PAPER

Implantable Temperature Measurement System Using the Parametron Phenomenon*

Yoshiaki SAITOH†, *Member*, Akira KANKE††, Isamu SHINOZAKI†**, *Nonmembers*, Tohru KIRYU††, *and* Jun'ichi HORI†, *Members*

SUMMARY Adapting the principle of parametron oscillation, a small implantable temperature sensor requiring no internal power supply is described. Since this sensor's oscillation frequency is half that of the excitation frequency, the oscillated signal can be measured from the reception side, free of any signal, interference, simply by positioning the sensor and the excitation antenna so that: 1) they are separated up to 95 cm in the air; 2) a 41 cm gap, the phantom equivalent of the thickness of the human abdomen maintain between them. In the temperature-dependent quartz resonator sensor, oscillation occurs only when frequency and temperature correspond. The excitation power is then adjusted so that the frequency bandwidth narrows. As a result, the margin of error in measuring the temperature is minimized: (±0.07°C).

key words: *parametron phenomenon, temperature sensor, quartz resonator, oscillation-center frequency, excitation power*

1. Introduction

While hyperthermia is currently attracting a great deal of attention as a possible cancer treatment, careful monitoring is necessary. Cancer cells are known to die at 42.5°C, while normal ones survive, until temperatures reach about 44°C. Thus internal body-temperature must be maintained at between 42.5 and 44°C for a long time.

Various researchers, testing either fully implanted sensors [1]–[7] or swallowable capsules [8]–[10] using passive elements have succeeded in measuring biomedical signals by remote control. The obvious advantages; -first, the virtual elimination of the threat of infection, due to the fact that the sensors require no through-skin connections; -second, the elimination any need for an internal power supply, making the sensors ideal for long-term implantation.

Farrar et al. [8], Hill and Allen [1], and Zervas et al. [2] developed passive sensors based on the L-C resonant circuit and measured the resonant frequency modulated by the internal pressure. Tsuji et al. [9] recorded intragastric temperatures with ultrasonic using a quartz resonator. These methods require alternate transmission and reception because the sensor's signal is blocked by a more powerful ones directly emanating from the excitation system itself, or its harmonics. Expressed another way, the sensor's signal could not be received and transmitted simultaneously, and therefore required a complicate system capable of synthesizing this action. A method of energizing oscillation circuits by mean of electromagnetic coupling, from outside the body, was studied by Nagumo et al. [9] and Barbaro and Macellari [3]. Kato et al. [4] developed a method of modulating an emitted signal in the oscillation circuit. In order to do this however, the sensor's circuit became much more complicated. Other problems arose, as well. We found that the antenna performed poorly, unless it was set close to sensing device, [1]–[3], [10] or placed very near the patient, [8], [4]. Moreover, the coupling angle between the sensor and antenna proved to be critical [8]–[10].

In previous reports, we discussed the technology involved in implantable thermometric equipment, used in treating hyperthermia [5], [6], which employed a quartz resonator whose resonant frequency varied with body temperature. A distinct disadvantage with this system, however, lay in the fact that a lead wire had to be extended from the sensor implanted deep within, to the hypodermic-sensor coil.

To circumvent the problem, we develop a temperature sensor capable of being implanted for months at a time, unencumbered by either wires or internal power supply. Operating on the principle of parametron oscillation, the sensor detects a radio signal which, in turn, triggers a corresponding oscillation at a frequency one-half that of the excitation frequency [11]. Since the transmitter lacks a low-frequency component, The excitation frequency exerts no influence, whatsoever, on the receiver. Thus, we can increase excitation power, thereby permitting even greater separation between the sensor and the antenna, and nearly unrestricted measurement. A temperature-sensitive quartz resonator connected to the parametron oscillator serves to restrict oscillation to the frequency directly corresponding to the temperature of the resonator. This sensor, then, safely effectively maintain overall body temperature, during hyperthermia.

Manuscript received September 29, 1995.

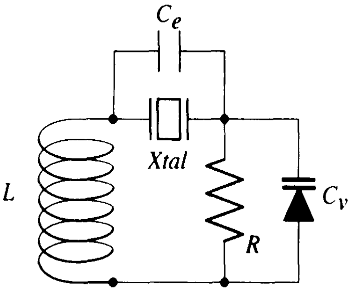
Manuscript revised February 27, 1996.

