Spectrum Analysis of Respiration and Heartbeat Signals Measured by A Non-Contact PVDF Piezoelectric Film Based Sensor

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ABSTRACT

A very sensitive respiration sensor is developed using a simple poly-vinylidene difluoride (PVDF) piezoelectric film for monitoring the respiration activity of people who have sleep disorders such as sleep apnea syndrome (SAS). The respiration sensor is meant for at-home care use and is designed to be attached to a bed underneath a subject so that the respiration activity can be monitored without direct physical contact. A charge amplifier and a band elimination filter which were required for accurate respiration monitoring were also developed in this study. The output signals of the respiration sensor were measured while a subject repeated breathing and cessation every 30 s. In order to investigate the measured signal in detail, the measured signal was analyzed by using a fast Fourier transform algorithm. This confirmed that the measured signal contains not only the respiration signals but also the heartbeat signals of the subject. By using digital filters with appropriate cutoff frequencies, the respiration and the heartbeat signals were successfully separated.

KEYWORDS

PVDF, piezoelectric film, respiration, heartbeat, fast Fourier transform

1 INTRODUCTION

In recent years, it has been recognized that sleep disorders can cause serious problems in daily life [1, 2]. For example, people who have sleep apnea syndrome (SAS) have the risk of drowsy driving which may result in a fatal traffic accident. However, it is not easy to diagnose SAS by oneself because the symptom appears only while sleeping. Today, therefore, SAS screening tests are mandatory for many public transportation drivers and long-distance truck drivers.

At medical facilities such as hospitals, polysomnography (i.e. sleep studies) is done by measuring a combination of respiration activity, eyeball movements, brain waves, electromyograms (EMG) and electrocardiograms (ECG) so that sleep disorders of a patient can be examined thoroughly [3]. All of these measurements use contact-type sensors. On the other hand, for at-home care, a pulse oximeter is more commonly used to monitor respiration status. A pulse oximeter measures oxygen saturation (SpO_2) in the blood and by detecting a decrease of the SpO_2 level, apnea status can be detected [4, 5]. However, there is always some time-delay for SpO_2 levels to decrease after breathing has stopped. Respiration activity can be monitored by an air flow mask sensor as well. However, it has a big drawback in its discomfort to the patient due to having to be worn over the face. Also such masks can lead to measurement errors by deviation in the contours of the face from person to person. Furthermore, non-contact monitoring systems which measure the movement of a patient’s chest by with microwaves, infrared light and ultrasonic waves have been proposed. However, they are yet to be in practical use because of their poor sensitivity.

In this work, a very sensitive respiration sensor was developed using a very simple poly-vinylidene difluoride (PVDF) piezoelectric film. The new respiration sensor is meant to be used at home of outpatient care and it can be attached to a bed underneath a person without physical contacts. The output signals of the respiration sensor are measured while a subject repeats breathing and not breathing for every 30 s. Through a detailed data analysis, it was confirmed that the respiration sensor could measure not only the respiration signals but also the heartbeat signals of the subject.

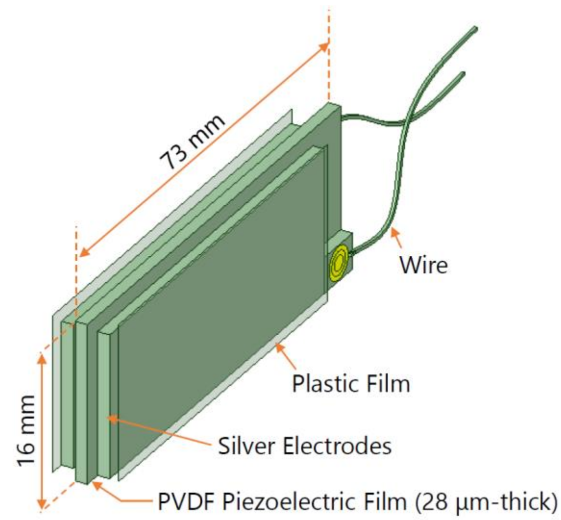

Figure 1. Schematic of a PVDF piezoelectric film (DT2-028K/L, Tokyo Sensor Co. Ltd.) used for the respiration sensor.

