

## Development of Unconstrained Bio-signals Sensing Devices by Piezo Ceramic

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**ABSTRACT :** This paper describes a novel noninvasive, unconstrained and unconscious bio-signals sensing bed. The sensing bed detects heartbeat, respiration, body movement and posture change of a person laying or sleeping on the bed. These bio-signals provide not only the basic medical information but also the sophisticated sleeping condition information. Thus it can be used to monitor health condition of healthy persons spending their home at night as well as the patient persons in hospital. Further it can detect the emergent change in the physical condition at home and/or hospital. The basic device used in the sensing is the piezo-ceramics bonded to the stainless steel plate which is sandwiched by floor and four feet of a bed. Thus no special bed is required. The devices detect the bio-signals above generated as mechanical vibrations. The device has the wide dynamic range and high SN ratio so that it can detect from the micro-vibration due to heart beat to the change in the force acted when a person rides on the bed without saturation. It clearly detects the heart beat and respiration as well as it detects how a person on the bed moves. The devices can be applied to variety of health monitoring including sleep and medical application for diseases for the circulatory system and those accompanied with itchy.

**Keywords :** unconstrained bio-sensing, heartbeat, respiration, posture changing

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### 1. INTRODUCTION

In the aging society, it is more important for senior citizens to maintain and further improve their health and to lead active lives than staying in hospital. Monitoring of bio-signals in various situations in the home, outdoor and bed room is helpful for daily control of health conditions. In the day time, the use of wrist actigraphy provides not only the activities but the sleeping condition at night. Variety of researches has carried out in conjunction of the day time activity and sleep [1], [2], [3]. Recently authors have presented an ambient intelligent approach for ubiquitous health monitoring at home which detects the bio-signals when a person is on flooring, on tatami mat, in the bathtub, and in the lavatory at home [4] based on the pneumatic method [5]. This method also detects the bio-signal in day time. Further, authors expand this idea to the outside of home by using a mobile phone by designing a low frequency microphone for detecting bio-signals [6]. The method which complements the bio-signals in the night time

is the bed sensing method and typical examples are in the literatures [7], [8],[9],[10],[11],[12]. This paper is one of the bed sensing methods. The bed sensing methods detects body movements, the heart beat and respiration through mechanical vibration by for example highly sensitive accelerometer or pressure vibration in a mattress in which a very sensitive pressure sensor is plugged in. Thus if the gain of the sensor is set to detect the heart beat which is detected as the very small vibration, body movement saturates the sensing devices. Further even the sensor is sensitive, a pre-amplifier with high gain and filters to enhance the heart beat signal were required.

In this paper, a bed sensing method with wide dynamic range and high SN ratio so that it can detect from the micro-vibration due to heart beat to the change in the force acted when a person rides on the bed, without saturation, and without preamplifier thus without any voltage resource. The sensing device generates the voltage corresponding to the bio-signals of heart beat, respiration, body movement and changes in the laying posture of a person on the bed.

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## 2. BED SENSING SYSTEM

### 2. 1 System

Fig.1 shows the proposed bed sensing system. The four piezo-ceramics bonded to the stainless steel plate to support the weight of a bed and person on it are set between the floor and the four feet of bed. Because the piezo-ceramic have the capacitive characteristics as will be described in the following section, in the steady state condition when the constant force acting to the stainless plate and force by the weight and gravity is balanced, the output voltage changes from zero voltage.

