Impact Resilience Measurement of Elastic Materials by using Active Tactile Sensor

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Abstract

This paper proposes an active tactile sensor driven by using piezo-electrical actuator. It consists of a silicon diaphragm having piezoresistive strain sensors for measuring displacement of the diaphragm, and a piezoelectric actuator for driving the sensing element. The proposed active tactile sensor has an advantage in that it can detect the multiple physical values, elasticity and impact resilience of a contact object, by analyzing the obtained step-response waveform. We fabricated the sensor element by using Micro-Electro-Mechanical-Systems (MEMS) technologies, and assembled it with a commercially available piezoelectric actuator in hybrid manners to produce the active tactile sensor. The sensor was 15 mm x 15 mm x 20 mm. Six different rubbers of different hardness ranging from A30 to A70 in Shore A, was used to evaluate the elasticity detection function of the sensor, and we confirmed that the output increased linearly with the increase in the rubber hardness (elasticity). We also evaluated two different rubber materials, urethane and damping rubbers, which had different values of impact resilience, and found that step responses of the sensor output were quite different between two (the damping rubber showed overshooting phenomena at the rise). We therefore concluded that the proposed sensor is capable of detecting two values, elasticity and impact resilience, of a contact object.

1. INTRODUCTION

Recent progress in Micro-Electro-Mechanical-Systems (MEMS) technologies has brought significant benefits to various industrial fields. Physical and chemical sensors have integrated with electric control circuits to realize small-sized intelligent systems. In particular, physical sensors, such as pressure, acceleration, flow, gyroscope, and inclination sensors have already been commercialized, and are now widely used in automobile, information, and medical instrument industries. MEMS technologies can also produce small-sized arrayed tactile sensor devices, which will provide an artificial intelligent skin for robot systems in the near future.

Many researchers have proposed various types of tactile sensors for detecting contact information by using MEMS technologies[1-4]. In general, they have used static or resonant operation modes. In the static mode, the sensor basically detects the contact force acting between the sensor surface and the contact object by using a strain gauge [5-6] or variable capacitance [7-8]. The sensors are easily arranged in an arrayed manner during fabrication if one needs a 2-D contact force distribution of the objects. In the resonant mode, the sensor detects the elasticity of the contacted object by using the change in resonance characteristics [9]. However, these previous works only focused on the detection of a single physical value (contact force or elasticity). Engel et al. recently combined several sensor elements on the same chip to detect multiple physical values [10].

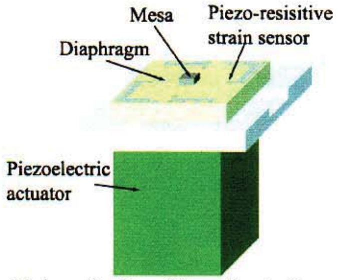

Fig. 1 Schematic view of the active tactile sensor

These previously reported tactile sensors therefore cannot detect multiple physical values by just a single sensor structure like the tactile function of human skin. We previously proposed an active tactile sensing system consisting of sensing and actuating elements to detect multiple physical values using a single sensor structure. We also developed two different types of system actuating sensor structures. One is external pneumatic actuation, and the other is MEMS-based magnetic actuators [11-12]. We confirmed that they were able to detect plural physical values, such as contact force, elasticity, and viscosity of rubber materials they were in contact with. Recently, damping rubber materials that have low impact resilience have been coming into wide use as shock absorbers in such products as the soles of sports shoes and in laptop computer carrying cases. We think that the impact resilience is also an important value to understand the characteristics of elastic materials. We therefore evaluated two physical values, impact resilience and elasticity, of contacted rubber materials by applying a piezoelectric actuator device, and we describe the results of evaluation in this paper.

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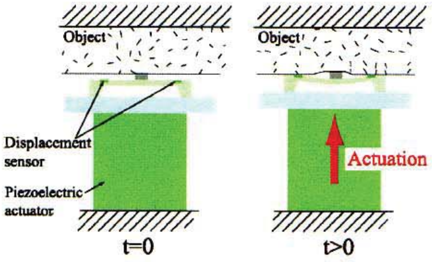
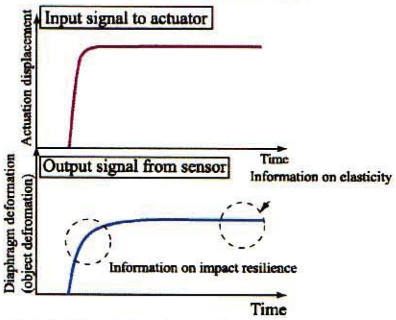


(a) (b)

Cross-section view



(c) Principle of elasticity and impact resilience detection using the active tactile sensor.

