Design and Experimental Validation of a Stress-Controlled Pressure Sensor for Wearable Pulse Monitoring

Havva Çeliktaş Oğuzcan
Department of Electrical and Electronics Engineering
Antalya Bilim University
Antalya, Turkey
Email: havva.celiktas@antalya.edu.tr

Mustafa İlker Beyaz
Department of Electrical and Electronics Engineering
Antalya Bilim University
Antalya, Turkey
Email: mibeyaz@antalya.edu.tr

2021 IEEE International Symposium on Applications of Ferroelectrics (ISAF) | 978-1-6654-0444-0/20/$31.00 ©2021 IEEE | DOI: 10.1109/ISAF51943.2021.9477371

***Abstract*—This paper presents a pulse sensor design scheme with adjustable preset pressure. The design consist of two PVDF layers sandwiching a PZT layer. While PZT is used to detect the pulse vibrations, PVDF layers are employed to adjust the pressure load on PZT. This enables more reliable and repeatable pulse wave measurements every time the sensor is worn on the skin. A basic design and an I-shaped design are simulated on COMSOL software under Piezoelectric Device module to show maximum performance that can be achieved under same pressure conditions. Off-the-shelf components were used for testing the sensor designs under the same externally applied load. The I-shaped design was shown to outperform the basic sensor design in both simulations and test results. This design can be employed in the development of reliable and repeatable pulse sensors, and poses significant potential in measuring the blood pressure.**

Keywords— pulse wave monitoring, blood pressure, wearable pulse sensor, piezoelectricity

I. INTRODUCTION

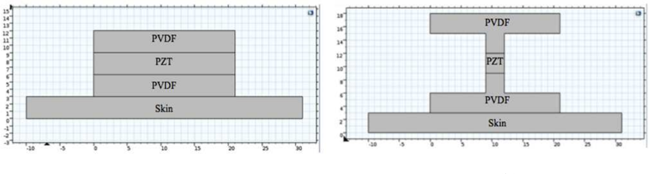
Pulse wave is one of the fundamental vital signs in health care. Consisting of a combination of the forward and reflected waves as well as the systolic peak and a dicrotic notch, pulse waves have a strong correlation with the cardiovascular system, and can provide important insight about arterial conditions [1-3]. In this respect, the pulse wave indicates comprehensive information about the waveform, velocity, amplitude, arterial elasticity, blood volume and cardiac cycle, which are significant in the diagnosis and monitoring of many cardiovascular diseases such as diabetes, arteriosclerosis and hypertension [4-11]. These cardiovascular diseases are few of the major reasons of worldwide mortality. The world health organization reports show that about to 17.5 million people suffer from cardiovascular diseases. Therefore, significant research efforts have been concentrated on pulse wave measurement systems in recent years [12-14].

Many wearable health monitoring device approaches have been proposed for performing pulse wave measurements [15-18]. These approaches have employed various detectors including acoustic, air/liquid, photoelectric, piezoelectric, and infrared sensors [19-23]. These sensors can be mainly divided into two categories based on the measurement techniques, namely optics-based sensors and pressure sensing based devices. The most common optics-based sensors are photoplethysmography (PPG) devices, where the pulse waves are detected by monitoring the blood volume in the vessel using a LED and a photodiode. However, such devices are vulnerable to light fluctuations, body movements, skin tone, and have high power consumption [2-3]. On the other hand, pressure sensing based devices take advantage of the skin vibrations, where precise vibration pulse signal from the human skin is converted to an electrical signal by employing a pressure or a strain sensor worn on the body [1,19]. Among such sensors, piezoelectric transducers have been predominantly used due to their direct conversion mechanism between the pressure and voltage as well as their simple structure [24-28].

