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EXPERIMENTAL STUDY OF THE INFLUENCE OF MASS LOADING ON THE SENSITIVITY OF A PIEZOELECTRIC SENSOR

This study investigates the effect of applied mass loading on the response of a piezoelectric sensor during the registration of mechanical vibrations, enabling an assessment of changes in its sensitivity to vibrational disturbances. An electronic circuit was designed based on a piezoelectric sensor, a signal amplifier, and an ESP32 microcontroller. An experimental study was carried out using various mass loads to determine the sensor's amplitude response and to establish the dependence of the output signal on the applied load mass.

Keywords: piezoelectric sensor, vibration detection, sensitivity analysis, experimental study.

ПІЛИПЕНКО Володимир, СТЕЛІМАХ Наталія

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ВПЛИВУ МАСОВОГО НАВАНТАЖЕННЯ НА ЧУТЛИВІСТЬ П'ЄЗОЕЛЕКТРИЧНОГО СЕНСОРА

У роботі представлено експериментальне дослідження впливу масового навантаження на чутливість п'єзоелектричного сенсора під час реєстрації механічних вібрацій. П'єзоелектричні датчики широко застосовуються у системах вимірювання коливань, контролю стану обладнання, системах безпеки та моніторингу конструкцій завдяки здатності перетворювати механічну енергію деформації у електричний сигнал. Одним із важливих факторів, що визначає точність і стабільність роботи таких сенсорів, є додаткове масове навантаження, яке змінює динамічні характеристики системи та впливає на її резонансні властивості.

У дослідженні розроблено експериментальну установку, що включає п'єзоелектричний сенсор типу PZT-5A, підсилювач сигналу, аналоговий компаратор та мікроконтролер ESP32, який забезпечує цифрову обробку та реєстрацію сигналів. Для створення контрольованого навантаження була спроектована спеціальна платформа, виготовлена методом 3D-друку з полімеру PETG, що забезпечує рівномірний розподіл маси та стабільну передачу механічних коливань до сенсора.

Експериментальні дослідження проводилися шляхом поступового збільшення маси навантаження в діапазоні від 0 до 150 г. У процесі експериментів аналізувалися зміни амплітуди вихідного сигналу та частоти спрацьовування сенсора під дією зовнішніх механічних збурень. Отримані результати показали, що за відсутності додаткового навантаження сенсор практично не реєструє слабкі механічні впливи. При збільшенні маси до 10 г спостерігається поява окремих імпульсів сигналу, що свідчить про початок фіксації вібрацій. Подальше підвищення маси до 80 г призводить до зростання амплітуди сигналу та підвищення чутливості системи, що пояснюється збільшенням інерційного ефекту платформи. Найбільш стабільна та інтенсивна реакція сенсора зафіксована при масі 150 г, коли система переходить у режим посиленого коливального відгуку.

Отримані результати підтверджують, що масове навантаження суттєво впливає на чутливість п'єзоелектричних сенсорів, змінюючи їхню власну частоту та умови виникнення механічного резонансу. Практичне значення дослідження полягає у можливості регулювання характеристик датчика шляхом підбору оптимальної маси платформи для конкретних задач. Запропонований підхід може бути використаний під час розроблення систем моніторингу вібрацій і сейсмічної активності, інтелектуальних конструкцій для виявлення механічних пошкоджень, а також у пристроях збору енергії механічних коливань.

Ключові слова: п'єзоелектричний сенсор, вібраційний моніторинг, масове навантаження, чутливість датчика, експериментальне дослідження, ESP32.

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INTRODUCTION

Piezoelectric sensors are widely used in industry, scientific research, and security systems for measuring vibrations, impacts, and pressure. They operate on the direct piezoelectric effect, which enables the conversion of mechanical energy into an electrical signal [1]. The magnitude of this electrical signal is proportional to the amplitude of deformation of the crystalline material, making such sensors highly sensitive and accurate even under low-amplitude vibrations.

The sensitivity of piezoelectric sensors is influenced not only by the material type but also by the geometry of the sensing element, substrate characteristics, mounting conditions, natural frequency, and the mass of additional

loads [3]. Additional masses alter the dynamic properties of the system, particularly by reducing its natural frequency and increasing damping, which leads to variations in signal amplitude.