2 DEVELOPMENT OF A RESPIRATION SENSOR

2.1 Piezoelectric Film Used for Respiration Sensor

Figure 1 shows the PVDF piezoelectric film (DT2-028K/L, Tokyo Sensor Co. Ltd.) used for developing the respiration sensor in this study. The thickness and the area of the PVDF piezoelectric film are 28 μm and 16 mm × 73 mm, respectively. Both faces of the PVDF piezoelectric film are covered by silver electrodes with an area of 12 mm × 62 mm, and the electrodes are physically protected and electrically isolated by plastic film. The PVDF piezoelectric film generates electrical charge signals in proportion to the mechanical stress or strain, and it is suitable for measuring tiny forces because of its high sensitivity and that it generates very large signals even when only slightly moved [6].

2.2 Structure of the Respiration Sensor

Figure 2 (a) shows the structure of the respiration sensor developed in this study. As shown in the figure, the two side edges of the PDVF piezoelectric film are affixed to the two

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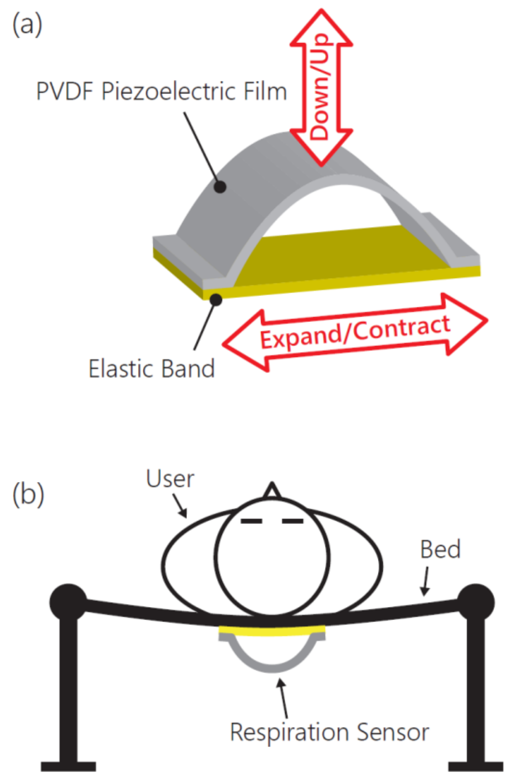

Figure 2. (a) Structure of the respiration sensor developed using a piezoelectric film. (b) An illustration of the respiration sensor attached on a bed underneath the abdomen of a person.

side edges of an elastic band so that the PDVF piezoelectric film can flex. As the elastic band either expands or contracts, the curvature of the PDVF piezoelectric film changes, and consequently a charge is generated. This sensor structure allows the PDVF piezoelectric film to generate a large charge signal from a very small expansion and/or contraction of the elastic band. The respiration sensor is designed to be attached on a bed underneath a person as shown in Fig. 2 (b). As the person lying on the bed breathes, the elastic section expands and contracts periodically, and therefore the charge is generated in the PVDF piezoelectric film. By measuring the charge signal of the sensor, the respiration activity of the person can be monitored without being in direct contact with the subject.

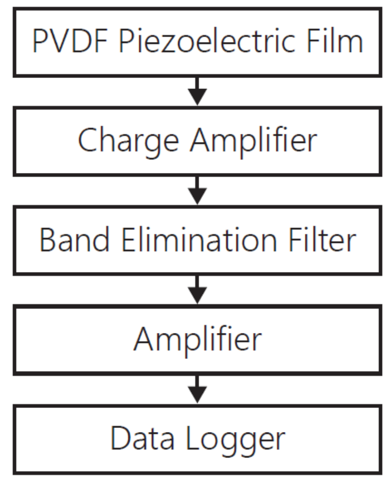

Figure 3. Block diagram of the measurement circuit for the respiration sensor.

2.3 Measurement Circuit

Figure 3 shows a block diagram of the measurement circuit used for the respiration sensor. The PVDF piezoelectric film is connected to a charge amplifier so that the charge generated in the PVDF piezoelectric film is accumulated with time and converted to voltage signals. The charge amplifier was designed to accept both positive and negative charge signals from the PVDF piezoelectric film but to output only positive voltage signals in the range from 0 V to the DC power supply voltage, typically 3 V. In order to suppress the AC 60 Hz noise from the AC/DC power-supply, the output signal from the charge amplifier was fed into a band elimination filter. A high Q-factor band elimination filter using a twin T-type band elimination filter and an OP amplifier with positive feedback circuit was employed. The filtered signals were amplified by a factor of 4000 through an amplifier and recorded with a data logger.

