DOI: 10.46793/41DAS2025.095Z

MEASUREMENT OF PIEZOELECTRIC PROPERTIES OF HYDROGELS

Fatima ZIVIC[1*], Marija BRANKOVIC[2], Danilo PETROVIC[3], Petar TODOROVIC[4], Nenad GRUJOVIC[5]

[1] 0000-0003-2509-187X, Faculty of Engineering, University of Kragujevac, Sestre Janjic 6, Kragujevac, Serbia, E-mail: zivic@kg.ac.rs;

[2] 0009-0003-5228-4172, Institute for Information Technologies, University of Kragujevac, Jovana Cvijića bb, 34000 Kragujevac, Serbia, E-mail: marija.brankovic@uni.kg.ac.rs;

[3] 0009-0000-2292-8297, Faculty of Engineering, University of Kragujevac, Sestre Janjic 6, Kragujevac, Serbia, E-mail: petrovicdanilo1999@gmail.com;

[4] 0000-0003-3260-1655, Faculty of Engineering, University of Kragujevac, Sestre Janjic 6, Kragujevac, Serbia, E-mail: petar@kg.ac.rs;

[5] 0000-0002-8765-2196, Faculty of Engineering, University of Kragujevac, Sestre Janjic 6, Kragujevac, Serbia, E-mail: gruja@kg.ac.rs;

1. Introduction

Soft piezoelectric materials, such as hydrogels, have gained importance for diverse biomedical applications due to the possibility to mimic biological tissues, including cell signaling [1]. It is complex to accurately characterize their piezoelectric activity due to spatial inhomogeneity of the material, low electric outputs, instability of the signal, viscoelastic damping and high impedance. Also, determination of piezoelectric coefficients, important for analytical and numerical modelling is still challenging.

Measuring the low voltage output from piezoelectric hydrogels, which are soft and often deformable, requires highly sensitive instruments and careful noise mitigation. Common tools include high-impedance voltmeters, lock-in amplifiers, picoammeters, and low-noise or charge amplifiers to capture and condition weak signals. Techniques like Kelvin (four-terminal) sensing help reduce errors from contact resistance, especially in high-impedance materials. Advanced systems, such as portable devices with electrochemical impedance spectroscopy (EIS), enable precise low-current measurements. For evaluating piezoelectric coefficients, methods like laser Doppler vibrometry (LDV) and piezoresponse force microscopy (PFM) are used, often supported by numerical analysis for complex soft materials.

This paper presents measurement methods for piezoelectric hydrogels, with case study of custom measurement setup for low output voltage from actuated piezoelectric hydrogels and key aspects of good system design.

2. Piezoelectric hydrogels

Piezoelectric gels, or PiezoGels, are unique gels with crystalline structures exhibiting a polar arrangement [2]. PiezoGels are a type of piezoelectric material that generates electricity under mechanical stress. They consist of a 3D network of hydrophilic polymers with a unique crystalline, asymmetric structure, enabling efficient energy generation for sensors and biomedical uses. They also offer high sensitivity, chirality, strong electroactivity, stable polarization, and excellent extracellular matrix mimicry [2]. It is transparent, easily adaptable, and shape-changing; soft, flexible, stretchable, and biocompatible [2]. Piezoelectric hydrogels can be made from organic, inorganic, or hybrid materials. Traditional devices use piezoelectric polymers and ceramic oxides like perovskites. In polymeric hydrogels, interconnected polymer chains form a network that retains water. Natural polymers used include silk, collagen, starch, gelatin, chitosan, agarose, fibrin, dextran, alginate, heparin, and hyaluronic acid. Synthetic polymers used in the fabrication of hydrogels include polyvinyl alcohol (PVA), polyglycerol, sodium polyacrylate, polyacrylic acid, polyethylene oxide (PEO), polyacrylonitrile (PAN), and polyacrylamide (PAM), along with other synthetic polymers and copolymers. There is limited mention of hydrogels based on ceramic oxides in the literature. Among perovskite ceramic oxides, the most common in piezoelectric hydrogels are barium titanate (BaTiO3), lead titanate (PbTiO3), potassium niobate (KNbO3), and lead zirconate titanate ([Pb(Zr, Ti)O3]). Hydrogels based on supramolecular piezoelectric materials are organic and hybrid materials characterized by simple synthesis, mechanical flexibility, multifunctionality, and adaptability.

