Piezotronics, model 209C02) was used as a force measurement reference. A load cell (Measurement Specialties Inc., model ELFS-T3E-20L) was used as reference sensor to measure the static force between the sample and shaker's piston (diameter 4 mm). A pre-compression by the static force is required to keep the sample in place and to prevent the piston from 'jumping off' the surface during the measurement. Approximately 3 N static force and sinusoidal 1.4 N (peak-to-peak) dynamic force were used in the measurements.

The output charge generated by the PVDF sensors during cyclic exposure to the normal force was measured using a custom-made charge amplifier and a 16-bit AD converter. The data was acquisition to a laptop computer through USB-interface and an in-house made software. The sensor sensitivity measured this way is closely related to the longitudinal piezoelectric coefficient d_{33}, which describes the electric polarization generated in the same direction as the stress is applied. The normal sensitivity is defined by the charge generated by the sensor divided by the normal force used to excite the sensor. The unit of normal sensitivity is thus C/N.

D. *Lateral force sensitivity measurements*

For piezoelectric sheer sensitivity measurements, the PVDF array was fixed on one side of an elastic PDMS membrane, which generate the lateral strain on the sensors. The PDMS membrane, which was slightly longer that the PVDF array in stretching direction, was attached to the clamps of a mechanical tester (Stable Microsystems TA. XTPlus texture analyzer) and allowed the elongation of the PDMS (see Fig. 1a). The distance of the clamps into which PDMS film was fixed was approximately 6 cm. After mounting the sample to the clamps, the sample was prestrained with a force of 0.5 N to straighten the PDMS film vertically. Sinusoidal cyclic elongation of the PDMS film was performed using 1 Hz frequency for 10 cycles. Different oscillation amplitudes, in the range of 20 – 1000 µm were tested. The lateral force applied on PDMS was then transferred into the PVDF array and the resulting output charge of PVDF sensors were measured using an in-house made charge amplifier. The same charge amplifier was used here as above in the case of normal force sensitivity measurements, except here the data from the four parallel input channels were captured simultaneously.

E. *Analysis of force and charge output data*

The force and output charge data were analyzed using Matlab software. As a preprocessing step, the data was cropped to include only the cyclic part. Next, a sinusoidal fit was performed on both force and charge data. For the force data, the fitted parameters included offset, amplitude and phase of the sinusoid. For the charge data, the fitted parameters included one phase, four offsets (one per each channel) and four amplitudes (one per each channel). The lateral sensitivities were calculated by dividing the charge amplitudes with the force amplitudes (unit: C/N). We also computed root mean square error (RMSE) between the charge data and the fitted sinusoid (units: C). This can be taken as a measure of precision of the sensors (figure of merit for the sensors). Force precision was calculated by dividing the RMSE with the lateral sensitivity (unit: N).

III. RESULTS AND DISCISSION

A. *Normal force sensitivities*

The sensitivity measurements for each sensor in the PVDF array were repeated four times for each sensor from slightly different position on the square shape electrode; between the measurements the static force was relieved and the sensor was re-positioned for a new measurement. The normal force sensitivities and standard deviations for four sensors in the PVDF array are shown in Table I. There measured sensitivity values were slightly different for four adjacent sensors, which is most likely related to non-homogeneity of the PVDF film properties. The average sensitivity of four sensors was (25.5 ± 1.5) pC/N.

TABLE I. SUMMARY OF NORMAL FORCE SENSITIVITY VALUES FOR PVDF ARRAY SENSORS

Sensor	Normal sensitivity (pC/N)	STD error of sensitivity (pC/N)
Sensor 1	25.4	1.1
Sensor 2	23.5	1.4
Sensor 3	28.6	2.2
Sensor 4	24.3	1.2

B. *Force and charge output curves*

Examples of typical force curve and sensor output curves, along with the fitted sinusoids for three smallest oscillation amplitudes are shown in Fig. 2. When comparing the charge output curves in the cases of different oscillation amplitudes, it can be noticed that the signal to noise ratio (SNR) decreases when the oscillation amplitude is decreased, as expected. When considering the charge output curves in the case of 100 µm oscillation amplitude, clear differences could be observed in the outputs of different sensor channels: a) the charge amplitudes were different for each channels, sensor 1 showing ~ triple the amplitude of sensor 3; b) some of the sensors were more stable than others. The signals from sensors 2 and 3 were more stable, sinusoidal fit being a good approximation of the data, while sensor 1 showed less stability and sensor 4 showing least.

