Development of Contact-Pressure and Shear-Stress Sensing System for Application to a Haptic Display

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Abstract

Sensor system for haptic display is important to achieve the feedback of the sense of force in the actuator control. We have proposed a haptic sensor system composed by thin and flexible sensor unit to measure contact pressure and shear stress.

In this study, a sensor system of both the contact pressure and the bi-axial shear stress, which can measure the three dimensional vector information, was developed by improving our previously-developed sensor unit. The wearable sensor system applied to human body and investigates the stress value in several cases of motions. The effectiveness of the sensor was discussed through those actual measurements.

Key words
Shear Stress, Thin and Flexible Sensor, Sensor System, Distribution, Haptic Display

1. Introduction

Several kinds of conductive polymers are suitable for small actuator materials because they have some special characteristics, such as light weight and large force generated by low electric voltage. The force is more than 10 times larger than that of human skeletal muscle. Micropump and active catheter actuator systems are being developed by taking the advantages of such characteristics [1]. However, a lot of ingenuities are still required to establish the actuator mechanism. On the other hand, in the haptic sensor system, in particular, measurements of shear stress, there are few studies on the development of sensor system for shear stress measurements [2, 3, 4]. Furthermore there is no report for development of very thin and flexible sensor for measurement of shear stress distributions on the contacting interfaces.

We have been developing a haptic display system using conductive polymer materials. A sensing system of contact pressure and bi-axial shear stress measurements can be combined with conductive-polymer actuator, and the haptic information acts in the control process as feedback of applied stresses.

So far, study on contact pressure measurement in vivo has been carried out using thin and flexible sensor [5]. We recently developed a capable sensor unit constructed by thin and flexible materials. The sensor could measure both the contact pressure and the shear stress [6].

In this study, a sensor system of both the contact pressure and the bi-axial shear stress, which can measure the three-dimensional vector information, was developed by improving our previously-developed sensor unit. The wearable sensor system applied to human body and we investigated the stress value in several cases of motions. The effectiveness of the sensor system was discussed through those actual measurements.

2. Methods

2.1 Sensor

The sensor system should be thin and flexible and they can simultaneously measure both the contact pressure and the shear stress acting at the contacting interfaces. The sensor is made of the electroconductive ink, 50\textmu m in thickness, and the copper-clad laminate film, 85\textmu m in thickness. Electroconductive ink has an important characteristic that electrical resistance decreases with increasing applied pressure. The copper-clad laminate film was utilized for the electrode of the sensor. A copper thin film was etched by means of conventional photolithography technique.

Sensor structure is composed of electroconductive ink layer sandwiched by a couple of electrodes. Figure 1 shows the mechanism of measurement of contact pressure. In this study, we define the normal stress as contact pressure. Figure 2 shows the mechanism of measurement of shear stress. When the contact pressure is applied, subsequently, the electroconductive ink layer is compressed, the electrical resistance of electro-conductive ink decreases. On the other hand, when the shear stress is applied and the area superimposed by a couple of electrode increases by the electrode shifts, and then the electrical resistance between a couple of electrodes decreases. When the shear stress acts to reduce the superimposed area, the electrical resistance between the electrodes increases. A sensing unit including contact pressure and shear stress measurement parts is shown in Fig. 3.

In our previous study [6], the developed sensor unit could not detect the shear stress applied direction whether position or negative because the electrodes did not have the half superimposed region in contrast to structure as shown in Fig. 2.

Figure 4 shows the electrode pattern newly designed for measurements of distributions of contact pressure and biaxial shear stress. This sensor has 13×15mm\textsuperscript{2} measurement area, in which four sensing units are integrated. The measurement area of one sensing unit is 6.7×5.8mm\textsuperscript{2}. Figure 5 shows the electrode patterns for measurement of contact pressure and biaxial shear stress for one location. The measurement area of sensing unit is 7.5×7.5mm\textsuperscript{2}. Figure 6 shows a photo image of the sensor. The sensor has been sealed with a PP film.
2.2 Measurement principle

When the contact pressure or the shear stress is applied to the unit, electric resistance between upper and lower electrodes changes. The changes in electric resistance can be obtained as voltage changes by utilizing the bridge circuit. Therefore voltage detection system provides the measurements of applied contact pressure and shear stress.

Change in electric resistance in measurement part of shear stress includes the effects of contact pressure change. To remove the effects from resistance change, a principle of two gauges method of the Wheatstone bridge circuit was used. As shown in Fig. 7, $R_1$ and $R_2$ are resistances between sensor electrodes for shear stress and contact pressure measurements, respectively and $R$ is constant resistances fixed on the circuit board. The electrodes of the measuring part in Fig. 3 were designed so that the electric resistance between them becomes equal under stress free condition. We can assumed that all resistances in the bridge circuit are the same, $R$, under pressure and shear stress free condition and the bridge circuit is in equilibrium state. Relational expression between voltage input to the sensor $E$ and output voltage of the bridge circuit $e$ is represented as follows:

\[
E = a_1 e + b_1
\]

\[
e = a_2 E + b_2
\]
At first, principle of two gauge method in Fig. 7(a) is given in Eq. (1).