Understanding these effects is essential for achieving accurate measurements in vibration and seismic monitoring systems. Previous studies have demonstrated that the use of piezoelectric sensors combined with amplification and digital signal processing enables the detection of low-amplitude vibrations and the registration of short-duration events [2].

Investigating the influence of mass loading on sensor sensitivity is important not only under laboratory conditions but also for applications in remote object detection, equipment monitoring, and early-warning systems for vibrational events [4][5].

MATERIALS AND METHODS

For the experiment, a PZT-5A piezoelectric sensor was used, characterized by high sensitivity to mechanical deformation and low internal impedance. The sensor was mounted on an aluminum plate measuring $100 \times 50 \times 2$ mm to ensure uniform load distribution and stable mechanical support.

Signal processing was implemented using an ESP32 DevKit-based circuit, which served as the central processor and digital signal processing unit. The ESP32 allows software control of trigger thresholds, acquisition of digital data from the analog comparator, and transmission of the data to a computer or cloud platform via Wi-Fi or Bluetooth protocols. Arduino IDE was used for programming, providing a simple and convenient environment for configuring signal-reading logic and threshold parameters.

The circuit includes an amplification and comparison stage for the signal generated by the piezoelectric sensor. The sensor output is fed into an analog comparator, where it is evaluated relative to a reference voltage set by a potentiometer. The comparator output produces a digital HIGH or LOW signal, which the ESP32 interprets as the presence or absence of vibration. This approach minimizes low-amplitude noise and ensures reliable signal detection [6].

The experiments were performed by gradually adding mass to a platform positioned above the sensor. The applied mass ranged from 0 to 150 g. For each stage, the corresponding digital output values were recorded and could be displayed on a monitor or logged to a file for subsequent analysis.

SYSTEM DEVELOPMENT

An electronic vibration-sensing circuit was developed to convert mechanical oscillations into a digital signal suitable for further processing by a microcontroller. The circuit (Figure 1) consists of three

Piezoelectric sensor – serves as the primary transducer that, based on the piezoelectric effect, generates an electrical voltage in response to mechanical deformation or vibrational disturbances. The selected sensor type is characterized by high sensitivity to low-amplitude vibrations, enabling the detection of even minor environmental changes.

1. **Amplifier and comparator** – an analog signal-processing block that increases the voltage level from the piezoelectric element to a value suitable for digital interpretation. The comparator performs threshold conversion by comparing the instantaneous signal amplitude with a reference value set by a potentiometer. When the threshold is exceeded, the output forms a logical “1,” corresponding to the presence of a vibrational event.

2. **ESP32 microcontroller** – the central control unit of the system, responsible for digital acquisition of the comparator signals. Owing to its built-in data-processing capabilities, the ESP32 can analyze the frequency and intensity of vibrations, store the information, or transmit it wirelessly via Wi-Fi or Bluetooth.

The operational principle of the circuit is as follows: when vibrations occur, the piezoelectric sensor generates a voltage that is amplified and fed to the comparator. If the signal level exceeds the defined threshold, the ESP32 registers the event as a detected mechanical disturbance. When required, the microcontroller can transmit the data to a personal computer or a cloud environment for further analysis.

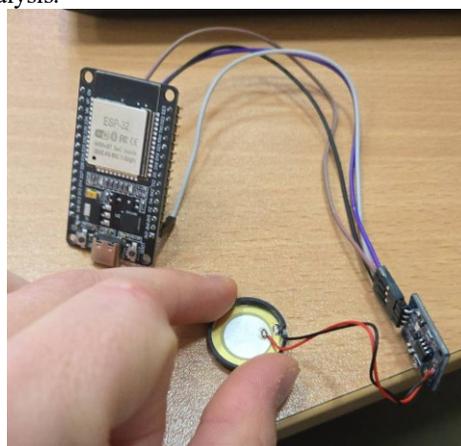


Fig. 1. Basic vibration sensor circuit

To ensure stable transmission of mechanical vibrations to the piezoelectric element, a dedicated platform for applying mass loads was designed. Its primary purpose is to uniformly distribute pressure across the sensor surface, preventing localized deformation while enhancing the inertial effect during oscillations.