The piezoelectric pressure sensors developed for pulse wave measurements generally suffer from signal drift as the piezoelectric element is exposed to different bias pressures each time the sensor is worn on the body. This limits the amount of valuable information that can be extracted from the pulse wave, and may introduce reliability problems. To address such issues, we propose a stress-controlled piezoelectric pressure sensor, which allows pulse sensing under the same preset pressure conditions and potentially enables reliable estimation of blood pressure from the pulse wave. This paper presents the sensor design, finite element simulations, and partial test results using off-the-shelf components.

II. DESIGN AND SIMULATIONS

The device is designed by considering the pulsation in the artery, and consists of two PVDF sheets sandwiching a PZT layer. While PZT is used to detect the vibration of the skin, PVDF layers are employed to adjust a default pressure on PZT. When the sensor is attached to human wrist for pulse monitoring, the PZT can be operated under the same pressure conditions continuously by monitoring and modifying the voltage on PVDF layers. The advantage of this sensor design lies in its stability and measurement repeatability. Schematic drawings of the (a) basic design, and (b) I-shaped design are shown in Fig. 1a and b, respectively.



(a) (b)

Figure 1. Schematic drawings of the (a) basic design structure, (b) I-shaped design.

PZT-4A was selected as the pulse sensing component due to its high piezoelectric constant (d_{33}) and electromechanical coupling factor (k_{33}), which shows its capability to achieve high polarization per applied force and

978-1-6654-0444-0/21/$31.00 ©2021 IEEE

efficiency in energy conversion, respectively. On the other hand, the sensor must be conformal with the skin since the bottom of the sensor structure is in contact with body. Accordingly, PVDF was chosen due to its high compliance, which is a measure of the deformation that occurs when stress is applied. In addition, PVDF is biocompatible, which is required to be able to make direct contact with the skin. The device dimensions were designed small enough such that it can fit into a smart watch or a smart band. PZT and PVDF material constants [29-30], skin parameters [31-33], and design dimensions are shown in shown in Table I.

TABLE I. DESIGN PARAMETERS

	Property	***PZT***	***PVDF***
Material Constants	d_{33} (pC/N)	410	30
	k_{33}	0.75	0.2
	Compliance ($\times 10^{-9}$ m/N)	0.02	0.1
	Relative Permittivity (F/m)	1800	10
I-shaped design	Height (mm)	3	6
	Width (mm)	3	21
Basic design	Height (mm)	3	3
	Width (mm)	21	21
Skin Parameters	Density (kg/m^3)	1109	
	Young Modulus (MPa)	0.5	
	Poisson's Ratio	0.49	

The designs are simulated in COMSOL software under Piezoelectric Devices module. Initially, the basic design was modeled with the exact dimensions and material properties listed on Table I. Herein, skin parameters were taken from the related literature [31-33]. The top of the PVDF layer was fixed and a boundary load was applied vertically upward on the skin-sensor interface. A healthy human has a systolic and a diastolic blood pressures of 16 kPa and 10 kPa, respectively. Therefore, pressure values falling into this range were applied as the boundary load, while the voltage induction across the PZT in 33 direction was simulated. The voltages generated on the PZT in both designs at16 kPa are shown in Figs. 2-3.

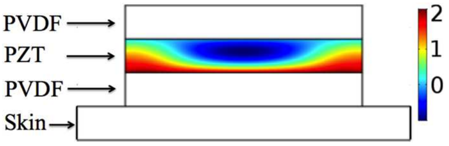


Figure 2. Simulation result of the voltage induction across the PZT in the basic design.

