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Wide-range Load Sensor Using Quartz Crystal Resonator for Biological Signal Detection

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***Abstract*—A load sensor with high sensitivity, a wide measurement range, and a small size was developed by using an AT-cut quartz crystal resonator (QCR). The quartz crystal generates a charge that is proportional to the external force. Because it has high sensitivity and excellent temperature stability, it has been used for various sensors. In particular, a QCR has an inherently superior static-load-sensing characteristic. However, a QCR is fragile and easily broken by a stress concentration. Moreover, a retention mechanism is required to efficiently transmit the load, and it is necessary to fix the QCR firmly to avoid a horizontal force. Moreover, it is very difficult to miniaturize the retention mechanism because the fabrication and assembly process is complicated. We previously proposed a miniaturized sensor element that was developed using microfabrication. The QCR load sensor had an enormously wide force-sensing range of greater than 10^4 N. However, the output was easily affected by a change in the parasitic capacitance around the QCR. The objective of this study was to improve the load-measurement resolution and stabilize the sensor output for application to biological signal detection. We fabricated a QCR sensor with a sensitivity of 973 Hz/N and succeeded in detecting multiple biological signals (respiration, heartbeat, and posture) with using proposed QCR load sensor.**

I. INTRODUCTION

High-sensitivity, high-speed-response, and small-size load sensors are desired in many fields, including the medical field, life support robotics, and industrial robotics. Once such a high-performance load sensor is developed, it will be possible to handle fragile objects and/or heavy objects intelligently using a single robot. Moreover, health management will be realized by the simultaneous detection of multiple biological signals such as body pressure (high load), pulse/blood pressure (small load), and respiration (small load) on a bed/chair.

Although there have been several reports of load sensors that use strain gauges [1], piezoelectric vibration [2], or capacitance change, none of the conventional sensors meet the previously mentioned requirements. Recently, to realize such a high-performance load sensor, we have focused on a quartz crystal, which is one of the piezoelectric elements and has self-sensing capability. A quartz crystal generates a charge that is proportional to the external force, and has excellent properties, including high sensitivity, temperature stability, and frequency stability. Quartz crystals have been used for various sensors, including gas sensors [3], temperature sensors [4], and DNA sensors [5]. Research has also been conducted on their use as force sensors. The piezoelectric force sensors fabricated by the Kistler Corporation are commercially available. The sensing principle of these force sensors is the detection of the charge generated by an external force. However, force sensors based on this principle have the disadvantage of being easily affected by electric drift and noise. Therefore, they are not suitable for static force sensing.

On the other hand, a quartz crystal resonator (QCR) generates a periodic signal with high stability based on vibration. The resonant frequency of a QCR changes with high linearity depending on the external force [6–7]. Therefore, a highly sensitive load sensor with a wide measurement range can be realized using a QCR. In addition, the whole system can be miniaturized, because the frequency output can be directly processed as a digital signal without using an analog-to-digital converter.

However, a QCR is fragile and easily broken by a stress concentration. Moreover, a retention mechanism is required to efficiently transmit the external load to the QCR, and it has to be fixed firmly in place to prevent a horizontal force [8–11]. Miniaturizing the retention mechanism is quite difficult, because the fabrication and assembly process is complicated. We previously developed a miniaturized sensor element by using microfabrication [12–13]. However, its output was easily affected by a change in the parasitic capacitance around the QCR.

In this study, our goal was the precise detection of biological signals. To increase the sensitivity and reduce the total volume of the packaged sensor, we propose a new design for a QCR load sensor with a miniaturized retention mechanism, which efficiently transmits a load to the QCR. We improved the sensor output by reducing the hysteresis of the sensor and the effect of the parasitic capacitance.

