# A Piezoelectric Heart Sound Sensor for Wearable Healthcare Monitoring Devices

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**Abstract.** Heart disease is the leading cause of death all around the world. And heart sound monitoring is a commonly used diagnostic method. This method can obtain vital physiological and pathological evidence about health. Many existing techniques are not suitable for long-term dynamic heart sound monitoring since their large size, high-cost and uncomfortable to wear. This paper proposes a small, low-cost and wearable piezoelectric heart sound sensor, which is suitable for long-term dynamic monitoring and provides technical support for preliminary diagnosis of heart disease. First, the theoretical analysis and finite element method (FEM) simulation have been carried out to determine the optimum structure size of piezoelectric sensor. Subsequently, the sensor is embedded into the fabric-based chest strap to verify the detection performance in wearable scenarios. An existing piezoelectric sensor (TSD108) is used as reference. The designed sensor can acquire complete heart sound signals, and its signal-to-noise ratio is 2 dB higher than that of TSD108.

**Keywords:** Wearable · Heart sound sensor · Finite element method · Signal-to-noise ratio

## 1 Introduction

### 1.1 A Subsection Sample

Nowadays, heart disease is the leading cause of death all around the world [1]. In 2016, heart diseases killed 17.9 million people, i.e. three in every ten deaths [2]. The heart sound signal contains a lot of heart information, giving a preliminary suggestion for further diagnosis. Long-term and dynamic monitoring of early and sudden heart attacks to capture transient, non-sustainable abnormal heart sounds play a crucial role in diagnosis [3]. The stethoscope are widely used in auscultation, however it has many limitations for continuous monitoring. For instance, the stethoscope is difficult to be wearable and the hand-held measurement introduces friction noise. Echocardiography (echo), cardiac magnetic resonance images (other diagnostic equipment such as MRI) and computed tomography (CT) have high cost and high requirements for medical personnel. Therefore, providing economical and accurate long-term dynamic monitoring methods is an urgent task for researchers.


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Heart sound sensors play a vital role in heart sound detection systems, and many researchers are currently engaged in the research and exploration of heart sound sensor. Chen et al. designed a heart sound detection system based on the new XH-6 sensor, it collected the slight heart sound signals, displayed in real-time and saved the Phonocardiography (PCG) [4]. Hu et al. designed a chest-worn accelerometer for cardiorespiratory sound monitoring based on the asymmetrical gapped cantilever, the cantilever was composed of bottom mechanical layer and a top piezoelectric layer separated by a gap [3]. Ou et al. presented a novel electronic stethoscope based on micro-electro-mechanical-system (MEMS) microphone. The heart sounds were recorded and displayed with mobile APP [5]. Zhang et al. proposed the double-beam-block microstructure heart sound sensor based on the piezoresistive principle and MEMS technology [6]. Malik et al. utilized a high quality Littmann chest piece to pick up body sounds and then fed into a microphone sensor for conversion to electrical signals. The converted signals were processed by the signal conditioning circuit, and the external speaker was used to amplify the processed signals [7]. Above all, the sensor can be divided into two categories: piezoelectric-based and microphone-based according to the principle of sensor [8–12]. However, the microphone-based method is usually easy to pick up excessive ambient noise, and requires a higher frequency response range of microphone. The piezoelectric-based overcomes this problem, and the energy loss during the sound propagation is small.

## 2 Sensor Design

### 2.1 System Design

Considering the practical application scenarios, the system should be portable and wearable for long-term monitoring. A completed heart sensing system is composed of chest strap embedded with sensor, acquisition module, display module and analysis system. The overall system is shown in Fig. 1. First, the piezoelectric sensor is embedded into the chest strap with a fixed structure. During the auscultation process, the users wear the strap where the sensor position keep contact with the chest wall. The acquisition module consists of a microcontroller, signal conditioning circuit and a Bluetooth 4.0 unit, which samples the heart sound signals and transmits the data to the software for real-time display. Besides the heart sound can be listened using the earphone.

