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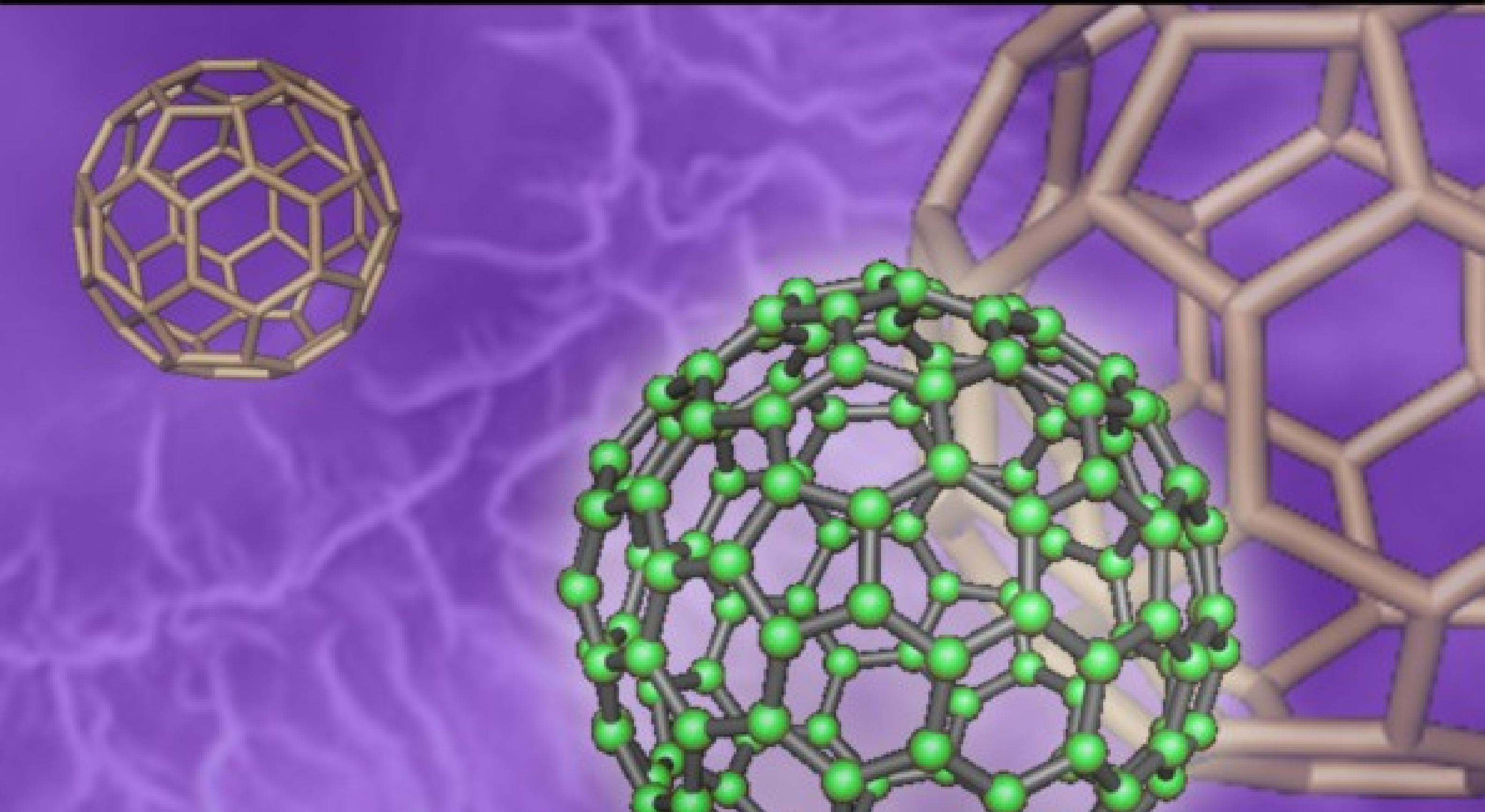

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Respiration and Heartbeat Measurement for Sleep Monitoring Using a Flexible AlN Piezoelectric Film Sensor

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Abstract: Respiratory and heartbeat monitoring during sleep provides basic physiological information for diagnosis of sleep disorders. This paper proposes a new method for non-invasive and unconstrained measurement of respiration and heartbeat during sleep. A flexible piezoelectric film sensor made of aluminum nitride (AlN) material is used for signal acquisition. The total thickness of this sensor is less than 40 μm; the thin thickness makes it imperceptible when integrated into a bed. In addition, the AlN film sensor has good sensitivity, so that pressure fluctuation due to respiration and heartbeat can be measured when a subject is lying on this sensor. The pressure fluctuation measured can be further separated into signals corresponding to respiration and heartbeat, respectively. In the proposed method, the signal separation is achieved using an algorithm based on empirical mode decomposition (EMD). From the experimental results, it was found that respiration and heartbeat signals can be successfully obtained with the proposed method. *Copyright © 2009 IFSA.*

Keywords: Aluminum nitride (AlN) film, Piezoelectric sensor, Sleep monitoring, Cardio-respiration measurement, Empirical mode decomposition

1. Introduction

Sleep apnea syndrome (SAS) is one of the common sleep disorders, and it has attracted increasing interest during the past decades. It is of clinical importance to be able to diagnose SAS in early stages. Up to present, overnight polysomnography (PSG) has been widely recognized as a standard method for sleep researches, which measures simultaneously airflow, electrocardiogram (ECG), electroencephalogram (EEG), electro-olfactogram (EOG), body movements, *etc.* during sleep [1].

