Development of Food Texture Sensor Using Two Magnetic Sensing Elements

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***Abstract*—An effective evaluation method of food texture is required for food development. A conventional evaluation method is sensory test-based evaluation. Although the sensory test directly evaluates food texture, it requires many subjects and high cost. Another evaluation method is a use of food texture instruments. The instruments quantify food texture. However, its sensor has the simple function which measures load. Its evaluation performance is not enough for food texture evaluation. In this paper, we propose a food texture sensor. The sensor is based on a human tooth, and has the structure which is composed of a contactor, an elastomer membrane and a base. Two kinds of sensing elements detect displacement of the contactor. The sensing elements work as fast and slow adaptive receptors. In this paper, first the structure and function of human tooth are described. Second, the structure of the sensor is illustrated, and the principle is explained. Finally, a fabricated prototype is demonstrated. In addition, the effectiveness of the sensor is confirmed through experiments using the prototype and foods.**

I. INTRODUCTION

Masticating and ingesting food are essential for us, human beings, to maintain our life. During the mastication process, we perceive mainly three stimuli. Two of them are tastes and smells which have important roles for decision of the food's flavor. They are perceived by senses of taste and smell. The other one is a physical relationship between the tooth and food, called as food texture.

Expression of food textures uses various kinds of onomatopoeia in Japanese. For example, crispiness is expressed as ”SAKU SAKU”, ”PARI PARI”, and so on. As well as taste and smell, food texture evaluation is important for food developers. To evaluate food texture, in general, human subjects chew a test food and answer questionnaire questions. In most cases, only qualitative results are obtained from the questionnaire answers. It is difficult for the qualitative results to evaluate the difference between sensitive food textures.

To evaluate food textures, some food texture instruments have been used [1][2]. Commercially available food texture instruments are mainly composed of a load cell, a motorized slider and analysis software. They plot relationship between force and displacement, and analyze the food textures from the relationship. In these instruments, the sensor to obtain the food texture is a load cell which measures one-dimensional force [3]. It seems that the one-dimensional force is too simple to evaluate food textures. On the other hand, several researchers have reported evaluation methods using acoustic signal [4]-[6]. Taniwaki et. al have proposed a method of food texture measurement using acoustic vibration [7]. They obtained the acoustic vibrations to measure crispy texture of four kinds of potato chips, and analyzed them using texture indexes. Makino et. al reported a bone conduction-like acoustic sensor system [8]. The system had acrylic teeth, an acrylic bone and two acoustic emission sensors, and classified four characteristic crispy foods. Using the acoustic vibration is effective and reasonable for the measurement of the crispy texture.

Human evaluates food texture using own tooth and jaw. Mechanoreceptors around the tooth detect stimuli based on the food texture. In the case of human skin, it has four kinds of receptors: Meissner corpuscles, Merkel cells, Pacinian corpuscles, Ruffini endings [9][10]. They are classified as slow adaptive receptors and fast adaptive receptors. The slow adaptive receptors detect static signals and have the same role as the load cell in the food texture instruments. On the other hand, the fast adaptive receptors detect changes of stimuli as dynamic signals. Hence, the acoustic sensors work as the fast adaptive receptors. Because these receptors detect different stimuli, we can recognize the complicated food texture after signal processing in our brain. In the case of the tooth, the slow and fast adaptive receptors work in the same manner [11][12]. Therefore, the food texture sensor which has the slow and fast adaptive elements for measurement is effective for the complex food texture measurement.

In this study, we propose a food texture sensor which has two sensing elements with different characteristics. The food texture sensor has a structure based on a human tooth. The sensor has two kinds of sensing elements. One is a giant magneto resistive element. Another is an inductor. They work as the slow and the fast adaptive element, respectively. This paper describes the detailed structure of the sensor, and shows a prototype sensor. In this paper, first the structure and function of human tooth are described. Second, the structure of the sensor is illustrated, and the principle is explained. Finally, a fabricated prototype is demonstrated. In addition, the effectiveness of the sensor is confirmed through experiments using the prototype and foods.