†The authors are with the Faculty of Engineering, Niigata University, Niigata-shi, 950-21 Japan.

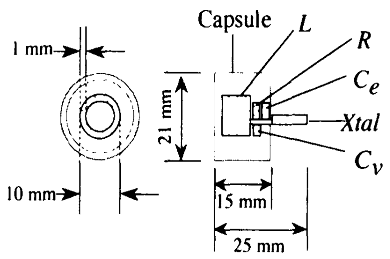
††The authors are with the Graduate School of Science and Technology, Niigata University, Niigata-shi, 950-21 Japan.

*This work was supported partly by the Grant-in-Aid for Science Research, (c) 03650340, 1991.

**Presently, with the Ministry of Finance.



(a) The circuit of the sensor.



(b) The structure of the sensor.

Fig. 1 Prametron-temperature sensor. C_e: Capacitor. C_v: Varactor. L: Coil. R: Resistor. *Xtal*: Quartz resonator.

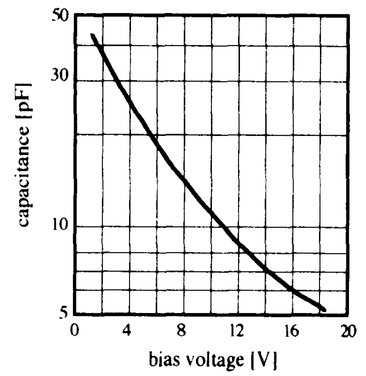


Fig. 2 Relationship between bias voltage and the capacitance of a varactor (SV101).

2. Parametron-Temperature Sensor

Periodically changing the inductance of coil L or capacitor C in the L-C circuit causes negative resistance, which in turn causes frequency-oscillation equal to one-half of the excitation frequency. The principle derived from this phenomenon, known as "parametron oscillation," was first discovered by Goto [11], who used it to create a parametron computer.

The sensor's basic circuitry, (Fig. 1 (a)) consists of a coil, a varactor, and a resistor. Varactor's capacitance changes as a function of bias voltage. Figure 2 shows the relationship between the two (TOSHIBA SV101) [12]. Bias voltage for the varactor is provided by the resistor; any alternation in this voltage automatically trigger parametron oscillation, having a standard wide-band frequency.

The parametron oscillator's frequency range can be restricted near to one closely approximation the series-

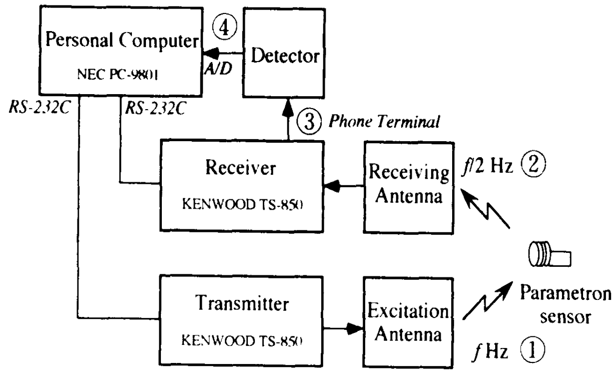


Fig. 3 Measurement system.

resonant frequency of the quartz resonator, by inserting the resonator into the circuit.

Since the impedance of the quartz resonator rises to very high levels, in all but the series-resonant frequency, the excitation power is assumed to be damped, while voltage to the varactor is attenuated to low level at the frequency. We therefore connect a small value of capacitor in parallel with a quartz resonator and effectively boost the radio-frequency excitation to the varactor.

Figure 1 (b) shows the sensor with the quartz resonator extending out from the plastic case, while the coil, varactor and capacitor are enclosed within it.

3. Measurement System

Figure 3 illustrates the composition and setup of the measuring equipment, which employs a set of computer-controlled transceivers. Those transceiver units scan standard frequencies, so that those received always equal exactly half of the excitation frequency. During sensor-oscillation, a sine-wave is continuously beamed from the receiver. The oscillating signal is fed into the computer and the frequency of the oscillating signal converted to a temperature figure.