\[
e' = \frac{1}{4} \left( \frac{\Delta R_1 - \Delta R_2 + \Delta R_3 - \Delta R_4}{R_1} \right) E'
\]

(1)

R1 and R_2 are resistances between sensor electrodes for shear stress and contact pressure measurements. Since \(\Delta R_i\) and \(\Delta R_p\) indicate the amount of change in those resistances from initial state,

\[
e = \frac{1}{4} \left( \frac{\Delta R_2 + \Delta R_4}{R} \right) E
\]

(2)

Denoting amount of change in electrical resistance only due to applied contact pressure by \(\Delta R_i\), and amount of change in electrical resistance only due to applied shear stress by \(\Delta R_p\),

\[
\begin{align*}
\Delta R_i &= \Delta R_2 + \Delta R_4 \\
\Delta R_p &= \Delta R_1 + \Delta R_3
\end{align*}
\]

(3)

By substituting Eq. (3) into Eq. (2), the change in electric resistance due to only shear stress is extracted as:

\[
e' = \frac{1}{4} \left( \frac{\Delta R_1 - \Delta R_2 + \Delta R_3 - \Delta R_4}{R} \right) E
\]

(4)

Contact pressure is measured as change in voltage among \(R_i (= R)\). This voltage \(V\) is given by Eq. (5).

\[
V = \frac{R}{R + R_p} E
\]

(5)

The contact pressure and bi-axial shear stresses are obtained from a sensor unit. We used two bridge circuits in a sensing unit to eliminate the voltage change by contact pressure from voltage changes in the two measurement parts of shear stresses. The measurement part of shear stress in \(x\) direction constructed of a couple of slim shaped electrodes was combined with the measurement part for contact pressure as one bridge circuit. Another one was consisted of the measurement parts for shear stress in \(y\) direction and measurement part for contact pressure. The resistance in measurement part for contact pressure is commonly used in the two bridge circuits.

2.3 Experimental method

We performed measurements of contact pressure and shear stress to examine the effectiveness of the developed sensor system. To apply exact values of contact pressure and shear stress to the sensor, we made the calibration apparatus shown in Fig. 8. In this apparatus, actuators generate the contact pressure and shear stress complexly to the sensor attached on an X-Y stage.

To discuss effectiveness of the newly developed integrated sensor system, the distribution of contact pressure and shear stresses at the finger contacting area was measured during lifting water bottle up and down. The sensor was fixed on the thumb by double faced adhesive tape as shown in Fig. 9.

Next, we measured the shear stress and contact pressure generated between sandals and bottom of foot during walking. We attached six sensors to the sandal as shown in Fig. 10.

3. Results

The three calibration curves of contact pressure under applied shear stress 0, 5 and 10 kPa applied are shown in Fig. 11. The active range of the pressure was found to be from 0 to 15 kPa.

The three calibration curves of shear stress under applied contact pressure 5, 10 and 15 kPa are shown in Fig. 12. The active range of the shear stress was found to be from 0 to 15 kPa.

Results of the measurement of combined loading of contact pressure (5 kPa) and shear stress in \(x\) and \(y\) direction (-15-15 kPa) are shown in Fig. 13. This shows biaxial stresses could be measured with positive and negative directions.

Figure 14 shows an example of changes in contact pressure and shear stresses on thumb when the bottle was lifted up and down. The x axis corresponds to vertical direction. Contact pressure and shear stresses were measured appropriately.

We focused on shear stresses in forward direction at thenar and heel during walking, and Fig. 15 shows changes in shear stress at 2ch and 6ch. The peak of shear stress on heel appeared in the early phase of gait cycle. And the peak of shear stress in backward direction at thenar was measured in the late phase of gait cycle.

4. Discussions

The output voltage of this sensor system increased linearly with increasing the applied shear, stress and the value changed independently from the contact pressure value, as shown in the results of three axial loading test, Fig. 12. The results indicated that the combinations of electrodes in the sensor unit worked as a part of bridge circuit of ‘two gage method’. We showed that bi-axial shear stress and contact pressure could be measured and independently through complex lading test. We mention this point in the discussion part.

This thin and flexible sensor could be attached on a variety of places of human body. The measurement system was expected to use in medical and engineering subjects in which, the contacting condition under three
dimensional stress was important to evaluate the mechanical function of the interface. This thin and flexible type sensor could be attached on a variety of places of human body. The measurement system was expected to use in medical and engineering subjects in which, the contact states under three dimensional stress condition was important to evaluate the function of the interface.

5. Conclusions
A measurement system of contact pressure and shear stress was developed for feedback to actuators in haptic display. The usefulness of the thin and light weight sensor system, which can be flexibly attached to fingers and sole was shown through some experiments.

As a result of experiment using complex loading of the provided contact pressure and shear stress, it was shown that the pressure and shear stresses could be appropriately and independently measured. From experiment supposing some practical conditions, feasible results were obtained by the sensing system. Thus the effectiveness of the developed system was shown.
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References