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INVESTIGATION OF LOW-COST PIEZOELECTRIC FORCE SENSOR

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Abstract. The use of piezoelectric force sensors is well-established in industrial systems and devices, but their adoption in consumer products has been limited due to the high cost of implementation as well as complex peripheral electronics. This paper proposes an alternative approach to force sensing using commonly available piezoelectric buzzer elements, which could potentially reduce the cost of such sensors and promote their integration into consumer products. The paper represents experimental investigations of output characteristics of two different piezoelectric force sensors, which are based on disc-shaped buzzers. The goal of the investigation is to indicate and experimentally confirm electromechanical characteristics of proposed piezoelectric sensors under different sensing and signal management conditions. The results of the investigations showed that piezo buzzers have the potential to serve as cost-effective force sensors in consumer products as well as in different mechatronic systems.

Keywords: force sensor, force measurement, piezoelectric materials, disc shaped piezoelectric buzzers.

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1. Introduction

Static force measurement is an important part of many mechatronic systems. Dynamic manipulator grip force adjustment relies on real-time static force measurements. Force measurement is also important to obtain accurate force feedback in robotic manipulators and surgical or other medical robotics. The manipulators can act safely in uncharted environments because force control is provided at each joint thanks to force sensing, which allows one to close a control loop around the force signal at each joint. This was discussed by (Edsinger-Gonzales & Weber, 2004). These applications have several constraining requirements like small size, low weight, low cost of production and implementation, and relatively low power consumption of the sensing circuitry. Over the past few decades, various methods of electromechanical force sensing have emerged to meet these requirements. These include sensors that use piezoresistive, capacitive, and piezoelectric technologies. Among these, piezoelectric (PE) sensing has become particularly popular because it employs a direct piezoelectric effect that is effective at measuring dynamic forces, as the well as the sensor itself does not require a power supply. Furthermore, piezoelectric force sensors have notable advantages over other types of sensors, including greater mechanical durability, resistance to noise, simple design, and clamping. However, piezoelectric force sensors have a major drawback that limits the usefulness of PE sensors in the realm of static force measurements. When piezoelectric force sensors are subjected to a static force, the electrostatic charge induced by the force starts to decrease exponentially. This decrease can be described using an equation that involves the amount of charge after a certain time, the original value of the generated charge, the resistance of the feedback resistor, the total capacitance of the sensor system, and the measurement time. The product of resistance and capacitance ($R \times C$) is known as the discharge time constant (DTC), which represents the time it takes for the induced charge to decrease by 37% of its initial value. If the DTC is sufficiently long and appropriate signal processing techniques are used, quasi-static forces can be measured. However, there are still limitations on the time window to measure static forces due to current leakage (Kim et al., 2021). Several review articles on general piezoelectric force sensors have been published (Morales & Zaghloul, 2018; Lee et al., 2014; Van den Ende et al., 2010). However, those articles mainly focus on direct piezoelectric sensing of dynamic and quasistatic force with very limited information on static measurement. Currently, piezo-based force sensors are rarely used in consumer goods. This could be attributed to the relatively high cost of piezoelectric effect-based force transducers compared to the more common load cells that use the piezoresistive effect. For example, in 2023 piezoelectric force sensor ordered in small quantities costs over 100 EUR (Alibaba, n.d.-a), while strain gauge with similar measured force range can be ordered for less than 30 EUR (Alibaba, n.d.-b).

This paper represents the investigation of piezoelectric force sensors which are based on standard piezoelectric buzzers that are composed with custom design housings. The goal of the investigations was to experimentally indicate the electromechanical and operation characteristics of the proposed force sensors under different input forces, as well as signal management conditions.

2. Design of piezoelectric force sensors

The designs of force sensors are based on two different piezoelectric buzzers which are fitted into custom-designed housings. The buzzers used to compose the sensors are commercially available, while housings were designed and manufactured by additive manufacturing technology (3D printing). The isometric and exploded views of the sensors are shown in Figure 1.