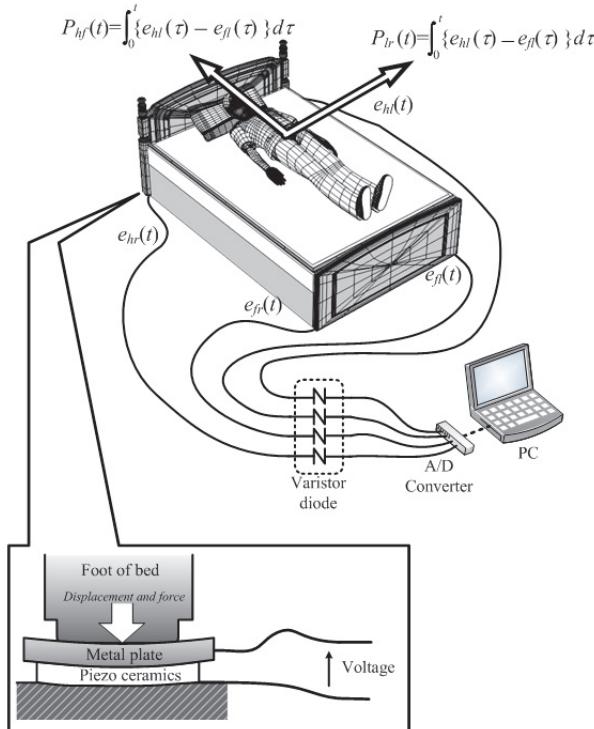


Fig. 1 Bed sensing method by piezo ceramics

The variables and constants for the piezoceramic devices and the system shown in Fig. 1 are defined as follows:

#### [Piezoceramics]

$A$  [C/m] or [N/V]: force factor of the piezo-ceramic device

$m$  [kg]: mass on the device, which is part of the mass of the bed and the person on it

$k$  [N/m]: stiffness constant of the metal stainless steel plate

$d$  [Ns/m]: damping coefficient of the metal plate

$C$  [F]: capacitance between the piezo-ceramic devices

$R$  [ $\Omega$ ]: input resistance of the processor

$t$ [s]:	time
$x_i(t)$ [m]:	displacement of the stainless steel plate by external strain or bend
$x(t)$ [m]:	resultant displacement of the stainless steel plate
$f(t)$ [N]:	force generated by the device
$q_i(t)$ [C]:	electric charge generated by external strain or bend to the ceramics
$q(t)$ [C]:	resultant electric charge in the ceramics
$e(t)$ [V]:	output voltage between the electric resistance
$x_{hr}(t)$ [m]:	displacement of the device plate set at the head, right corner
$x_{hl}(t)$ [m]:	displacement of the device plate set at the head, left corner
$x_{fr}(t)$ [m]:	displacement of the device plate set at the foot, right corner
$x_{fl}(t)$ [m]:	displacement of the device plate set at the foot, left corner
$e_{hr}(t)$ [V]:	output voltage due to $x_{hr}(t)$
$e_{hl}(t)$ [V]:	output voltage due to $x_{hl}(t)$
$e_{fr}(t)$ [V]:	output voltage due to $x_{fr}(t)$
$e_{fl}(t)$ [V]:	output voltage due to $x_{fl}(t)$
$P_{fh}(t)$ [Vs]:	integrated value of the difference of $e_{fl}(t) - e_{hl}(t)$
$P_{rl}(t)$ [Vs]:	integrated value of the difference of $e_{hr}(t) - e_{hl}(t)$
[Bed]	
$g$ [m/s <sup>2</sup> ]:	magnitude of the acceleration of gravity
$M$ [kg]:	weight of the bed with a person on it
$L$ [m]:	length of the bed
$L_f$ [m]:	length from the center of gravity to the foot of the bed
$L_h$ [m]:	length from the center of gravity to the head of the bed
$W$ [m]:	width of the bed
$W_l$ [m]:	length from the center of gravity to the left side of the bed
$W_r$ [m]:	length from the center of gravity to the right side bed of the bed
$D$ [Ns/m]:	damping coefficient of the bed
$l(t)$ [m]:	displacement of the center of gravity of the bed from the head to foot

	direction due to change in position of the person on the bed
$w(t)$ [m]:	displacement of the center of gravity of the bed from the left to right direction due to change in position of the person on the bed
$\theta_{fh}(t)$ :	tilting angle of the bed from the foot to head direction
$\theta_{rl}(t)$ :	tilting angle of the bed from the right to left direction

Furthermore, in the system shown in Fig. 1, in order to detect position changes by the person on the bed, we integrated the difference of two outputs  $e_{hl}(t), e_{fl}(\tau)$  from the left side and  $e_{hl}(t), e_{hr}(t)$  from the head side as follows:

$$\begin{aligned} P_{fh}(t) &= \int_0^t \{e_{fl}(\tau) - e_{hl}(\tau)\} d\tau \\ P_{rl}(t) &= \int_0^t \{e_{hr}(\tau) - e_{hl}(\tau)\} d\tau \end{aligned} \quad (1)$$

