Tomography analysis for stress measurement method based on electrical conductivity distribution

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1. Introduction

Electrical impedance tomography (EIT) is a noninvasive internal visualization technique that can infer the internal electrical conductivity/impedance distribution of the target from surface electrode measurements. Comparing to the traditional internal imaging technique, such as X-ray, CT and magnetic resonance imaging, EIT is much more economic and harmless as no radiation source is required and only a little current is injected into the body. EIT has been intensively used in the medical field for preventive medicine or screening for disease. Also, some tactile sensors[1)] have been developed based on the EIT method for the robotic field[2)] in the recent decades. This research aims to verify the applicability of EIT method in stress measurement, and how the conductivity changes with stress. The research target is conductive rubber whose conductivity change is supposed to be related to stress change. Herein, the complete electrode model[3)] was used to analyze the conductivity variation in rubber, which considers the effects of the electrodes and the contact resistance between the electrolyte and the electrodes. Several fundamental assumptions are made for conductivity reconstruction: Electric and magnetic fields will not change with time; Conductivity is independent with electric fields; No internal current resource; External resource is applied through electrodes. The mathematical model is composed of the following equations:

$$\nabla \cdot (\sigma \nabla u) = 0, \qquad x \in \Omega \tag{1}$$

$$u + z_m \sigma \frac{\partial u}{\partial n} = U_m, \qquad x \in \mathrm{e}_m, m = 1,2,\dots,M \tag{2}$$

$$\int_{\mathrm{e}_m} \sigma \frac{\partial u}{\partial n} dS = I_m, \qquad x \in \mathrm{e}_m, m = 1,2,\dots,M \tag{3}$$

$$\sigma \frac{\partial u}{\partial n} = 0, \qquad x \in \partial\Omega | \cup_{m=1}^{M} \mathrm{e}_m \tag{4}$$

where σ is the conductivity distribution, u is the electric potential distribution, n is the outward unit normal of boundary $\partial\Omega$, M is the number of electrodes and e_m denotes the m^{th} electrodes, z_m are the contact resistance, I_m are the injected currents and U_m are the corresponding potentials on the electrodes, and Ω is the object. Since the problem is severely ill-posed, generalized Tikhonov regularization is used in order to obtain stable solutions. The solution is given by Eq.(5), where $\boldsymbol{J}$ is the Jacobian of U with respect to σ, and $\boldsymbol{L}_R$ is the regulation matrix.

$$\Delta\sigma = (\mathbf{J}^T\mathbf{J} + \boldsymbol{L}_R^T\boldsymbol{L}_R)^{-1}(\mathbf{J}^T\Delta U) \tag{5}$$

2. Load Area Detection

The conductive rubber sheet using EIT method can serve as a tactile sensor to detect load area. As shown in Fig. 1, a circular conductive rubber sheet (made by Tigers Polymer Corporation) with a diameter of 20 cm and a thickness of 2 mm was used in the loading test. The adjacent simulation and measurement pattern were adopted for EIT imaging, and the excitation resource was 10 mA constant DC current. The total number of 16 electrodes were set around the sheet, and the drops of voltage between the adjacent electrodes were measured every time when the excitation electrodes are changed. For pressure measurement, the voltage needs to be measured before loading and after loading. Then, the conductivity change can be calculated by the difference between the measured voltages, using Eq. (5). In the load tests shown in Fig. 1 (right), a dead load of 90 N was used, and Fig. 1 (left) shows the load areas. The conductivity reconstruction figures were plotted by EIDORS[4)] toolkit. Also, the load area can be detected using a square 3-mm-thick conductive rubber sheet as shown in Fig. 2. After loading, the conductivity changes inhomogeneously and matches the shape and location of load area. The load area can be detected regardless of the shape of the conductive rubber sheet. However, the detected load areas do not represent the contact areas under the load areas because of the distribution of elastic deformation around the load areas.

3. Stress Measurement

The relationship between conductivity change and load process was studied by uniaxial compression test (see Fig.3). The 2-mm-thick circular conductive rubber sheet was tested with a 1.1-cm-diameter circular load area in the center. The average variation of all the nodes within the area is regarded as the conductivity change. All the conductivity change is compared with the initial non-load state, so the conductivity change at the beginning is 0. As shown in Fig. 4, the conductivity changed significantly in the first loading process, then stabilized later. As the conductivity change cannot return to 0 S/cm after unloading to 0 Pa and a slightly unrecoverable deformations were observed, the rubber sheet is not perfectly elastic.

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Additional test using 1-mm-thick conductive rubber sheet under the same condition were reported in Fig.5. The linear fitting lines between the conductivity change and the pressure in the range of 0-316 kPa of both tests were slightly different. Although the conductivity is linearly decreased with the increasing pressure, the coefficient of determinations (R^2) were only 0.5-0.6. As the conductivity gradually increases with the elapsed energizing time, the variation might be due to the thermal aging characteristics.

