Proceedings of the 29th Annual International
Conference of the IEEE EMBS
Cité Internationale, Lyon, France
August 23-26, 2007.

Monitoring of Respiration and Heartbeat during Sleep using a Flexible Piezoelectric Film Sensor and Empirical Mode Decomposition

Nan Bu, Naohiro Ueno and Osamu Fukuda

Abstract— **Cardio-respiratory monitoring during sleep is one of the basic means for assessment of personal health, and has been widely used in diagnosis of sleep disorders. This paper proposes a novel 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 in this study. This sensor measures pressure fluctuation due to respiration and heartbeat on the contact surface when a subject is lying on it. Since the AlN film sensor has good sensitivity, 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). Experiments have been conducted with three subjects. The experimental results show that respiration and heartbeat signals can be successfully obtained with the proposed method.**

I. INTRODUCTION

Sleep apnea syndrome (SAS) is one of the common sleep disorders, and it has attracted increasing interest in the past years. It is of clinical importance to be able to diagnose SAS in early stage. To date, overnight polysomnography is widely recognized as the gold-standard for sleep research, which typically measures airflow, electrocardiogram (ECG), electroencephalogram (EEG), electro-olfactogram (EOG), body movement, *etc*., simultaneously [1]. However, the measurement requires attachment of sensors, such as thermistors and electrodes, to patients' body, which may cause patients discomfort.

Several methods have been developed to assess physiological information during sleep in non-invasive and unconstrained manners. Nishida *et al.* [2] and Aoki *et al.* [3] used visual information measured with cameras to achieve in-sleep respiration monitoring. Although these methods need no contact with patients, there are limitations that the measurement systems are costly and not appropriate for public healthcare and at-home medical applications.

Alternatively, attempts have been made to measure pressure fluctuation induced by respiration and heartbeat during sleep, using air mattresses [4], [5], an under-pillow sensor [6], and pressure sensors [7], [8]. For example, a pneumatic biomeasurement method is adopted in [4]. In this method, human movements act on the air in a mattress, and a supersensitive pressure sensor is used to detect the corresponding air pressure changes. In [7], thin film pressure sensors made of piezoresistive polymer are attached to the surface of bed, and respiration and posture signals are obtained from the pressure distribution. After the pressure fluctuation due to respiration and heartbeat has been measured, there is another problem that how to extract these components correctly. To this end, traditional methods are usually based on filtering with predefined frequency bands [4], [5]. On the other hand, wavelet transformation (WT) is an alternative approach [6], [8]. All the methods mentioned have their own advantage and disadvantage.

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, proposed by Ueno *et al.* [9], is used for signal acquisition. Piezoelectric film sensors are utilized in unconstrained cardio-respiratory monitoring during sleep, for reasons that these sensors are sensitive and only respond to dynamic change of pressure. Also, thin thickness of these sensors enables that they can be easily installed in sheets and beds used in daily life, and may not affect the sleep of patients. Wang *et al.* [8] have developed a polyvinylidene fluoride (PVDF) piezopolymer sensor for unconstrained in-sleep cardio-respiratory monitoring. However, one major disadvantage of PVDF material is the difficulty in soldering PVDF to make electric connection. Usually, conductive epoxy or spring clips are used instead, which may then lead to problems of stability and fatigue durability. The piezoelectric sensor used in this study is made of aluminum nitride (AlN). The AlN layer is deposited on a polyimide film, and a laminated sensor structure was developed to obtain high sensitivity and flexibility [9]. Since AlN keeps piezoelectric characteristics at temperature up to 1150 ℃, this sensor shows excellent thermal and chemical stability, and this property facilitates a variety of practical applications [10].

Empirical mode decomposition (EMD), proposed by Huang *et al.* [11], is employed to extract signals corresponding to respiration and heartbeat from the data measured. Different from decomposition methods based on WT, this method is data-driven, and one does not need to define a mother wavelet beforehand. With this technique, any complicated signal can be decomposed into a definite number of high frequency and low frequency components, which are called intrinsic mode functions (IMFs). This technique is suited for analysis of nonlinear and non-stationary biosignals [12], [13], and can extract local temporal structures like heartbeat superimposed on respiration signals [14].