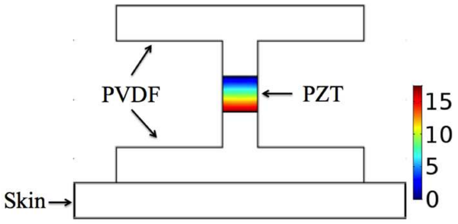
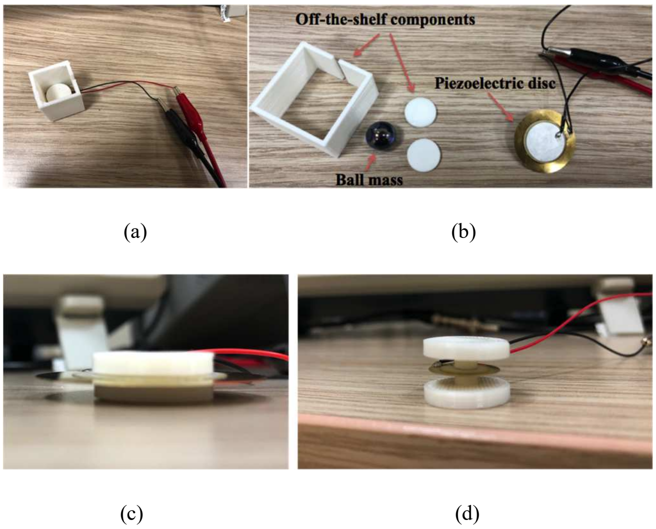


Figure 3. Simulation result of the voltage induction across the PZT in the I-shaped design.

Fig. 2 and Fig. 3 clearly show that the I-shaped sensor design can generate 17.5 volts, while the basic structure yielded 2.1 V. This evidently proves the advantage of the I-shaped design over the basic design in terms of sensing performance.

III. TESTING AND DISCUSSIONS

Initially, off the shelf components were employed in the test setup for characterizing the designs. 3D-printed components were manufactured using PLA (polylactic acid) to replicate PVDF layers. PZT-4A piezoelectric disc was used for the PZT layer with a thickness and diameter of 0.5 mm and 35 mm, respectively. Pulse effect was generated on the PZT by dropping a ball from a height of 5 cm and the voltage induced by this effect was measured and recorded by a Tektronix MDO3024 oscilloscope. Both designs were also tested under the same conditions. Photographs of the experimental setup with components, basic design, and I-shaped design are shown in Figs. 4a-d, respectively. Experimental results of the basic design and the I-shaped design are shown in Fig. 5 and Fig. 6, respectively.



(a) (b)

(c) (d)

Figure 4. Pictures of the (a-b) components in the experimental setup, (c) basic design, and (d) I-shaped design .

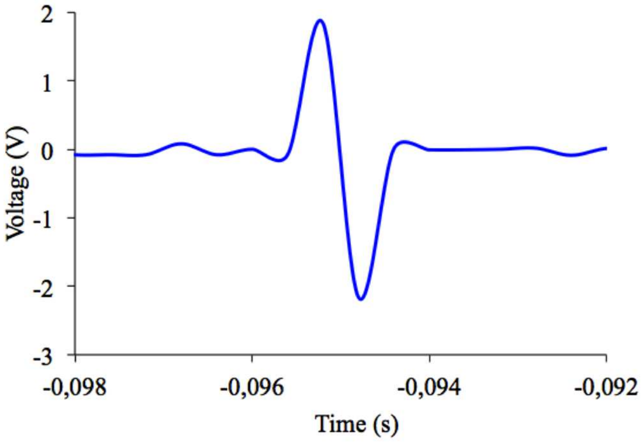


Figure 5. Experimental results of the voltage induction across the PZT in the basic design.

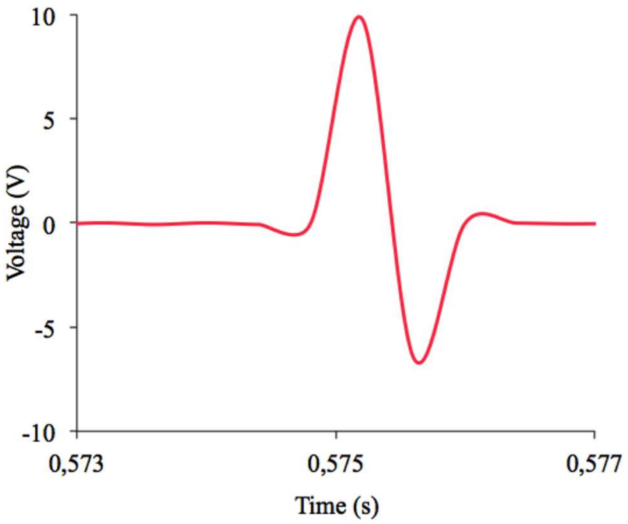


Figure 6. Experimental results of the voltage induction across the PZT in the I-shaped design.

