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Piezoelectric cantilever force sensor sensitivity measurements

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Piezoelectric cantilever force sensor sensitivity measurements

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Abstract. A cantilever based small force measurement system performance was evaluated. The cantilevers consisted of commercially available piezo discs and metal probe tips. The evaluation was carried out with an analog front end amplifier, Arduino Due and Matlab and Labview software packages. The studied cantilever force measurement devices were found capable of sensing forces as low as 17 micro Newtons.

1. Introduction

In the field of small force measurement, several potential methodologies have been proposed and reported. The main categories in a small force measurement principles can be listed based on the utilised physical phenomena are elastic, electrostatic, electromagnetic, resonance, Van Der Waals and Casimir force, fluid flow and capillary, biochemical and radiation pressure methods [1].

Cantilever force measurement principle belongs to elastic force measurement methods where cantilever is mechanically coupled to an elastic material such as piezo crystal [2]. Piezo crystal utilisation here is beneficial since the applied force causes mechanical movement in the crystal which influences charge separation in piezo crystal which can be measured either with a charge amplifier ($Q = It$) or with a voltage amplifier and capacitive load ($Q = CU$). Cantilevers as a force measurement system have also been proposed in many different configurations including AFM tip, silicon microstructure cantilevers, PDMS molded cantilevers and mixed variations of these. The force measurement with the cantilevers are mainly based on two principles. Thus also the visual and electrical measurements have been reported.

In this paper, an electrically measurable cantilever sensor system was evaluated. We present a cost effective approach to the small force measurement by applying an elastic measurement principle to a commercial piezo disc with an attached cantilever tip. Additionally, we demonstrate an Arduino based hardware to be utilized in the measurement system. The question in interest here being whether it is possible to reliably measure small forces in the range of µN to mN with developed system.

2. Methods

Overview of the measurement setup is shown in Figure 1a. The fabricated piezoelectric cantilever sensors shown in were characterized by pressing on them with a probe attached to calibrated load cell, while measuring the charge output generated by the piezo at the same time. The different components are detailed in the following sections.

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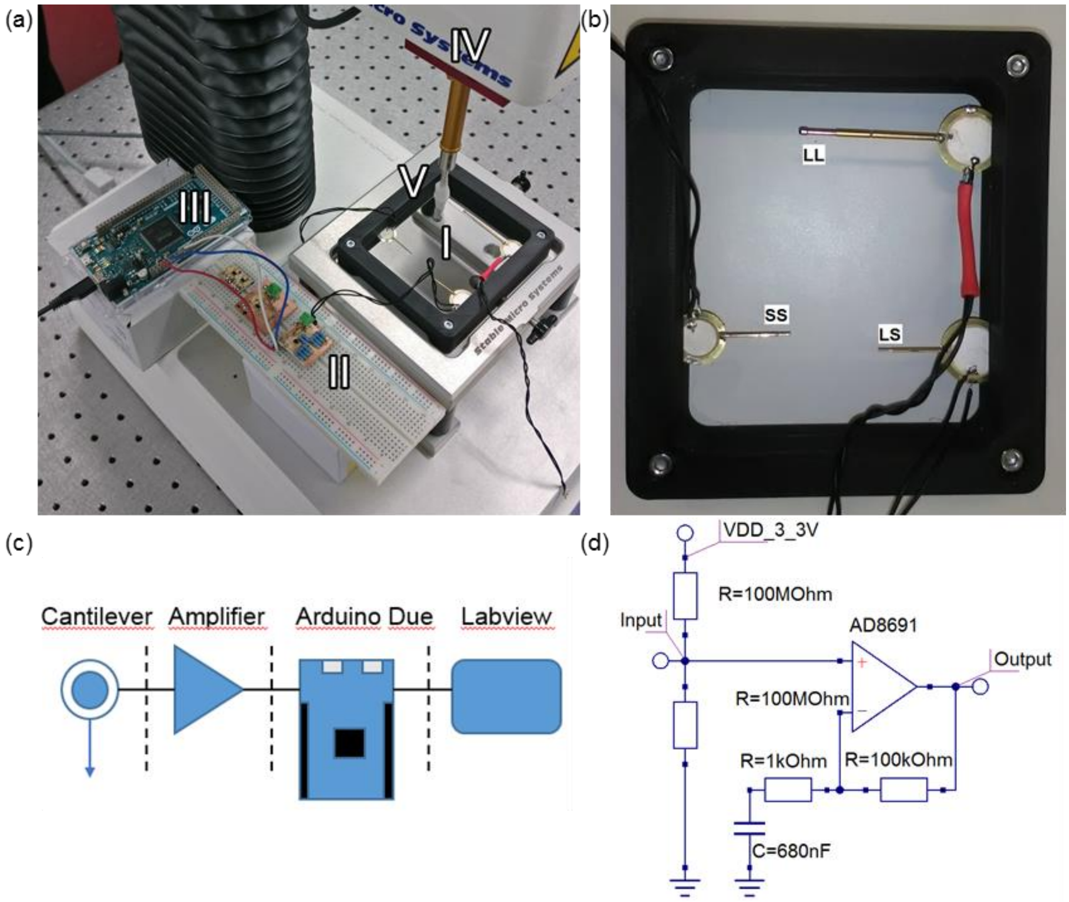