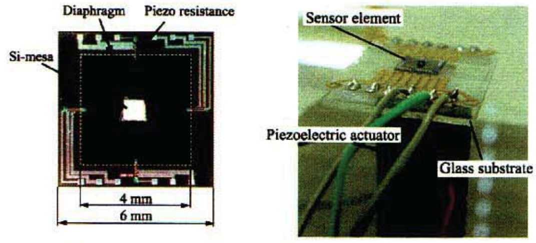
Fig. 2 Detection principle of the active tactile sensor

2. PRINCIPLE OF THE TACTILE SENSOR

Figure 1 is a schematic view of the piezoelectrically actuated tactile sensor structure. It consists of a silicon diaphragm with a silicon mesa and a piezoresistive strain sensor to measure the displacement of the sensing mesa, a piezoelectric actuator to drive the mesa, and a glass plate for combining the sensing and actuator elements. The sensing operation and the detection principle are as follows (Fig. 2).

Sensing operation

We used a step input to evaluate the impact resilience and elasticity of the contacted objects. We at first applied the step voltage, as a driving signal, to the piezoelectric actuator (the contacting mesa element is suddenly driven towards the object by the stretching of the piezoelectric actuator). As a result, the object and sensing diaphragm are deformed upward and downward, respectively, according to the physical properties of the object (Fig. 2(b)). Therefore, we can detect the elasticity and impact resilience of the object by analyzing the obtained step-response waveform, as shown in Fig. 2(c). We used MEMS technologies to fabricate the displacement sensor element. Therefore, the sensor has an advantage in that it is able to arrange the number of sensor elements in an arrayed manner in the same plane. This means that the sensor can detect the impact resilience and elasticity of the contacted objects at once, as information of 2D distribution.



(a) Fabricated displacment sensor element (b) Assembled piezoelectrically driven tactile sensor

Fig. 3 Photograph of sensor element and assembled active tactile

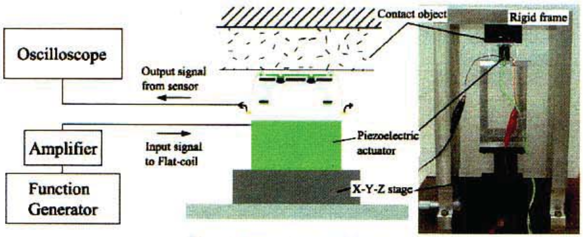


Fig. 4 Experimental setup

Detection principle

Elasticity detection:

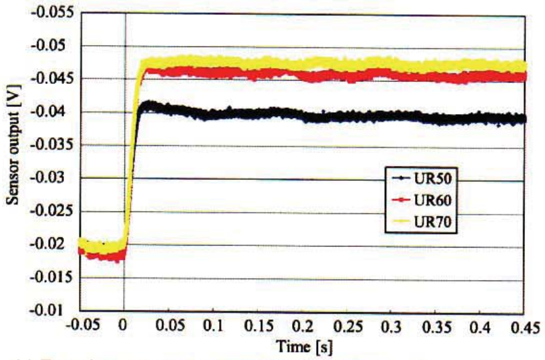
The final displacement value of the sensing diaphragm in the steady state depends on the elasticity of the contact objects. Therefore, the sensor can detect the elasticity of the object by measuring the displacement values of the diaphragm by the strain gauge in the steady state.

Impact resilience detection:

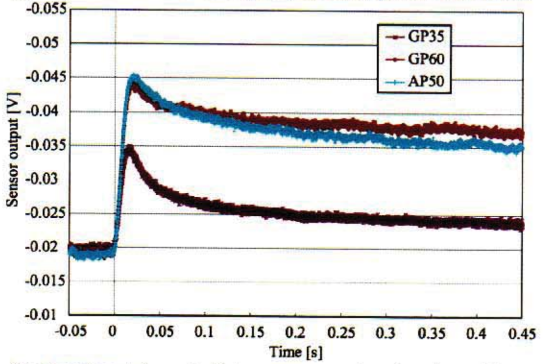
The rising characteristic on the step-response waveform depends on the impact resilience of the contact objects. Therefore, the sensor can detect the impact resilience of the object by the waveform feature in the rising region.