This paper is organized as follows: Section II explains details of the proposed signal acquisition system using a flex-

The authors are with the On-site Sensing and Diagnosis Research Laboratory, National Institute of Advanced Industrial Science and Technology (AIST), 807-1, Shuku-machi, Tosu, Saga, 841-0052, JAPAN. bu@ieee.org

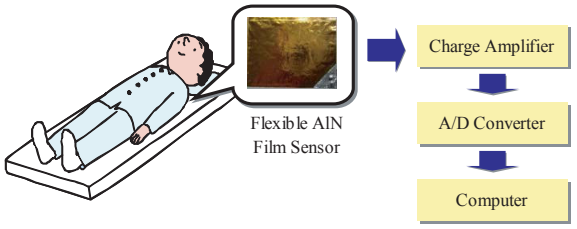

Fig. 1. Schematic view of the proposed signal acquisition system.

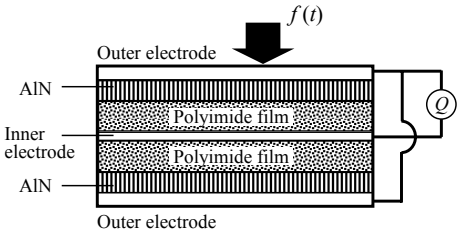

Fig. 2. Laminated structure of the flexible AlN film sensor.

ible piezoelectric film sensor and the EMD-based algorithm for extraction of respiration and heartbeat signals. In Section III, performance of the proposed method is verified with experiments of three healthy subjects. Finally, Section IV concludes this paper.

II. METHOD

A. Signal Acquisition using a Flexible AlN Film Sensor

A schematic view of the proposed signal acquisition system is shown in Fig. 1. The expansion and contraction of the lungs and heart result in movement of the thorax. When a human being lies on his back, the movement of thorax causes pressure fluctuation, $f(t)$, on the contact surface between his back and the bed, which can be detected and monitored to determine respiration and heart rate.

For signal acquisition, a flexible AlN film sensor is placed under one's back, and the location close to the heart is preferred. This sensor consists of three Pt electrode layers, two AlN layers, and two polyimide films (see Fig. 2); the total thickness is less than 40 μm. The thin thickness and flexibility makes this sensor fit well with surface of human body. Since the inner electrode is shielded by the outer electrodes, this sensor is robust to noise. Also, two AlN layers improve the sensitivity. A charge amplifier is used to convert the sensor's output into voltage signals.

Fig. 3 depicts an example of the pressure fluctuation signals. It is clear that small waves are riding on the main wave corresponding to respiration.

B. Extraction of Respiration and Heartbeat Signals

1) Decomposition: The pressure fluctuation $f(t)$ is decomposed using the EMD method. The EMD method is a sifting process that estimates IMFs [11]. The IMFs must fulfill two conditions: the number of extrema and that of zero-crossing must differ at most by one; the mean value

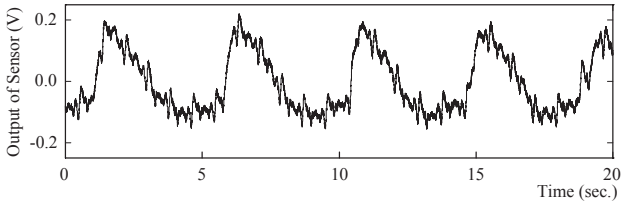

Fig. 3. An example of the pressure fluctuation measured with a flexible AlN film sensor.

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 extrema (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 ith 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 WT analysis. For details of EMD, please refer to [11]. Also, an on-line version of the EMD method is introduced in [15].