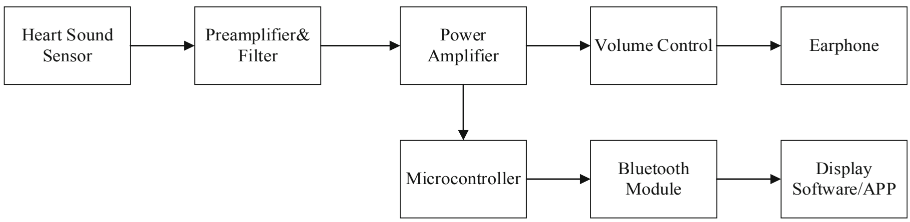



**Fig. 1.** Schematic block diagram of the heart sound sensing system

In this paper, the piezoelectric vibrator is selected as the sensitive component of the heart sound sensor. Based on the positive piezoelectric effect, while receiving external force of the chest wall vibration, the internal charges on both sides move relatively, resulting in potential difference. The change of potential difference reflects as the strength of heart sound signal.

Based on the principle of heart sound detection, this paper improves some existed sensors on the market, in order to design a smaller, thinner heart sound sensor which is suitable for long-time wearing. According to the prior knowledge, the structure diagram of the designed sensor is shown in Fig. 2, which consists of piezoelectric vibrator, cavity, protective shell and flexible film. The influence of piezoelectric vibrator and cavity size on the sensitivity of heart sound detection is the focus of this chapter. The real working environment of piezoelectric sensor will be simulated to determine the optimum size of piezoelectric vibrator and cavity. And then a sensor that meets the needs of comfort and long-term monitoring of heart sounds will be designed and implemented.

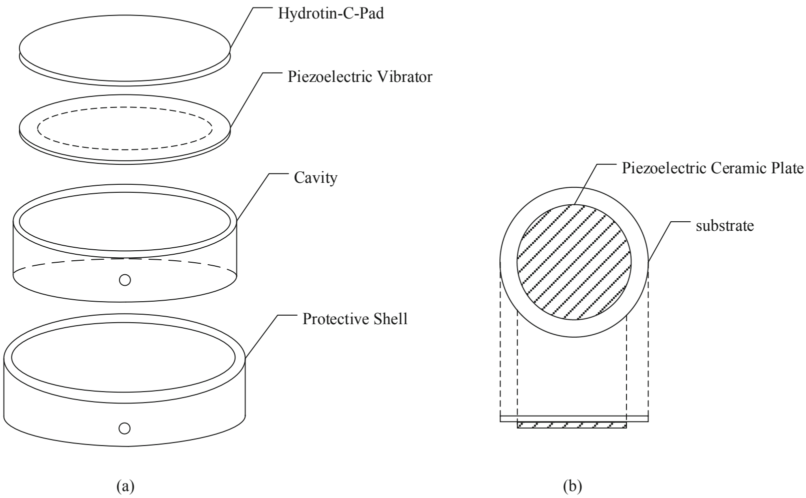
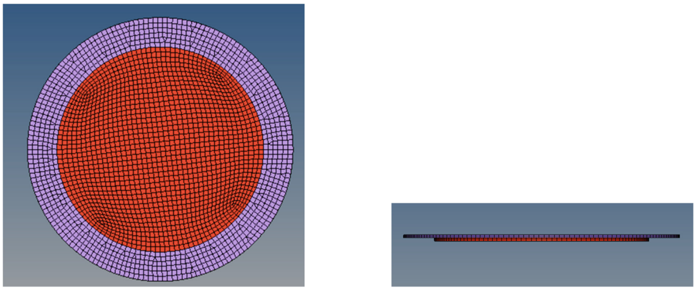



**Fig. 2.** Structure diagram of the piezoelectric sensor ((a) overall structure (b) piezoelectric vibrator structure)

## 2.2 Modelization

There are some limitations in the scientific theory and experiment. The infinite element method (FEM) can be used to simulate and analyze the structure of sensors so that the mechanical performance parameters are obtained. And then the designed heart sound sensors will be evaluated [13].

We first use the ANSYS software to build a mesh model of the piezoelectric vibrator. It is assumed that the vibration of the piezoelectric vibrator is a small deflection bending problem. When establishing the mesh model, the piezoelectric vibrator is divided into two parts: piezoelectric ceramic plate and metal substrate. The piezoelectric material (ceramic plate) is solid 5, which is a hexahedral element with 8 nodes. The substrate unit is solid 45, which is a commonly used structural element. They are bonded together by Glue command. The mesh model of the piezoelectric vibrator is shown in the Fig. 3.