Piezoelectric hydrogels are used in biomedicine to detect signals, promote healing, and boost tissue activity. In wearables, they monitor biological signals and support energy harvesting They also play a significant role in robotic systems [3]. As sensors, they detect fluid flow, vibrations, and flow direction. Integrated with ultrasonic transducers, they also aid diagnostics and internal condition monitoring [3].

3. Measuring low piezoelectric outputs

Measuring low voltage outputs from piezoelectric hydrogels (typically in the millivolt to a few volts range) requires sensitive techniques tailored to their soft, hydrated, and often deformable nature [2], [3]. Measurement methods for low voltage output from piezoelectric hydrogels commonly involve instruments with high sensitivity and take care to mitigate different influences that can interfere and affect output signals [4]. Stability of piezoelectric output signals, presence of noise and high impedance are recognised challenges, and it is still subject of research.

Common approaches include using a high-impedance voltmeter to preserve the hydrogel's low voltage output, a lock-in amplifier to detect low-level AC signals in noisy environments, and a picoammeter for current measurement. Various amplifiers are used, such as low-noise amplifiers to boost small signals for DAQ systems, and charge amplifiers that convert piezoelectric charge to voltage, ideal for dynamic signals due to their ability to handle the capacitive nature of piezo materials. Analogue signal conditioning is used for filtering and amplification before digitization. High sensitivity oscilloscope is used to view time-domain signals, especially for dynamic loading and is commonly paired with pre-amplifier and differential probes for noise immunity. Four-terminal (Kelvin) sensing uses combination of electrodes for current injection and voltage sensing, thereby eliminating the effects of contact and lead resistances [4]. This configuration is good for soft materials with a high impedance, as voltage loss across contacts can cause significant inaccuracy.

Advanced instruments have emerged focusing on measuring low electricity (~100 pA), such as small mobile devices combining potentiostat, galvanostat and frequency response analyser (FRA) for electrochemical impedance spectroscopy (EIS) that can be used as the highly sensitive background system for multichannel measurements, including supporting piezoelectric measurements [5].

Experimentally measuring piezoelectric coefficients is crucial for designing new composites, but direct methods are mostly limited to piezoresponse force microscopy (PFM), where AFM tip applies voltage to material surface and record resulting piezo response Most approaches instead calculate effective values, often using numerical methods for complex analysis. Laser doppler vibrometry (LDV) detects surface vibration velocities using laser interferometry. By applying electric field and measuring displacement, the effective piezoelectric coefficient can be calculated with high precision, even in soft or liquid-supported films. Certain interferometers can be adapted to track displacements from piezoelectric actuation, suitable for sub-nanometer displacement measurements.

4. Case study of custom measurement setup

Components of the measurement setup for low output voltage from actuated piezoelectric hydrogels are shown in Fig.1.

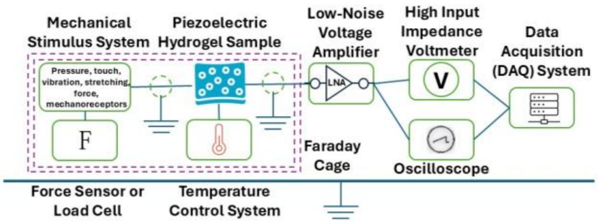

Fig. 1. Schematics of the measurement setup for low output voltage from actuated piezoelectric hydrogels.

Piezoelectric hydrogel sample generates voltage under mechanical stress produced by the mechanical stimulus system that can be provided by exerting pressure, touch, vibration, stretching, force or mechanoreceptors. The measurement setup for the low output voltage of a piezoelectric hydrogel needs to be highly sensitive and designed to minimize noise and impedance mismatches. The components typically used in such a setup are shown in Fig. 1, with piezoelectric hydrogel sample under mechanical stress generating the voltage. Mechanical stimulus system is used to apply a controlled force or strain to the hydrogel [6]. It can be provided by using various systems, such as linear actuator, vibration shaker, manual press with known force, or universal mechanical devices. Electrodes are usually made of gold, silver, carbon, or conductive inks and attached to both ends of the hydrogel or embedded in it [4]. Coaxial or triaxial shielded cables are used to minimize electromagnetic noise.