3. EXPERIMENTS

The sensor element of silicon diaphragm structure with a piezoresistive strain gauge was fabricated using MEMS technologies. Figure 3(a) shows the top view of the sensor element. The sensor element is 6.0 mm x 6.0 mm x 425 μm, and the diaphragm was 4.0 mm x 4.0 mm x 10 μm. The detection range of this sensor depends on the elasticity of the diaphragm. We used a commercially available piezoelectric actuator that was 11 mm^2 x 18 mm. The piezoelectrically driven active tactile sensor was produced by assembling the sensor element and the actuator element (Fig. 3(b)). The total size of the sensor was 15 mm x 15 mm x 20 mm. Figure 4 shows the experimental setup. The sensor was placed on the x-y-z stage, and we controlled the initial contact depth between the mesa on the diaphragm and the contact object by adjusting the z-stage movement. We set the initial contact depth at 1.0 μm.



(a) Experimental result of step response using urethane rubbers



(b) Experimental result of step response using damping rubbers

Fig. 5 Step-response waveform of the urethane and damping rubbers

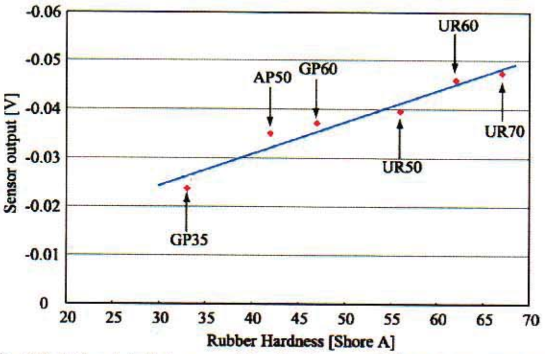


Fig. 6 Relationship between rubber hardness and the sensor output at steady state after saturation for step input

We prepared several kinds of rubber, which had different degrees of hardness ranging from A30 to A70 in Shore A hardness, and we also evaluated two different rubber materials, urethane and damping rubbers, which had different values of impact resilience. Recently, the damping rubbers were commercially used as shock absorbers in such products as the soles of sports shoes and in laptop computer carrying cases, and they had low values of impact resilience compared with those of the urethane rubbers. Table 1 shows the specifications of the sample rubber materials. The piezoelectric actuator was stretched about 4 μm by applying a driving voltage of 30 V, and the displacement of the diaphragm was measured from the output signal of the piezoresistive strain gauge on the diaphragm.

Table 1 Characteristics of the rubber object

Object	Material	Rubber Hardness [Shore A]	Impact Resilience [%]
UR50	Urethane Rubber	56	50
UR60		62	40
UR70		67	50
GP35	Damping Rubber	33	2
AP50		42	6
GP60		47	2

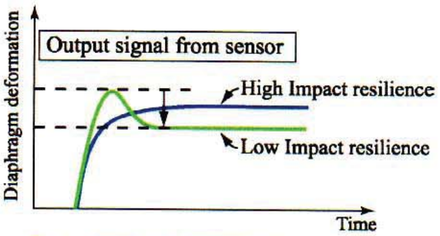


Fig. 7 Principle of impact resilience detection

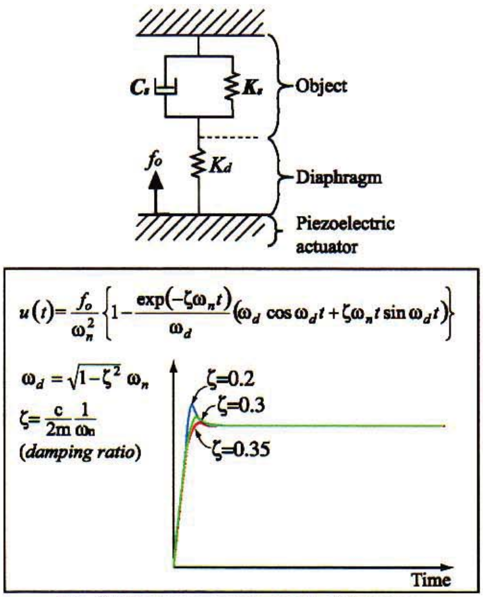
Figures 5(a) and (b) show the step-response waveform of the urethane and damping rubbers, respectively. The parameter in each graph is the elasticity of the rubber materials. We found that there was a difference in rising characteristics between the urethane and damping rubbers. With the urethane rubber materials, the output signal from the strain gauge sensor reached the steady-state value within 16 ms without overshooting (Fig. 5(a)). In contrast, with the damping rubbers, the output signal showed overshooting at the early stage of the response, and then gradually fell to a steady-state value (Fig. 5(b)). The overshoot phenomenon was in the case of the damping rubber materials, which have low values of impact resilience. This time, we shortened the measurement time to clearly understand the rising characteristics (time: 0 – 0.45 s). Therefore, we used the value of the sensor output at 0.45 s, as the steady-state value in this experiment. However, the output signal did not reach the steady-state value completely in the case of the damping rubber materials. To increase the accuracy of the steady-state value, we are now planning to do the same experiment with a longer measurement time.