(a) (b)

**Fig. 3.** Mesh model of the piezoelectric model (a) vertical veiw (b) front view

## 2.3 Simulation

The piezoelectric vibration is composed of a substrate made of H65 brass and a piezoelectric ceramic plate of PZT-4. And the material of cavity is also H65 brass. They are bonded together with polyurethane glue. The material properties used in the simulation are shown in Table 1. In order to determine the size of piezoelectric vibrator and cavity, the influence of the parameters of the substrate and the piezoelectric ceramic plate on the sensitivity of the piezoelectric sensor are respectively compared and analyzed; then the influence of the sensitivity on the piezoelectric sensor was verified by changing the cavity height. According to the simulation results, the parameters of heart sound sensors are determined. Finally, to verify the feasibility of the piezoelectric vibrator, the static and dynamic simulation of the selected piezoelectric vibrator are tested.

**Table 1.** Material properties

| Material | H65 Brass | PZT-4 | H62 brass | Polyurethane |
|---|---|---|---|---|
| $Density(g/m^3)$ | 8.5 | 7.5 | 8.5 | 1.07 |
| Young's modulus $(10^{11} N/m^2)$ | 1.3 | – | – | 0.13 |
| Poisson's ratio | 0.3 | – | 0.30 | 0.42 |
| Tensile strength (MPa) | $\geq 390$ | – | 410-630 | – |
| Extensibility (A%) | $\geq 25/20$ | – | 15.0 | – |

The material parameters of piezoelectric ceramic plate are as follows: dielectric constant is ε, piezoelectric constant matrix is $d \times 10^{10}\mathrm{C/m^2}$, stiffness matrices is $K \times 10^{10}\mathrm{N/m}$ [14].

$$\text{where } \varepsilon = \begin{bmatrix} 804.6 & 0 & 0 \\ 0 & 804.6 & 0 \\ 0 & 0 & 804.6 \end{bmatrix}, d = \begin{bmatrix} 0 & 0 & -4.1 \\ 0 & 0 & -4.1 \\ 0 & 0 & 14.1 \\ 0 & 0 & 0 \\ 0 & 10.5 & 0 \\ 10.5 & 0 & 0 \end{bmatrix},$$

$$K = \begin{bmatrix} 13.2 & 7.1 & 7.3 & 0 & 0 & 0 \\ 7.1 & 13.2 & 7.3 & 0 & 0 & 0 \\ 7.3 & 7.3 & 11.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.6 \end{bmatrix}$$

**Parameters of Piezoelectric Sensors**

First, the size of the circular piezoelectric vibrator is determined, the vibrator is composed of a piezoelectric ceramic plate and substrate. Therefore, the influence of the diameter of piezoelectric ceramic plate and substrate on its sensitivity are studied. In the simulation, the diameter of substrate ranges from 10–50 mm, and the diameter of piezoelectric ceramic plate ranges from 10–30 mm (the diameter of the substrate does not exceed that of the ceramic plate). The thickness of the substrate and the ceramic plate is 2 mm. A uniform load of 2 kPa is applied to the surface of piezoelectric vibrator [15]. The sensitivity is reflected by the displacement of the center point of the piezoelectric vibrator as shown in Fig. 4. It is not difficult to see from the figure that the displacement of the center point of the piezoelectric vibrator decreases with the increase of the diameter of the piezoelectric ceramic plate and increases with the increase of the diameter of the substrate.