3 MEASUREMENT OF RESPIRATION SIGNALS

3.1 Output Signals of the Respiration Sensor

The output signals of the respiration sensor were recorded using a data logger while the subject repeated breathing (ventilation) and not

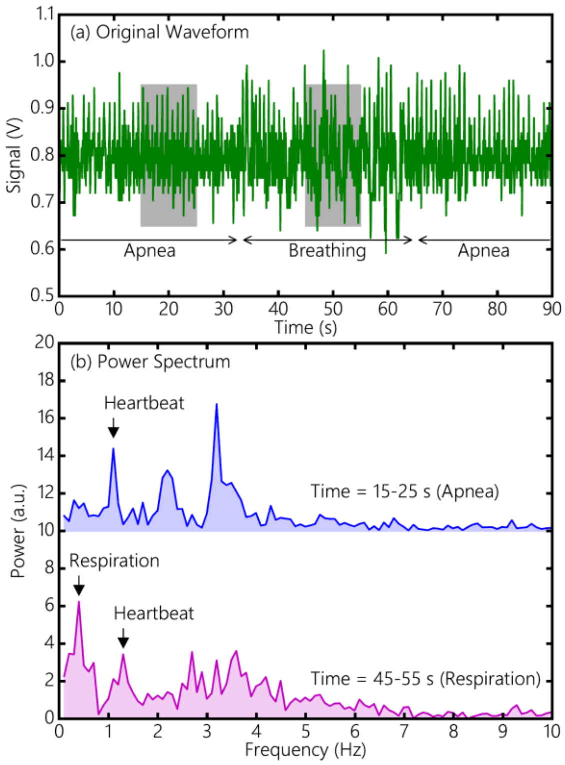

Figure 4. (a) Output signals of the respiration sensor measured for 90 s while the subject repeated breathing and not-breathing (apnea) for approximately every 30 s. (b) Power spectra obtained from the data measured while the subject was not breathing (15 - 25 s) and breathing (45 - 55 s) which are high-lighted in Fig.4 (a).

breathing (apnea) every 30 s as shown in Fig. 4 (a). The baseline of the waveform is approximately at 0.8 V. As shown in the figure, the measured waveform is not very clean due to the noise. So it was not easy to recognize the respiration status (either breathing or apnea). Therefore, in order to investigate the measured waveform in detail, a fast Fourier transform (FFT) analysis was carried out. The discrete Fourier transforms of the measured waveform were computed by using the `fftpack` package in `SciPy` [7], an open-source `Python` library. Figure 4 (b) shows the power spectra obtained from the data while the subject was not breathing (15 - 25 s) and breathing (45 - 55 s) which are high-lighted in Fig.4 (a). For clarity, these spectra are shown with the baseline offset by 10. In the spectrum computed from the data during breathing, it is clear that there is a large peak at around frequency of 0.4 Hz. This peak is not very obvious in the spectrum computed from the data during apnea, therefore, the peak at around 0.4 Hz can be attributed to the respiration activity of the subject. On the other hand, another peak at around 1.1-1.3 Hz are found in both spectra of breathing and apnea commonly. These peaks may be attributed to the heartbeat signals of the subject. There are other peaks at frequencies higher than 2 Hz. They could be the high harmonics of the respiration and the heartbeat signals, but that has not been confirmed yet.

3.2 Separation of Respiration and Heartbeat Signals by Using Digital Filters

Since the waveform measured by the respiration sensor seems to contain both the respiration and heartbeat signals, an attempt of separating these two signals by using software filters was made. In order to extract the respiration signals, the measured waveform shown in Fig. 5 (a) was processed by a digital low-pass filter (5th-order Butterworth filter) with the cutoff frequency of 1 Hz so that the higher frequency components including the heartbeat signals were eliminated. The respiration signals are more clearly seen after the processing as the large positive and negative peaks are shown in Fig. 5 (b). The positive and the negative peaks are attributed to the inhale and exhale activities of the subject. On the other hand, a digital band-pass filter (5th-order Butterworth filter) was applied to the measured waveform so that the heartbeat signals were extracted as shown in Fig. 6 (c). In order to eliminate the respiration signals and the noise at higher frequencies, the lower and the upper cutoff frequencies were set to be 0.5 and 2 Hz, respectively. In the filtered waveform, positive and negative peaks appear periodically approximately every 1 s. Therefore, these peaks are due to the components at 1.1-1.3 Hz in the power spectra shown in Fig. 4 (b), and may be attributed to the heartbeat signals. In order to validate the heartbeat signals, the filtered