The platform was designed using 3D-modeling software and subsequently fabricated with a 3D printer using PETG polymer.

A 100% infill density was selected to provide maximum rigidity and ensure uniform load transfer to the piezoelectric element.

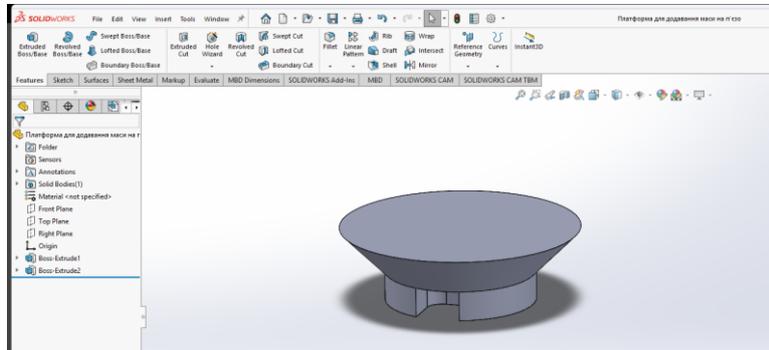


Fig. 2. 3D model of the platform for the piezoelectric sensor

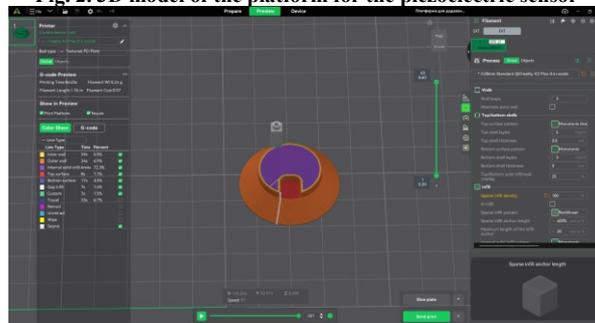


Fig. 3. Printing configuration in the PrusaSlicer environment

RESEARCH

To evaluate the influence of mass loading on the sensitivity of the piezoelectric sensor, a series of experiments was conducted. The aim of the study was to determine the dependence of signal amplitude and frequency on the mass of the platform installed on the sensor.

Each experiment was performed under identical conditions: the source of mechanical disturbance was the drop of an empty cardboard box within a 120 mm radius from the sensor.

Experiment 1

Only the sensor housing was installed without any additional weight. When the box was dropped, the sensor did not register any changes in the digital signal. This indicates that the mechanical impact energy was insufficient to activate the sensor without a load.



Fig. 4. Experiment 1: sensor without load

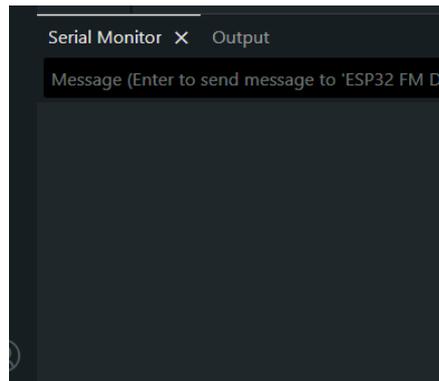


Fig. 5. Experiment 1: resulting digital signal

Experiment 2

A platform manufactured by 3D printing with a mass of 10 g was installed on the sensor. Repeating the experiment resulted in the appearance of isolated pulses on the digital output, indicating the onset of vibration detection by the sensor. The signal acquired a discrete and periodic character.