However, the measurement requires attachment of a lot of sensors, such as thermistors and electrodes for EOG and EEG, to patients' body, this may cause patients feel uncomfortable and consequently affects their sleep. Another problem of PSG is that the measurement needs specialists and it is mostly available in clinical environments and laboratories.

To deal with these problems, a lot of researches have been carried out in order to assess physiological information during sleep in non-invasive and unconstrained manners. One approach to the problems is to utilize visual information based on camera systems to achieve in-sleep respiration monitoring [2-4]. However, the measurement systems are costly, so that these methods are not appropriate for public healthcare and at-home medical applications. In addition, besides respiration movements, further information, such as heartbeat rate, is desired.

Cardio-respiratory measurement systems have been developed with wearable sensors. For example, Paradiso *et al*. have proposed knitted bioclothes, where strain fabric sensors based on piezoresistive yarns and fabric electrodes are integrated into clothes [5]. Similar systems have also been developed by Gramse *et al*. [6] and Catrysse *et al*. [7]. Furthermore, Choi and Jiang proposed a belt-type wearable device, which is composed with a couple of conductive fabric sheets and a piezoelectric film sensor for heartbeat and respiration detection, respectively [8].

Alternatively, many attempts have been made to measure pressure fluctuation induced by respiration and heartbeat during sleep using pressure sensitive mattress/bed. One category of these researches uses pneumatic or hydraulic pressure measurement [9]-[13]. A mattress, filled with air or water, is placed under body. During measurement, pressure fluctuation acts on the filling in the mattress, and a highly sensitive pressure sensor is used to detect the corresponding pressure changes.

On the other hand, from 1989, piezoelectric thin films, made of polyvinylidene fluoride (PVDF) piezopolymer, have been investigated as a means to directly sense the pressure fluctuation induced by respiration, heartbeat, and body movements [14-17]. Since the PVDF piezoelectric film has small thickness, it can be easily installed in sheets and beds used in daily life, it can measure the physiological variables unobtrusively. Due to piezoelectric effect this sensor is only sensitive to change of pressure, and this feature offers a possibility to measure ballistocardiogram (BCG) during sleep. However, one major disadvantage of PVDF material is that the working temperature is low; PVDF is denatured at about 60 degree [15]. So that it is difficult to solder PVDF film to make electric connection. Usually, conductive epoxy or spring clips are used instead, which may then lead to problems of stability and fatigue durability.

In this paper, we propose a novel method for non-invasive and unconstrained measurement of respiration and heartbeat during sleep. A flexible piezoelectric thin film sensor is used for signal acquisition. This sensor is made of oriented aluminum nitride (AlN) thin film. The AlN layer is deposited on a polyimide film, and a laminated sensor structure is adopted to obtain high sensitivity and flexibility. Since AlN keeps piezoelectric characteristics at temperature up to 1150 degree, this sensor shows excellent thermal and chemical stability, and this property facilitates a variety of practical applications.

Another contribution of the present paper is a signal analysis method based on empirical mode decomposition (EMD), which is proposed in order to extract signals corresponding to respiration and heartbeat from the data measured. This decomposition method is totally data-driven, any complicated signal can be decomposed into a definite number of high frequency and low frequency components, which are called intrinsic mode functions (IMFs) [18]. The EMD technique is suited for analysis of nonlinear and non-stationary biosignals [19-20], and can extract local temporal structures like heartbeat superimposed on respiration signals [21].

This paper is organized as follows: Section II briefly introduces the flexible AlN piezoelectric thin film sensor. Then Section III explains the proposed signal acquisition system using the AlN film sensor and the EMD-based algorithm for extraction of respiration and heartbeat signals. In Section IV, performance of the proposed method is verified with experiments. Finally, Section V concludes this paper.

2. Flexible Piezoelectric AlN Thin Film Sensor

2.1. Aluminum Nitride (AlN) Film

Aluminum nitride (AlN) is one of piezoelectric ceramic materials. Because of its properties, epitaxially grown crystalline AlN has been deposited mostly on silicon wafers or sapphire substrates. Previous researches have reported that highly *c*-axis oriented AlN thin film can also be deposited on other flexible substrates, like aluminum foil [22], polyethylene terephthalate (PET) [23], and polyimide films [24]. Good piezoelectric properties can be obtained when AlN crystals grow with *c*-axis perpendicular to substrate (See Fig. 1). In this study, the AlN layer is deposited on polyimide film substrate. Polyimide film is reputed for its high thermal stability and low flammability; the upper working temperature is about 400 degree. Thicknesses of AlN layer and polyimide film are 1 μm and 8.5 μm, respectively. In addition, two platinum (Pt) electrode layers (0.1 μm) are evaporated to obtain induced electric charge. Stack structure of the AlN film is Pt-AlN-polyimide-Pt. For details of the preparation of AlN film, please refer to [24].