Our data cannot be used to conclude the exact reasons for the apparent differences between the channels, but one plausible

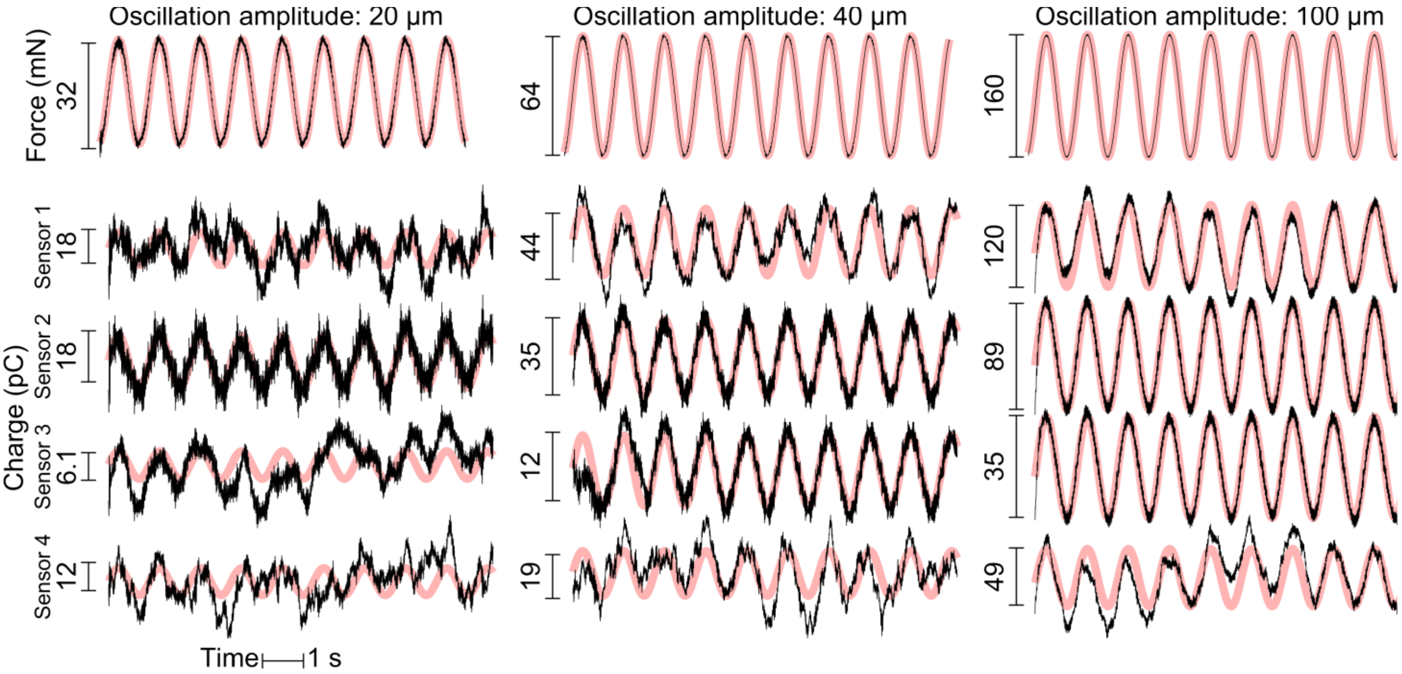

Fig. 2. Typical measured data plots and sinusoidal fits from force measurement and charge amplifier outputs from four different sensors in the case of (a) 20, (b) 40 and (c) 100 µm oscillation amplitude.

explanation is that there is delamination and slippage between the PVDF and PDMS films. This hypothesis is supported by the fact that no such big differences were observed in the normal force measurements, where the PDMS film was not present. We also observed complete delamination of the film with excessive strains (typically with strains above 0.5 %).

