engineering proceedings

MDPI

Proceeding Paper

A Single-Electrode, Textile-Based, Flexible Capacitive Pressure Sensor Array †

Ali Aghaei, Saba Sajjadieh *, Bahareh Ghalebi, Fatemeh Irannejad and Mohsen Shanbeh *

Department of Textile Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran; aliaghaey2008@gmail.com (A.A.); b.ghalebi@tx.iut.ac.ir (B.G.); f.irannejad@tx.iut.ac.ir (F.I.)

* Correspondence: saba.sajadieh97@gmail.com (S.S.); mshanbeh@iut.ac.ir (M.S.)

† Presented at the 5th International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles, Ghent, Belgium, 14–16 November 2023.

Abstract: Flexible capacitive pressure sensors have been widely developed to be used in electronic skin, human movement, real-time health monitoring, and human–machine interactions. This paper introduces a Flexible Capacitive Pressure Sensor Array (FCPSA) that is designed to reduce costs and can be integrated into commercial textiles, e.g., insoles. The FCPSA comprises a five-layer sandwich structure. The bottom layer is a conductive layer, operating both as interference shielding and the common electrode for the distributed capacitive sensor array, with a polyester double-jersey-knitted fabric acting as the dielectric material, segmented carbon woven fabrics as the top electrodes in the array, a polymeric film for electrical and moisture isolation, and a foam placed on the surface to improve comfort. A system including three CPSs and a data acquisition device is established for real-time pressure monitoring. In the range of 0–100 kPa, a capacity increase of 35% is observed, the linearity of which depends on the elastic behavior of the dielectric layer. This sensor array can be utilized for real-time pressure monitoring.

Keywords: capacitive pressure sensors; insole pressure sensors; textile sensors; conductive fabric

check for updates

Citation: Aghaei, A.; Sajjadieh, S.; Ghalebi, B.; Irannejad, F.; Shanbeh, M. A Single-Electrode, Textile-Based, Flexible Capacitive Pressure Sensor Array. *Eng. Proc.* **2023**, *52*, 13. https://doi.org/10.3390/engproc2023052013

Academic Editors: Paula Veske-Lepp, Frederick Bossuyt, Steve Beeby, Kai Yang and Russel Torah

Published: 16 January 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In recent years, researchers have made significant advancements in developing highly sensitive, flexible, lightweight, and wearable sensors. These sensors have found extensive applications in various fields such as electronic skins for robotics, real-time healthcare monitoring devices, and tactile information systems [1]. Based on the sensing and signal transducer mechanism, flexible pressure sensors can be categorized into three main types: capacitance, piezoresistivity, and piezoelectricity [2]. Among all types of sensors, flexible capacitive pressure sensors (CPSs) have significantly advanced the field of wearable electronics due to their large fabrication area, high pressure sensitivity, less reactivity to temperature drift, simple structure, and low power consumption. CPS design with a sandwich structure typically involves two parallel, flexible, conductive layers of electrodes and a dielectric layer. Capacitive sensing functions through the alteration of the gap between two parallel, flexible, conductive layers of electrodes, the overlapping area, or the dielectric permittivity. The variation in the separation gap is the most commonly used method for pressure sensing. The variation in the separation gap between parallel electrodes influences the capacitance in response to applied pressure. This phenomenon is known as compression/expansion. The dielectric layer in studies is typically composed of highly flexible porous, sponge-like, and foam-like materials. These materials are characterized by the presence of air/bubble gaps, which contribute to their high compressibility and ability to regain their original thickness after the pressure is released [3]. Min et al. [4] utilized plated Ni-Cu-Ni metals on a polyester fabric as an electrode layer and combined it with 100% polyester, woven, fusible interlining to create a flexible capacitive sensor. This sensor was then employed for the measurement of respiration rates.

The performance of CPSs can be evaluated based on several parameters, including linearity, stability, the limit of detection, response time, and sensitivity. These parameters are crucial in determining the suitability of a CPS for various applications [2]. Pruvost et al. [5] utilized a porous carbon black (CB) with PDMS as the dielectric material for a CPS. The resulting sensor exhibited exceptional sensitivity without requiring the transistor amplification of signals. Specifically, the sensitivity was measured to be 35.1 kpa^{-1} within the range of 0–0.2 kpa, and 6.6 kpa^{-1} within the range of 0.2–1.5 kpa. These highly discernible signals enabled the sensor to accurately measure both diastolic and systolic peaks of an arterial pulse wave.