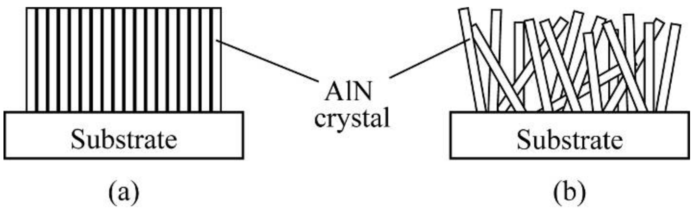

Fig. 1. AlN columnar crystal grown on substrate. (a) Oriented AlN crystals with *c*-axis perpendicular to substrate provide good piezoelectric properties, (b) AlN crystals with random orientation.

2.2. A Flexible AlN Thin Film Sensor

A flexible piezoelectric sensor is developed based on the thin AlN film and a laminated sensor structure is used to obtain high sensitivity and flexibility. Structure of the flexible AlN thin film sensor is shown in Fig. 2. An AlN film is folded up, so that we have two AlN layers laminated back to back. This makes the inner electrode be totally shielded by the outer electrode, so that (1) leakage of the induced electric charge can be prevented, and (2) the charge output may not be affected by changes in the environment electric field, this sensor is more robust to noise. On the other hand, this structure doubles the sensor sensitivity [24].

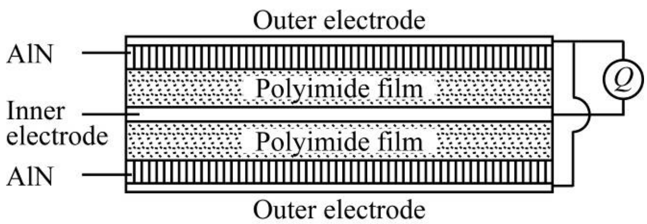

Fig. 2. Cross-sectional structure of the flexible AlN film sensor.

An access hole is made at one corner of the AlN film for the inner electrode (See Fig. 3 (a)). The sensor is covered with a copper film, which is deposited on a polyimide substrate film. Fig. 3 (b) is a picture of an AlN thin film sensor. Finally, the AlN film layers and the copper cover film are glued together using silicone rubber, and coagulation of silicone rubber is achieved by pressing the sensor between two plates. Total thickness of the AlN thin film sensor is less than 40 μm. An example of the cross-section of AlN thin film sensor is shown in Fig. 4.

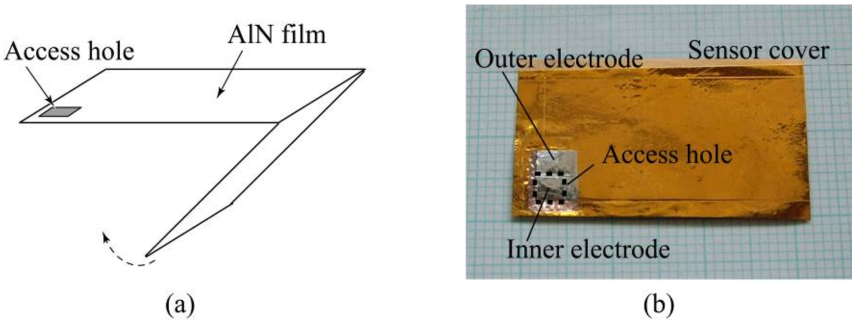

Fig. 3. The flexible AlN film sensor. (a) Folding up an AlN film to obtain a laminated sensor structure, a hole is made on one AlN film layer to enable access to the inner electrode. (b) A picture of an AlN thin film sensor.

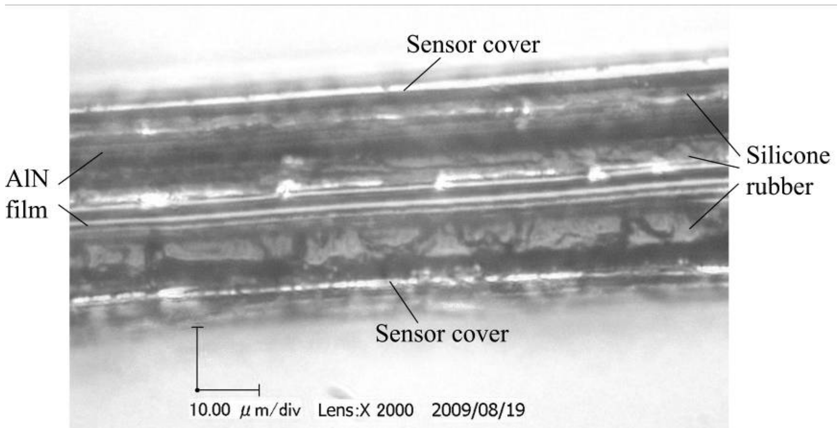

Fig. 4. Cross-section of an AlN thin film sensor, the thickness of this sensor is 30 μm. This picture was taken with a digital microscope (VHX-100, Lens: VH-Z450, Keyence).