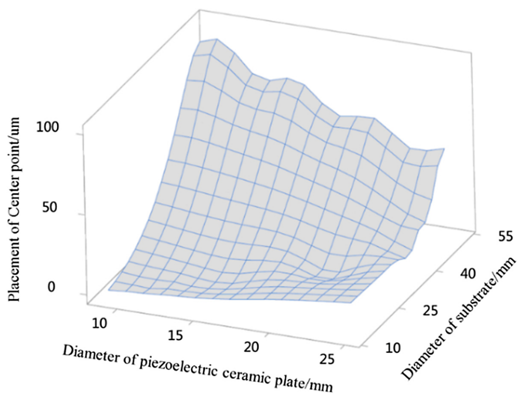



**Fig. 4.** Influence of different diameters of substrate and piezoelectric ceramic on the sensitivity of heart sound detection

When designing a circular piezoelectric vibrator, if a relatively larger diameter substrate and a smaller diameter ceramic plate are used, the output displacement is larger, but the rigidity is lowered as well as the output load is reduced. Meantime the larger diameter of the substrate is not conducive to the wear-ability. Considering the practicability and wear-ability, the center point of the figure is selected, that is, the diameter of piezoelectric ceramic plate is 15 mm, and the diameter of substrate is 27 mm.

Subsequently, whether the cavity height affects the deformation of the piezoelectric vibrator is verified. According to the single variable principle, the piezoelectric vibrator selected previously is used in this experiment. The single variable is the height of the cavity (the cavity diameter is consistent with the piezoelectric vibrator). The cavity height varies from 2–10 mm, and a uniform load of 2 kPa is applied to the piezoelectric vibrator. And then we observe the change of sensitivity of the piezoelectric vibrator with the height of cavity. As displayed in Fig. 5, the height of the cavity has little effect on the displacement output of the circular piezoelectric vibrator, which is almost negligible.

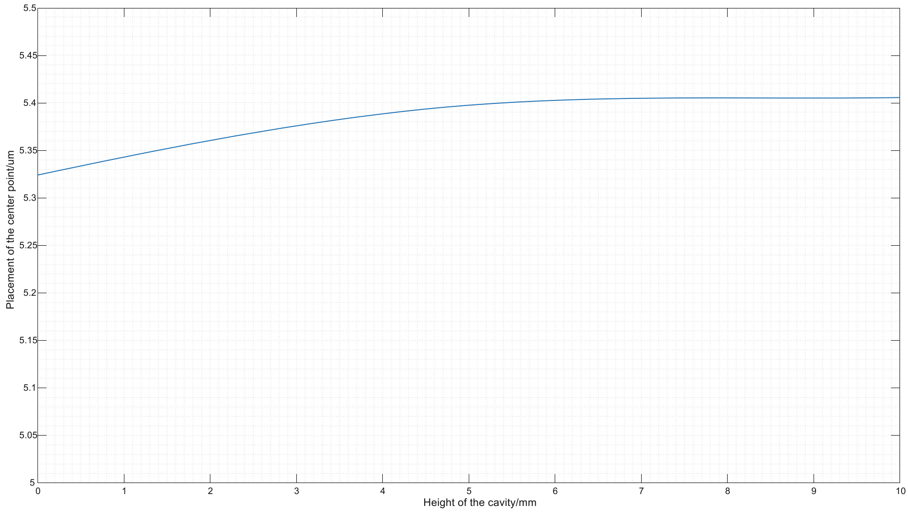



**Fig. 5.** Cavity height and center point displacement curve of piezoelectric vibrator

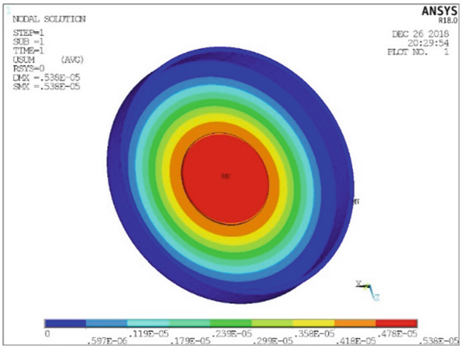



**Fig. 6.** Deformation diagram of piezoelectric sensor (Color figure online)

In summary, the size of the sensor designed in this paper is as follows: the diameter of the substrate is 27 mm, the diameter of piezoelectric ceramic piece is 15 mm, the height of the cavity is 3 mm, and the outer diameter is the same as the substrate. The deformation diagram is shown in Fig. 6 and the colors represent the displacement of the sensor.