Considering low level signals and potential noise disturbance, signal conditioning and measurement instruments are needed also, such as low-noise voltage amplifier or pre-amplifier, and high input impedance voltmeter or electrometer [7]. Low-noise voltage amplifier or pre-amplifier is required because piezoelectric signals are usually in the microvolt (µV) or millivolt (mV) range. High input impedance voltmeter or electrometer will prevent loading effects that could distort the measurements. Furthermore, oscilloscope can be used to observe transient signals in real time [8]. Data acquisition (DAQ) system is needed for digitizing and logging the signal, preferably with high resolution (≥16-bit ADC) and high impedance input.

Noise reduction and environmental controls are necessary to provide additional stability, such as Faraday cage and vibration isolation table. Faraday cage represents enclosure to shield the experiment from ambient electrical noise. Vibration isolation table minimizes mechanical noise from the environment. Proper grounding of all components is needed to reduce ground loops and interference.

Additional components are usually also present, such as force sensor or load cell to measure the applied force and correlate with voltage output. Temperature control system can be also provided to control the temperature since hydrogel properties can be temperature sensitive [9].

Mitigating noise and impedance mismatch in the measurement of low-voltage outputs from actuated piezoelectric hydrogels is crucial for obtaining accurate and reliable data [10]. These materials often generate very small electrical signals, and any distortion or loss can significantly affect signal interpretation. The critical elements that need to be addressed are:

- Impedance matching
- Minimizing noise
- Signal conditioning
- Connection quality and lead design
- Adequate grounding and isolation
- Environmental control
- Calibration and validation

Impedance matching is very important [10], [11] since piezoelectric hydrogels typically have high output impedance. If the input impedance of the measurement device is too low, signal attenuation and energy loss will occur. Possible solution is to utilize high input impedance buffer using a voltage follower circuit based on an operational amplifiers (op-amp) or instrumentation amplifier (in-amp) with input impedance $>10^9$ Ω. For piezoelectric outputs, a charge amplifier is very beneficial since it converts the high-impedance charge signal to a voltage, preserving the signal integrity. Low-noise preamplifier or low-noise, high-input-impedance amplifier close to the hydrogel can efficiently minimize signal loss over leads.

Minimizing noise is extremely important since the piezo signals are highly sensitive to it. The noise sources can originate from 1) electromagnetic interference (EMI) and RF noise, 2) thermal and Johnson noise or 3) mechanical noise. Preventing EMI and RF noise is typically done by using shielded cables, Faraday cage and proper grounding, as previously mentioned. Thermal and Johnson noise is present in all resistors and conductive materials and represents the random electrical noise generated by the thermal agitation of electrons in a conductor, even when no external voltage is applied. Thermal noise is caused by the thermal motion of charge carriers in any resistive material, and it is unavoidable and inherent to all electronic systems. To mitigate this effect, low-noise op-amps are suitable with minimal input bias current and voltage noise density. Also, if possible, cool environment with reduced temperature to lower thermal noise is beneficial, though that depends on the experimental setup feasibility. Mechanical noise can be mitigated by using vibration damping table to reduce unwanted or unintended activation of the piezoelectric effect in a hydrogel. Electrical wires can also affect piezoelectric signals [12], and strain decoupling can prevent it like using flexible leads or strain reliefs for cables to prevent mechanical disturbance from wires affecting the hydrogel. It will prevent additional complex loading through enabling separation or isolation of specific strain components (like axial, shear, or bending strains) in a hydrogel, especially important when multiple types of strain are present simultaneously.

Signal conditioning is done through filtering to remove unwanted noise and interference from the signal, by using a bandpass filter matching the expected frequency range of the piezoelectric signal to suppress low-frequency drift and high-frequency noise. Averaging is also used through software-based ensemble averaging (averaging multiple repetitions of a signal) across multiple actuation cycles to improve signal-to-noise ratio (SNR).

Connection quality and design of leads are crucial for ensuring signal integrity having significant effects on signal quality. As short leads as possible are more beneficial for piezoelectric signals in this case, since long leads act as antennas and introduce noise [12]. Coaxial cables showed the best performance, but simple twisted-pair wires will also reduce EMI and improve signal quality. Low-leakage connectors will prevent current loss due to surface leakage, especially in humid or aqueous environments.