The plots demonstrate that the I-shaped design generated 10 V, while the basic design provided around 2 V during the tests. Accordingly, the test results prove that the I-shaped structure clearly outperforms the basic structure. The induced voltage amplitudes in the tests and simulations are not exactly the same due to the differences in applied pressure and materials in both settings. However, the ratio of the voltages are rather close, demonstrating a good agreement between the experiments and simulations. This clearly proves that the I-shaped design has a higher voltage advantage and suits better to be integrated into a smart watch or smart band for a more sensitive and reliable pulse wave detection. Future experiments will include PVDF components to operate the PZT under preset pressures.

IV. CONCLUSION

Stress-controlled pressure sensor designs were developed for a reliable pulse wave sensor. Compared to similar devices previously reported in the literature, the novelty and advantage of the I-shaped design presented here lies in its stability and measurement repeatibility for the pulse wave monitoring, leading to improved reliability. In this study, two designs namely the basic design and the I-shaped design are presented. The sensor design consist of two PVDF layers sandwiching a PZT layer. PVDF sheets enable to introduce an adjustable pressure load on the PZT. Simulations were performed to observe generated voltages on the PZT under normal blood pressure range. When a boundary load of 16 kPa is applied to top of the PVDF layer it has been observed that the generated voltage on the PZT from the I-shaped design outperforms by eight times from the basic design. Experiments conducted using off-the-shelf components demonstrated that the I-shaped design and basic design provided about 10 V and around 2 V, respectively. Further development and implementation of this sensor design will allow the realization of reliable pulse wave monitors that can also be used to measure the blood pressure.

REFERENCES

[1] Y. Sun, Y. Dong, R. Gao, Y. Chu, M. Zhang, X. Qian, and X. Wang, “Wearable pulse wave monitoring system based on MEMS sensors,” Micromachines, vol. 9, no. 2, pp. 90, Feb 2018.

[2] J. He, P. Xiao, W. Lu, J. Shi, L. Zhang, Y. Liang, C. Pan, S. W. Kuo, and T. Chen, “A Universal high accuracy wearable pulse monitoring system via high sensitivity and large linearity graphene pressure sensor,” Nano Energy, vol. 59, pp. 422-433, May 2019.

[3] T. V. Nguyen, Y. Mizuki, T. Tsukagoshi, T. Takahata, M. Ichiki, and I. Shimoyama, “MEMS-Based Pulse Wave Sensor Utilizing a Piezoresistive Cantilever,” Sensors, vol. 20, no.4, pp. 1052, Feb 2020.

[4] R. Asmar, A. Benetos, J. Topouchian, P. Laurent, B. Pannier, A. M. Brisac, R. Target, and B. I. Levy, “Assessment of arterial distensibility by automatic pulse wave velocity measurement: validation and clinical application studies,” Hypertension, vol. 26, no. 3, pp. 485-490, Sep 1995.

[5] K. Cruickshank, L. Riste, S. G. Anderson, J. S. Wright, G. Dunn, and R. G. Gosling, “Aortic pulse-wave velocity and its relationship to mortality in diabetes and glucose intolerance: an integrated index of vascular function?,” Circulation, vol. 106, no. 16, pp. 2085-2090, Sep 2002.

[6] J. Blacher, M. E. Safar, A. P. Guerin, B. Pannier, S. J. Marchais, and G. M. London, “Aortic pulse wave velocity index and mortality in end-stage renal disease,” Kidney International, vol. 63, no. 5, pp. 1852–1860, May 2003.