**Dynamic Simulation**

To avoid resonance caused by the close working frequency and natural frequency of piezoelectric sensors, the dynamic characteristics of piezoelectric sensors are analyzed, including natural frequency and modal analysis, which is only related to the structure of piezoelectric sensors regardless of external loads. Considering that the behaviors such as speaking, breathing and exercise are unavoidable during their daily life, the frequency range of this dynamic characteristic experiment is set from 10–20000 Hz.

The first to 6th order modal shape diagram obtained by simulation (the corresponding natural frequencies are shown in Table 2.) show that the first mode of the piezoelectric sensor is similar to its static displacement under uniform load, and the corresponding natural frequency is 2236.1 Hz. The clinically valuable frequency range of heart sound is usually 10–600 Hz, so the sensor meets the application requirements.

**Table 2.** $1^{st}$–6th order natural frequencies of piezoelectric vibrator

| Order | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Frequency (Hz) | 2236.1 | 4524.5 | 4534.2 | 8422 | 8457.3 | 10447 |

**Static Simulation**

To verify the performances of stress concentration, the static simulation has been carried out. The 2 kPa load has been applied to the piezoelectric vibrator. The stress distribution diagram is shown in Fig. 7(a). By defining the path, the stress distribution curve in the X direction has been extracted, as shown in Fig. 7(b). The unit of the vertical axis in Fig. 7(b) is Pa, and the horizontal axis corresponds to the external diameter length of the sensor.

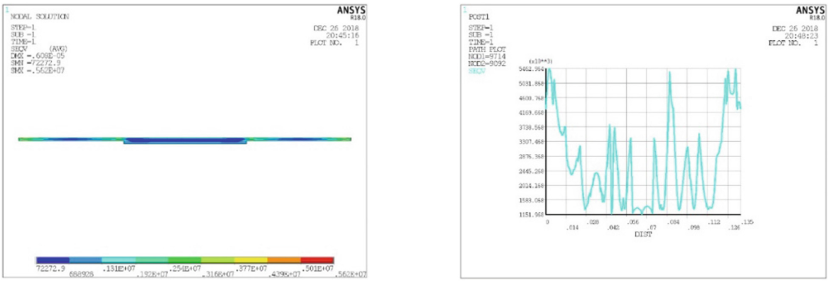



**Fig. 7.** (a) Stress distribution diagram (b) Stress distribution curve

From the results of the static simulation, it can be seen that the maximum stresses occur in the stress concentration areas, this is, the position of the piezoelectric ceramic plate. The detection sensitivity can be guaranteed.

### 2.4 Fabrication

After determining the size of sensor components, it needs to be packaged according the designed structure. The piezoelectric vibrator is bonded to the cavity with reference to the traditional stethoscope structure; the flexible film made of Hydrotin-C-Pad [16] material is covered on the surface of the vibrator considering the performance of piezoelectric vibrator and the transmission quality of heart sound, so as to improve the wear-ability of the sensor; The PVC plastic shell is used as the protective layer to prevent sweat corrosion. Finally, the above components are adhered by the polyurethane glue to ensure the sensor sealing property (Fig. 8).

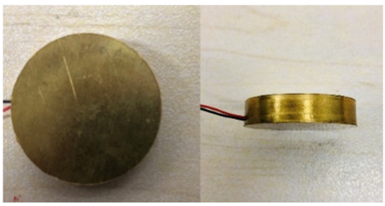


**Fig. 8.** The designed sensor prototype

## 3 Experiment and Results

### 3.1 Preparation

To verify the availability and performance of the designed sensor, TSD108 sensor is selected as the reference group in this chapter, as shown in Fig. 9(b). Piezoelectric sensor and TSD108 sensor are connected to the BIOPAC System (model: MP150, BIOPAC Systems INC., USA) to collect heart sound signals. TSD108 is a physiological sounds microphone developed by the BIOPAC Company. The TSD108 acoustical transducer element is a piezo-electric ceramic disk, which is bonded to the interior of a metallic circular housing. Its similar structure and detection principle with the designed sensor makes it suitable as the reference device in the experiment, besides it has high sensitivity.