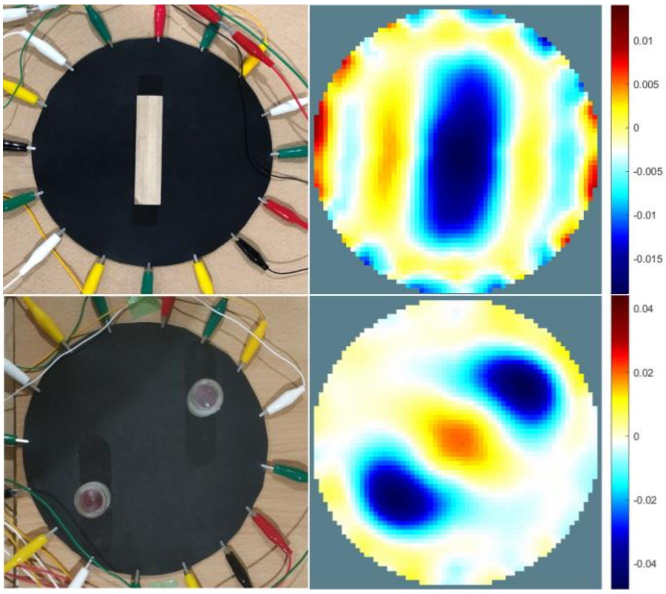

Fig 1. (Left) Loading area, (Right) Conductivity change after loading of circular sheet

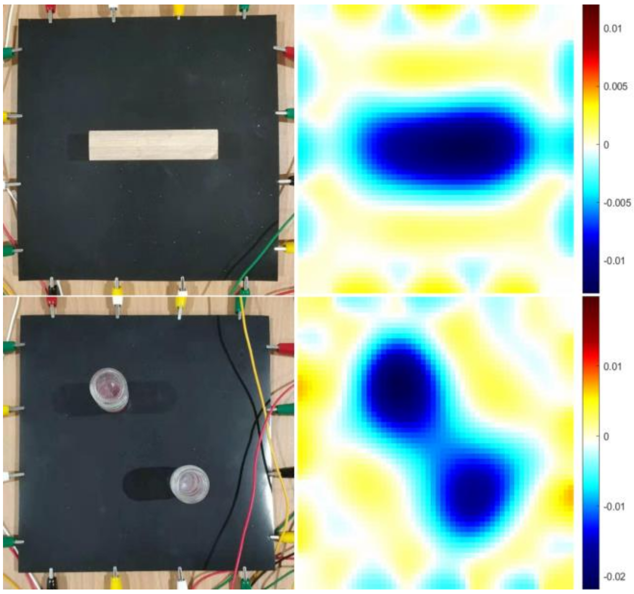

Fig 2. (Left) Loading area, (Right) Conductivity change after loading of square sheet

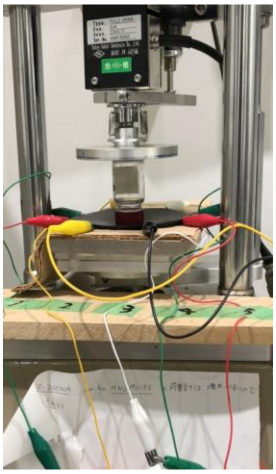

Fig3. Uniaxial compression test (8 electrodes mode)

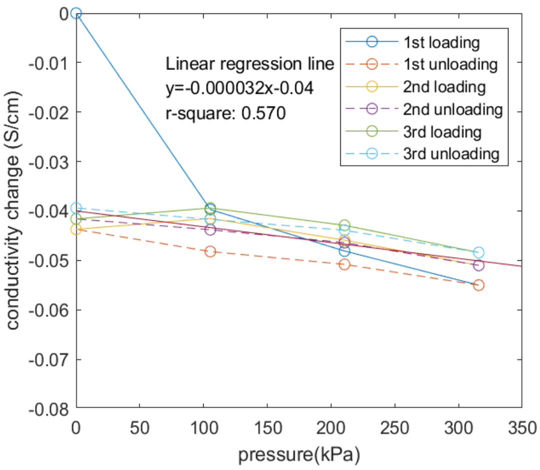

Fig 4. Conductivity change of 2mm sheet under load

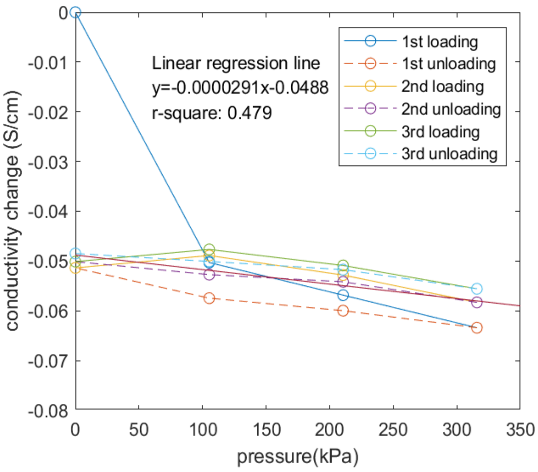

Fig 5. Conductivity change of 1mm sheet under load

4. CONCLUSIONS

Conductive rubber has been extensively used in sensor development because of its piezoresistive property and economic price. The conductive rubber is machinable to cater different demands, and EIT is a quite mature technology. Although the effect of heat, magnetic field and electrode deformation, measuring sensitivity and calibration method are still unsolved, the 2D stress measurement ability of the device is reasonably confirmed.

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