[7] Z. Lou, S. Zhang, W. Yang, and Z. A. Yang, “Research on Characteristic Information of Pulse Wave,” Journal of Beijing University of Technology, vol. 3, pp. 71–79, 1996.

[8] G. Mancia, R. Fagard, K. Narkiewicz, J. Redon, A. Zanchetti, M. Böhm, and et al. “2013 ESH/ESC practice guidelines for the management of arterial hypertension: ESH-ESC the task force for the management of arterial hypertension of the European Society of Hypertension (ESH) and of the European Society of Cardiology (ESC),” Blood Pressure, vol. 23, no. 1, pp. 3-16, 2014.

[9] S. Laurent, J. Cockcroft, L. Van Bortel, P. Boutouyrie, C. Giannattasio, D. Hayoz, and et al. “Expert consensus document on arterial stiffness: methodological issues and clinical applications,” European Heart Journal, vol. 27, no. 21, pp. 2588-2605, Sep 2006.

[10] C. Vlachopoulos, K. Aznaouridis, and C. Stefanadis, “Prediction of cardiovascular events and all-cause mortality with arterial stiffness: a systematic review and meta-analysis,” Journal of the American College of Cardiology, vol. 55, no. 13, pp. 1318-1327, 2010.

[11] A. Covic, and D. Siriopol, “Pulse wave velocity ratio: the new “gold standard for measuring arterial stiffness,” Hypertension, vol. 65, no. 2, pp. 289-290, 2015.

[12] Y. H. Kao, P. C. P. Chao, and C. L. Wey, “Towards maximizing the sensing accuracy of an cuffless, optical blood pressure sensor using a high-order front-end filter,” Microsystem Technologies, vol. 24, no. 11, pp. 4621-4630, Nov 2018.

[13] K. H. Huang, C. M. Chang, F. W. Lee, T. D. Wang, and Y. J. Yang, “Highly-sensitive linear tactile array for continuously monitoring blood pulse waves,” Sensors and Actuators A: Physical, vol. 280, pp. 261-270, Sep 2018.

[14] D. Zambrana-Vinaroz, J. M. Vicente-Samper, C. G. Juan, V. Esteve-Sala, V, and J. M. Sabater-Navarro, “Non-Invasive Device for Blood Pressure Wave Acquisition by Means of Mechanical Transducer,” Sensors, vol. 19, pp. 4311, Oct 2019.

[15] Y. P. Hsu, and D. J. Young, “Skin-coupled personal wearable ambulatory pulse wave velocity monitoring system using microelectromechanical sensors,” IEEE Sensors Journal, vol 14, no. 10, pp. 3490-3497, Oct 2014.

[16] D. B. McCombie, A. T. Reisner, and H. H. Asada, “Adaptive blood pressure estimation from wearable PPG sensors using peripheral artery pulse wave velocity measurements and multi-channel blind identification of local arterial dynamics,” 2006 International Conference of the IEEE Engineering in Medicine and Biology Society, IEEE, 2006.

[17] C. Dagdeviren, Y. Su, P. Joe, R. Yona, Y. Liu, Y. S. Kim, and J. A. Rogers, “Conformable amplified lead zirconate titanate sensors with enhanced piezoelectric response for cutaneous pressure monitoring,” Nature Communications, vol. 5, no. 1, pp. 1-10, 2014.

[18] N. Luo, W. Dai, C. Li, Z. Zhou, L. Lu, C. C. Y. Poon, and et al. “Flexible piezoresistive sensor patch enabling ultralow power cuffless blood pressure measurement,” Advanced Functional Materials, vol. 26, no. 8, pp. 1178-1187, 2016.

[19] T. Yang, X. Jiang, Y. Zhong, X. Zhao, S. Lin, J. Li, and et al. “A wearable and highly sensitive graphene strain sensor for precise home-based pulse wave monitoring,” ACS Sensors, vol. 2, no. 7, pp. 967-974, 2017.

