Development of contact pressure and shear stresses sensor for touch panel

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Abstract
Touch panels are widely used to detect contact conditions between fingers and screens, as human interface devices. The touch sensor used in smartphones has been significantly developed in recent years, and the sensor can recognize not only contact position, but also changes in contact pressure. However, previously proposed touch panels have not been able to measure shear stress. Measurements of the shear stress can facilitate the realization of more sensuous and functional operations through the touch panels. Thus, a sensor for the contact pressure and shear stress measurements was fabricated in this study, in which a conductive polymer was used as a pressure-sensitive material. Sensing units were constructed from transparent materials and integrated to be a 4 × 4 array structure. The calibration tests were performed under combined stresses with the contact pressure and the shear stress in multi-axis loading. The sensor system can detect the distributions of three-axis stress components on surfaces. The stress components were simultaneously measured under several types of finger slide motions. The possibility of quantitative measurements of the stresses acting on touch panels was confirmed by considering transparency of the sensor.

Keywords: Shear stress, Contact pressure, Stress distribution, Touch panel, Haptic measurement

1. Introduction

Touch panels are widely used to detect the contact conditions between fingers and screen surfaces, as human interface devices. Touch sensor technologies used in smartphones have greatly progressed in recent years, and touch panel sensors can recognize not only contact position, but also changes in contact pressure acting between fingers and the screen. Shear stress detections are important for sensory operations, and the pointing control on wide panels without large finger motion. Several methods are proposed to measure the shear stress applied on the panel by means of force sensing at the panel edge area during finger sliding motion (Heo et al., 2013, Nakai et al., 2014a, 2014b). And another method to evaluate the shear stress by means of the detection of contact condition change such as the shift of center of contact pressure during the finger sliding motion was proposed as an indirect method (Heo and Lee, 2013). It is expected to detect both the contact pressure and the shear stress directly at the contact position on the display for use as touch panel interfaces. Measurements of both the contact pressure and the shear stress applied on the contact surfaces of the human body are also highly expected to be used in various fields, such as sports engineering and bioengineering studies. Many researches have focused on the pressure acting on the surfaces of the human body, for example, gripping a handle (Kalra et al., 2015, Scalise and Paone, 2015) and foot pressure distributions for gait analysis (Khurelbaatar et al., 2015). Compact-sized sensors that can measure both the contact pressure and the shear stress were recently developed for use in the study of human and/or robot interfaces. Many kinds of tactile sensing devices have been proposed by using various material components (Wan et al., 2017). Several types of tri-axis sensors have been developed using strain gages (Baki et al., 2013), optical devices (Takeshita et al., 2016), piezoelectric beams (Takahashi et al., 2013), and piezoelectric polymer films (Kärki et al., 2009). The high degree of flexibility has been achieved by
using soft materials and liquid layers for construction of the sensor elements (Noda et al., 2014). In recent years, thin and flexible sensors using a pressure-sensitive element constructed from conductive polymer material have been developed (Sasagawa and Narita, 2017), and simultaneous measurements of both the contact pressure and shear stress have been achieved by using these sensors (Sasagawa and Tokiyoshi, 2010, Sasagawa et al., 2013). These sensor thicknesses can be built thinner than the other type sensors because these sensors are constructed by using only thin layers as same as sheet-type contact pressure sensors. The sheet-type structure is available to measure the stresses applied at various interfaces and provides a quantitative evaluation method of contact conditions. The sensors used in touch panels are expected to be thin, transparent, and able to measure with high resolution. Previously developed sensors have several limitations regarding transparency of the component materials. Therefore, in this study, the construction of sensing units from transparent materials is attempted. Moreover, a sensor design is proposed for multipoint stress sensing in the sheet-type structures. Independent stress sensors are minimized and integrated to be a 4×4 array for detecting stress distribution on the wide area of the contact surface. The usefulness of the sensor is discussed in actual stress measurements under the certain load applications, and the example of finger slide motions.

2. Materials and methods

2.1 Pressure-sensitive material

Currently, conductive polymers are expected to be utilized in various fields and have already been used for pressure measurements. A type of polymer material, such as polythiophene, has electric conductivity as a result of applying or removing electrons in a conjugated π orbit by doping. The conductance of the conducting foam, which is composed of polyurethane and polypyrrole, is found to change linearly with the force applied (Brady et al., 2005). The conductive polymer composed of polyethylene dioxythiophene (EL-P series, Orgacon Agfa-Material) was used as a pressure-sensing element in this study. In order to confirm the pressure sensitivity, specimens were fabricated by sandwiching a conductive polymer layer between two copper electrodes, as shown in Fig. 1. Three types of specimens having different thicknesses of 6, 15, and 21 μm of the conductive polymer layer were prepared by means of screen printing process. Contact pressure was applied to the specimen by using a universal material testing machine. The result of this compression test is shown in Fig. 2. The resistance of the conductive layer decreased with increasing contact pressure. The initial resistance depending on surface conditions reduced and the pressure-resistance profile was stable in the case of large layer thickness more than 21 μm.