The experiment required 6 student volunteers to wear a chest strap at room temperature of 26 °C. The chest strap was fixed at about 2 cm below the chest nipple with a certain initial pressure, requiring the wearer to stand still, the diagram of the acquisition system is shown in Fig. 9(c). The written consent was acquired from each participant before the experiment. And this was a non-clinical study performed on healthy subjects without any harming procedure. Therefore, ethical approval was not sought for execution of this study. According to the Nyquist's sampling law, the sampling frequency was set at 2 kHz and a record of 120 s collection. The collected two groups of heart sound datasets were further compared and analyzed in MATLAB. In this paper, the heart sound signals of one of the volunteers are randomly selected for analysis and comparison.

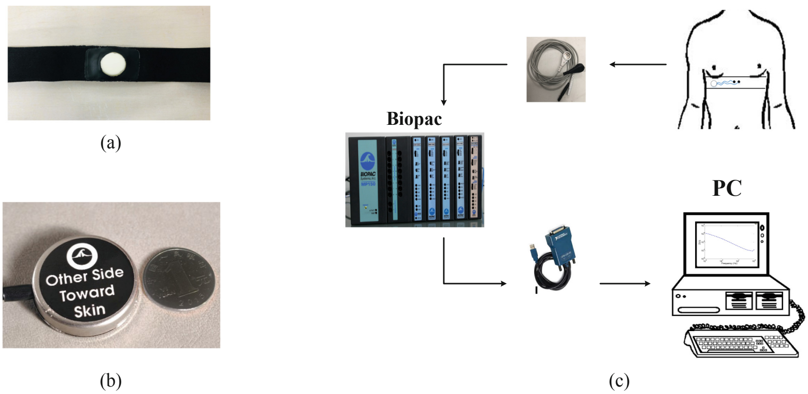



**Fig. 9.** Diagram of the acquisition system ((a) chest strap with piezoelectric sensor (b) TSD108 sensor (c) acquisition system)

## 3.2 Results

It can be seen from Fig. 10 that the first and second heart sound (S1 and S2) are obvious and its cardiac cycle is about 700 ms, and the corresponding heart rate is about 85 beats/min. The ratio of the S1S2 interval and S2S1 interval is approximately 1:2, which is consistent with the normal heart sounds standard. In addition, the maximum value collected by the designed sensor and TSD108 is respectively 0.06 V and 0.02 V. Thus the sensitivity of piezoelectric sensor is higher than that of TSD108 sensor under the same conditions.

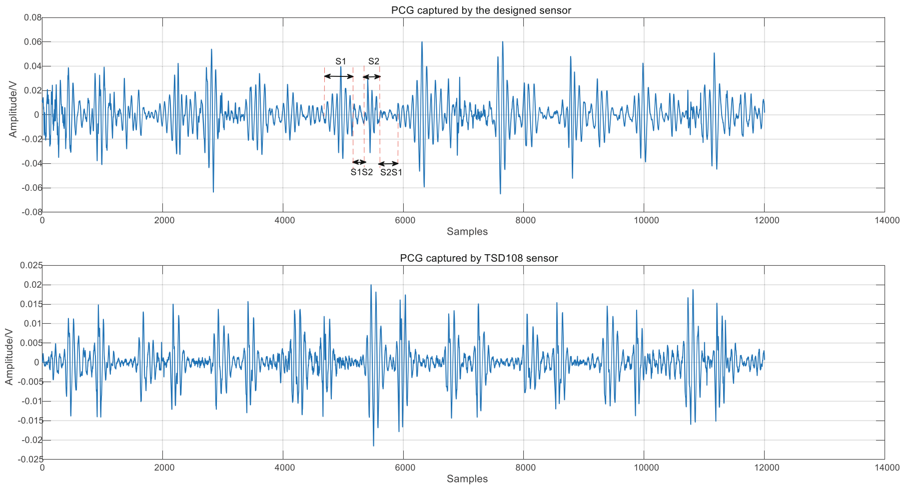
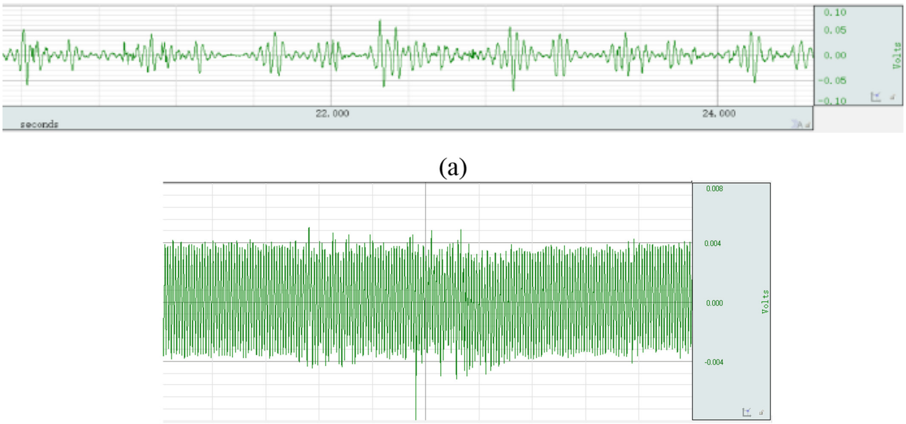