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

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

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 $(i = 1, 2, \cdots, n)$, 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

$$x_r = \sum_i h_i \quad (PF_i \in [0.1, 0.5] \text{ Hz}), \tag{2}$$

$$x_h = \sum_i h_i \quad (PF_i \in [1.0, 10] \text{ Hz}), \tag{3}$$

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

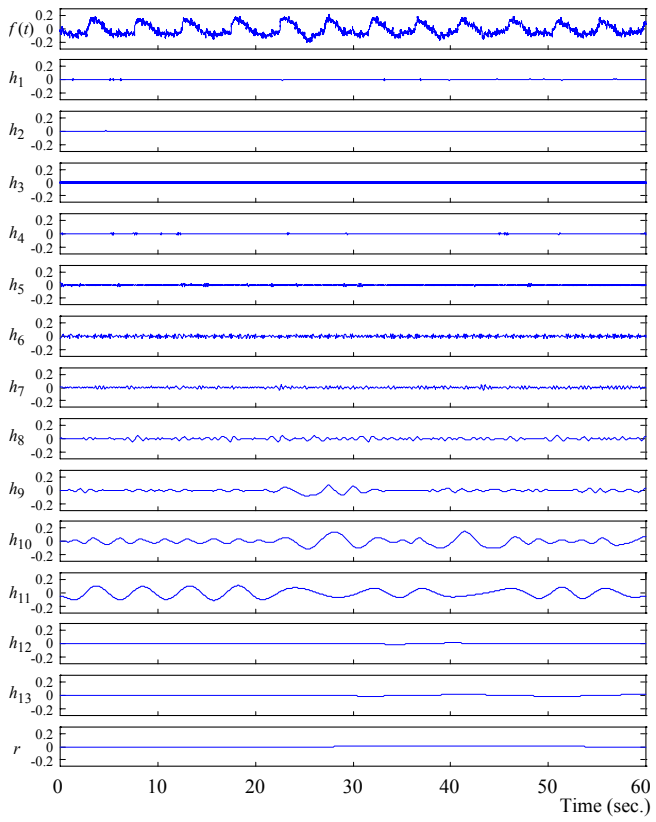

Fig. 4. Examples of the intrinsic mode functions (IMFs) and the residue decomposed from the pressure fluctuation $f(t)$ (Subject A).

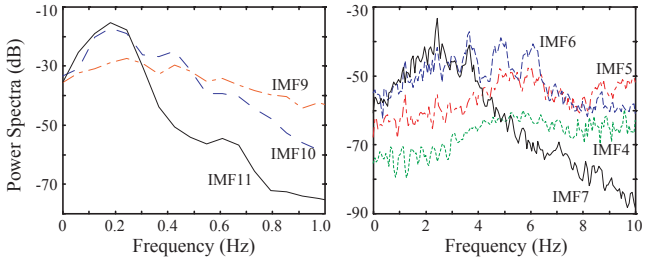

Fig. 5. Power Spectra of the IMFs corresponding to respiration (left) and heartbeat (right).

III. EXPERIMENTAL RESULTS

Three healthy subjects (two female, one male) participated in the experiments. Two sets of data were measured when the subjects slept on a sheet and on an air mattress, respectively. During the experiments, the subjects were comfortably sleeping.

A flexible AlN piezoelectric film sensor was attached to the bed using signal-coated tape. Dimension of the AlN sensor was 20 mm × 30 mm. Signals of the AlN sensor were input into a charge amplifier (Model-4001B, Showa Sokki Corp.). The sensitivity of the charge amplifier was 50 pC/mV. In order to evaluate the proposed method, recordings of respiration and ECG were performed via a telemetry system (MT11, NEC Medical Systems Corp.). A belt-type respiration sensor was wrapped around subject's epigastric

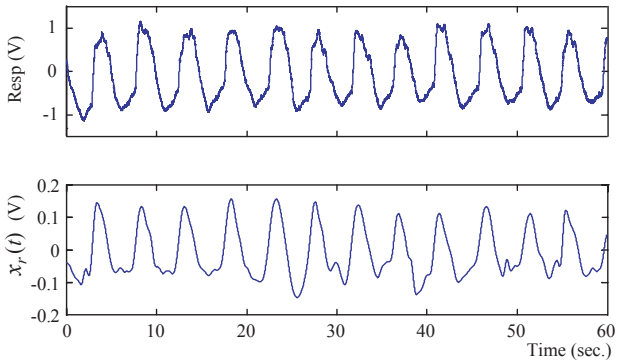

Fig. 6. Examples of respiration signals (top) and the component of respiration, $x_r(t)$, (bottom).