Figure 1. (a) Overview of the experimental setup. I: cantilevers. II: amplifier. III: arduino microcontroller for A/D conversion. IV: load cell. V: probe. (b) The cantilevers in three configurations LL, LS and SS. (c) Block diagram of the measurement system. (d) The schematic of the front end amplifier.

2.1. Piezoelectric cantilever sensor

There were three different piezo disc cantilever configurations (see Figure 1b) used in the measurements. The first sensor (named LL) consisted of 20 mm diameter piezo disc, Farnell P/N 1758379, and a 30 mm metal pin probe which was soldered to the piezo disc metal plate. The second consisted of 20 mm piezo disc, Farnell P/N 1758379, and a 15 mm metal pin probe (named LS) while the third one (named SS) 12 mm diameter piezo disc, Farnell P/N 1758373, and a 15 mm metal pin probe. These were marked as LL, LS and SS cantilevers in the measurements respectively. In the measurement setup the forces were applied to the probe tip whereas the piezo disc was at fixed position at the opposite side.

2.2. Excitation and force measurement setup

Texture analyzer (Stable Microsystems TA.XTPlus with 500 g load cell) was used for applying and measuring an excitation force applied on the cantilever. To press down on the cantilever, a spherical probe (SMS P/5S) was carefully aligned to press down on the end of the cantilever.

During the experiments, the probe was moved down at a speed of 1 mm s^{-1} until a set preload was reached, 1 mN in most experiments, indicating that the cantilever had been contacted. From that point onwards, the probe moved down and up with a sinusoidal wave mode by an amplitude of 5-50 μm, at a relatively slow frequency of 0.5 Hz.

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2.3. Cantilever sensor output measurement setup

The measurement system was constructed with an operational amplifier based biased voltage amplifier, piezo disc cantilever, Arduino due board and a Labview software. The cantilevers were attached to a fixture which can be seen in Figure 1 along with the cantilevers. The force measurement setup was constructed with XTPLus texture analyzer (Stable microsystems). Figure 1c shows the block diagram of the measurement setup. Three different cantilever sensor configurations were measured.

The schematic of the measurement system voltage amplifier is presented in Figure 1d. The front end amplifier circuit consists of an Analog Devices AD8691 operational amplifier which is in non-inverting amplifier configuration. It had a voltage gain of 100 and this was arranged with a resistive feedback loop. The non-inverting input of the amplifier was biased to the middle of the operating voltage (VDD_3_3V) with two 100 MΩ resistors thus enabling a symmetrical response from a piezo voltage level input signal. The amplifier output was connected to a 12-bit Arduino Due analog to digital converter input and the signal was being sampled with Arduino Due at 250 Hz sampling frequency. No additional sampling filter was used as the spectrum content of the measured cantilever signal was observed to meet Nyquist criterion. The sampled data was logged to a file for further analysis through USB/serial port communication with Labview software package.

2.4. Data analysis

The cantilever sensor output data was processed in a raw format without applying any filtering or noise cancelling methods. Voltages measured with the analog-to-digital converter were transformed to corresponding measured voltages (Figure 2). Later a sinusoidal curve fitting was performed both to the voltage and force measurement data in Matlab to obtain amplitude values and RMS error figures.