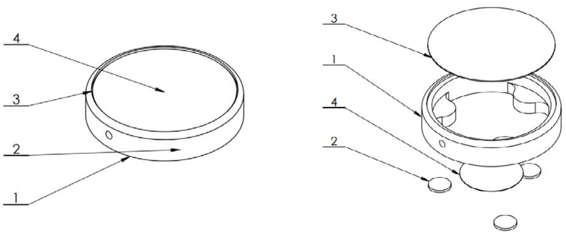
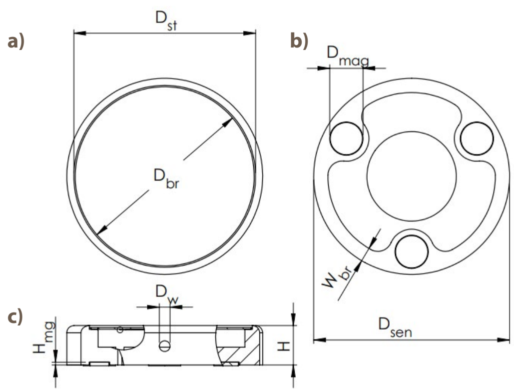


Figure 1. Isometric and exploded views of piezoelectric force sensors: 1 – 3D printed fixture; 2 – magnet – used for fixing the sensor to ferromagnetic surfaces; 3 – passive brass layer; 4 – piezoelectric disc



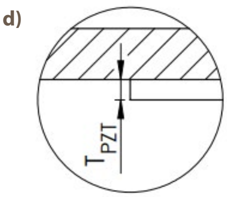


Figure 2. Schematics of sensors: a – top view; b – bottom view; c – side view with section view; d – enlarged section view which represents thickness of piezoceramic disc

As can be found in Figure 1, the sensors are based on an unimorph disc formed from brass disc and piezoelectric disc made from soft piezo ceramic material PZT – 5A. Unimorph piezoelectric disc will act as an active part of the sensors. The disc is glued to a special design housing, which is made of polylactide (PLA) plastic via additive manufacturing technology. Finally, at the bottom of the housing are placed magnets which are used to clamp sensors to bodies made of ferromagnetic materials. Figure 2 and Table 1 contain schematics and geometrical characteristics, which fully represent geometry of the sensors.

As can be found in Figure 2 and Table 1 the sensors have only one main difference, i.e., their diameters are different. It allows the investigation of force response and other parameters under different geometrical conditions and by this way indicates the most promising geometrical parameters of the piezoelectric force sensor.

Table 1. Geometrical parameters of force sensors

Parameter/ Sensor	Sensor D50	Sensor D27	Description
D_{br}	50 mm	27 mm	Diameter of piezoelectric unimorph disc
D_{sen}	55 mm	29 mm	Diameter of the sensor
W_{br}	4 mm	4 mm	Thickness of the wall
D_w	3 mm	3 mm	Wire hole diameter
H_{mg}	1 mm	1 mm	Height of the magnet
H	11 mm	11 mm	Height of the sensor
D_{st}	50.8 mm	27.5 mm	Diameter of the piezo disk seat
D_{mag}	9 mm	9 mm	Diameter of the magnet
T_{br}	0.45 mm	0.45 mm	Thickness of the brass disc
T_{ptz}	0.18 m	0.18 mm	Piezoceramic element thickness

Experimental investigation of piezoelectric force sensors to perform experimental investigations prototypes of sensors were made. The prototypes were made with strict respect to geometrical parameters which are given in Table 1. Views of prototypes are given in Figure 3.

Therefore, to perform experimental investigations of sensors experimental setup was built. Schematics of experimental setup is given in Figure 4.

The experimental setup consisted of a computer (Figure 4 – a) which was used for data recording and processing, digital multimeter (Figure 4 – b) which was used for voltage measurements and data transfer to the computer, voltage rectifier (Figure 4 – c) which was used for voltage conversion from alternating (AC) to direct (DC) voltages and was composed from low loss Shottky diodes, digital force sensor (Figure 4 – d) which was used to apply force to sensor as well as to measure and transfer it values to computer and finally piezoelectric force sensor (Figure 4 – e) which was clamped to flat ferromagnetic surface.

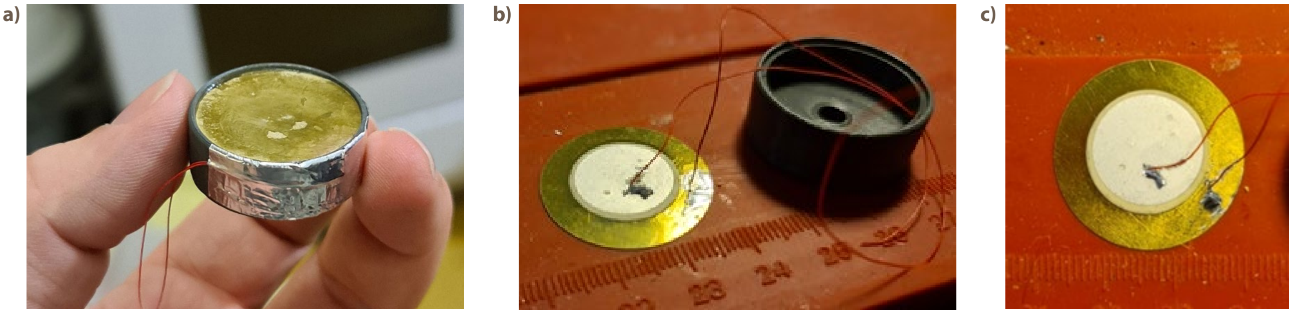


Figure 3. Prototypes of sensors: a – side view; b – top view; c – view of unimorph disc