4. Sensor Characteristics

4.1 Optimum Value of Sensor's Coil and Capacitor

After connecting a capacitor and quartz resonator in parallel, the distance between the sensor and the excitation antenna, d_e, was measured by varying capacitance in the air (Fig. 4). We used a quartz resonator with a frequency of 10.605 MHz, and a 17-turn air-core coil (2.84 μH) with a diameter of 10 mm. The power to the unit was set at 10 W. The d_e showed its maximum at a capacitance of 22 pF.

Figure 5 represents the measurable d_e, with variations in the number of turns in the coil. The quartz resonator and the excitation power were the same as those illustrated in Fig. 4. The d_e was extended to a maximum of 95 cm at an inductance of 2.84 μH (17-turn coil) and a capacitance of 22 pF.

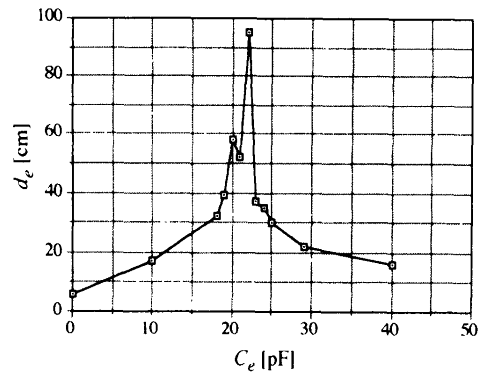


Fig. 4 Characteristics of C_e vs. d_e. C_e: Capacitance of the capacitor. d_e: Distance between the sensor and the excitation antenna. Excitation power = 10 W.

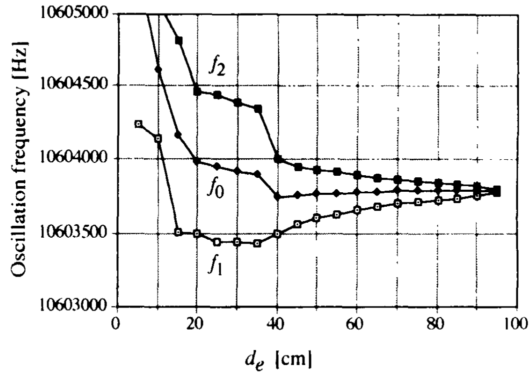


Fig. 6 Characteristics between d_e and oscillation frequency. d_e: Distance between the sensor and the excitation antenna. f_1: Oscillation-start frequency. f_2: Oscillation-stop frequency. f_0: Oscillation-center frequency. Excitation power = 10 W.

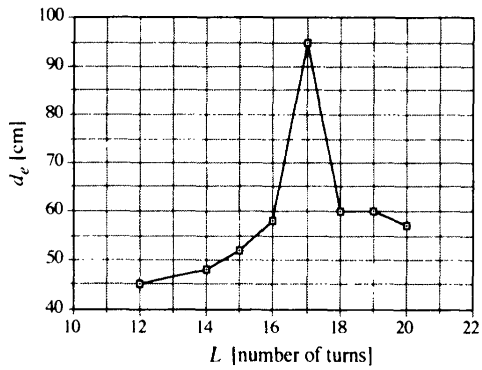


Fig. 5 Characteristics of L vs. d_e. L: Coil. d_e: Distance between the sensor and the excitation antenna. Excitation power = 10 W.

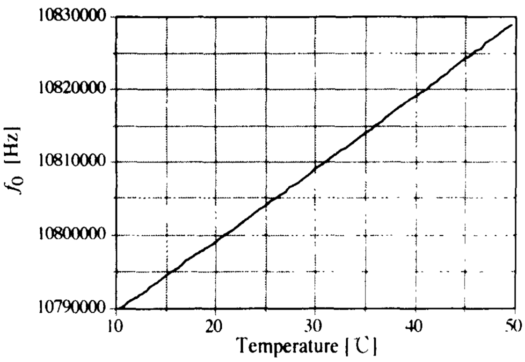


Fig. 7 Relationship between temperature and f_0. f_0: Oscillation center frequency. Excitation power = 10 W.