2.2 Stress detection

The mechanism of contact pressure detection is shown in Fig. 3(a). The sensor is constructed by a couple of electrodes located at the both sides of the conductive polymer layers. In this structure, when contact pressure is applied, the polymer is compressed. The electric resistance between these electrodes, \( R_p \), decreases with the compression. Thus,
this sensor can measure the contact pressure as the resistance change. The mechanism of shear stress detection is illustrated in Fig. 3(b) (Sasagawa et al., 2013). The electric resistance between electrodes, $R_\tau$, is determined by the partial overlapping area of each electrode when it is assumed that the electric current flows through the shortest path. The lower electrode is initially placed so that the overlapping area with the upper electrode is to be a half shift of the lower electrode. When the shear stress is applied from left to right on the upper electrodes, the overlapping area decreases, and the electric resistance between them increases. However, when the shear stress is applied to the opposite direction, the overlapping area increases, and electric resistance decreases. The shear stress detection area has both effects of compression and shear stress under complex loading conditions.

![Diagram of stress-sensing sensors for contact pressure and shear stress measurements.](image)

**Fig. 3** Mechanism of stress-sensing of sensors for (a) contact pressure measurements, (b) shear stress measurements.

### 2.3 Sensor system

Transparent sensors, which can simultaneously measure both the contact pressure and the shear stress, were developed in this study. The lower and upper electrode patterns were fabricated by an etching process using the conventional photolithography technique, as shown in Fig. 4. Indium tin oxide (ITO) was sputtered on a glass plate of 415 μm thickness as a lower electrode, and the ITO was also sputtered on a polyethylene terephthalate (PET) film of 125 μm thickness as an upper electrode. This lower electrode consisted of a measuring part of contact pressure with $0.62 \times 0.62$ mm$^2$, and two measuring parts for bi-axial shear stresses on the surface with $1.75 \times 0.88$ mm$^2$. The thickness of the lower and upper electrode was 20 nm and 30 nm, respectively. The conductive polymer, polyethylene dioxythiophene, was separately coated on the each electrode area with 30 μm thickness by means of screen printing. This thickness was enough for perform the stability of resistance change in contact pressure in this study. The electrodes with sensing elements were overlapped with a precise positioning. The electric current flowed from the
upper electrode to the lower electrode through the conductive polymer layer. The initial state of overlapping area of the shear stress measuring part was designed to be 0.384 mm$^2$, which is equal to the area of contact of the pressure measuring part, and the resistances between the upper and lower electrodes in the pressure and the shear stress measuring parts ($R_p$, $R_τ$) became the same value under stress-free condition. The surface of upper electrode was covered with a polyurethane thin film of 25 µm thickness to fix the upper and lower layers and to protect the electrode. Total thickness of the sensor was 596 µm. The size of one measurement unit is 3.5×3.5 mm$^2$, and 4×4 measurement units were integrated for stress distribution measurements.

When contact pressure or shear stress was applied to the sensor, electric resistance between upper and lower electrodes changed. The electric resistance change could be measured as a voltage change by utilizing a bridge circuit. The changes in electric resistance of the sensing part of shear stress include the effect of contact pressure change. A principle of the two gauge bridge circuit was used to remove the effects from the resistance change (Sasagawa et al., 2013). The resistance change by shear stress is including the directional information of positive and negative senses and the shear stress vector is constructed with XY stress components measured at the sensing areas, as shown in Fig. 4.

Two bridge circuits were used to eliminate the voltage change by contact pressure from voltage changes in the two measuring parts of shear stresses in a sensor unit. The resistance of contact pressure measuring part is commonly used in the two bridge circuits. Stresses were converted from the measured output voltage according to the result of calibration tests. The tri-axial stress components containing the contact pressure and bi-axial shear stresses at each integrated 4×4 measurement unit could be sequentially obtained. Original software for visualization of tri-axial stress distribution was developed in Visual C#. The actual sampling rate of the stress distribution measurement was 8 Hz, including the data processing for visualization of tri-axial stress and the screen display in real time.

3. Experimental procedure

Calibration tests were conducted in order to convert the electrical signal output from the bridge circuit to the tri-axial stress values. A calibration system was constructed from the bi-axial moving stage, which was controlled independently by micrometers and could apply the contact pressure and shear stress to the sensor. The loading forces were measured by load cells attached to the stage. The range of applied pressure was from 0 to 15 kPa in the test, and the shear stress was applied from 0 to 10 kPa under the constant pressure 10 and 15 kPa. The contact between the sensor surface and the loading device for the shear stress applied was kept by double-faced tape. The calibration tests are required for every sensor because there are manufacturing variations in screen printing process.