## 2. 2 Characteristics of a piezo ceramic device

The overall transfer function of the piezo-device is given by a serial connection  $G_1(s) \cdot G_2(s) \cdot G_3(s)$  of three transfer functions;

$$G_1(s) = \frac{A}{C} \text{ [V/m]}: \text{ translation factor from the}$$

displacement to voltage

$$G_2(s) = \frac{sCR}{1+sCR} \text{ [Non-dimension]: high pass filter}$$

$$G_3(s) = \frac{s^2 + \frac{d}{m}s + \frac{k}{m}}{s^2 + \frac{d}{m}s + \frac{k}{m} + \frac{A^2 s R}{m(1+sCR)}} \quad \text{[Non-dimension]: resonance and anti-resonance filter}$$

The transfer function  $G_2(s)$  has the high pass filter characteristics with the time constant of  $CR$  [s] or cut-off frequency  $\frac{1}{2\pi CR}$  [Hz]. The capacitance  $C$  [F] determined by the dielectric constant of the material of piezo-ceramic and the cross sectional area and thickness of the ceramics has the value ranging from

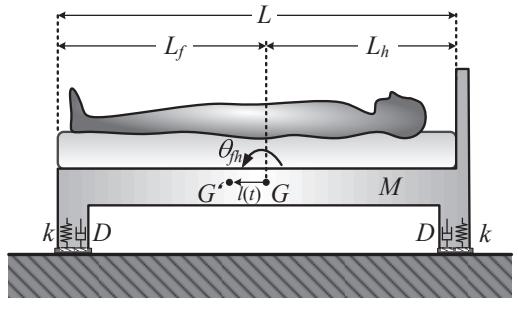
$0.001\mu F$  to  $0.1\mu F$ . The input load resistance is actually the input impedance of the AD converter or passive filter which normally around  $1M\Omega$ . Thus the cut-off frequency ranges around 1.6Hz to 160Hz. The transfer function  $G_3(s)$  shows resonance and anti-resonance characteristics and has the resonance frequency

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m} \left(1 + \frac{A^2}{kC}\right)} \text{ and the anti-resonance frequency}$$

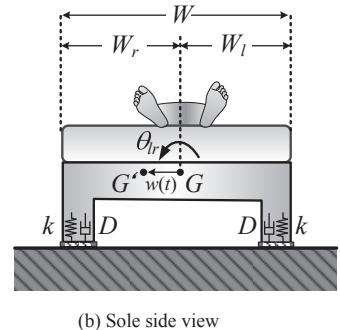
$$f_a = \frac{1}{2\pi} \sqrt{\frac{k}{m}}.$$

## 2. 3 Posture change of the person on bed and sensor output system

When a person stays on the bed calmly, the piezo ceramic device directly catches the micro-vibration due to the motion of heart beat and respiration. Here we consider how the posture changing of the person to the bed generates the output signal  $P_{fh}(t)$  and  $P_{rl}(t)$  in Fig.1.



(a) Side view



(b) Sole side view

Fig. 2 Mathematical model of bed

Fig.2 shows a situation when a person lies on the bed with changing the posture. The change of the posture yields the bed tilting and the shift in the center of gravity. First we consider the situation that the bed tilts and foot side sinks around the center of gravity of bed. Suppose the center of the gravity shifts from  $G$  to  $G'$  for the displacement  $l(t)$  as shown in Fig.2. The shift  $l(t)$  is very less than the lengths  $L$ ,  $L_f$  and  $L_h$ , ie.,

$l \ll L, L_f, L_h$ , thus the tilting angle  $\theta_{fh}(t)$  around G and G' are assumed to be same. The inertia moment  $I_{fh}$  of the bed around the center of gravity G' is given by the bed size and weight assuming the mass of the bed with person on it is uniform, as follow;

$$I_{fh} = M \cdot \frac{L_f - l}{2L} \cdot (L_f - l)^2 + M \cdot \frac{L_h + l}{2L} \cdot (L_h + l)^2 \cong \frac{M}{2L} (L_f^3 + L_h^3) \quad (2)$$