When external force is applied to the sensor in its thickness direction, electric charge is generated on the electrodes. Then, a charge amplifier is used to convert the sensor's output into voltage signals. Suppose that an AlN film sensor is in the *x*-*y* plane. Given the external force as *f*, the output charge *Q* is

$$Q = \int_x \int_y d_{33} \sigma(x, y) dx dy \,, \tag{1}$$

where d_{33} is the piezoelectric charge coefficient, and $\sigma(x, y)$ represents the stress distribution over the sensor. It is assumed that d_{33} is 1.3 pC/N for this sensor [24]. For stress with uniform distribution, Eq. (1) can be derived as

$$Q = d_{33} A \sigma \,, \tag{2}$$

where σ is the uniform stress, and A is the electrode area. Fig. 5 gives a typical frequency response (for the range of [0.1, 70] Hz) of the AlN film sensor when external force is applied in the thickness direction. Similar frequency response of AlN films has also been reported in previous researches [23-24].

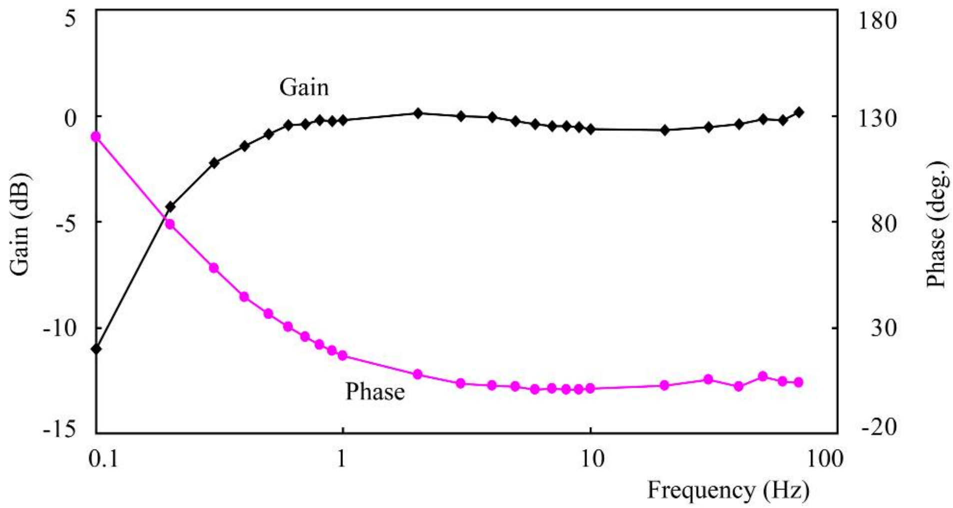

Fig. 5. Frequency response characteristics of the AlN thin film sensor.

3. The Proposed Method

3.1. Signal Acquisition using a Flexible AlN Film Sensor

A schematic view of the proposed signal acquisition system is shown in Fig. 6. The expansion and contraction of the lungs and heart result in movement of the thorax. When a human being lies in a supine position, the movement of thorax causes pressure fluctuation, $f(t)$, on the contact interface between his back and the bed, which can be detected and further used to extract physiological information on respiration and heartbeat.

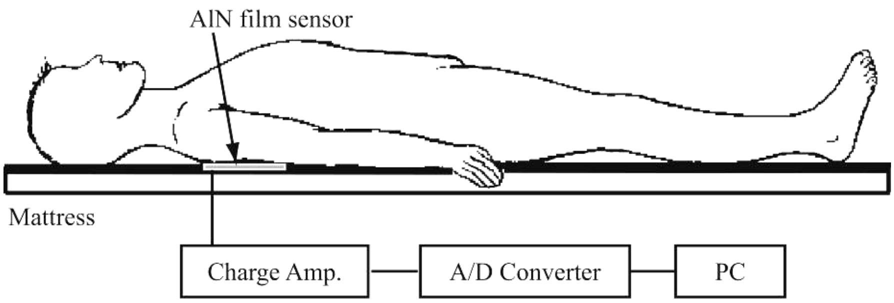

Fig. 6. Schematic view of the proposed signal acquisition system.

For signal acquisition, a flexible AlN film sensor is placed under one's back, and the location close to the heart is preferred. The thin thickness and flexibility makes this sensor fit well with surface of human body. Fig. 7 depicts examples of the pressure fluctuation signals. It is clear that small waves are riding on a basal wave corresponding to respiration movements.

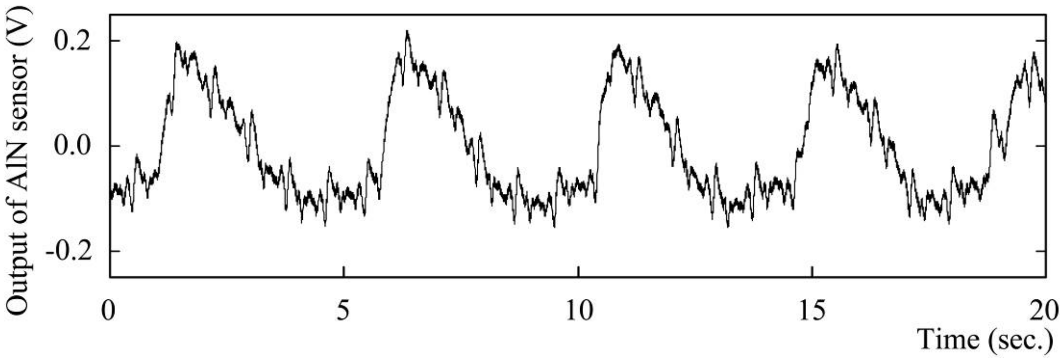

Fig. 7. Examples of the pressure fluctuation measured with a flexible AlN film sensor.