II. FOOD TEXTURE SENSOR

A. Tooth structure

A structure of a human tooth is shown in Fig. 2. The human tooth is mainly composed of three layers: enamel, dentine, and dental pulp. The enamel covers over a top part of a tooth, called crown. The enamel is the hardest tissue in a human body and is not regenerative by itself. The dentine is an inner tissue of the

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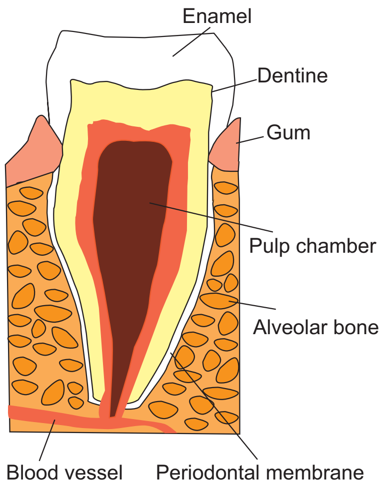

Fig. 1. Human tooth structure.

enamel and has softness and pain sensations. In comparison to the enamel, the dentine is regenerative on the side of the dental pulp to protect it. The dental pulp has nerve fibers, blood vessels, and lymphatic vessels. A periodontium includes cement, an alveolar bone and a periodontal membrane. The cement is the soft tissue which surrounds to cover around tooth root. The alveolar bone is a bone which sustains the base of tooth. The periodontal membrane is located between the tooth and the alveolar bone, and is a connective tissue which has a good elasticity. Its thickness is approximately 0.2 - 0.3 mm. The periodontal membrane fixes the tooth on the alveolar bone, and reduces an impact force in masticating. In addition, the periodontal membrane has mechanoreceptors which detect the deformation of the membrane [13]. The mechanoreceptors are classified as two kinds: slow adaptive receptors and fast adaptive receptors. It is considered that the two receptors have important roles in food texture recognition.

Consequently, the food texture sensor should have the following functions.

- A flexible membrane under a tooth part
- Two kinds of sensing elements

In this study, we design a food texture sensor equipped with the two functions.

B. Principle

A human recognizes load and vibration in masticating based on the movement of a tooth part. The movement of the tooth deforms the periodontal membrane. Because the membrane is thin, the movement is small. Hence, the sensing elements in the food texture sensor require high sensitivity. In addition, the wiring between the tooth part and the base part through the membrane causes wiring breakage. In order to prevent from breaking of wire, the wireless structure between them is required. Therefore, this study applies magnetic field strength measurement to the food texture sensor.

The cross-section view of the food texture sensor is shown in Fig. 2. The structure of the sensor mainly has the tooth part

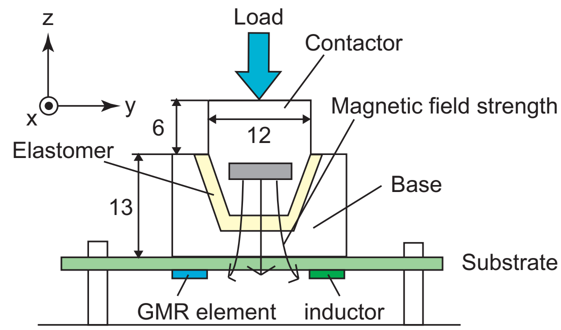

Fig. 2. Sensor structure.

and the substrate part. The tooth part includes the contactor, the elastomer membrane and the base. The contactor is solid and directly contacts food with the circular upper surface. The shape of the contactor is a circular truncated cone. The contactor has a permanent magnet inside itself. The magnet has a cylindrical shape. The elastomer is made of a urethane material and is 3 mm in thickness. Its hardness is 15 in Asker-C. The base is solid and receives the elastomer and the contactor. To easily fabricate the tooth part, the size of the base is approximately twice in comparison to a human molar tooth and is 26 mm in diameter. The upper side of the substrate part is flat and fixes the tooth part with an adhesive. The bottom side has four giant magneto resistive (GMR) elements and four inductors. Their output lines are connected to an amplifier circuit.

The principle of measurement is as follows. When the load occurs on the contactor, the contactor is pushed. The elastomer deforms based on the load. Hence the contactor moves down. Because the base does not move by the load, the magnetic field strength to the GMR elements and inductors changes. The GMR elements change the output voltage based on the magnetic field strength. On the other hand, the inductors output the induced voltages based on the change of the magnetic field strength. Therefore, the GMR elements and inductors work as the slow and fast adaptive receptors, respectively. The output voltages of the GMR elements determine the z axis displacement by a regression equation. Those of the inductors quantify the vibration occurred on the contactor.