The usefulness of the sensor was discussed through actual stress measurement tests under the finger contacting condition. The tri-axial stresses were applied to the sensor by a finger slide motion in the left-right direction and the up-down direction in several situations. The identification of contact positions and measurements of the applied stress vectors were confirmed in these experiments.

Fig. 4 Electrode patterns of stress distribution sensor. ITO electrodes were fabricated by etching process.
4. Results

The calibration result of contact pressure measured in a sensor unit is shown in Fig. 5(a). The relationship between contact pressure and output voltage was investigated in the test. The output voltage increased with increasing contact pressure. The calibration results of shear stress measured in the same sensor are shown in Fig. 5(b)(c). Figure 5(b) is the result of the shear stress measurement in X-axis direction, and (c) is that in Y-axis direction. In these cases, the relationships between the shear stress and output voltage were investigated under the applied contact pressures of 10 and 15 kPa. The relations were almost linear in both cases. There were no differences in the characteristics of the output voltage change with shear stress, even if the contact pressure was changed. This result indicated that the effect of contact pressure change on the shear stress sensing part was eliminated by the bridge circuit. Therefore, shear stress could be independently measured in the complex loading conditions.

Figure 6(a) shows the appearance of the sensor area. Transparency of the sensing part can be confirmed in the picture. An examination of visualization of tri-axial stresses acting in finger operation is shown in Fig. 6(b). The contact pressure value is shown by color change of the square areas, and the resultant shear stress vectors calculated by each shear stress components measured at the sensor are indicated by the arrow direction and length. The direction and magnitude of the shear stress vector and the contact pressure at the only finger-contacting position were clearly measured without sensuous delay under the 8 fps visualizing condition.

5. Discussions

Touch-panel-mounted devices require the functions of both the detection of contact area and display of the screen. The developed sensor could measure not only the contact pressure, but also the shear stresses on the contact surface plane. This is a useful function for the construction of haptic devices. Several types of sensors for haptic display were proposed and used for the evaluation of human interfaces (Yousef et al., 2011). It is usually required that the three-dimensional components are constructed to measure the tri-axial forces (Baki et al., 2013). The scale limitation for miniaturization existed in the construction of the force-sensing unit. Recently, MEMS technology provided the micron structure sensor, and a tactile sensor for shear stress measurements was produced in the scale of sub-millimeter thickness (Takahashi et al., 2013). Our sensor is also able to be made thin, when the thin film is used for substrate replaced the glass plate, and the scale can be reduced better than others because the sensing function is based on just sheet-shift on a two-dimensional plane. Human-user interfaces typified by touch panels also require high degree of transparency of the sensor unit. Although the transparency of the sensing area compared unfavorably with other areas, the transparency could be confirmed by recognizing the letters displayed on an LCD through the sensor, as shown in Fig. 6(a).
The calibration result of contact pressure showed dead-band characteristics on pressure detections lower than 4 kPa because of the high resistance of the sensor due to slight contact between the electrodes and the sensing material layer. It is possible to eliminate the dead-band effect by improving the fabrication technique for laminating process which also has to achieve the precision positioning for each layer processing. Although the sensitivity can be partly controlled by changing fixed-feedback resistances in the bridge circuit, higher sensitivity for measuring several tens of Pa level (Huang et al., 2017) may be required to evaluate the finger action in a soft touch situation. The pre-compression by sealing the sensor panel may be effective to improve the contact condition. In contrast to the contact pressure, shear stress was successfully measured in the small stress range. Thus, finger operation, including shear stress information, could be detected in the sensor system. And although the response of the sensor was enough for real time visualization around 10 Hz, rapid response characteristics are requested to use this sensor for evaluations of haptic sensing in motion analysis. The confirmations of durability and measurement reproducibility to cyclic loading were requested for the future development of sensor productions. A high-degree of integration of the tri-axis stress sensor is also useful for several kinds of researches in optimizations of tool design in medical, sports, and welfare-aided engineering fields. The optimization of the wiring design and the high precision line fabrication techniques are required to make the high integration sensor system and to perform the high resolution measurements for future applications.

6. Conclusion

A thin sensor for contact pressure and shear stress measurements was fabricated in this study. Conductive polymer was used as a pressure sensitive material in the sensor. The sensing units were constructed from transparent materials and integrated to be a 4×4 array structure. Therefore the sensor was applied to measure the stress distribution at finger operations. The possibility of quantitative measurements of the stresses acting on touch panels was confirmed by considering transparency of the sensor.

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