C. *Sensor characteristics as a function of applied forces*

Table II summarizes the obtained fitted amplitudes and sensitivities (force amplitude over charge amplitude), as well as RMSE values of charge output data fits, for different sinusoidal elongation amplitudes. It can be seen that no clear trend in the sensitivity could be seen for all of the sensors until when the oscillation amplitude was increased to 200 µm, when we see that the sensitivity goes down and the RMSEs of the fits go up. Thus, 200 µm and 1 mm oscillation amplitude data were discarded from further analyses. From the remaining data, the sensitivities were plotted as a function of oscillation amplitude in Fig. 3. No clear trend in sensitivity could be observed for all channels; some go slightly up, while others go slightly down, but the changes are not large. We conclude that the sensor is fairly linear for small strains.

D. *Force precision*

Fig. 4 summarizes the root mean square errors of the charge signals as a function of lateral sensitivity. A large lateral sensitivity relative to RMSE is better; thus dividing the RMSE with the lateral force sensitivity can be taken as a measure of the precision of the sensor. In Fig. 4, it is apparent that the sensor 2 showed the best precision (6.7 mN in one case), while the sensor 4 showed the worst precision (43 mN in one case). The same conclusion can also be reached by looking at Fig. 2; it is apparent that sensor 2 signal is mostly sinusoidal even with 20 µm amplitude, while the sinusoidal fit is poor for the sensor 4.

TABLE II. SUMMARY OF DATA FROM SENSOR SENSITIVITY MEASUREMENTS DURING SINUSOIDAL CYCLIC ELONGATION

Oscillation Amplitude (µm)		20	40	100	200	1000
Force (mN)		32	64	160	270	1400
Charge (pC)	***Sensor 1***	18	44	120	—	340
	Sensor 2	18	35	89	27	380
	Sensor 3	6.1	12	35	47	250
	Sensor 4	12	19	49	43	300
Sensitivity (pC/N)	***Sensor 1***	570	690	740	—	250
	Sensor 2	580	540	550	99	270
	Sensor 3	190	190	210	170	180
	Sensor 4	370	300	300	160	220
Root mean square error (RMSE) of charge (pC)	***Sensor 1***	8.2	8.2	14	10	39
	Sensor 2	4.3	3.6	4.3	8.4	62
	Sensor 3	4.5	2.2	1.9	4.8	33
	Sensor 4	7.2	7.3	13	13	18

IV. DISCUSSION AND CONCLUSIONS

The developed method for exposing thin film sensor to lateral forces is quite delicate and thus, several experimental issues must be considered when analyzing the results and their reliability.

The force measurements were performed until the lower limit on the mechanical tester equipment; smaller amplitudes than 20 µm were not tested because the electric motor of the tester could not move in smaller steps. The measurements

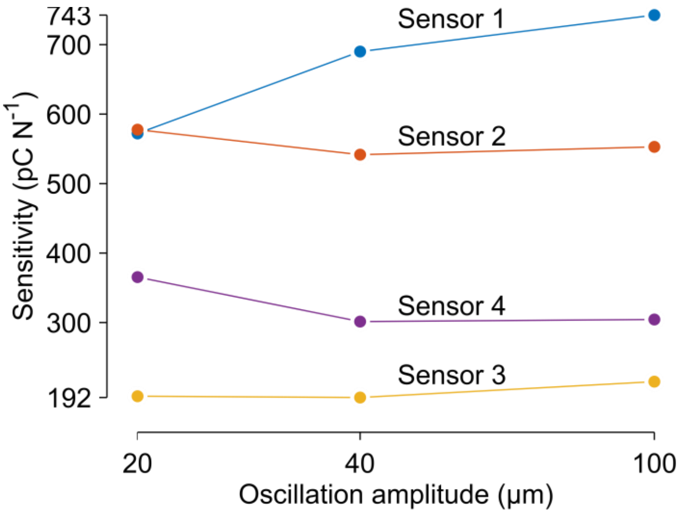

Fig. 3. Plot of sensor sensitivity as a function of elongation oscillation amplitude.

performed with smallest forces are closest to ideal case because then the elongation causes less deformations to the PDMS film and PVDF-assay.