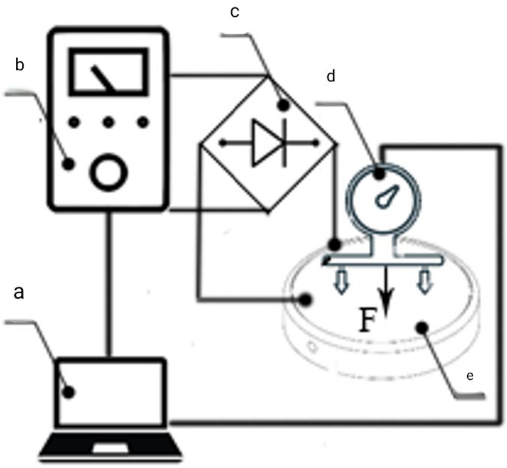


Figure 4. Schematics of experimental setup: a – computer; b – digital multimeter with data logging function; c – voltage rectifier; d – digital force sensor with data logging function; e – sensor prototype

Firstly, measurements of sensors open circuit voltage relation to applied force were performed. For this purpose, experimental setup without voltage rectifier (Figure 4 – c) was used while piezoelectric force sensor was connected directly to digital multimeter (Figure 4 – b). The force, via force sensor (Figure 4 – d) was directly applied to canter of sensors evenly till it value reaches around 10 N. Results of measurements for sensors D27 and D50 are given in Figure 5.

As can be found in Figure 5a, piezoelectric sensor D50 generates around 2.2 V_{rms} at the moment of force application i.e. then it reaches 1.8 N. After force application up to 11,44 N, the output voltage decreases and reaches zero. Therefore, it shows that even increase of force by small steps does not cover losses which occur due internal resistance of piezo ceramics as well as due to the input resistance of the multimeter. On the other hand, at the moment of input force elimination the sensor generates up to 7 V_{rms} (13.38 N) which occurs due to stress releasing at piezo ceramics and parasitic vibrations of the sensor. The voltage, after stress realising decreases exponentially, as in the case of force application, due to the internal resistance

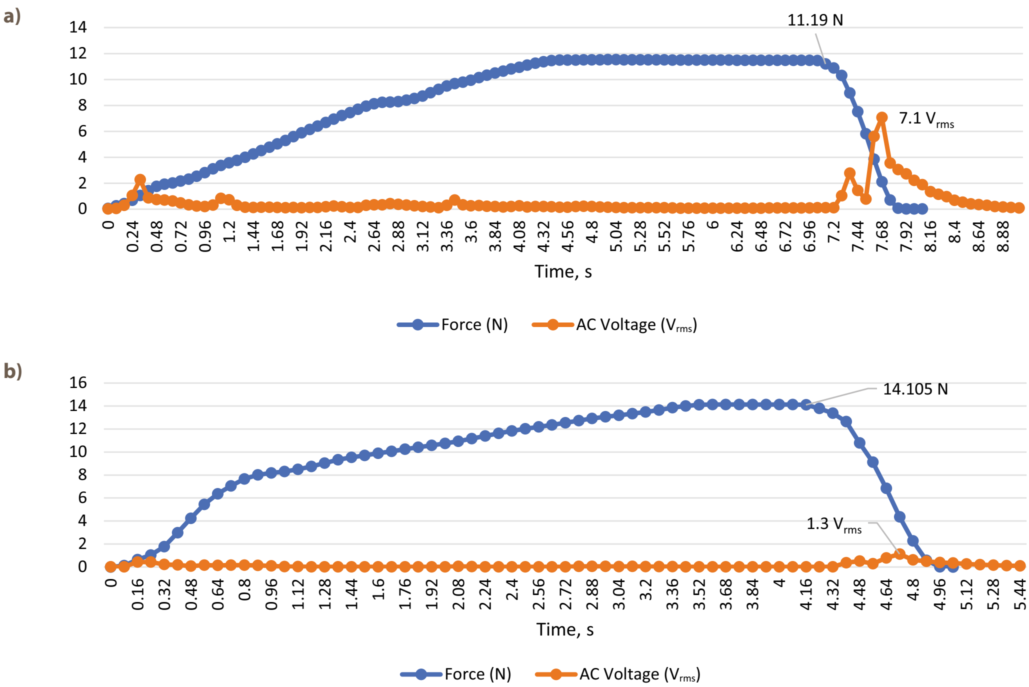


Figure 5. Open circuit voltage to input force characteristics of sensors: a – sensor D50; b – sensor D27