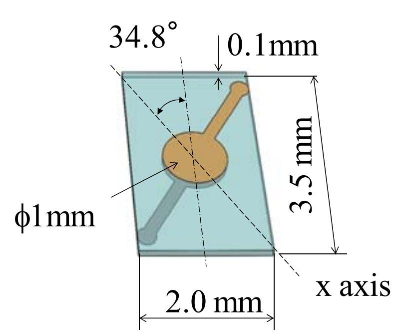

Figure 1. Schematic of quartz crystal resonator

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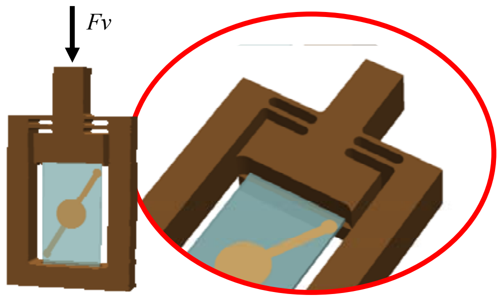

Figure 2. Schematic of retention mechanism

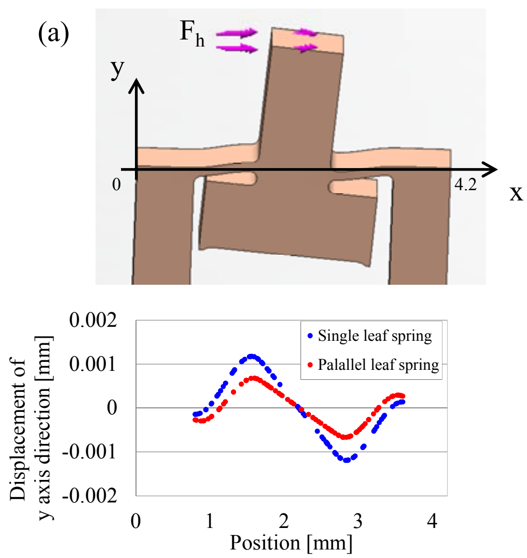

Figure 3. Deformation analysis of retention mechanism

II. Concept of QCR Sensor

A. Quartz Crystal Resonator

An AT-cut quartz crystal has a high resonance frequency and superior temperature stability at room temperature. When an alternating voltage is applied between two metal electrodes on the QCR, a thickness-shear vibration oscillates along the quartz crystal's electrical axis (x-axis) (Fig. 1). When an external load is applied to the QCR, its resonance frequency changes. The sensitivity of the sensor depends on the cutting direction of the QCR. The width of the current QCR was decreased from 3.0 mm to 2.0 mm compared with our previous work [13]. With a decrease in the cross-sectional area, the internal stress of the QCR increased and the sensitivity of the sensor was improved.

Stable vibration of the QCR is needed to improve the force-measurement resolution. The stability is related to the Q factor of the QCR. An oscillation failure occurs when using a QCR with a low Q factor. Therefore, a high Q factor is needed. The miniaturization of a QCR tends to produce a low Q factor. We have to consider the electrode thickness, electrode diameter, shape of the QCR, and wiring for the QCR. In this research, the electrode thickness was set at 250 nm and the electrode diameter was set at 1 mm. Copper wire with a diameter of 0.05 mm was used. The Q factor deteriorates with

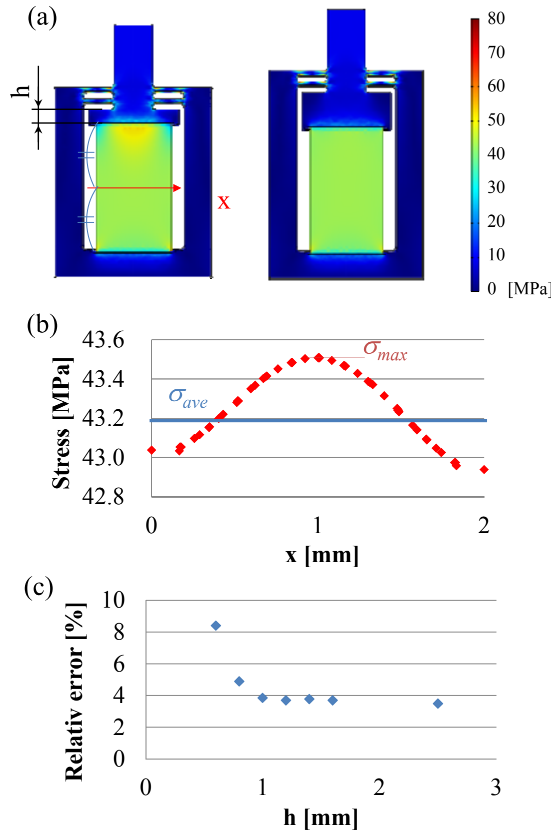

Figure 4. Stress distribution of QCR (height of push bar is changed)

a disturbance in the mechanical and electrical vibrations of a QCR. Vibration is generated from the center electrode of the QCR. The position of the wiring pad and the load application point should be away from the center electrode. Therefore, the height of the QCR was increased from 3.0 mm [13] to 3.5 mm to improve the Q factor. The load was applied at an angle of 34.8° to the x-axis of the AT-cut QCR. Stress sensitivity is not changed by temperature fluctuation from this direction. A schematic of the QCR is shown in Fig. 1.