In previous research endeavors, it has been observed that the arrangement of upper and lower electrode layers within CPS devices leads to the formation of parallel capacitors [2,6]. While this configuration has proved to be effective, our motivation for this study lies in exploring an alternative optimized and affordable design for CPSs. Specifically, a modified sensor design with capacitors in a series configuration is fabricated to improve both performance and versatility. This research introduces a Flexible Capacitive Pressure Sensor Array (FCPSA) that is designed to reduce costs and can be integrated into commercial textiles, e.g., insoles.

2. Materials and Methods

The FCPSA is composed of a five-layer sandwich structure, as illustrated in Figure 1. The top electrodes are segmented carbon woven fabrics; a polyester double-jersey-knitted fabric acts as the dielectric material, and the bottom conductive layer, which, in our samples, is aluminum foil, is a common electrode that protects the device from external electromagnetic interference. Therefore, the bottom layer operates both as interference shielding and the common electrode for a capacitive sensor array.

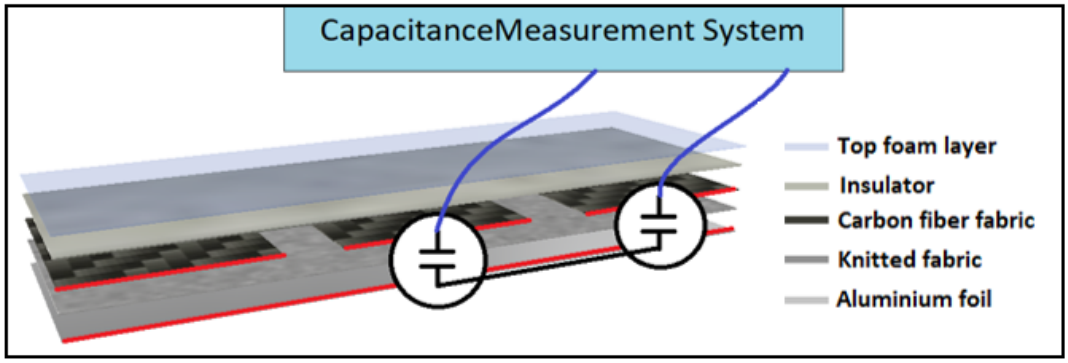


Figure 1. Schematic diagram of flexible capacitive pressure sensor.

A polymeric film is used to cover the top electrode. The purpose of this additional layer is to provide electrical and moisture isolation, and foam is placed on the surface to improve user comfort.

The dimensions of the sandwich structure are 3 × 10 cm. The bottom electrode is made of aluminum foil with dimensions of 3 × 10 cm and a thickness of 50 microns. Three 2.5 × 2.5 cm segments of carbon plain woven fabric with a density of 7 per cm for the warp and weft are utilized as the top electrodes. These segmented top electrodes are spaced 0.5 cm apart on the 1 mm thick dielectric.

Compression tests of the FCPSA were conducted using a Zwick tensile tester (CRE test method) with a 0.05 N preload and a 2 mm/min test speed.

The capacitance values of the fabricated sensors (Figure 2) were measured using an 8-channel capacitance meter device with a 0.1 pf accuracy and a 50 Hz sampling rate.

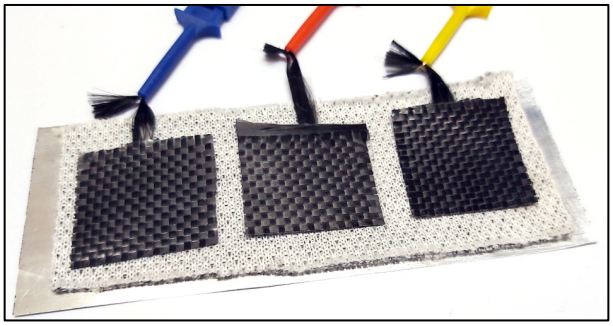


Figure 2. Fabricated flexible capacitive pressure sensor.

3. Results

The presented sensor structure forms an array of series parallel plate capacitors (a type of capacitor that has an arrangement of electrodes and insulating dielectric material). The capacitance value for this structure is calculated by employing equation (1). Each pair of carbon fiber electrodes and the bottom common electrode can be considered as two capacitors in a series configuration.

$$C = K\varepsilon_0 \frac{A}{d} \quad (1)$$

where K is the relative permittivity of the dielectric insulating material, ε_0 is the vacuum permittivity, A is the area between parallel plates, and d is the distance between plates. Using the series capacitor value formula, the capacitance for each pair of segmented electrodes with the same structure can be calculated as one capacitor value divided by two. As illustrated in Figure 3, applying pressure in the range of 0–100 kPa decreases the distance between plates and increases the capacitance of samples. When low pressure (0–20 kPa) is applied, changes in capacitance have a steep slope, while at higher pressures, up to 100 kPa, capacitance increases linearly. This can be addressed both as the non-linear behavior of fabric when compressed and the inversely proportional capacitance to the dielectric layer thickness. The results showed that the compression stress–strain behavior of the sensor array plays a significant role in the overall capacitance of each sensor segment. The dielectric constant in fabric, a porous dielectric layer, is another parameter that determines the sensor capacitance. Our results indicated that this parameter can be estimated to be effectively equal to the air dielectric constant.