On the other hand, it was observed that forces larger than 200 mN (at the oscillation amplitudes of 200 µm and 1 mm) caused curvature of the PVDF sensor array, which created also other contributing forces than the aimed lateral strain force. This curvature can create contributions from other piezoelectric coefficients of the PVDF film to the sensor outputs.

In addition to the curvature, the use of forces over 200 mN caused significant delamination of PVDF array from the PDMS film and thus, the lateral strain force is not fully transferred to the sensors and the charge measurement is no longer reliable. Significant delamination was observed with excessive strains (over 0.5 % strains), so it is possible that some slippage between the PVDF and the PDMS films took place even much earlier. Further work is needed to confirm whether this is the case; optical measurement during the straining might confirm this. Increasing the adhesion between the films through surface treatment or adhesives could solve the delamination issue and prevent the possible slippage.

The charge output measurements were relatively noisy even without the application of the lateral strain. This noise is from the measurement electronics as well as noise and interferences coupling from the environment. This could be improved by shielding the system in Faraday cage or by applying filtering to the signals either online or offline. This noise is reflected in the RMSE values and decreasing it would improve the reported precision of the sensors.

To conclude, a new method for lateral force measurement was developed here. The piezoelectric sensitivities of an array of four PVDF sensors were measured using a normal force exposure and a lateral force exposure. These lateral force sensitivities were over 20 times larger than normal force sensitivities. However, it is not clear how the measured elongation force measured from PDMS film is transferred onto the surface of the PVDF array sensors.

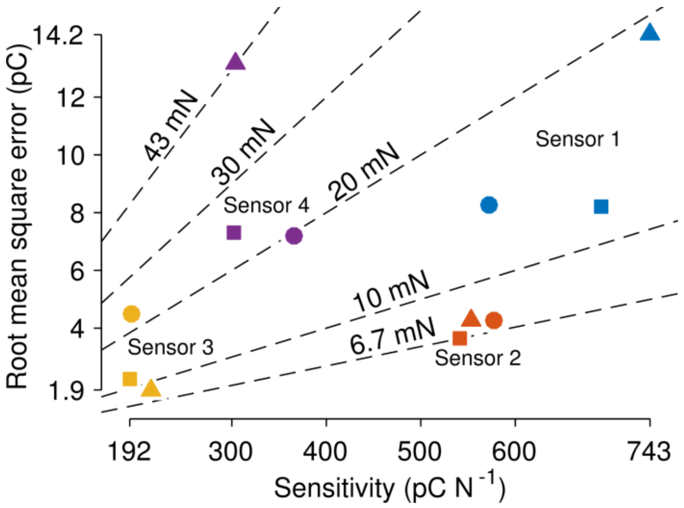

Fig. 4. RMSE of the sinusoidal fit as a function of lateral sensitivity. Large lateral sensitivity relative to RMSE is better. Force precision was calculated by dividing the RMSE with the lateral sensitivity. Sensor 2 shows the best precision in terms of RMSE per lateral sensitivity, 6.7 mN. Sensor 4 showed the worst, 43 mN. Oscillation amplitude: ● 20 µm. ■ 40 µm. ▲100 µm.

ACKNOWLEDGMENT

We acknowledge funding from the Academy of Finland (Dec. No. 310527 and 299087). We thank Arno Pammo from Tampere University of Technology for the fabrication of PDMS films and electrodes for PVDF sensor arrays.

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