C. Design

The numbers of the GMR elements and inductors are four each. In order to realize high accuracy and low bias, these elements are uniformly placed on the circular line as shown in Fig. 3. Fig. 3 shows the bottom side of the substrate. The circular dotted line shows the position of the base part on the upper side, and is 20 mm in diameter. The elements are placed inner the dotted line. The GMR elements have an axis in sensitivity, and detect the magnetic field strength in the direction of the diameter of the dotted line. The inductors have no axis in sensitivity.

D. Calibration

The GMR elements in the food texture sensor output static voltages based on the magnetic field strength. The displacement of the contactor decides the magnetic field strength on the

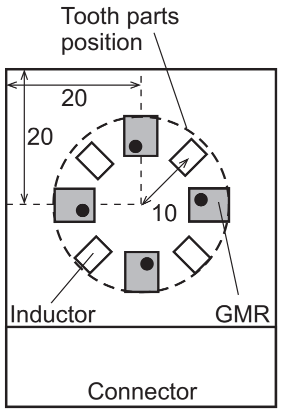

Fig. 3. Design of bottom side of substrate.

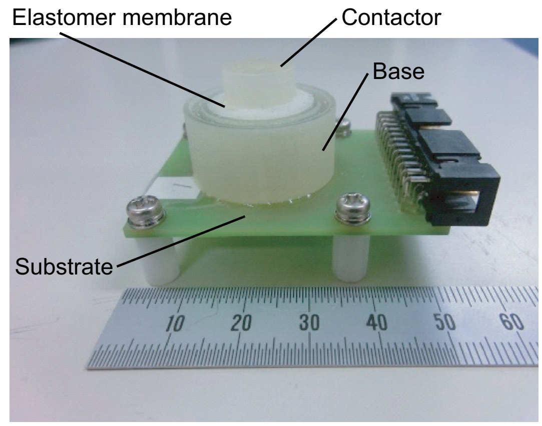

Fig. 4. Prototype.

GMR elements. Therefore, an appropriate equation determines the displacement of the contactor based on the output voltages. The geometric positional relationship between the magnet and the GMR elements decides a regression equation. The equation of the z axis displacement Δz is given by

$$\Delta z = C_0 + \sum_{i=1}^{4} \left(\frac{C_{2i-1}}{v_i} + \frac{C_{2i}}{v_i^2} \right), \tag{1}$$

where $C_j (j = 0, \cdots, 8)$ are the coefficient constants, $v_i (i = 1, \cdots, 4)$ are the output voltages of the GMR elements. To determine the displacement of the contactor, C_j should be decided in advance. In this study, we obtain the combinations of the displacements and the GMRs' voltages in the range of -2.0 - 0.0. The number of the combinations is 20. The coefficient constants C_j are decided from the combinations by a multiple regression analysis.

Commercially available food texture instruments measure load as a reaction force. Because the membrane in the tooth part is made of an elastomer, the membrane can be expressed through a linear elastic model. The force determined by the linear model is proportional to the displacement of the contactor and is easily calculated from the displacement. Hence we use the displacement instead of the force in this paper.

III. Experiments

A. Prototype

We fabricated a prototype sensor. The prototype is shown in Fig. 4. The contactor and the base were created by a rapid prototyping technique. The contactor is composed of two parts. After including the cylindrical magnet, they were assembled. The elastomer membrane between the contactor and the base was made by pouring liquid polyurethane in their gap. The tooth part was fixed on the substrate by an adhesive. The four GMR elements (AA004-02 manufactured by NVE Co.) and the four inductors (ELJFB102JF manufactured by Panasonic Co.) were soldered on the bottom side of the substrate. The black part in the right side of Fig. 4 is a connector which connects to an amplifier circuit.

B. Measurement system

A connection block diagram of measurement system is shown in Fig. 5. The system is mainly composed of the food texture sensor, the amplifier circuit, the PC including the A/D converting board, and the motorized linear stage.

The PC controls the motorized linear stage (SGSP33-200(Z) manufactured by Sigma Koki Co.). The sensor is fixed to the motorized stage. The motorized stage moves the sensor and presses food. The reaction force makes the contactor's displacement, and changes the output voltages of the sensor. The amplifier circuit amplifies the output voltages from the sensor. The output voltages of the GMR elements and inductors are amplified to 32 and 10000 times magnification, respectively. The amplified voltage is converted to a digital value by the A/D conversion board (AIO-161601UE3-PE manufactured by CONTEC Co.). The sampling frequency is 1 kHz. The PC records the digital values, and calculates the z axis displacement of the contactor based on the output voltage of the GMR elements.