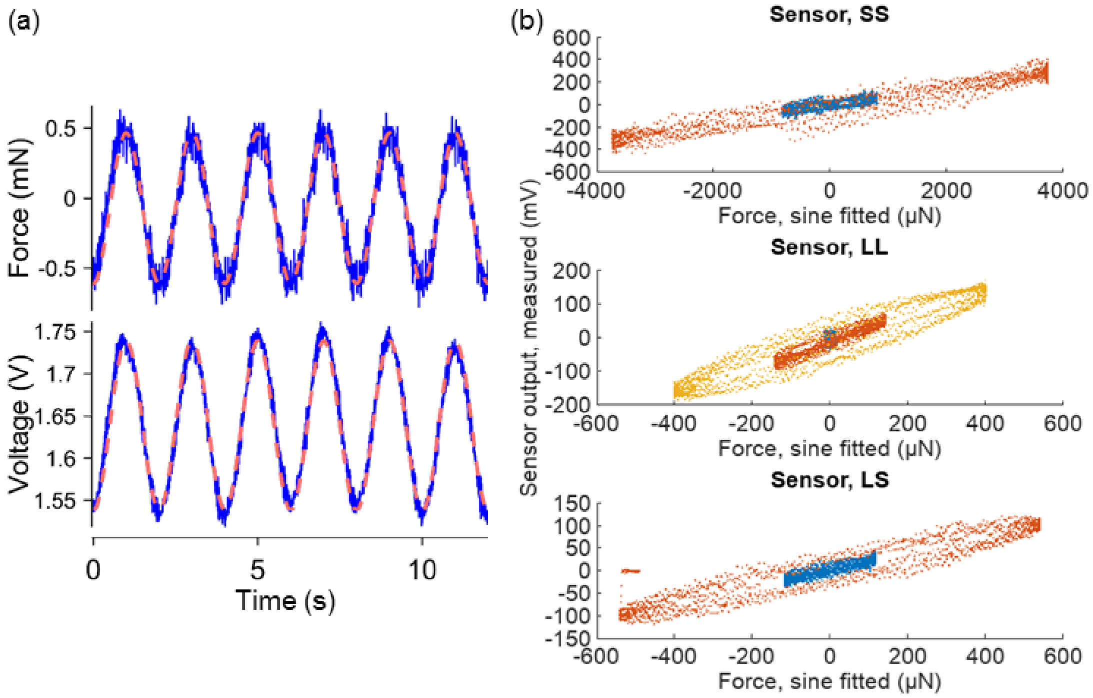

Figure 2. (a) Raw data from force and output voltage measurements (solid, blue) with fitted sinusoidals (dashed, red) for sensitivity calculations. The data is from sample LS with an oscillation amplitude of 20 μm (Table 1). (b) Sensor output voltage raw data plotted as a function of sine fitted data of excitation force.

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3. Results and discussion

Figure 2a shows example plots of measured voltage and force in time domain and the sinusoidal fitting curves. Fig 2b shows sensor output voltages as a function of sine fit force excitation, which shows how the sensor output relates to the force excitation. The measurement results are summarized in Table 1. The measured mean to peak voltages ranged from 25 to 310 mV while the force mean to peak amplitude varied between 0.13 and 3.9 mN. The cantilever sensitivity was computed using Matlab software package by fitting a sinusoidal curve to the measurement data (force and voltage outputs) and then from the fitted parameters voltage amplitude was divided by force amplitude value. The computed sensitivity values ranged from 81 V/N (small piezo, small tip) to 440 V/N (large piezo, large tip). The RMS error level of the sensor voltage output varied between 9.6 mV and 40 mV. Dividing the sensitivity with the RMS error of the sensor output yielded force measurement resolution ranging from 17 µN to 493 µN.

Table 1. Summary of measured sensitivities for three sensors (LS = large piezo plate, short cantilever, SS = small piezo plate, short cantilever, LL = large piezo plate, long cantilever). Sinusoidal oscillation frequency was 0.5 Hz.

Sample	Oscillation amplitude (µm)	Preload force (mN)	Force amplitude (mN)	Voltage output amplitude (mV)	Sensitivity (V/N)	RMS Error (mV)	Resolution (µN)
SS	5	1	0.79	65	81	19	230
SS	20	5*	3.9	310	81	40	490
LS	5	1	0.13	25	190	9.6	50
LS	20	1	0.54	100	190	10	53
LL	5	1	0.037	16	440	7.4	17
LL	20	1	0.16	63	400	15	37
LL	50**	1	0.4	150	390	12	31

*Larger preload used here due to larger force amplitude range observed for this particular sensor.

**Higher amplitude was used here to obtain a force comparable with the other used sensors.

4. Conclusion

In this work, we have demonstrated and calibrated in-house developed cost effective piezoelectric cantilever sensor setup for measuring forces well below 1 mN range. The method has potential to be applied to much smaller forces still since only the capability of this approach was studied.

5. References

[1] Jones, Christopher W and Leach, Richard K 2008, Review of Low Force Transfer Artefact Technologies (*Middlesex UK, National Physical Laboratory*).

[2] Khan, Aboo Bakar, M. J. Siddiqui, and Man Mohan Singh 2013, Theoretical analysis of piezoelectric cantilever sensor, *Emerging Research Areas and 2013 International Conference on Microelectronics, Communications and Renewable Energy (AICERA/ICMiCR), 2013 Annual International Conference on. IEEE.*