3.2. Extraction of Respiration and Heartbeat Signals

1) Decomposition: The pressure fluctuation $f(t)$ is decomposed using the empirical mode decomposition (EMD) technique. The EMD method is a sifting process that estimates intrinsic mode functions (IMFs) [18]. The IMFs must fulfill two conditions: the number of extremes and that of zero-crossing must differ at most by one; the mean value between the upper and lower envelops must close to zero. The EMD process involves the following steps:

a) Initialize residue series $r=f(t)$, and the index number of IMF i as 1.
b) Identify the extremes (both maxima and minima) of r.
c) Generate the upper and lower envelopes by connecting the maxima and minima points separately with cubic spline interpolation.
d) Point by point average the two envelops to determine the local mean value m.
e) Subtract out m from r to obtain an IMF candidate $h=r-m$.
f) Test whether h is an IMF or not:
   - If h is not an IMF, replace r with h and repeat from step (b);
   - If h is an IMF, extract the i^{th} IMF $h_i = h$.
g) Update the residue series as $r=r- h_i$, and the index $i=i+1$, repeat steps (b) to (f) by sifting the residual signal. The process ends when r satisfies a predefined stopping criterion.

The sifting process decomposes $f(t)$ into locally orthogonal modes that are zero-mean oscillatory components. Since the process is adaptive, no deformation would be introduced like wavelet analysis and band-pass filtering. For details of EMD, please refer to [18]. Also, an on-line version of the EMD method has been introduced in [25].

2) Reconstruction: After the EMD process, the pressure fluctuation $f(t)$ can be expressed as

$$f(t) = \sum_{i=1}^{n} h_i + r \,, \tag{3}$$

where n is the number of IMFs. Then, the IMFs corresponding to respiration and heartbeat are determined according to their peak frequencies. In this study, the IMF whose peak frequency, PF_i (i=1,2,…,n), is in the range of 0.1-0.5 Hz is determined as a component of respiration, while the range for heartbeat is 1.0-10 Hz. Then, we can reconstruct the signals of respiration and heartbeat as

$$x_r = \sum_i h_i \qquad (PF_i \in [0.1, 0.5] \text{ Hz}) \,, \tag{4}$$

$$x_h = \sum_i h_i \qquad (PF_i \in [1.0, 10] \text{ Hz}) \,, \tag{5}$$

respectively. With these data, further investigation can be conducted to estimate respiration sinus arrhythmia (RSA), heart rate variability (HRV), sleep status, *etc.*

4. Experiments

In order to evaluate the proposed method, signal measurement and decomposition of respiration and heartbeat components were conducted.

4.1. Experimental Conditions

A flexible AlN piezoelectric film sensor was attached to the mattress using signal-coated tape. Dimension of the AlN sensor was 20 mm in width and 30 mm in length. Signals of the AlN sensor were input into a charge amplifier (Model-4001B, Showa Sokki Corp.). The sensitivity of the charge amplifier was set at 20 mV/pC. In order to evaluate the proposed method, recordings of respiration and ECG signals were performed via a telemetry system (MT11, NEC Medical Systems Corp.). A belt-type respiration sensor was wrapped around subject's epigastric region, and the locations of electrodes for ECG measurement were right shoulder (positive), left waist (negative), and left shoulder (ground). Then, the voltage signals from both the AlN sensor and the telemetry system were acquired with a 14-bit A/D converter (USB-6009, National Instruments), and the sampling frequency was 500 Hz in these experiments. During the experiments, the subjects slept comfortably on a mattress, and they were instructed to relax. Measurement of the sensor signals was conducted when subjects fell asleep.

4.2. Experimental Results

Fig. 8 shows examples (60 seconds) of the IMFs and the residue decomposed from the pressure fluctuation $f(t)$ of one subject (female, 25 years old). The EMD process produces thirteen IMFs and one residue signal. The first three IMFs can be treated as noise signals, while the 12th and the 13th IMFs are trend in the data. The major part of the recordings is contained in the other IMFs. According to the frequency ranges mentioned in the previous section, the IMFs corresponding to respiration and heartbeat are determined. The power spectra of these IMFs are illustrated in Fig. 9.

Then, x_r and x_h are reconstructed using Eqs. (4) and (5), respectively. The respiration component, x_r, which is sum of the 9th to the 11th IMFs, is shown in Fig. 10. It can be observed that the respiration component agrees well with the respiration signals measured with the traditional sensor. Since the locations of two sensors differ, a small time lag can be found between two signals.