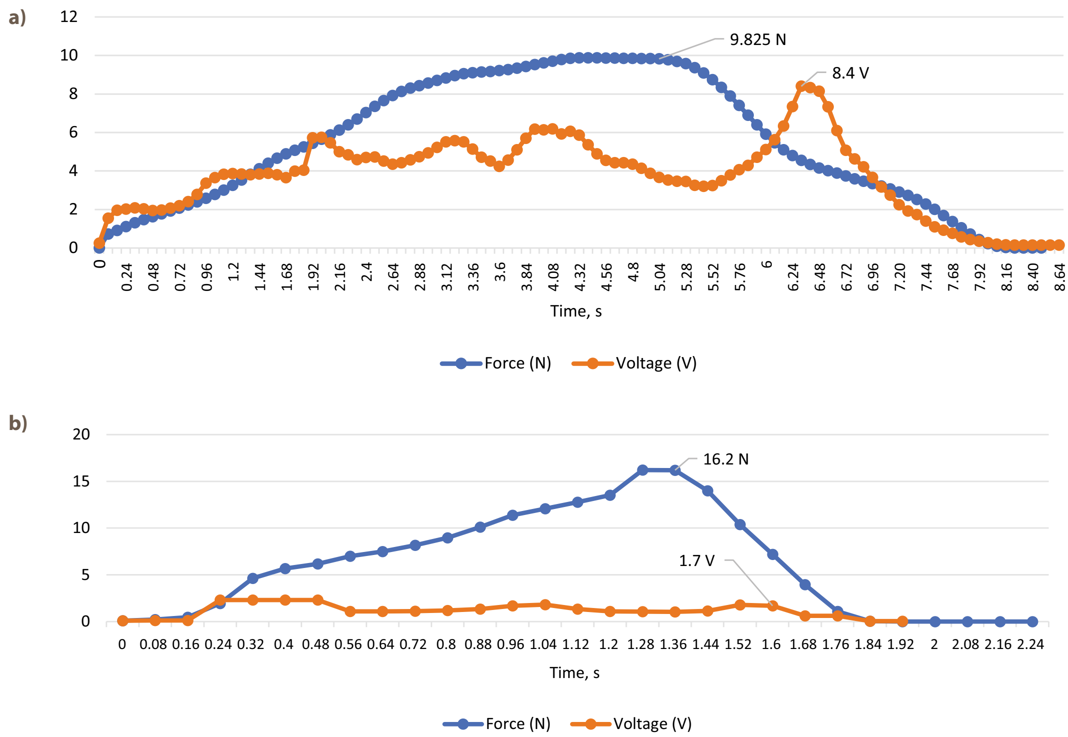


Figure 6. Applied force to output voltage characteristics of sensors with voltage rectifier:
a – sensor D50; b – sensor D27

of piezoceramics and input resistance of the multimeter. Figure 5b shows the results of measurements of piezoelectric sensor D27. As in the case with D50, at the beginning of force application, the sensor generates 0.44 V_{rms} (0.81 N) while after that output voltage decreases to zero due to internal and external resistances. However, during a moment of input force elimination the sensor generates up to 1.3 V_{rms} (13.38 N) due to release of accumulated stress and decreases exponentially.

Therefore, it can be found that output characteristics of sensors are only related to rapid changes of input forces i.e. application and releasing events due to the huge impact of internal and external resistances as well as charge saturation in piezoelectric material. Moreover, it can be found that the geometrical characteristics of the sensor have a notable impact on output characteristics due to the capability of storing internal stresses. The next stage of the investigation was dedicated to measurements of sensor characteristics while output voltage was rectified by a diode bridge (Figure 4 – c). The results of the following measurements are given in Figure 6.