4.2 Oscillation-Frequency Characteristics

Oscillation frequency was measured when the distance from the sensor to the receiving antenna, d_r, was fixed, but d_e allowed to adjust from 10 cm to 100 cm. The excitation power was set at 10 W, while its frequency varied from 10.603 to 10.605 MHz. We denote the oscillation-start and stop frequencies as f_1 and f_2, respectively, while that of the center is denoted as:

$$f_0 = (f_1 + f_2)/2. \qquad (1)$$

The measurement results shown in Fig. 6 illustrate how frequencies f_1 and f_2 increased as d_e was shortened. d_e's influence on f_0 was negligible, ranging from 40 to 95 cm. Figure 6 also shows that the parametron sensor oscillated in a limited frequency bandwidth, which set at

$$f_w = f_2 - f_1. \qquad (2)$$

The shorter d_e was, the wider f_w became. Even if d_e was fixed and d_r was altered, it appeared to have little influence on frequencies f_1, f_2, f_0 and f_w.

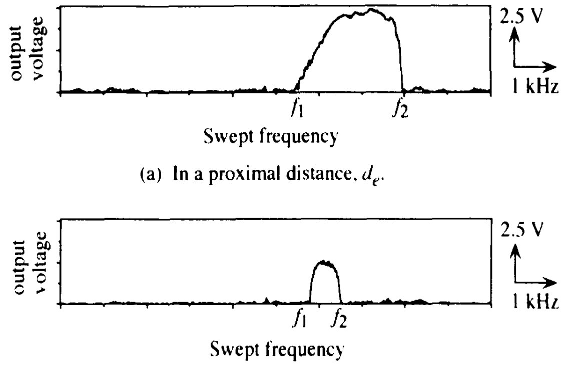
4.3 Relationship between Temperature and Oscillation Center Frequency

The oscillation-center frequency f_0 was measured, by placing a sensor in a plastic beaker filled with 1000 cc of water, and gradually lowering the temperature. d_e and d_r were fixed, and excitation power was set at 10 W. Figure 7 shows the linear relationship between the temperature and f_0. The parameters were estimated by the least squares method. In our experiment, temperature (T) could be obtained by

$$T = -1.078 \times 10^4 + 9.997 \times 10^{-4} f_0 \quad [^\circ\mathrm{C}]. \qquad (3)$$

4.4 Measurement Eliminating the Influence of Distance between the Sensor and Excitation Antenna

Other factors, such as temperature, being constant, the ability of a sensor to oscillate a fixed frequency, no matter what the position of the antenna, is a much sought-after characteristic. Accordingly, we worked out a method that completely eliminates the influence of d_e. Figure 8 illustrates the receiver scans all available frequencies. When detected output was not influenced by d_e, not only did f_0 stabilize, but f_w narrowed considerably as shown in Fig. 8 (b). Figures 6 and 8 illus-



(a) In a proximal distance, d_e.

(b) In an extended distance, d_e.

Fig. 8 Detected outputs of the receiver. d_e: Distance between the sensor and the excitation antenna.

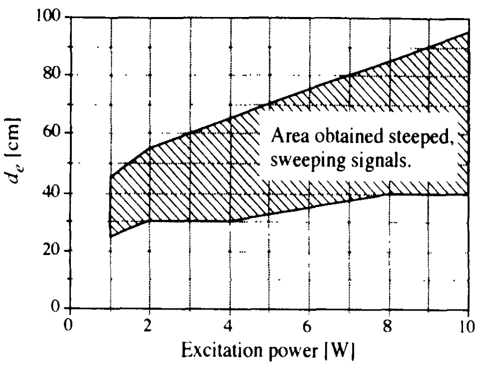


Fig. 9 Characteristics between excitation power and d_e. d_e: Distance between the sensor and the excitation antenna.

trate how we eliminated the influence of d_e by obtaining steep, sweeping signal output with a narrow f_w.

We next investigated an optimum d_e that produces signals similar to those in Fig. 8(b) just described by increasing the excitation power (Fig. 9). We obtained a steeped, sweeping signal with the small power in proximity, and contrariwise by enlarging the power in an extended distance.

We next investigated the influence of this same signal on f_w, while varying the excitation power. The steeped, sweeping signal was obtained in f_w; (800 Hz or less). Figure 10 shows the characteristics of d_e and f_0. The data was obtained while adjusting the excitation power so that f_w was arranged less than 800 Hz. Compared with the fixed excitation power, we were able to obtain an accurate f_0 regardless of distance, d_e.