Fig. 11 depicts the first ten seconds of ECG signals and the heartbeat component extracted from the pressure fluctuation $f(t)$ shown in Fig. 8. A temporal structure, which is surrounded by a dotted square, can be recognized in the extracted heartbeat component in Fig. 11. This temporal structure repeats, and each one corresponds to a heartbeat in the ECG signals. The heartbeat component, x_h, can be considered as a kind of ballistocardiogram (BSG) [26]. Using indexing techniques of time series, e.g. dynamic time warping [27], such temporal structure can be recognized for calculation of heartbeat rate.

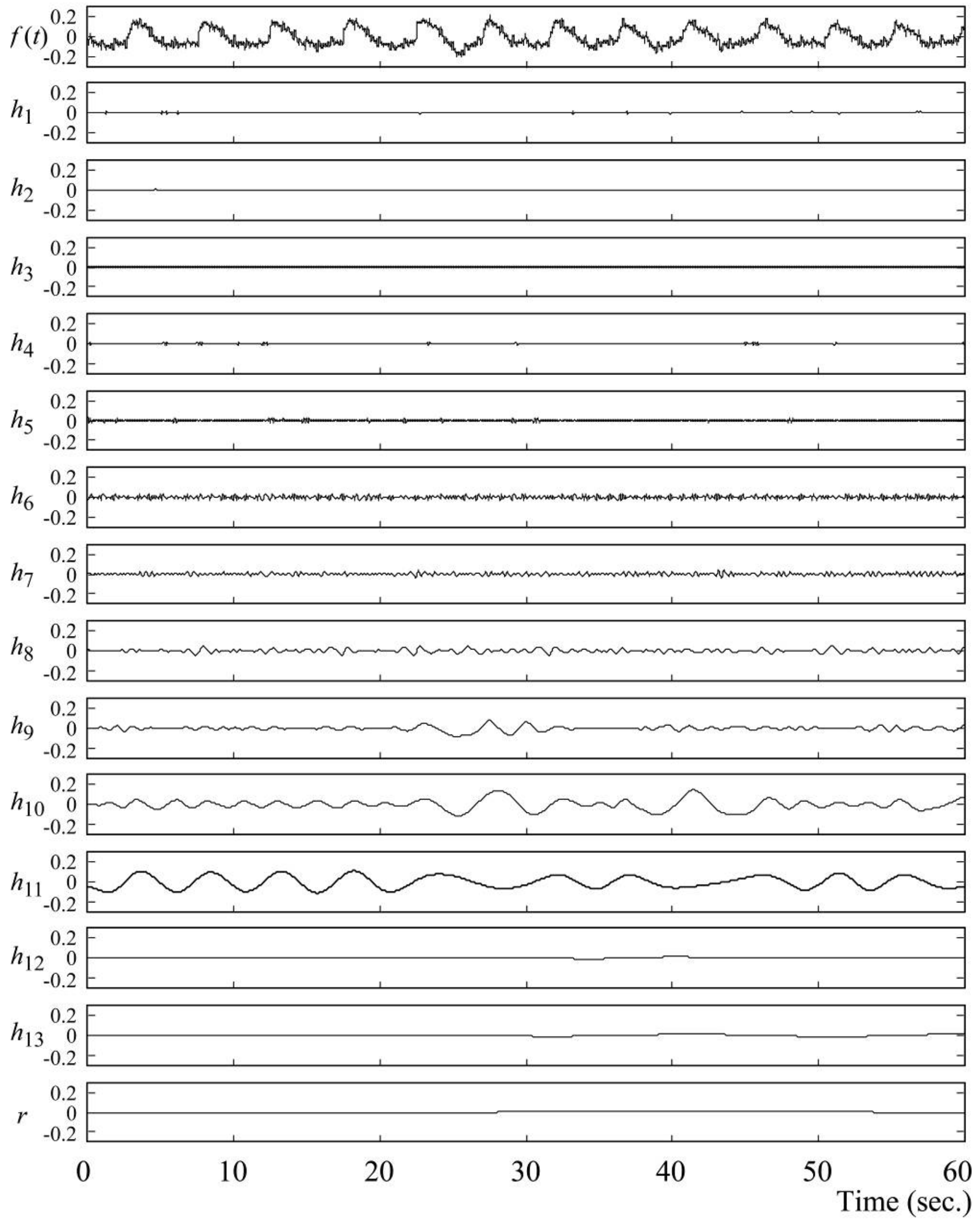

Fig. 8. Examples of the IMFs and the residue decomposed from the pressure fluctuation $f(t)$.