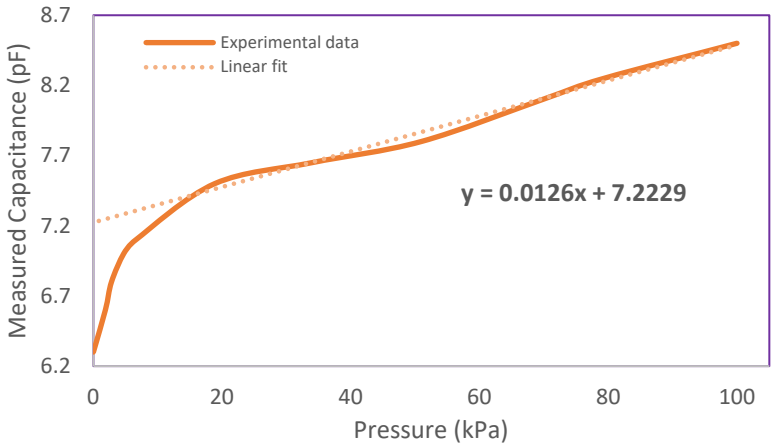


Figure 3. Capacitance—pressure curve for a pair of segments, one as the reference electrode and the other as the sensor.

Our design for the sensor array consists of a knitted fabric as a dielectric layer, sandwiched between two conductive layers. Figure 2 depicts that each pair of segments in the

segmented conductive layer can be considered as two capacitors connected in series. For distributed sensor array measurement applications, one segment of the pressure sensor array can be considered as a reference to calibrate or compare other segments and eliminate environmental effects.

4. Conclusions

The presented design for the capacitive pressure sensor structure is a promising sensor array and can be utilized to fabricate low-cost and high-performance pressure sensors. High sensitivity and steep increases at low pressures, alongside linear responses at high pressures, make the structure an appropriate candidate for application in electronic textiles, human–machine interfaces (HMIs), electronic skin, and insole pressure measurement systems. Compared to state-of-the-art designs, this structure relies only on a single conductive layer specifically fabricated for this purpose, which simplifies the design and fabrication of this structure.

Author Contributions: Conceptualization, A.A. and M.S.; methodology, S.S.; software, B.G. and F.I.; formal analysis, A.A.; investigation, S.S., B.G. and F.I.; writing—original draft preparation, S.S., A.A., B.G. and F.I.; editing, M.S.; supervision, M.S.; project administration, A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are included within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Tao, J.; Dong, M.; Li, L.; Wang, C.; Li, J.; Liu, Y.; Bao, R.; Pan, C. Real-time pressure mapping smart insole system based on a controllable vertical pore dielectric layer. *Microsyst. Nanoeng.* **2020**, *6*, 62. [CrossRef] [PubMed]
2. Li, R.; Zhou, Q.; Bi, Y.; Cao, S.; Xia, X.; Yang, A.; Li, S.; Xiao, X. Research progress of flexible capacitive pressure sensor for sensitivity enhancement approaches. *Sens. Actuators A Phys.* **2021**, *321*, 112425. [CrossRef]
3. Mishra, R.B.; El-Atab, N.; Hussain, A.M.; Hussain, M.M. Recent progress on flexible capacitive pressure sensors: From design and materials to applications. *Adv. Mater. Technol.* **2021**, *6*, 2001023. [CrossRef]
4. Min, S.D.; Yun, Y.; Shin, H. Simplified structural textile respiration sensor based on capacitive pressure sensing method. *IEEE Sens. J.* **2014**, *14*, 3245–3251.
5. Pruvost, M.; Smit, W.J.; Monteux, C.; Poulin, P.; Colin, A. Polymeric foams for flexible and highly sensitive low-pressure capacitive sensors. *NPJ Flex. Electron.* **2019**, *3*, 7. [CrossRef]
6. Vu, C.C.; Kim, J. Highly elastic capacitive pressure sensor based on smart textiles for full-range human motion monitoring. *Sens. Actuators A Phys.* **2020**, *314*, 112029. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.