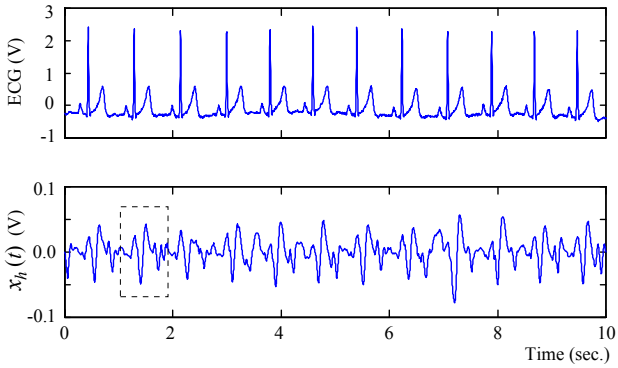

Fig. 7. Examples of ECG signals (top) and the component of heartbeat, $x_h(t)$, (bottom).

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.

A. Evaluation Experiments

Data measured when the subjects slept on a sheet was examined. Fig. 4 shows examples of the IMFs and the residue decomposed from the pressure fluctuation $f(t)$ of Subject A (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 body of the recording is contained in the rest 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. 5.

Then, x_r and x_h are reconstructed using (2) and (3), respectively. The respiration component, x_r, which is sum of the 9th to the 11th IMFs, is shown in Fig. 6. 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 the signals.