B. Retention Mechanism and Packaging

As mentioned above, a QCR is fragile and easily broken by a stress concentration. Thus, a good retention mechanism is required to efficiently transmit the load. Here, we propose a retention mechanism that has parallel flat springs. We unified the retention mechanism to simplify the assembly process (Fig. 2). This unification of the sensor parts contributed to a reduction in the hysteresis. We determined the dimensions and material properties of the sensor by a finite element analysis using COMSOL Multiphysics 4.3b (COMSOL Inc.). We reduced the influence of unexpected loads on the QCR by adopting parallel leaf springs for the retention mechanism. Fig. 3(a) shows the results of a deformation analysis of the retention mechanism when a horizontal force (F_h) of 1 N was applied. Fig. 3(b) shows the y-axis displacements of single and parallel leaf retention mechanisms. We confirmed that the deformation of the parallel leaf springs was reduced

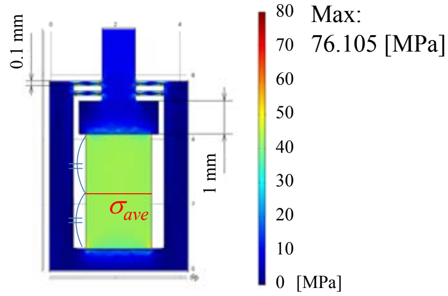

Figure 5. Stress distribution of QCR (h = 1 mm)

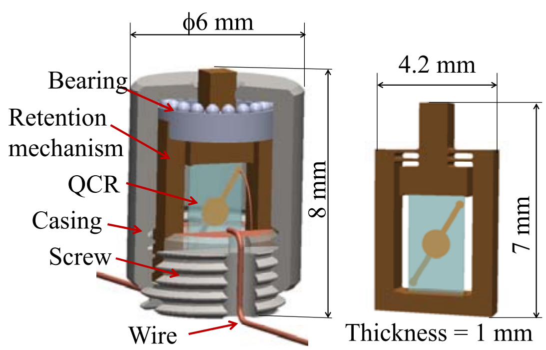

Figure 6. Schematic of QCR load sensor

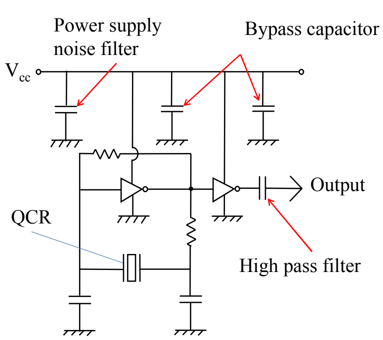

Figure 7. Schematic of oscillation circuit

compared with the case of using a single leaf spring. A smaller displacement against a horizontal force is preferable. Therefore, we adopted the parallel leaf springs. A uniform stress should be applied to the QCR for precise measurement. We evaluated the stress distribution on the QCR. Fig. 4(a) shows the results of an analysis when a perpendicular compressive load of 10 N was applied to the QCR. Fig. 4(b) shows the stress distribution at the center of the QCR. Fig. 4(c) shows the relationship between height h of the push bar in Fig. 4(a) and the relative error between σ_{ave} and σ_{max}. The relative error decreases with an increase in the value of h. When h is 1 mm or greater, the relative error remains constant. From this analysis, considering the need to miniaturize the retention mechanism, a value of 1 mm was selected for h.

From Fig. 5, we confirmed that the QCR was loaded with a uniform compressive stress distribution along the x-axis. The perpendicular compressive load was 10 N, whereas the loaded compressive stress of the QCR was 43 MPa (8.6 N, where the sectional area of the QCR was 0.1 × 2.0 mm). We defined the ratio of the compressive load applied to the QCR to the vertical component of the external load as the "load conversion efficiency." The load conversion efficiency of this retention mechanism was 86%, whereas that of the conventional one was 70% [13]. Therefore, it is expected that the resolution will be improved. The allowable stress for an AT-cut quartz crystal is 150 MPa. Considering the load conversion efficiency, the maximum allowable load of this sensor is 35 N.