The tilting motion around G or G' from a steady state condition is then given as;

$$I_{fh} \frac{d^2\theta_{fh}(t)}{dt^2} + D \frac{d\theta_{fh}(t)}{dt} + k(L_f - l)^2 \theta_{fh}(t) + k(L_h + l)^2 \theta_{fh}(t) = Mg l(t) \quad (3)$$

and the displacement of the stainless plate of the piezo-ceramic devices foot and head side are given as follows;

$$\begin{aligned} x_f(t) &= (L_f - l)\theta_{fh}(t) \cong L_f \theta_{fh}(t) \\ x_h(t) &= -(L_h + l)\theta_{fh}(t) \cong -L_h \theta_{fh}(t) \end{aligned} \quad (4)$$

Thus the difference  $x_{fh}(t)$  between the head and foot side  $x_f(t) - x_h(t)$  is given by;

$$x_{fh}(t) = x_f(t) - x_h(t) = (L_f + L_h)\theta_{fh}(t) = L\theta_{fh}(t) \quad (5)$$

The transfer function of  $x_{fh}(t)$  with respect to  $l(t)$  is then given as;

$$x_{fh}(s) = \frac{MgL}{I_{fh}s^2 + Ds + k(L_f^2 + L_h^2)} l(s) = G_{fh}(s)l(s) \quad (6)$$

with the natural frequency of

$$f_{fh}(s) = \frac{1}{2\pi} \sqrt{\frac{k(L_f^2 + L_h^2)}{I_{fh}}} = \frac{1}{2\pi} \sqrt{\frac{2k(L_f^2 + L_h^2)}{M(L_f^3 + L_h^3)}} \quad \text{and the steady state gain of } \frac{MgL}{k(L_f^2 + L_h^2)}.$$

Similarly, supposing

$$I_{rl} \cong \frac{M}{2W} (W_r^3 + W_l^3), \text{ when the center of the gravity shift}$$

to from right to left, the transfer function of  $x_{rl}(t)$  with respect to  $w(t)$  is given by;

$$x_{rl}(s) = \frac{MgW}{I_{rl}s^2 + Ds + k(W_r^2 + W_l^2)} w(s) = G_{rl}(s)w(s) \quad (7)$$

with again the natural frequency of angular vibration

$$f_{rl}(s) = \frac{1}{2\pi} \sqrt{\frac{k(L_r^2 + L_l^2)}{I_{rl}}} = \frac{1}{2\pi} \sqrt{\frac{2k(L_r^2 + L_l^2)}{M(W_r^3 + W_l^3)}} \quad \text{and the}$$

steady state gain of  $\frac{MgW}{k(W_r^2 + W_l^2)}$ . Thus the transfer function of  $P_{fh}(t)$  and  $P_{rl}(t)$  with respect to  $l(t)$  and  $w(t)$ , respectively are given as follows;

$$P_{fh}(s) = \frac{1}{s} \cdot G_1(s) \cdot G_2(s) \cdot G_3(s) \cdot G_{fh}(s) \cdot l(s) \quad (8)$$

$$P_{rl}(s) = \frac{1}{s} \cdot G_1(s) \cdot G_2(s) \cdot G_3(s) \cdot G_{rl}(s) \cdot w(s) \quad (9)$$

In the following frequency range;

$$\frac{1}{2\pi CR} < f < f_r, f_a, f_{fh}, f_{rl} \quad (10)$$

the transfer functions eq.(8) and eq.(9) show the proportional characteristics and thus in the time domain, they are given by;

$$P_{fh}(t) = \frac{ARLMg}{k(L_f^2 + L_h^2)} \cdot l(t) \quad (11)$$

$$P_{rl}(t) = \frac{ARWMg}{k(W_r^2 + W_l^2)} \cdot w(t) \quad (12)$$

Thus the output  $P_{fh}(t)$  in Fig.1 or eq.(1) is proportional to  $l(t)$ , the shift of center of gravity of bed or the human motion from head to foot side and the output  $P_{rl}(t)$  in Fig.1 or eq.(1) is proportional to  $w(t)$ , from left to foot side, respectively.