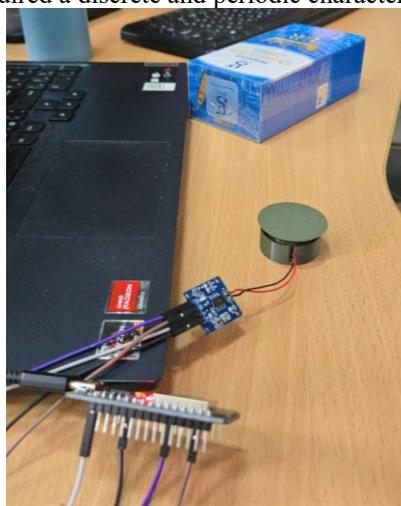


Fig. 6. Experiment 2: sensor with 10 g platform

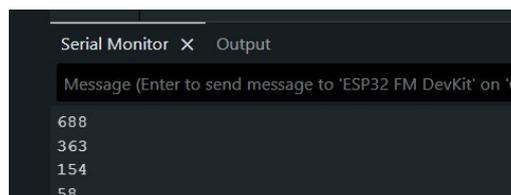


Fig. 7. Experiment 2: digital signal at 10 g load

Experiment 3

An additional mass of 80 g was added. As a result, the signal amplitude increased, the pulses became more pronounced, and the overall sensitivity of the system improved. This can be explained by the increased inertia of the platform, which enhances the mechanical impact on the piezoelectric element during external disturbances.



Fig. 8. Experiment 3: sensor with 80 g platform

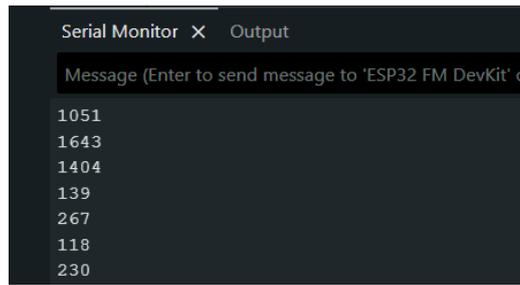


Fig. 9. Experiment 3: stabilized signal at 80 g load

Experiment 4

The total mass of the platform was increased to 150 g. During the drop of the box, the sensor registered a significantly larger number of events, and the signal amplitude increased several times. This is attributed to the heavier mass entering a self-induced oscillatory mode, generating additional mechanical influence on the sensor.



Fig. 10. Experiment 4: sensor with 150 g platform

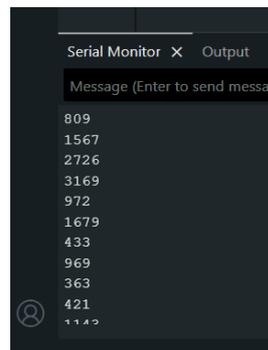


Fig. 11. Experiment 4: signal at 150 g load

RESULTS AND RELEVANCE

After processing the experimental data, a graph of the dependence of the digital signal amplitude on the applied mass load was constructed (Figure 3.1)

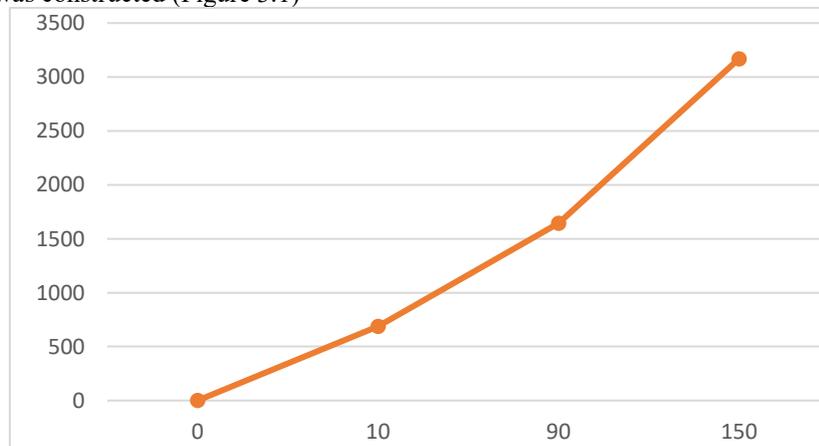


Fig. 12. Dependence of piezo-sensor signal amplitude on mass load

Analysis of the obtained dependence revealed the following patterns:

- **Up to 10 g**, the signal remains unstable and sporadic. This is explained by the insufficient inertia of the system, where even moderate vibrations do not create enough mechanical deformation of the piezoelectric element.
- **In the range of 10–80 g**, an increase in triggering frequency and signal amplitude is observed. Increasing the mass reduces the natural frequency of the system and enhances the mechanical resonance effect, allowing even minor external disturbances to produce a noticeable electrical response from the sensor (Houlding, 2014) [5].
- **At 150 g**, the signal becomes stable and intensive, indicating that the optimal mass for exciting the piezoelectric element in a resonant mode has been reached. In this state, the system generates maximum output amplitude even with low external energy input.