For sensor packaging, we employed a screw mechanism that made it possible to apply a preload to the retention mechanism. The linearity of the sensor was improved by preloading. We arranged a relay point for the wiring to reduce its resistance (Fig. 6).

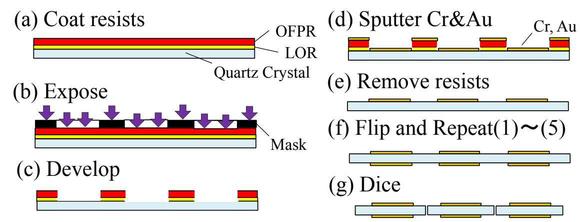

Figure 8. Fabrication process of QCR

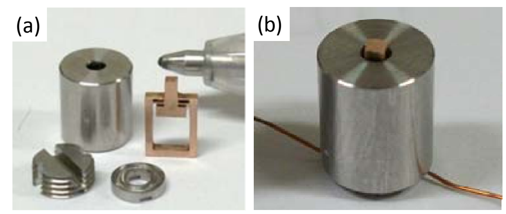

Figure 9. Fabiricated QCR load sensor

Oscillation Circuit

To obtain stable oscillation at the resonance frequency, the vibration signal must be amplified by using an oscillation circuit (Fig. 7). An oscillation circuit that used a CMOS inverter was adopted to miniaturize the circuit board. A bypass capacitor, power supply noise filter, and high-frequency filter were all integrated to reduce noise. This oscillation circuit can be miniaturized and placed near the QCR.

III. Fabrication of QCR Sensor

A. QCR

Fig. 8 shows the fabrication process for the QCR. Micromachining was used to fabricate an AT-cut quartz crystal plate (100 µm thick) with both sides polished. Electrode patterns were formed using photolithography and a liftoff process. In photolithography, lift-off resist (LOR 5B, KAYAKU MICROCHEM Co., Ltd.) was used to create an undercut profile (Fig. 8). After photolithography was applied to the quartz crystal plate, Cr and Au films were deposited AT-cut quartz crystal substrate, after photoresist OFPR800

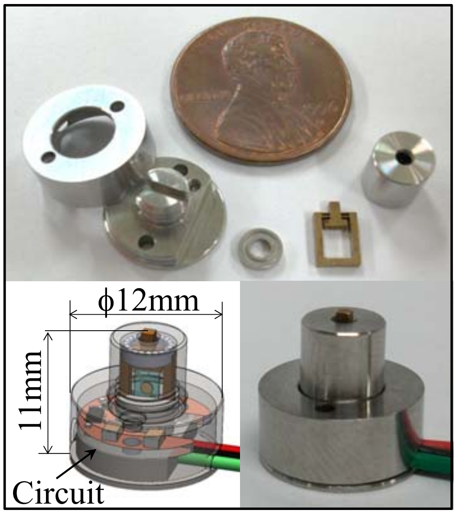

Figure 10. QCR load sensor with circuit

(15 cp, TOKYO OHKA KOGYO Co., Ltd.) and LOR were patterned, and the Cr–Au film was removed using a stripper. This was done on both sides of the AT-cut quartz crystal substrate. Both surfaces of the patterned quartz plate were cut using a dicing saw (DAD-522, Disco Co.), and a large number of resonators were fabricated simultaneously. The Q factor of the QCR was calculated to be 54,000 using equation (1).

$$Q = \frac{2\pi f \cdot L_1}{R_1} \tag{1}$$

Here, the equivalent electrical resistance (R_1) was 47.5 Ω, and the inductance (L_1) was 26.1 mH, which was measured using an impedance analyzer (ZA5403, NF Component CO.).

B. Retention Mechanism and Packaging

Fig. 9(a) shows the fabricated parts of the QCR load sensor. The retention mechanism was fabricated using end milling. Phosphor bronze, which has an excellent spring characteristic, was used for the retention mechanism. SUS304, which has high rigidity and excellent corrosion resistance, was used for the casing and screw. Fig. 9(b) shows the fabricated sensor.