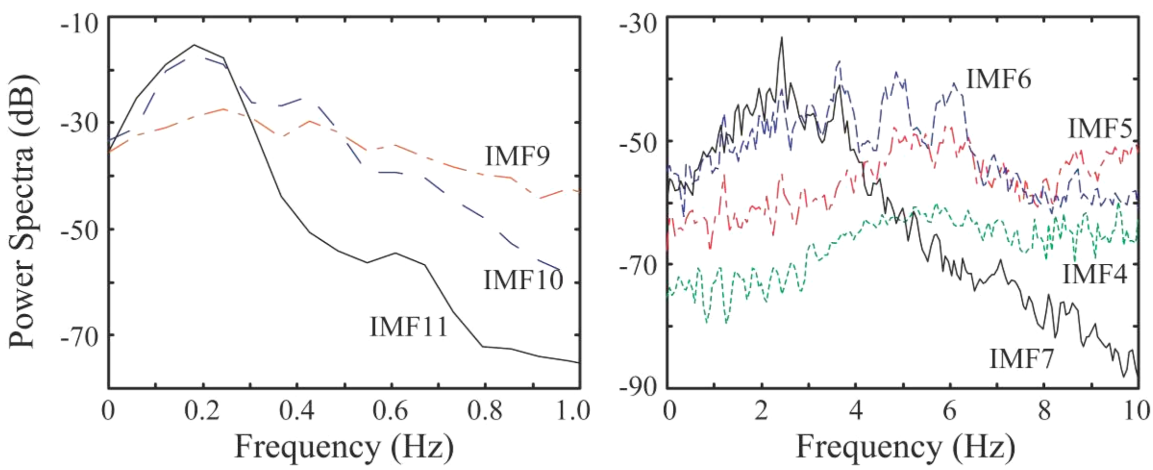

Fig. 9. Power Spectra of the IMFs corresponding to respiration (left) and heartbeat (right).

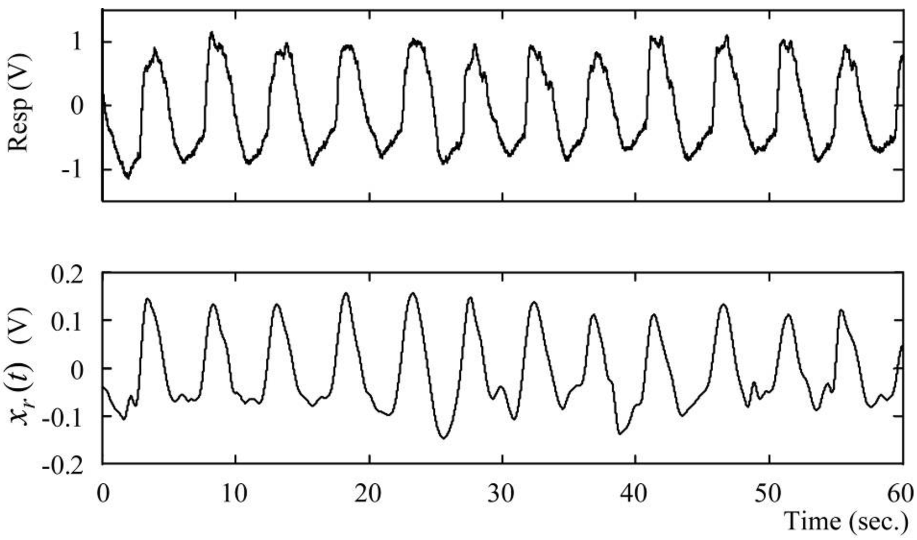

Fig. 10. Examples of respiration signals (top) and the component of respiration $x_r(t)$ (bottom).

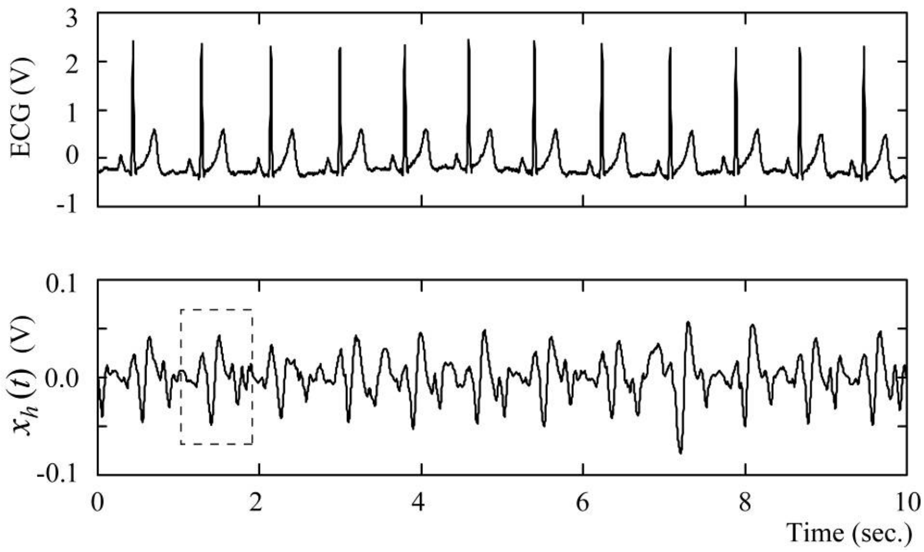

Fig. 11. Examples of ECG signals (top) and the component of heartbeat $x_h(t)$ (bottom).

Fig. 12 depicts examples of the experimental results of another subject (female, 37 years old). It should be noticed that the data of heartbeat in Figs. 12 (c) is the first ten seconds. The data is enlarged to show the details. From this figure, the patterns of both respiration and heartbeat can be clearly recognized; the temporal structures corresponding to heartbeat are marked with dotted squares.