However, excessive increase in load may lead to nonlinear response or even mechanical damage to the piezoelectric disk. Excessive mass generates high bending moments at the contact point, which may cause micro-cracks in the crystalline structure or delamination of the electrode layer, reducing long-term stability of the sensor [7].

Additionally, too large a mass shifts the natural frequency of the system to a lower range, which may reduce measurement accuracy and introduce parasitic oscillations of the platform.

On the other hand, the results demonstrate the potential of such piezoelectric structures for the development of autonomous vibration and impact sensors that may be used in:

- vibration and seismic monitoring systems;
- smart structures for detecting mechanical damage;
- energy harvesting devices where mechanical vibration energy is converted into electrical energy.

The obtained results confirm that proper selection of the mass load allows tuning the sensitivity of the piezoelectric sensor to a specific frequency range, opening opportunities for further adaptation of the system to various engineering applications.

CONCLUSIONS

As a result of the experimental study, the influence of mass loading on the amplitude response of a piezoelectric sensor integrated into a system with an amplifier and an ESP32 microcontroller was determined. The findings allow formulating the following conclusions:

1. Increasing the mass load on the piezoelectric element leads to an almost linear increase in system sensitivity due to the enhanced inertial effect of the platform and increased amplitude of mechanical vibrations.

The optimal loading range that provides stable and reproducible signal growth without distortions is 10 to 150 g.

2. Excessive mass may cause broadband vibration modes and the appearance of additional resonant frequencies, complicating accurate identification of vibration events.

3. The obtained results are consistent with theoretical models in which mass load affects the natural frequency of the system and creates conditions for partial mechanical resonance.

4. The practical significance of the study lies in the possibility of adjusting the sensitivity of the piezoelectric sensor by changing the platform mass, which can be applied in vibration–seismic monitoring systems, impact sensors, and energy harvesting modules.

References

1. Zhou, W., Du, D., Cui, Q., Lu, C., Wang, Y., He, Q. "Recent Research Progress in Piezoelectric Vibration Energy Harvesting Technology." *Energies*, 2022, 15(3), 947. <https://www.mdpi.com/1996-1073/15/3/947>
2. Houlding, D. "High Sensitivity Vibration Sensor Using Arduino." Blog post, 22 Feb 2014. <https://davidhoulding.blogspot.com/2014/02/high-sensitivity-vibration-sensor-using.html>
3. Alameh, A.H., et al. "Effects of Proof Mass Geometry on Piezoelectric Vibration Sensor." *Sensors & Actuators A: Physical*, 2018. <https://pubmed.ncbi.nlm.nih.gov/articles/PMC5982937>
4. Andosca, R., et al. "Experimental and Theoretical Studies on MEMS Piezoelectric Vibrational Energy Harvesters with Mass Loading." *Sensors & Actuators A: Physical*, 2012. <https://www.researchgate.net/publication/257347042>
5. Jiang, X., et al. "Sensitivity of Piezoelectric Stack Actuators." *Sensors*, 2023, 23(23), 9542. <https://www.mdpi.com/1424-8220/23/23/9542>
6. Houlding, D. (2014). High Sensitivity Vibration Sensor Using Arduino. *Internet of Things*. Доступно за посиланням: <https://davidhoulding.blogspot.com/2014/02/high-sensitivity-vibration-sensor-using.html>
7. Matvienko, S., Tymchyk, G., Vonsevych, K., & Stelmakh, N. (2025). Research on the possibility of reducing the error in measuring the phase shift of radio signals. *Інформатика, Автоматика, Pomiar W Gospodarce I Ochronie Środowiska*, 15(3), 67–72. <https://doi.org/10.35784/iapgos.7261>