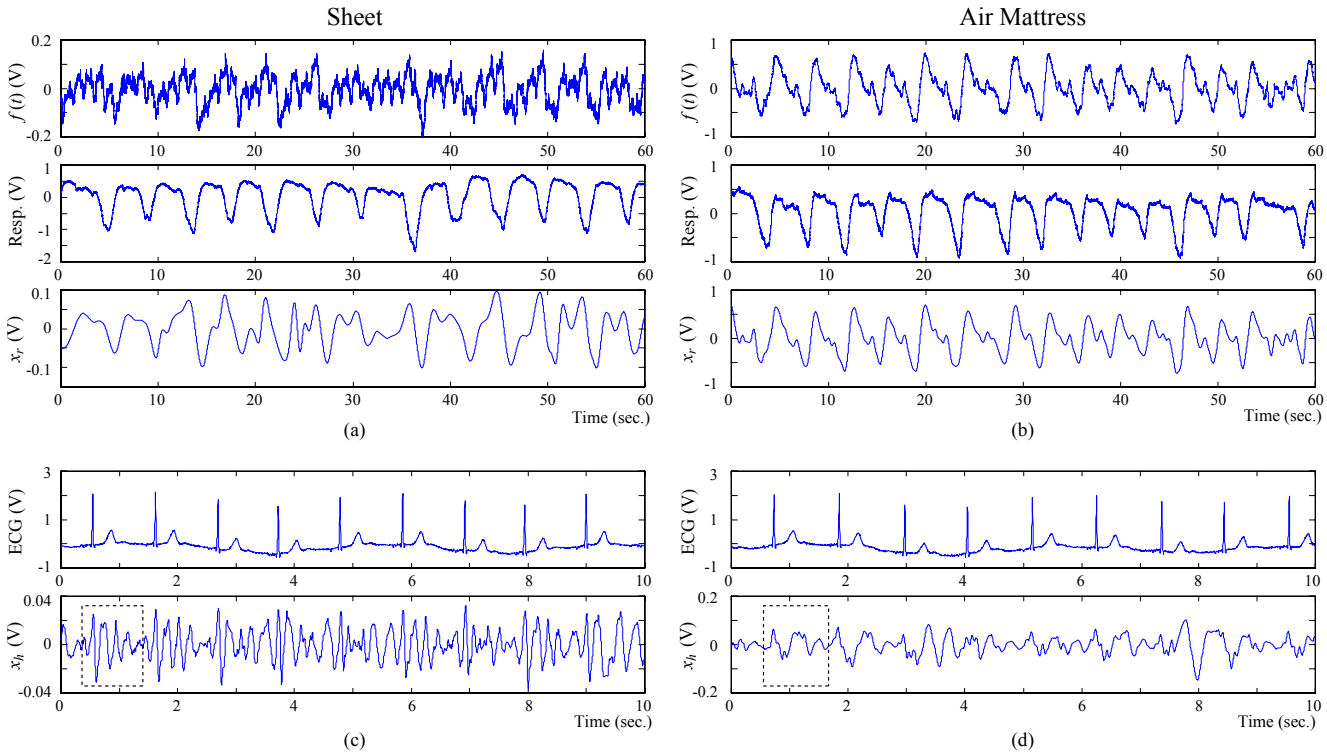

Fig. 8. Comparison between experiments using sheet and air mattress (Subject B). (a), (b): Pressure fluctuation $f(t)$, respiration signals, and the extracted component of respiration $x_r(t)$; (c), (d): ECG signals and the extracted component of respiration $x_h(t)$.

Fig. 7 depicts the first ten seconds of ECG signals and the heartbeat component extracted from the pressure fluctuation $f(t)$ shown in Fig. 4. A temporal structure, which is surrounded by a dotted square, can be recognized in the extracted heartbeat component in Fig. 7. This temporal structure repeats, and each one corresponds to a heartbeat in the ECG signals. Using indexing techniques of time series, e.g. dynamic time warping [16], this temporal structure can be recognized for calculation of heart rate.

In the experiments of subjects B and C, similar results were obtained. Some examples of experimental results of Subject B is shown in the following subsection.

B. Comparison Experiments

Experimental data measured when the subjects slept on sheet and air mattress was compared. In the experiments using sheet and air mattress, attempt was made to locate the AlN sensor to the same place. Fig. 8 depicts examples of the experimental results of Subject B (female, 37 years old). It should be noticed that the data of heartbeat, which is shown in Figs. 8.(c) and (d), is the first ten seconds of data in Figs. 8.(a) and (b). The data is enlarged to show the details.

In both experimental conditions, the respiration and heartbeat information can be recognized from the signals, x_r and x_h, which are extracted from pressure fluctuation $f(t)$. Comparing the pressure fluctuation of two conditions, amplitude of the data measured using air mattress is larger than that using sheet. This is due to the difference in elastic characteristics between the sheet and the air mattress. Also, the signal to noise ratio in case of air mattress is better than that of sheet. From Figs. 8, the patterns of both respiration and heartbeat can be clearly recognized, the temporal structures corresponding to heartbeat are marked with dotted squares in Figs. 8.(c) and (d). On the other hand, it should be noted that the trend of pressure fluctuation in each respiration cycle is different between two conditions. Characteristics of the *bed* affect the dynamics of pressure fluctuation, and they must be considered in further data analysis and investigation processes.

In Fig. 8.(a), x_r does not agree well with the respiration signals around 25 second, however, it is correctly extracted from the pressure fluctuation. 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.

IV. CONCLUSION

In this study, a non-invasive and unconstrained method was 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. Then, comparison experiments were conducted between measurement using a sheet and an air mattress.

In the future research, additional experiments are needed to evaluate the proposed method over other subjects, and comparison between healthy subjects and patients with sleep apnea is helpful to improve the proposed method. 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.

V. ACKNOWLEDGMENTS

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

REFERENCES

[1] T. Penzel and R. Conradt, "Computer based sleep recording and analysis", *Sleep Med. Rev.*, vol.4, 2000, pp. 131-148.