**Fig. 10.** PCG tested by the designed heart sound sensor and TSD108 sensor




(a)

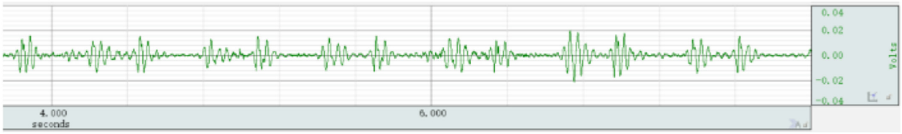
(b)

**Fig. 11.** SNR test of piezoelectric sensor: (a) heart sound signals (b) output without heart sound signals

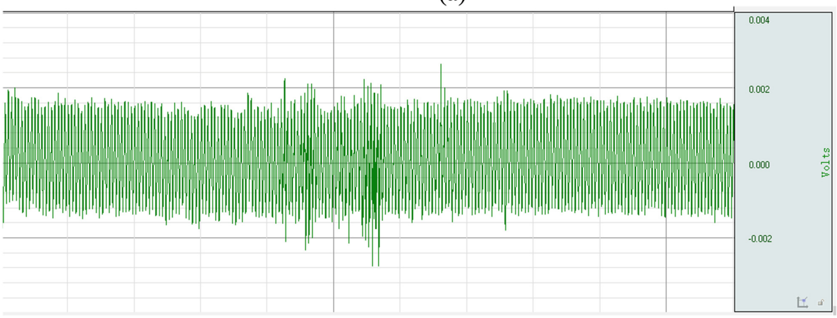
To further verify the performance of the designed piezoelectric sensor, the signal-to-noise ratio (SNR) testing experiment of the piezoelectric sensor and TSD108 sensor have been conducted. The formula of SNR can be converted into the ratio relation of voltage amplitude, that is, SNR = [20lg(Vs/Vn)] dB.

First the piezoelectric sensor has been tested, and the test results of the heart sound are shown in Fig. 11(a), and it is determined that the maximum value of the heart sound signals is 0.05 V. The output of the sensor without the heart sound signals are shown in

Fig. 11(b), and the noise signals is 4 mV. Therefore, the SNR of the piezoelectric sensor is 21.94 dB. Subsequently, TSD108 sensor has been tested. As shown in Fig. 12 (a), the maximum of heart sound signals is 0.02 V; and the noise signal is 2 mV as shown in Fig. 12(b). So the SNR of TSD108 sensor is 20 dB. The above test results indicate that the SNR of the piezoelectric sensor is 2 dB higher than the TSD108 sensor.




(a)




(b)

**Fig. 12.** SNR test of TSD108: (a) heart sound signals (b) output without heart sound signals

## 4 Conclusion

In this paper, a small, low-cost and wearable piezoelectric heart sound sensor has been designed and implemented for long-term dynamic monitoring and preliminary diagnosis. The major contribution includes: the optimum structure design of the sensor has been determined through ANSYS simulation analysis and experimental verification. The sensor is embedded into the fabric-based chest strap to verify the detection performance in wearable scenarios. The test of sensor performance is conducted by using the BIOPAC Systems. The heart sound waveform measured by the designed sensor is significantly correlated with that of the TSD108 sensor. Besides, it exhibits better detection performance, its sensitivity and signal-to-noise ratio are improved.

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