Of note here, is the consideration that any changes in the coupling angle, between the sensor and antenna will drastically reduce sensor efficiency, and system performance, in general. In our experiment, stable sensitivity was obtained by adjusting the excitation power in the same way as mentioned above.

4.5 Temperature Measurement in a Phantom

The temperature of a phantom (TX-151) was measured. Electrical constants were determined to be equivalent

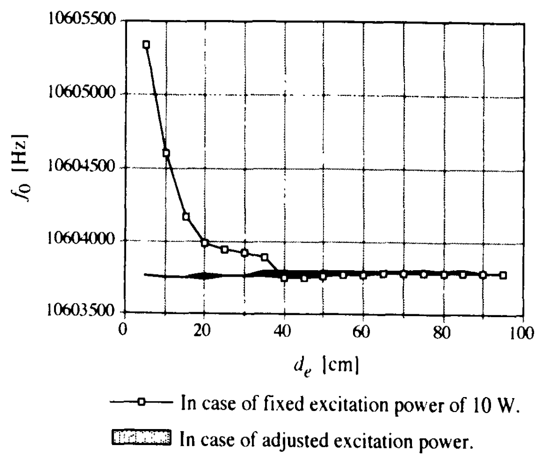


Fig. 10 Characteristics between d_e and f_0. d_e: Distance between the sensor and the excitation antenna. f_0: Oscillation-center frequency.

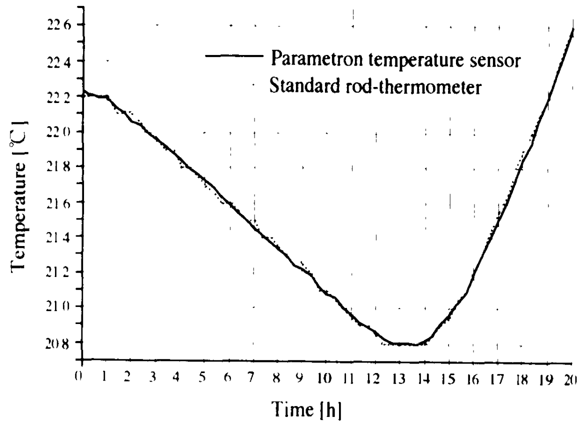


Fig. 11 Long-time measurement of temperature in a phantom.

to those derived from muscle (relative permittivity = 80, electric conductivity = 0.5[S/m]). This particular phantom measured 32 cm in diameter as well as height; approximately the thickness of a normal human abdomen. Temperatures at the center of the phantom varied in equivalence with room temperature. A standard rod-thermometer was installed immediately beside the sensor. The d_r and d_e were 47 cm and 41 cm, respectively. The excitation power was set at 10 W. For this test, the maximum measuring error was established as 0.07°C, while absolute average error was 0.02°C (Fig. 11). Although an accuracy level of only 0.1°C is usually required for this type of hyperthermia temperature measurement, this sensor system more than satisfied the specification.

5. Discussion

5.1 Sensor and Measurement System

Though both the size and shape of the sensor shown in Fig. 1(b) are still far from being within acceptable limits, as regards their use in medical treatment. We think that, in the very near future, the size of the sensor will be reduced to approximately 3.5 mm in diameter. This can be accomplished by replacing the current, air-core model with one that uses a ferrite-core coil. The length of the sensor can also be reduced by integrating the passive element.

Two computer-controlled transceivers, one set to transmit-only and the other set to receive-only, are used in the measurement system. Frequency-step width and the sweep-speed are both freely adjustable, and can be performed either automatically or manually with a timer to remind us to measure the temperature at the desired intervals.

5.2 Influence of the Distance from the Sensor to the Excitation Antenna

As shown in Fig. 6, when d_e was proximal, f_w be widened. When excitation power is applied to the sensor, negative resistor increases near the resonant frequency. Excitation power was adjusted so that f_w be narrowed, eliminating the influence of d_e. As a result, the receiver's output voltage waveform squared allowing precise measurement of f_1 and f_2. We were then able to measure a stable f_0.