C. QCR Load Sensor Packaging with Circuit

The QCR load sensor and oscillation circuit were connected by wiring. Parasitic capacitance exists in the wiring. Therefore, we integrated the QCR load sensor and oscillation circuit, which reduced the sensor output error caused by this parasitic capacitance. Furthermore, the oscillation circuit was covered with a metal case, which moderated the fluctuation of the sensor output by providing an electrostatic shield. The QCR load sensor and oscillation circuit were 12 mm in diameter and 11 mm in height (Fig. 10).

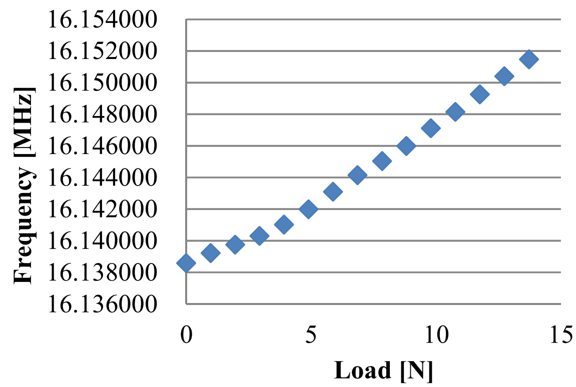

Figure 11. Results of loading experiment without preload

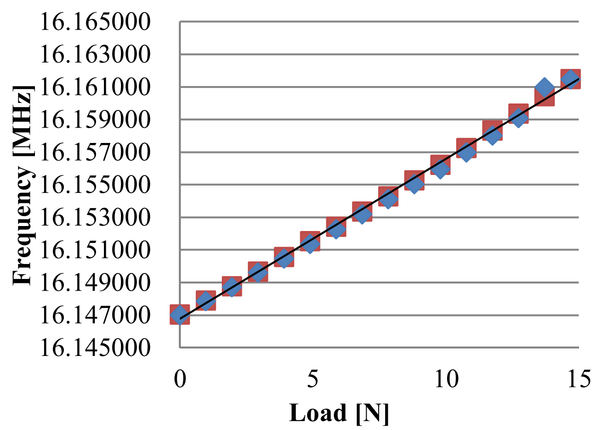

Figure 12. Results of loading experiment with preload

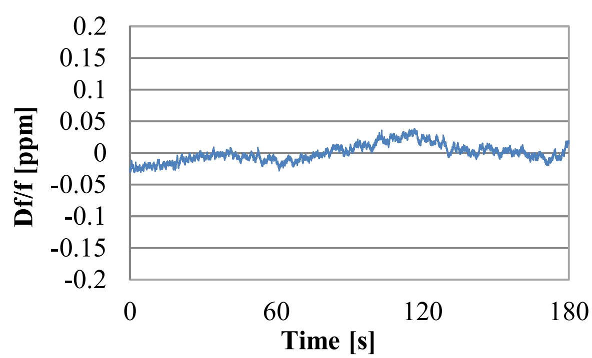

Figure 13. Stability of sensor output

IV. CHARACTERISTIC EVALUATION OF QCR SENSOR

A. Loading

We calibrated the fabricated QCR load sensor by loading a weight. A voltage of 5 V was applied to the oscillation circuit, and the sensor output was measured using a frequency counter (53131A, Hewlett Packard). Fig. 11 shows the results for the load–frequency relationship without preloading. The sensor output did not change linearly, because of a gap between the parts. A preload had to be applied to obtain a good performance. Fig. 12 shows the results for the load–frequency relationship with preloading. In this experiment, loads of 0 N to 15 N were applied in 1-N increments and unloaded from 15 N to 0 N in 1-N decrements. The results of this experiment showed that the fabricated QCR load sensor with preloading had a very good linear property. The nonlinearity was calculated to be 1.13% of the full scale (FS). The hysteresis of the sensor was calculated to be 1.78% FS, and the sensitivity of the sensor was high (973 Hz/N).