### 3. VERIFICATION EXPERIMENTS

#### 3. 1 Measurement Device and System

Fig.3 shows the measurement system. The diameter of the piezo-ceramics was 20mm which was bonded on a brass metal with the diameter of 25mm. It is one used for buzzer with the cost of half dollars. The device was bonded once again on a stainless steel plate with thickness of 1mm and diameter of 50mm. A washer with the thickness of 2mm, inner radius 15mm and outer radius 25mm was set under the plate and the bottom was closed by an aluminum plate with the same size with the stainless disk above. The force factor  $A$  of the device was  $1 \times 10^{-3}$  C/m and the capacitance was  $0.01 \mu F$ .

Four devices were set between floor and the four bottom corner of the bed as shown in Fig.3. The weight of the bed is 60kg and the size is 1.0mx2.1m. It is the coil cushion bed. The data from the four devices were measured and AD converted with the sampling time of 1ms and scale range of  $\pm 1V$  by the data logger (NR2000, Keyence Co. ltd.).



Fig. 3 Measurement system

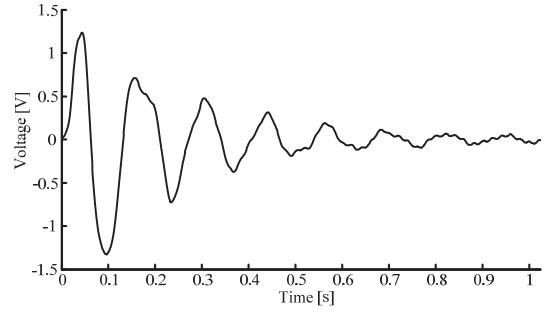
The noise level without passive low pass filtering was 5mV which is almost the hum noise. With the passive low-filter the noise level reduced to 0.1mV.

First, to know the dynamics of the bed system, we lightly hammered the center of bed and acquired the output  $e_{hr}(t)$ . Fig.4 shows the time response and the frequency response calculated by FFT for 1024 data.

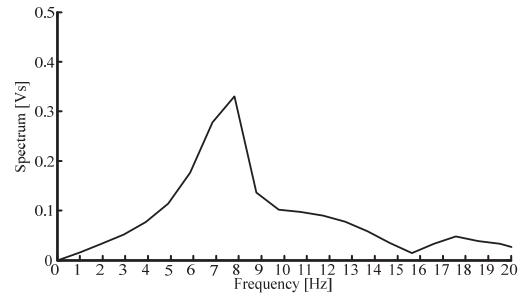
The resonance frequency of the system is 7.8Hz which shows the overall dynamics of the bed sensing system including the resonance characteristics of the sensor device and the natural frequency of the bed vibration.

### 3. 2 Signal Processing

The data  $e_{hr}(t)$ ,  $e_{hl}(\tau)$  and  $e_{fr}(t)$ ,  $e_{fl}(t)$  acquired through AD converter were band-pass filtered with band width from 3Hz to 7Hz to obtain the heart beat component. As the respiration frequency is around 0.3Hz, the respiration signal was obtained by band-pass filter with the band width from 0.1Hz to 0.5Hz.



(a) Impulse response by hammering the center of bed



(b) Frequency characteristics of the bed vibration

Fig. 4 Impulse response and frequency response of the bed sensing system

## 4. EXPERIMENTAL RESULTS

### 4. 1 Heart beat and respiration

Fig.5 shows the heart beat signal. Fig.5 (a) is signal measured by a pulse oximeter for a reference. Fig.5 (b) is the signal from the piezo-ceramic device set at head and right corner  $e_{fl}(t)$  and band pass filtered. The output signal from the device was full wave rectified and low-pass filtered by the moving average of 150 data in the processor. The signal level is around 10mV whose S/N ratio is 40dB. The periods of both waves are same and synchronizing. In the output signal from the piezo-ceramics includes the low frequency components of respiration. Other three outputs show the similar wave forms as  $e_{fl}(t)$  and thus we can measure the heart beat from any of four devices.