5.3 Oscillation-Frequency Bandwidth

In an ordinary parametron-oscillation circuit, oscillation occurs over a wide frequency bandwidth, f_w, as shown in Fig. 8 (a). The sensor used in this experiment, however, oscillated in a narrow f_w, and at a very suitable excitation power (Fig. 8 (b)) because of the quartz resonator installed in the parametron-oscillation circuit. The quartz resonator has a high Q and generates sharp oscillation peaks with a negative resistor generated by parametric effect. If the effect of the negative resistor is excessively high, the quartz resonator will merely act as a capacitor, and will oscillate in a wide f_w in the manner of an ordinary parametron.

5.4 Measurement in RF Hyperthermia

The following problems arise during temperature-measurement, in instances of RF hyperthermia:

(i) the improper operation of the measurement system;

(ii) the reaction of the human body to the insertion of the sensor;

(iii) the durability of the sensor.

The countermeasure to the electromagnetic interference measuring system is dealt with in (i). In heating experiments, an exposure of 500 W RF hyperthermia at 13.56 MHz did not result in discernible error in measurement. As concerns (ii), Magara et al. [6] discussed a sensor, similar to ours that did not disturb the temperature distribution of the object. Even if repeatedly heated for more than one hour, no abnormalities were recognized in the sensor (iii). In animal experiments as well, we confirmed that the sensor operated normally [6].

6. Conclusion

We applied the principle of parametron oscillation to a tiny sensor, which, after implantation requires no internal power supply. Since this sensor oscillates with a frequency of one-half of the excitation frequency, the signal can be measured, free of any influence by the excitation signal. When the excitation power to the sensor was efficiently supplied, the distance from the sensor to the excitation antenna, d_e could be separated up to a distance of 95 cm in the air and 41 cm in the phantom. Using the quartz resonator equipped sensor, we were easily able to calculate the temperature from the oscillation-center frequency. The power was adjusted so that the frequency bandwidth was sufficiently narrow. As a result, the temperature measurement using the particular phantom we applied, in this study, a maximum error of 0.07°C was obtained from the system.

We feel confident that, once the obvious advantages of this sensor become known, use it in clinics, will be widespread in the future. Its improved ability to automatically discriminate between parametron oscillation and noise substantially increases the reliability of the overall measurement system. The task which lies before us now, is to ways in which the equipment can be minimized.

References

[1] D.G. Hill and K.L. Allen, "Improved instrument for the measurement of c.s.f. pressures by passive telemetry," Med. & Biol. Eng. & Comput., vol.15, pp.666–672, Nov. 1977

[2] N.T. Zervas, E.R. Cosman, and B.J. Cosman, "A pressure-balanced radio-telemetry system for the measurement of intracranial pressure," J. Neurosurg., vol.47, pp.899–911, Dec. 1977.

[3] V. Barbaro and V. Macellari, "Intracranial pressure monitoring by means of a passive radiosonde," Med. & Biol. Eng. & Comput., vol.17, pp.81–86, Jan. 1979.

[4] Y. Kato, T. Kuroda, and T. Togawa, "Perioral force measurement by a radiotelemetry device," Am. J. Orthod. Dentofac. Orthop., vol 95, no.5, pp.410–414, May 1989.

[5] Y. Saitoh, R. Tanaka, M. Magara, M. Suzuki, T. Kiryu, and H. Makino, "A temperature measuring system with an implantable sensor for the hyperthermia," JJME, vol.24, no.1, pp.41–46, Feb. 1986.

[6] M. Magara, Y. Saitoh, T. Kiryu, and H. Makino, "Development of multichannel thermometer with implantable sensors for the hyperthermia," JJME, vol 25, no.4, pp.277–283, Dec. 1987.

[7] M. Magara, Y. Saitoh, T. Kiryu, H. Makino, and R. Tanaka, "Development of passive telemetry system for intracranial pressure measurement with corrector of errors caused by temperature variation," JJME, vol.27, no.1, pp.35–44, March 1989.

[8] J.T. Farrar, C. Berkley, and V.K. Zworykin, "Telemetering of intraenteric pressure in man by an externally energized wireless capsule," Science, vol.131, no.17, p.1814, June 1960.