B. *Stability of Sensor Output*

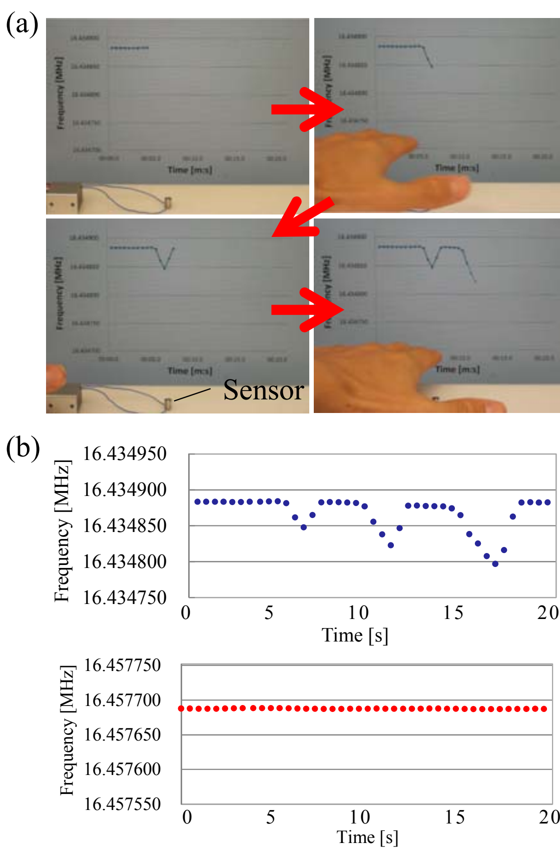

Figure 14. Fluctuation of sensor output under disturbance

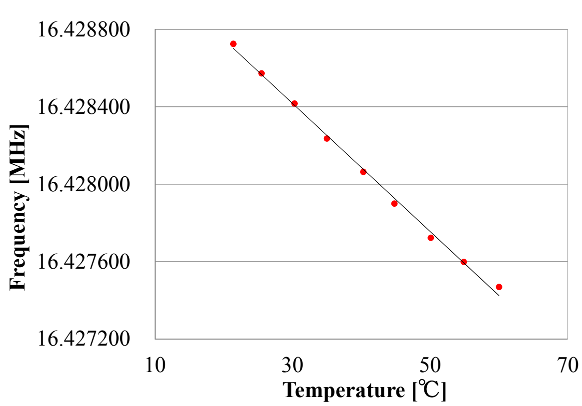

Figure 15. Relationship between temperature change and

The measured frequency stability of the sensor is shown in Fig. 13. The measurements showed that the fluctuation of the frequency of the sensor was 0.04 ppm or less. The fluctuation of the sensor output was calculated to be 0.66 mN or less.

Fig. 14(a) shows the conventional problem of the sensor output being changed by the parasitic capacitance. The sensor was connected to the circuit by wiring (about 10 cm in length). The sensor output changed when the sensor was shaded by a hand. The experimental results are shown in Fig. 14(b). A similar experiment was conducted using our QCR sensor and circuit. The experimental results are shown in Fig. 14(c). The fluctuation of the sensor output was drastically smaller than that for the conventional sensor.

C. *Temperature Characteristic*

The sensor output was measured when the temperature of the sensor was changed from 25°C to 60°C. The temperature of the sensor was measured using a thermocouple thermometer bonded to the sensor system (AD-5602, A&D Corp.). Fig. 15 shows the relation between the temperature and the sensor output when the temperature is increased from 25°C to 60°C. The temperature and sensor output have a linear relationship. Temperature compensation can be easily performed by using equation (2).

$$Y= -33.105x \cdot 10^{-6}+ 16.429 \qquad (2)$$

This sensor mounting system could be used at room temperature as well as temperatures in the vicinity of body temperature, and it is expected to be applicable in the medical and nursing fields.

V. Biological Detection

A. *Experimental Setup*

Fig. 16 shows the setup of a chair for the detection of biological signals. The fabricated QCR load sensor was fixed on the back of the chair to detect biological signals: respiration, heartbeat, and posture. To increase the contact area, the sensor was pinched between two semi-round bars. The sensor was positioned near the heart to detect the minute force generated by the heartbeat. In addition, a sensor was placed under a cushion so that the subjects felt comfortable in