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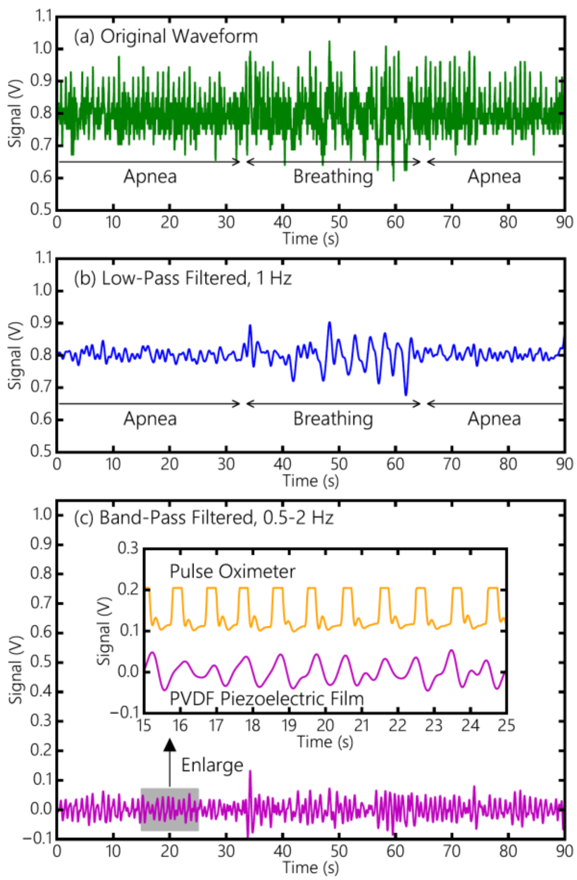

Figure 5. (a) Output signals of the respiration sensor (original waveform) measured for 90 s while the subject repeated breathing and not-breathing (apnea) for approximately every 30 s. (b) Waveform obtained by applying the digital low-pass filter to the original waveform. The cut-off frequency is 1 Hz. (c) Waveform obtained by applying the digital band-pass filter to the original waveform. The lower and upper cut-off frequencies are 0.5 and 2 Hz, respectively. (Inset of c) Comparison between the band-pass filtered waveform and the pulse oximeter waveform validating that the positive peaks appear after the filtering are attributed to the heartbeat signals.

waveform is compared with the heartbeat pulse waveform measured by a commercial pulse oximeter as shown in the inset of Fig. 5 (c). The positive peaks in the filtered waveform and the heartbeat pulses synchronize almost perfectly. Therefore, it can be confirmed that the waveform measured by the respiration sensor contains not only the respiration signals but also the heartbeat signals of the subject. Although the measured waveform was not very clean due to some noise, the respiration and the heartbeat signals can be extracted by using the software filters with the appropriate cutoff frequencies.

4 CONCLUSION

A very sensitive respiration sensor was developed using a PVDF piezoelectric film that can be attached to a bed so that the respiration activity can be monitored without direct physical contact with the subject. A charge amplifier and a band elimination filter which were required for accurate respiration monitoring were also developed. For testing purposes, the output signals of the respiration sensor were measured while a subject repeated breathing and not breathing for intervals of 30 s, and the measured waveform was investigated in detail. Through an FFT analysis, it was confirmed that the measured waveform contains not only the respiration signals but also the heartbeat signals of the subject. The respiration and the heartbeat signals could be extracted from the measured waveform by applying a low-pass and a band-pass software filter, respectively, with appropriate cut-off frequencies. Furthermore, with the filtered data, a real-time software data analysis for detecting respiration status (either breathing or apnea) and heart rate monitoring is possible.

ACKNOWLEDGEMENT

This work was financially supported in part by Program for Creating STart-ups from Advanced Research and Technology (START Program) in IoT field from Japan Science and Technology Agency, JST.

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