The measurement system is shown in Fig. 6. The motorized linear stage is placed vertically and moves the stage up and down. The PC controls the movement and velocity of the motorized linear stage, and presses the sensor toward food. Therefore, the system is operated similarly as commercially available food texture instrument.

C. Calibration

First, the calibration was performed with the measurement system. The motorized stage controlled the position of the food texture sensor. Hence, the food texture sensor was moved at the position in a contact state with a solid block. The motorized stage pressed the sensor, and sank the contactor into the base. The range of the displacement of the contactor was from -2.0 to 0.0 mm at an interval of 0.2 mm. The PC obtained the combination of the displacement and the output voltages. The number of two sets of the combination was 20. The coefficient constants C_j in (1) were decided based on the combinations by the regression analysis.

We calculated errors between Δz and target values using the combination data for evaluation. The average error and the maximal error were 0.11 and 0.19 mm, respectively. The noise included in the output voltages mainly caused the average error. However, the maximal error was within 10% of the range of Δz. This result showed that the food texture sensor is effective for measurement of displacement in pressing food.

D. Experiment using Crunchy Potato Snack

We performed an experiment of pressing a crunchy potato snack using the measurement system. The snack has a French fries shape and is approximately 5 mm in thickness. The system pressed the snack at the velocity of 7.5 mm/sec and obtained the output voltages. The displacement of the contactor was calculated from the output voltages of the GMR elements.

The relationship between time and the displacement is shown in Fig. 7. Fig. 7 also includes the output voltages of the inductor. The voltage instantaneously dropped at around 380 msec. The drop indicates the moment of contact between the contactor and the snack. Thereafter, the displacement gradually dropped at a constant slope. The contactor was sunk into the base in conjunction with the motion of the stage. At around 840 msec, the displacement rose, and the voltage of the inductor dropped again. Their changes showed the moment of fracture of the snack. The response of the voltage had a small delay in comparison to the displacement. It is considered that the amplifier circuit has delay, because the gain is large. It is necessary to improve the circuit.

The changes of the displacement and voltage show the characteristics of the slow and fast adaptive receptors, respectively. Therefore, we confirmed that the fabricated sensor has the response characteristics equivalent to human's sense.

E. Experiment using Fish Sausage

The displacement measured by the food texture sensor is proportional to load occurred on the contactor surface. Hence, the sensor should indicate the same behavior as a load cell. The sensor pressed a fish sausage to confirm its response. The fish sausage is approximately 15 mm in diameter and is very bouncy. The measurement system with the sensor pressed the fish sausage by 3.0 mm twice.

Figure 8 shows a relationship between time and displacement while pressing fish sausage twice. The displacements at the first and the second pressing were approximately -0.7 and -0.5 mm, respectively. The tendency, which the displacement at the second pressing is smaller than that of the first pressing, shows cohesiveness property of the food. Because the fish sausage has the cohesiveness property, the relationship in the result was reasonable. Therefore we confirmed that the food texture sensor is effective for evaluation of cohesiveness property.

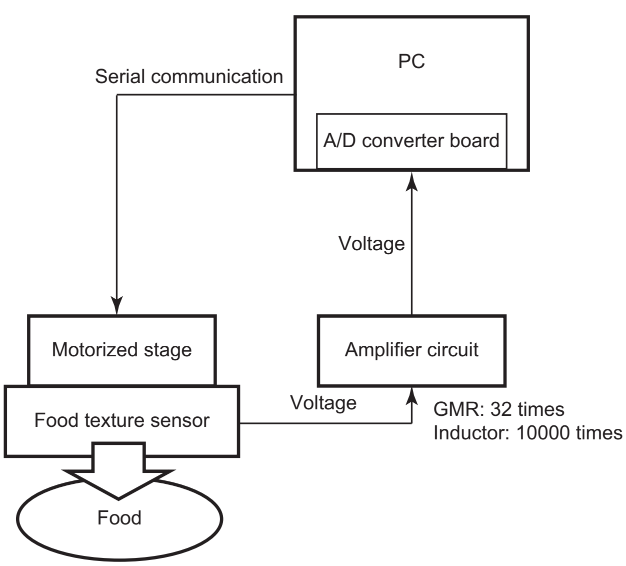

Fig. 5. Diagram of measurement system.