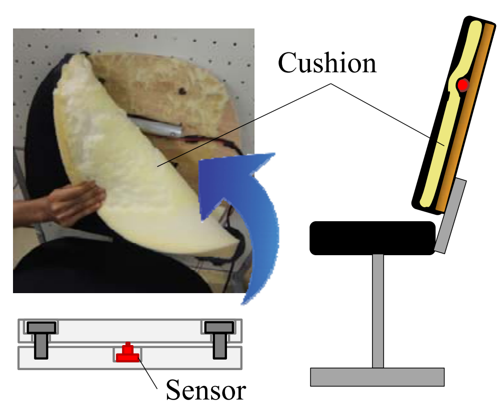

Figure 16. Setup of chair for detection of biological signals

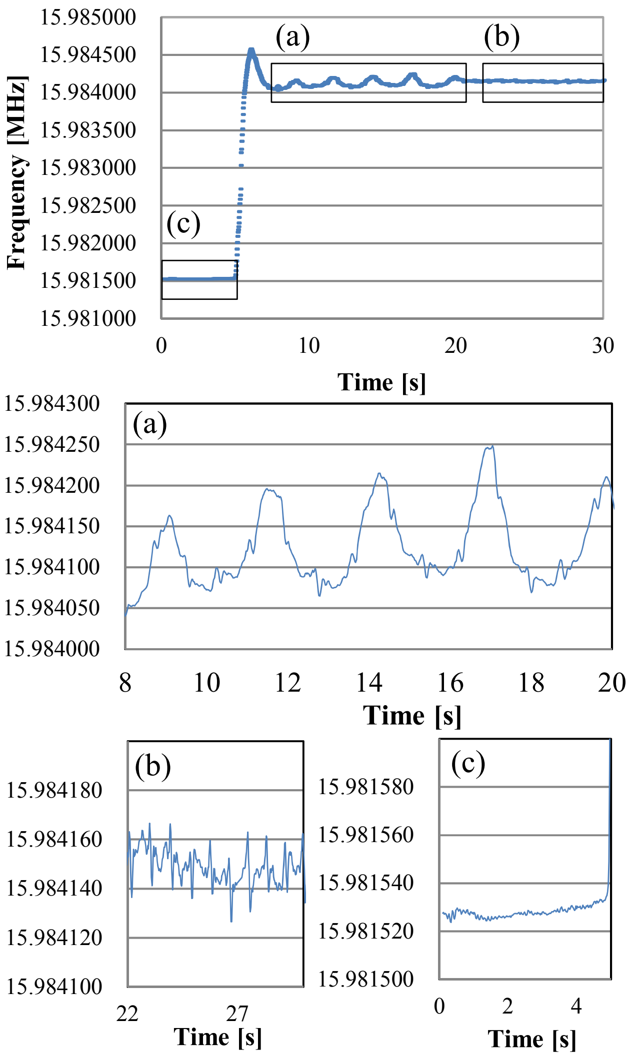

Figure 17. Results of measurements of biological signals

the chair.

In the experiment, measurements began without a load (the subject did not lean against the chair). Approximately 5 s later, the subject leaned back in the chair. Approximately 20 s later, the subject held his/her breath.

B. *Experimental Results*

Fig. 17 shows the measurement results on a subject (24 years old, male, 182 cm tall). The resonant frequency changed by approximately 3,000 Hz by leaning. When the subject leaned against the chair, the sensor output changed periodically (Fig. 17(a)). This periodic change was not observed while the subject held his breath. Therefore, this periodic change might have been caused by breathing. Moreover, smaller (~20 Hz) and faster (~0.9 s cycle) periodic changes were observed when the subject held his breath (Fig. 17(b)). Compared with the sensor output when the subject did not lean against the chair (Fig. 17(c)), this change was sufficiently large that it did not appear to be noise. The change was around 70 peaks/min. Thus, this smaller and faster periodic change might have been caused by the beating of the heart. The change is visible in Fig. 17(a). These results demonstrate that multiple biological signals (respiration, heartbeat, and posture) were successfully detected using our QCR load sensor.

VI. Conclusions

We succeeded in improving the sensor sensitivity and miniaturization of a QCR load sensor. The microfabricated QCR with the new retention mechanism had a high load-conversion efficiency. We also proposed a sensor packaging design, and integrated an oscillation circuit with the sensor. We solved the practical noise problem caused by parasitic capacitance. As a result, the accuracy and stability of the sensor were greatly improved. We succeeded in detecting multiple biological signals (respiration, heartbeat, and posture) by using the proposed QCR load sensor.

As a prospect for the future, the QCR load sensor requires a temperature compensator for long-term biological detection. Automatic detection by signal processing is also required.

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