Figure 6a shows that piezoelectric sensor D50 output characteristics almost evenly change with respect to the applied force. However, around 6 N force increment of output voltage stops and varies at the same level i.e. from 4 VDC to 6 VDC. It shows that piezoceramic has reached charge saturation and is not able to store more charge. So, it can be assumed that after that point input force is stored as mechanical energy in a passive layer of the sensor i.e. passive layer starts to act as a spring and stores input force. On the other hand, at the moment of force elimination output voltage reaches up to 8.4 VDC which is a result of a release of the stored mechanical energy in a passive layer as well as due to parasitic vibrations of the sensor. Moreover, compared to the results of open circuit measurements it can be found that the diode bridge partly eliminates the multimeter input resistance impact to voltage losses at the sensor.

Results given in Figure 6b, represent similar D27 sensor behaviour i.e. output voltage rises evenly with input force till 2.3 VDC at 4.46 N. After that, piezoceramic reaches its charge saturation and is not able to store it so increments of force are stored as mechanical energy in a passive layer of the sensor. Then force is eliminated and electrical and mechanical energy is released generating up to 1.7 VDC output voltage.

Therefore, on the basis of the results it can be assumed that piezoelectric sensors have a limit of charge storage which is directly related to characteristics of piezo ceramics while after that the passive layer starts acting as the main component and stores input put force which appears as output voltage during input force elimination moment.

3. Conclusions

Two piezoelectric force sensors were designed and investigated experimentally. The sensors have a simple design while their composition foresees the usage of low-cost materials and manufacturing processes. Furthermore, this design allows for the utilization of a magnetic clamping system. The piezoelectric material used in both the sensor and its housing is insensitive to external magnetic fields, enhancing their flexibility and usability. Based on the investigation's results, it can be concluded that the designed sensors can function as indicators for both force application and its removal. However, to detect positive and negative force changes, a more complex electronic interface is necessary. In addition, it was found that open circuit characteristics of sensors have a direct relation to internal and external resistances which occurs due to piezoelectric material usage as well as due to electronic interface. Furthermore, it was discovered that the piezoceramic materials utilized in constructing the sensors possess laminations affecting the storage of generated charge. These laminations constrain the linearity of the sensors' output characteristics concerning applied force. After the piezoelectric material reaches saturation from charge accumulation, the passive layer of the sensor becomes the primary component. This passive layer stores the input force as mechanical energy and releases it when the input force is removed. Therefore, based on these results can be concluded that a sensor with a bigger diameter of the passive layer has better electromechanical characteristics and can be used more efficiently, compared to a smaller one. Additionally, by analysing the output characteristics during the elimination of the input force, the total force applied to the sensor can be determined.

The insights obtained from this study pave the way for future research in several directions. Firstly, exploring advanced electronic interfaces to enhance the detection of both positive and negative force changes could significantly improve sensor performance. Additionally, further investigation into optimizing the composition and structure of piezoceramic materials could lead to sensors with improved linearity and sensitivity. Lastly, studying the practical application of these sensors in specific fields, such as robotics or biomechanics, would provide valuable insights into their real-world usability and potential advancements.

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Author contributions

AK and AČ responsible for the design and development; AK was responsible for data collection; AK was responsible for experimental investigations; AK and AČ were responsible for data interpretation. AK wrote the first draft of the article; AČ was responsible for draft editing.

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PJEZOELEKTRINIŲ JĖGOS SENSORIŲ TYRIMAS

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Santrauka

Pjezoeletriniai jėgos sensoriai jau seniai yra naudojami industrinėse sistemose ir prietaisuose. Bet šių jutiklių pritaikymas buitinėje technikoje bei kituose plataus vartojimo prietaisuose iki šiol buvo ribotas dėl didelių diegimo kaštų ir sudėtingos periferinės elektronikos, reikalingos pjezoelektrinių jėgos sensorių signalams interpretuoti. Šiame straipsnyje bus nagrinėjamas alternatyvus, plačiai paplitusių pjezogarsiakalbių (angl. *piezo buzzer*) panaudojimas jėgos matavimams atlikti. Straipsnyje pateikiami eksperimentiniai dviejų skirtingų pjezoelektrinių jėgos jutiklių, pagrįstų disko formos garsiakalbiais, charakteristikų tyrimai. Tyrimo tikslas – parodyti ir eksperimentiškai patvirtinti siūlomų pjezoelektrinių jutiklių elektromechanines charakteristikas skirtingomis matavimo ir signalo valdymo sąlygomis. Tyrimų rezultatai parodė, kad pjezogarsiakalbiai gali būti ekonomiški jėgos jutikliai tiek plataus vartojimo gaminiuose, tiek įvairiose mechatroninėse sistemose.

Reikšminiai žodžiai: jėgos jutiklis, jėgos matavimas, pjezoelektrinės medžiagos, disko formos pjezoelektriniai garsiakalbiai.