4. DISCUSSION

Here we discuss the proposed sensor's ability to detect the two physical values of elasticity and impact resilience.

Elasticity detection:

From the obtained data in Fig. 5, we plotted the relationship between the steady-state output value and the rubber



$$u(t)=\frac{f_o}{\omega_n^2}\left\{1-\frac{\exp(-\zeta\omega_n t)}{\omega_d}\left(\omega_d \cos\omega_d t+\zeta\omega_n t\sin\omega_d t\right)\right\}$$

$$\omega_d=\sqrt{1-\zeta^2}\,\omega_n$$

$$\zeta=\frac{c}{2m}\frac{1}{\omega_n}$$

(*damping ratio*)

Fig. 8 The sensor system model of detection

hardness measured by the durometer. The results are shown in Fig. 6. Durometer is used as a standard test method to evaluate the hardness of rubber materials. In this method, hardness means the depth of depression of the indenter at the moment the resilient force becomes equal to the pressure load of the measurement. We therefore used the values measured by the durometer as a standard values, and we compared those with the sensor output to evaluate the sensor performance. The steady-state values on the waveform strongly correlated with the rubber hardness. It linearly increased with the increase in the rubber hardness (elasticity). We therefore concluded that the sensor can detect elasticity from the step response.

Impact resilience detection:
Impact resilience of the rubber materials is defined as the ratio of energy an object has during impact and rebound when a test piece is struck by a falling object with a given mass from a given height. It is an indicator of the energy the material absorbs during the impact. The values of the impact resilience were measured using this conventional method shown in Table 1. On the contrary, our sensor evaluates the impact resilience of the object from the waveform feature in the rising region. We therefore used these values of impact resilience obtained by the conventional method as a standard, and we analyzed the relationship between the step-response waveform from the sensor output and the standard values of impact resilience. As described in the results, the overshooting phenomena at the early stage on the step-response waveform depended on the values of impact resilience of the objects (illustrated in Fig. 7). This means that the sensor can evaluate the differences in the impact resilience of contact objects from the rising characteristics on the waveform. To express the relationship between them quantitatively, we constructed a physical model. Figure 8 shows the constructed equivalent spring-damper model used to explain the overshooting phenomenon. With the model, the damping ratio ζ shown in the equation in Fig. 8 was related to the phenomenon. The overshooting phenomenon appears with the decrease in the value of ζ. The value in this model depends on the mass m of the diaphragm, the damper factor Cs of the object, and the natural angular frequency ω_n of this system. Therefore, we need to obtain the value of damping factor Cs to verify the model by doing further experiments. We now plan to evaluate damping factor Cs to advance to the next step in the verification of the model.

5. CONCLUSION

We have proposed a piezoelectrically driven active tactile sensor, which can detect the multiple physical values of elasticity and impact resilience in contact objects. The sensor was constructed from the sensor element of silicon diaphragm structure with piezoresistive strain gauge by using MEMS technologies and piezoelectric actuator for driving the sensor element. The sensor obtains the multiple physical values of contact objects from the step-response waveform. The sensor was 15 mm x 15 mm x 20 mm. We used several kinds of rubber, which had different hardness values ranging from A30 to A70 in Shore A hardness, to evaluate the elasticity detection function of the sensor, and also, we prepared two different rubber materials, urethane and damping rubbers, which had different values of impact resilience, to evaluate the impact resilience detection function. We confirmed the steady-state values on the waveform linearly increased along with increasing rubber hardness of the contact objects. We also found that there was a difference in rising characteristics between the urethane and damping rubbers depending on the values of impact resilience of the contact object. The overshooting phenomenon at the early stage of the response was observed only in the case of using damping rubbers. From these results, the sensor can evaluate the differences of the impact resilience of contact objects by analyzing the rising characteristics on the waveform. We also constructed a sensor system model to express the overshooting phenomenon quantitatively. We concluded the active tactile sensor is capable of detecting the elasticity and impact resilience of a contact object.

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