[2] Y. Nishida, T. Mori, H. Mizoguchi, and T. Sato, "Sleep apnea syndrome diagnosis based on image processing", *Journal of the Robotics Society of Japan*, vol.16, 1998, pp. 140-147. (in Japanese)

[3] H. Aoki, Y. Takemura, K. Mimura, H. Aoki and M. Nakajima, "A non-contact and non-restricting respiration monitoring method for a sleeping person with a fiber-grating optical sensor", *Sleep Biol. Rhythms*, vol. 1, 2003, pp. 249-250.

[4] T. Watanabe and K. Watanabe, "Noncontact method for sleep stage estimation", *IEEE Trans. Biomed. Eng.*, vol. 51, 2004, pp. 1735-1748.

[5] Y-J. Chee, J-M. Han, J-W. Youn and K-S. Park, "Air mattress sensor system with balancing tube for unconstrained measurement of respiration and heart beat movements", *Physiol. Meas.*, vol. 26, 2005, pp. 413-422.

[6] X. Zhu, W. Chen, T. Nemoto, Y. Kanemitsu, K. Kitamura, K. Yamakoshi, "Accurate determination of respiratory rhythm and pulse rate using an under-pillow sensor based on wavelet transformation", *Proc. of 27th Annual Inter. Conf. of the IEEE Engineering in Medicine and Biology Society*, 2005, pp. 5869-5872.

[7] Y. Nishida, T. Hori, "Non-invasive and unrestrained monitoring of human respiratory system by sensorized environment", *Proc. of 1st IEEE Intern. Conf. on Sensors*, Orlando, FL, 2002, pp. 62.4(1)-(6).

[8] F. Wang, M. Tanaka, and S. Chonan, "Development of a PVDF piezopolymer sensor for unconstrained in-sleep cardiorespiratory monitoring", *J. Intell. Mater. Syst. Struct.*, vol. 14, 2003, pp. 185-190.

[9] N. Ueno, M. Akiyama, K. Ikeda, and H. Takeyama, "A foil type pressure sensor using nitelide aluminum thin film", *Trans. of SICE*, vol. 38, 2002, pp. 427-432. (in Japanese)

[10] M. Akiyama *et al.*, "Flexible piezoelectric pressure sensors using oriented aluminum nitride thin films prepared on polyethylene terephthalate films", *J. Appl. Phys.*, vol. 100, 2006, Article No. 114318.

[11] N.E. Huang *et al.*, "The Empirical Mode Decomposition and Hilbert Spectrum for Nonlinear and Non-stationary Time Series Analysis", *Proc. Roy. Soc. Lond. A*, vol. 454, 1998, pp. 903-995.

[12] H.L. Liang, S.L. Bressler, R. Desimone, and P. Fries, "Empirical Mode Decomposition: A Method for Analyzing Neural Data", *Neurocomputing*, vol. 65-66, 2005, pp. 801-807.

[13] S. Charleston-Villalobos, R. González-Camarena, G. Chi-Lem, and T. Aljama-Corrales, "Crackle Sounds Analysis by Empirical Mode Decomposition", *IEEE Eng. Med. Biol. Mag.*, vol. 26, no. 1, 2007, pp. 40-47.

[14] R. Balocchi *et al.*, "Deriving the Respiratory Sinus Arrhythmia From the Heartbeat Time Series using Empirical Mode Decomposition", *Chaos, Solitons and Fractals*, vol. 20, 2004, pp. 171-177.

[15] G. Rilling, P. Flandrin, and P. Goncalvès, "On empirical mode decomposition and its algorithms", *in IEEE-EURASIP Workshop on Nonlinear Signal and Image Processing*, 2003.

[16] E. Keogh and C.A. Ratanamahatana, "Exact indexing of dynamic time warping", *Knowl. Inform. Syst.*, vol. 7, 2005, pp. 358-386.