Fig. 6 shows the respiration signal. Fig.6 (a) is the respiration blowing pressure from the nasal cavity measured by a low frequency microphone. Fig.6 (b) is the signal from the piezo-ceramic device set at head and right corner and band pass filtered. The signal level of the  $e_{hr}(t)$  was 0.5mV whose SN ratio is 14dB. The periods of both waves are same and synchronizing.

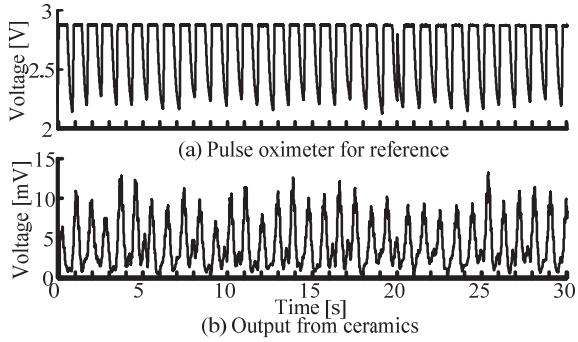


Fig. 5 Heartbeat signal

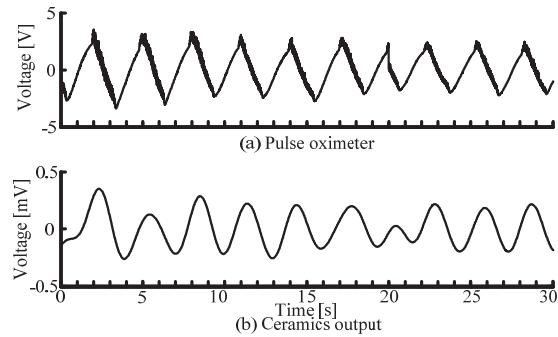


Fig. 6 Respiration signal

Other three outputs from the devices show the same period. The two outputs of the head side synchronize but those feet have the negative value of the head side outputs. This is because diaphragm of the person was upper area than the center of gravity of the bed cushion.

#### 4. 2 Turning over on the bed

Fig.7 shows a situation of a person lying on back, turning right side, left side and lying on back on bed. The four outputs from the devices were not saturated under the motion above. Under the photos in Fig.7, the change in  $P_{fh}(t)$  is shown in upper and that in  $P_{rl}(t)$  in lower. Because the head-feet motion was little,  $P_{fh}(t)$  changes little, whereas,  $P_{rl}(t)$  changes following to the body movements. When he began to turn right,  $P_{rl}(t)$  begins to increase to positive from zero; when he kept the same posture,  $P_{rl}(t)$  keep constant positive value; when he turn back to the center,  $P_{rl}(t)$  decreases to zero; and when he began to turn to left,  $P_{rl}(t)$  decreases to negative; when he kept the same posture,  $P_{rl}(t)$  keeps the constant negative value; and finally when he turn back to the center,  $P_{rl}(t)$  also increases to zero. The changes in  $P_{rl}(t)$  is proportional to those of the center of gravity of bed or the moving direction of the person on bed.