Adequate grounding and isolation is necessary and can be done in different ways, like differential measurements that can help in rejecting common-mode noise. For example, twisted pair wiring helps minimize the impact of electromagnetic interference by pairing signal lines and reducing the loop area for induced voltages. Isolated power supplies or battery-powered amplifiers are better since they eliminate power-line noise.

Environmental control through ensuring stability of humidity and temperature of the measuring setup is very important for piezoelectric hydrogels since they are sensitive to humidity and temperature, which can alter their electrical response.

Frequent calibration and validation of the measuring system is necessary by using known reference signals or standard piezoelectric materials since piezoelectric signals from hydrogels are very sensitive to different influences. It is beneficial to validate the linearity and frequency response of the entire signal chain before measuring actual samples.

5. Conclusions

Piezoelectric hydrogels are promising materials for tissue engineering, flexible wearables and sensing. However, accurate measuring of the output piezoelectric signals is complex and requires highly sensitive measurement setups. The critical elements that need to be addressed are impedance matching, minimizing noise, adequate signal conditioning, connection quality and lead design, adequate grounding and isolation, environmental control and regular calibration and validation.

Acknowledgments

This paper is supported by the project No. 451-03-137/2025-03/200107 and No. 451-03-136/2025-03/200378, Ministry of Science, Technological Development and Innovation, Republic of Serbia.

References

[1] Shi G, Su T, Li J, Wang A, Gao G, Tao B, et al. Biomimetic piezoelectric hydrogel system for energy metabolism reprogramming in spinal cord injury repair. *Theranostics* 2025;15:4955–69.

[2] Vijayakanth T, Shankar S, Finkelstein-Zuta G, Rencus-Lazar S, Gilead S, Gazit E. Perspectives on recent advancements in energy harvesting, sensing and bio-medical applications of piezoelectric gels. *Chem Soc Rev* 2023;52:6191–220.

[3] Du Y, Du W, Lin D, Ai M, Li S, Zhang L. Recent Progress on Hydrogel-Based Piezoelectric Devices for Biomedical Applications. *Micromachines* 2023;14:167.

[4] Sekitani T, Yokota T, Kuribara K, Kaltenbrunner M, Fukushima T, Inoue Y, et al. Ultraflexible organic amplifier with biocompatible gel electrodes. *Nat Commun* 2016;7:11425.

[5] Simić M. Portable Device for In-Situ Cyclic Voltammetry Measurements. 2024 47th *Int. Spring Semin. Electron. Technol. ISSE*, Prague, Czech Republic: IEEE; 2024, p. 1–5.

[6] Carravero Costa L, Pochard I, Buron CC, Jurin FE. Elaboration of Conductive Hydrogels by 3D Printer for the Development of Strain Sensors. *Gels* 2025;11:474.

[7] Mojena-Medina D, Martínez-Hernández M, De La Fuente M, García-Isla G, Posada J, Jorcano JL, et al. Design, Implementation, and Validation of a Piezoelectric Device to Study the Effects of Dynamic Mechanical Stimulation on Cell Proliferation, Migration and Morphology. *Sensors* 2020;20:2155.

[8] Azhari F, Tom C, Benassini J, Loh KJ, Bombardelli FA. *Design and characterization of a piezoelectric sensor for monitoring scour hole evolution*. In: Lynch JP, Wang K-W, Sohn H, editors., San Diego, California, USA: 2014, p. 906118.

[9] Guo X, Wang L, Jin Z, Lee C. A Multifunctional Hydrogel with Multimodal Self-Powered Sensing Capability and Stable Direct Current Output for Outdoor Plant Monitoring Systems. *Nano-Micro Lett* 2025;17:76.

[10] Koszewnik A, Grześ P, Walendziuk W. Mechanical and electrical impedance matching in a piezoelectric beam for Energy Harvesting. *Eur Phys J Spec Top* 2015;224:2719–31.

[11] Rathod VT. A Review of Electric Impedance Matching Techniques for Piezoelectric Sensors, Actuators and Transducers. *Electronics* 2019;8:169.

[12] Insabella RM, González MG, Acosta EO, Santiago GD. Dielectric antenna effects in integrating line piezoelectric sensors for optoacoustic imaging. *Meas Sci Technol* 2020;31:125103.