[9] J. Nagumo, A. Uchiyama, S. Kimoto, T. Watanuki, M. Hori, K. Suma, A. Ouchi, M. Kumano, and H. Watanabe, "Echo capsule for medical use (A batteryless endoradiosonde)," IRE Trans. Biomed. Electronics, vol.BME-9, pp.195–199, 1962.

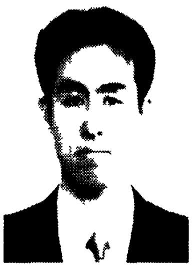
[10] T. Tsuji, T. Ohshima, K. Ohyama, D. Hashimoto, and T. Togawa, "Telemetry of intragastric temperature in man with quartz crystal resonator using ultrasonic detection," Report Institute Med. Dent. Eng., vol.24, pp.65–70, 1990.

[11] E. Goto, "On the application of parametrically excited nonlinear resonators," IECE, Trans. vol.38, no.10, pp.770–775, Oct. 1955.

[12] A. Ohto, "TOSHIBA Semiconductor Data Book, Rectifier and Thyristor," TOSHIBA Electronics, Tokyo, 1981.

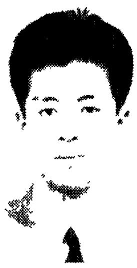
Yoshiaki Saitoh was born in Niigata Prefecture, Japan. He received the B.E. degree in electrical engineering from Niigata University, Niigata, Japan, in 1963, and the M.E. and Ph.D. degrees in electrical engineering from Hokkaido University, Sapporo, Japan, in 1965 and 1970, respectively. In 1965 he joined the staff of the Department of Electronics, Niigata University, as an Instructor. Since 1980, he has been a Professor in the Department of Information Engineering at Niigata University. His recent research interests include measurements and stimulation of the human organs, hyperthermia systems, and biomedical signal processing. Dr.Saitoh is a member of IEEE and the Japan Society of Medical Electronics and Biological Engineering.

Akira Kanke was born in Fukushima Prefecture, Japan. He received the B.E. and M.E. degrees in information engineering from Niigata University, Niigata, Japan, in 1991 and 1993, respectively. In 1993 he joined Fujitsu Limited. He is currently a candidate for the D.E. degree at Niigata University. His research interest is in biomedical measurement.



Isamu Shinozaki was born in Niigata Prefecture, Japan. He received the B.E. and M.E. degrees in information engineering from Niigata University, Niigata, Japan, in 1993 and 1995, respectively. Since 1995 he has been at the Ministry of Finance. His research interest is in biomedical measurement.

Tohru Kiryu was born in Niigata Prefecture, Japan, in 1952. He received the B.E. and M.E. degrees in electronics engineering from Niigata University, Niigata, Japan, in 1975 and 1977, respectively and the Dr. Eng. degree in computer science from Tokyo Institute of Technology, Tokyo, Japan, in 1985. From 1977 to 1978, he was an Assistant at the school of dentistry of Niigata University. From 1978 to 1995, he was with the Department of Information Engineering, Niigata University. Since 1995, he has been with the Graduate School of Science and Technology, Niigata University as a Professor. From June 1990 to March 1991, he studied at the NeuroMuscular Research Center at Boston University as a Visiting Scientist. He has been working on biomedical signal processing, especially time-varying spectral analysis, time-varying parameters estimation using nonstationary models and nonstationary stochastic process. For applications, his recent interests have been in myoelectric signal analysis during dynamic movements, muscular fatigue evaluation at a required time, and mental stress evaluation from multidimensional time-series. Dr.Kiryu is a member of IEEE, the Japan Society of Medical Electronics and Biological Engineering and the Japan Prosthodontic Society.



Jun'ichi Hori was born in Yamagata Prefecture, Japan, in 1963. He received the B.E. and M.E. degrees in information engineering from Niigata University, Niigata, Japan, in 1986 and 1988, respectively and the Dr. Eng. degree in computer science from Tokyo Institute of Technology, Tokyo, Japan, in 1996. In 1988 he joined the staff of the Department of Information Engineering, Niigata University, as an Assistant. His research interests include biomedical measurement and nonstationary signal processing. He is a member of IEEE and the Japan Society of Medical Electronics and Biological Engineering.