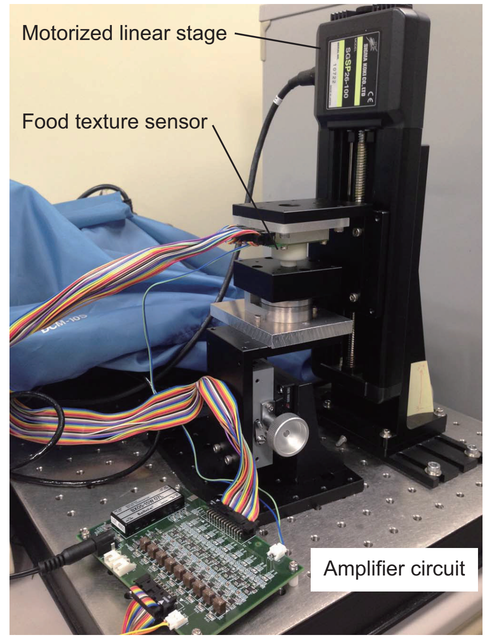

Fig. 6. Measurement system.

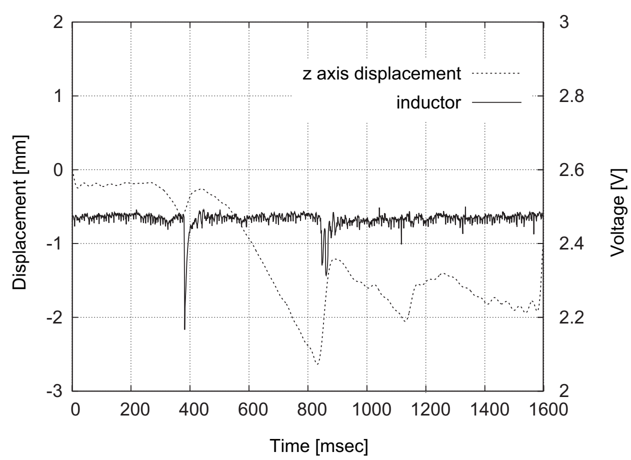

Fig. 7. Relationships between time and displacement and between output voltage of inductor while pressing potato snack.

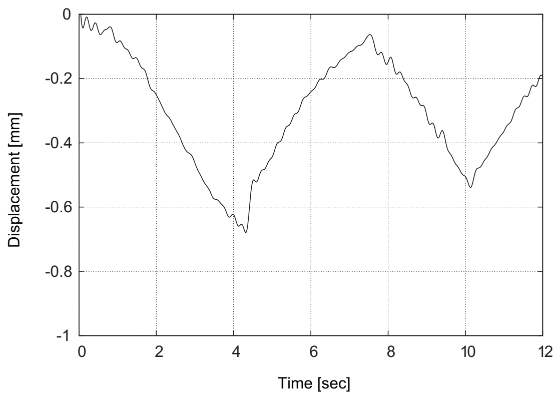

Fig. 8. Relationship between time and displacement while pressing fish sausage twice.

IV. Conclusion

A periodontal membrane under a tooth is elastic and has mechanoreceptors. When food touches the tooth, the periodontal membrane is deformed and simultaneously the mechanoreceptors generate nerve impulses. The mechanoreceptors are classified as two kinds: fast and slow adaptive receptors. Based on these findings, we proposed the food texture sensor. Its characteristics are as follows:

- The sensor has the elastic membrane under the contactor. The contactor moves by an external force.
- The sensor has two kinds of sensing elements: GMR elements and inductors. They work as slow and fast adaptive receptors, respectively.
- There is no wiring between the contactor and the substrate by using the permanent magnet. The structure is effective for water resistance and disconnection of the wiring.

To confirm the effectiveness of the sensor, the fabricated sensor performed the fundamental experiments. The outputs of the sensing elements quickly changed at the moment of fracture of the snack. The GMR elements continued the static outputs as long as the pressure remained. On the other hand, the inductors changed their outputs quickly at the moment when an external force occurred, but changed them again when the force was removed. Therefore we confirmed that the two elements in the sensor worked along the designed characteristics.

To apply the sensor to food texture measurement, a signal processing method which evaluates physical characteristics of food is required. At the next step, we will propose the method.

Acknowledgment

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