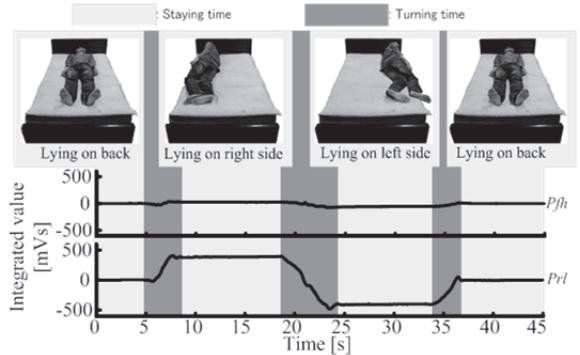


Fig. 8 Getting up and laying down motion without using hands

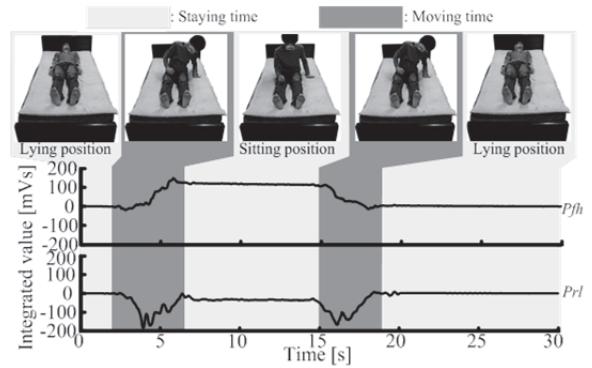


Fig. 9 Sitting up and lying down motion by using left hand

Fig.8 shows a situation, when a person gets up from a lying position to the forward sitting position and lies again. The person sat up not using both hands. Again the four outputs from the devices were not saturated under the motions above. Under the photos in Fig.8, the change in  $P_{fh}(t)$  and  $P_{rl}(t)$  are shown in upper and lower row, respectively. Because the left to right side motion in the sitting up was little,  $P_{rl}(t)$  changed little. Whereas, when the person began to get up,  $P_{fh}(t)$  begins to increase to positive; when he kept the same posture,  $P_{fh}(t)$  keeps constant positive value; when the person lie down,  $P_{fh}(t)$  decrease to zero. The changes in  $P_{fh}(t)$  is proportional to those of the center of gravity of bed or the moving direction of the person on bed.

Fig.9 shows the motion from sitting up to lying down with using left hand for self supporting. Again the four outputs from the devices were not saturated.  $P_{fh}(t)$  shows the similar changes as Fig.8, whereas  $P_{rl}(t)$  has the negative value when he pushing the bed by the left hand which means the center of the gravity of bed shift to left side. When the person did the same motion by using the right hand,  $P_{fh}(t)$  shows the similar changes as in Fig.9, but the  $P_{rl}(t)$  has the positive value when

he pushing the bed by the right hand.

## 5. DISSCUSIONS

The bed sensing system uses four piezo-ceramic devices sandwiched between the four feet of bed corners and the floor. The piezo devices are distortion sensor working without electric power supply, which generate the voltage proportional to the time-derivative of the distortion and are sensitive. The system AD converted these bio-signals directly from the devices without electrical pre-amplifier. Under the system above, we measured the heart beat with SN ratio of 40dB, respiration with that of 14dB, posture changes without saturation. The outputs of bed riding and leaving out motion which we did not showed, were of cause measured as the big signals but without saturation. The device has the wide dynamic range. Further because the device is battery free, and generate the output voltage, it can be used not only the bio-sensing device but also as a trigger signal when some event is occurring for the person on bed for a bio-signal micro-processor, which in practice is very effective to develop the equipment driven by small capacity battery for long time such as 1 year.

From the heart beat and body movement measurable by the sensing devices, we can estimate the sleep stages [13]. This method can be used as sleep stage estimator. The shifts of the center of the gravity of bed with person on it was estimated by the outputs  $P_{fh}(t)$  and  $P_{rl}(t)$ . The shift of the center of gravity is proportional to displacement of movements of person on bed. This yields to know how the person in bed is moving and the information can be used to assist patients who try to leave bed and variety of application.

## 6. CONCLUSIONS

This paper describes a novel bed bio-signal sensing method using four piezo-ceramic devices sandwiched between the four feet of bed at the bed corner and the floor, which guarantees the noninvasive, unconstraint and unconscious bio-measurement. The devices are battery free and generate voltages corresponding to heart beat, respiration, posture change for a person on bed. The dynamic range of the sensor is wide such that it can detect from the mechanical micro-vibration due to heart beat as the voltage of 10mV to bed riding or leaving force as the several volt without

saturation and with high SN ratio. Because of the high sensitivity of the device, no pre-amplifier was required to acquire the bio-signals above. These features of the devices are effective to develop bio-sensing equipments with low power consumption driven for at least one year by small battery.

The devices clearly detect the heart beat with the SN ratio of 40dB, the respiration with the SN ratio of 14dB. Further, from the integrated value of difference of voltage generated by the head side device and that by the foot side device, and from that by the left side and right side of bed, the posture change of the person on the bed was detectable. As one of the bed bio-sensing methods, the proposed method is valid in the sense of cost performance i.e., the device is the same one used in the buzzer of half dollar, realization of low power equipment, i.e., device is battery free and driven without pre-amplifier, and accurate and variety of bio-sensing, i.e., it detects from micro-bio-vibration signal to giant signal without saturation.

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