In Fig. 12 (b), x_r does not agree well with the respiration signals around 25 second. During the experiments, the subject snored occasionally. As the amplitude of pressure fluctuation is small, the extraction algorithm may be sensitive to artifacts or relatively large noises. Also, the locations of the AlN sensor and the traditional respiration sensor should be considered as well. The respiration sensor was used to measure respiration movement of the abdomen, while the AlN sensor was installed under the thorax. The disagreement may correctly represent different movements of the abdomen and the thorax during snoring. Further experiments are needed for detailed investigation.

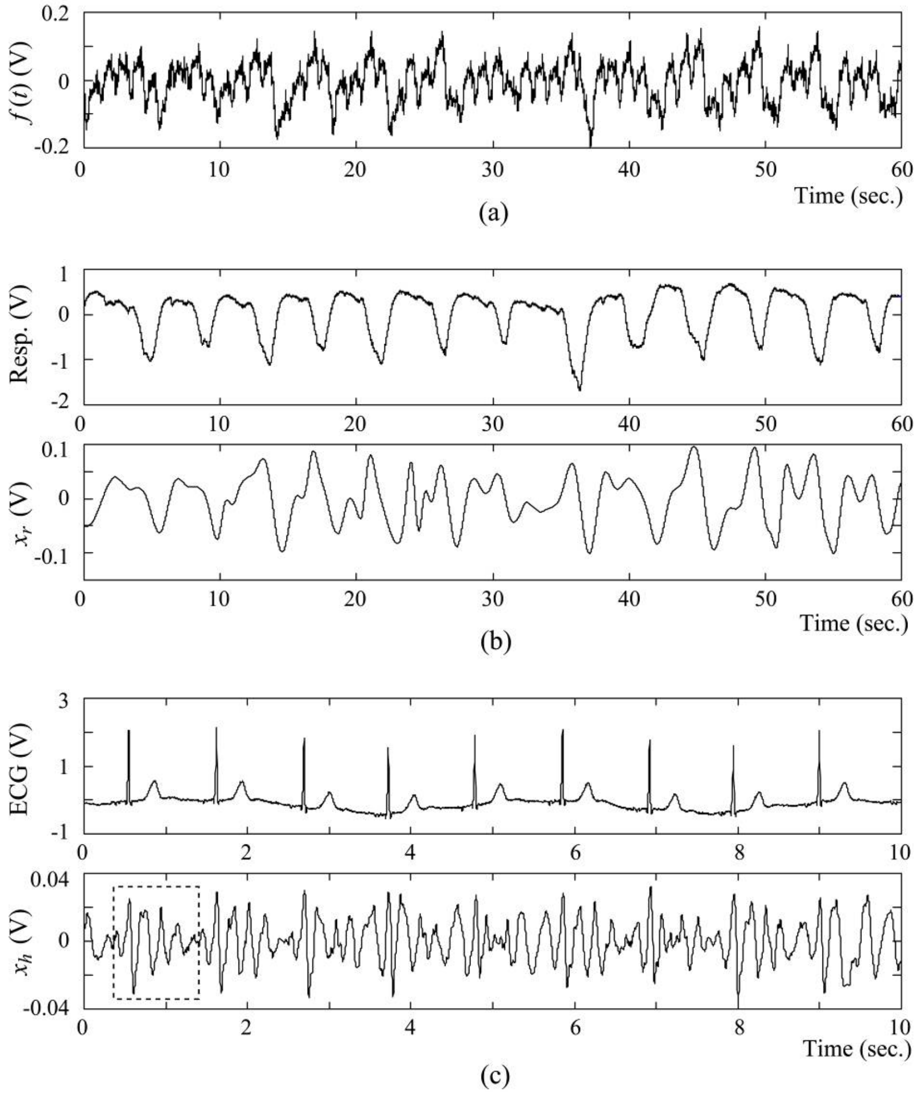

Fig. 12 Examples of experimental results. (a): Pressure fluctuation $f(t)$; (b): Respiration signals and the extracted respiration component $x_r(t)$; (c): ECG signals and the extracted heartbeat component $x_h(t)$.

5. Conclusions

In this study, a non-invasive and unconstrained method has been proposed for measurement of respiration and heartbeat information during sleep. The proposed method utilizes a novel flexible AlN piezoelectric film sensor for signal acquisition. Since this sensor is sensitive, both movements due to respiration and heartbeat can be measured. To separate the signals from noise and background trend, an EMD-based algorithm is used. Results in the evaluation experiments suggest that the proposed method can measure and extract signals of respiration and heartbeat successfully.

In the future research, we would like to increase the number of subjects, additional experiments are needed to evaluate the proposed method over other subjects. Comparison between healthy subjects and patients with sleep apnea is helpful to improve the proposed method. In addition, we would like to enhance the signal extraction algorithm used in the proposed method. Also, sleep conditions, such as thickness of clothes, characteristics of bed and placement of sensor, should be investigated. Moreover, a temporal recognition method is required for automated detection of the temporal structures in the signals.

Acknowledgements

The authors would like to gratefully acknowledge participation of the volunteers in this study.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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