[20] M. Akiyama, Y. Morofuji, T. Kamohara, K. Nishikubo, M. Tsubai, O. Fukuda, and et al. "Flexible piezoelectric pressure sensors using oriented aluminum nitride thin films prepared on polyethylene terephthalate films," Journal of Applied Physics, vol. 100, no. 11, pp. 114318, 2006.

[21] L. Zetang, and Z. L. Wang, "Air/liquid-pressure and heartbeat-driven flexible fiber nanogenerators as a micro/nano-power source or diagnostic sensor," Advanced Materials, vol. 23, no. 1, pp. 84-89, 2011.

[22] J. Park, M. Kim, Y. Lee, H. S. Lee, and H. Ko, "Fingertip skin–inspired microstructured ferroelectric skins discriminate static/dynamic pressure and temperature stimuli," Science Advances, vol. 1, no. 9, 2015.

[23] D. Y. Park, D. J. Joe, D. H. Kim, H. Park, J. H. Han, C. K. Jeong, and K. J. Lee, "Self-powered real-time arterial pulse monitoring using ultrathin epidermal piezoelectric sensors," Advanced Materials, vol. 29, no. 37, 2017.

[24] Y. Xin, X. Qi, C. Qian, H. Tian, Z. Ling, and Z. Jiang, "A wearable respiration and pulse monitoring system based on PVDF piezoelectric film," Integrated Ferroelectrics, vol. 158, no. 1, pp. 43-51, 2014.

[25] K. H. Huang, F. Tan, T. D. Wang, and Y. J. Yang, "A highly sensitive pressure-sensing array for blood pressure estimation assisted by machine-learning techniques," Sensors, vol. 19, no. 4, pp. 848, 2019.

[26] T. Katsuura, S. Izumi, M. Yoshimoto, H. Kawaguchi, S. Yoshimoto, and T. Sekitani, "Wearable pulse wave velocity sensor using flexible piezoelectric film array," In 2017 IEEE Biomedical Circuits and Systems Conference (BioCAS), IEEE, pp. 1-4, Oct 2017.

[27] J. McLaughlin, M. McNeill, B. Braun, and P. D. McCormack, "Piezoelectric sensor determination of arterial pulse wave velocity," Physiological Measurement, vol. 24 no. 3, pp. 693, 2003.

[28] T. W. Wang, and L. Shien-Fong, "Wearable piezoelectric-based system for continuous beat-to-beat blood pressure measurement," Sensors, vol. 20, no. 3, pp. 851, 2020.

[29] B. Qi, Q. Kong, H. Qian, D. Patil, I. Lim, M. Li, and G. Song, "Study of impact damage in PVA-ECC beam under low-velocity impact loading using piezoceramic transducers and PVDF thin-film transducers," Sensors, vol. 18, no. 2, pp. 671, 2018.

[30] E. Lefeuvre, G. Sebald, D. Guyomar, M. Lallart, and C. Richard, "Materials, structures and power interfaces for efficient piezoelectric energy harvesting," Journal of Electroceramics, vol. 22, no. 1-3, pp. 171-179, 2009.

[31] E. J. Chen, J. Novakofski, W. K. Jenkins, and W. D. O'Brien, "Young's modulus measurements of soft tissues with application to elasticity imaging," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 43, no. 1, pp. 191-194, 1996.

[32] M. Pawlaczyk, M., Lelonkiewicz, and M. Wieczorowski, "Age-dependent biomechanical properties of the skin," Advances in Dermatology and Allergology/Postępy Dermatologii i Alergologii, vol. 30, no. 5, pp. 302, 2013.

[33] M. L. Palmeri, A. C. Sharma, R. R. Bouchard, R. W. Nightingale, and K. R. Nightingale, "A finite-element method model of soft tissue response to impulsive acoustic radiation force," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol 52, no. 10, pp. 1699-1712, 2005.