Shear Stress Sensor for Soft Material with Built-in Piezoelectric Polymer Films

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***Abstract*—Currently, it becomes more important to anticipate the intention of the user who touches the product. However, in case of the soft material, the internal deformation and stress distribution, which is the information of the way of touch, are hard to be estimated nor observed using current interactive shear force sensors except for limited situations. In this study, we developed a sensor system, which is embedded in the soft material and measures shear deformation and stress distribution inside of soft material. The validity of this sensor system, which consists of the array of piezoelectric sensors of Polyvinylidene fluoride (PVDF), was tested by measuring the stress distribution of an artificial human skin.**

***Index Terms*—Embedded sensor, Soft material, Shear stress measurement, Piezoelectric sensor**

I. Introduction

Most of current shear force sensors are set at the contact surface or under the contact area. Thus, they cannot measure the condition inside of the material. Especially for the soft material whose structure is sometimes anisotropic or multi-layer, the measurement of the internal deformation and stress distribution is difficult to embed current shear force sensors. Furthermore, it is also difficult to estimate the internal stress distribution of such complex structure.

However, for instance, the observation of the distribution of shear force inside of soft tissue is demanded in the field of contact safety [1], [2] such as the anticipation of bedsores [3], [4] and friction blister when using a device which touches the human skin [5].

Therefore, in this study, a shear deformation and stress sensor system with piezoelectric polymer films embedded in soft material was developed. The designing principle and process will be firstly introduced, and the actual measurement of the shear force distribution in different underneath depth will be followed. It is also expected to be applied to the organic robotics, such as artificial skin of humanoid robot or prosthesis, or simulated organ for surgical practice and pathology.

II. Structure of sensing system

The basic structure of shear stress measuring system used in this study is shown in Fig. 1 (a). The sensing elements of PVDF are fixed perpendicularly to the surface and embedded in the soft substrate material.

A. Measuring principle using PVDF film

PVDF, which was manufactured in the form of micro film, was applied as sensing element. The PVDF films embedded in the soft material is deformed like a beam along with the deformation of the substrate material. The electric charges q_i induced by piezoelectric property vary along with different local stress [6]. Based on the idea that the sensor films are arranged inside of soft substrate with different embedded lengths as illustrated in of Fig. 1 (b), the three-dimensional distribution of stress can be obtained.

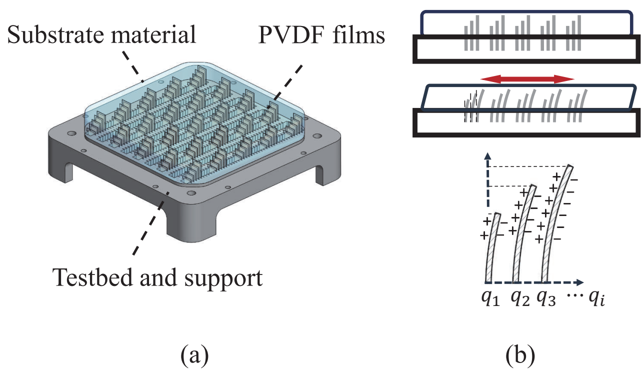

Fig. 1. Shear force measuring device

PVDF is usually attached to flexible plate such as PET sheet, whose rigidity decides the PVDF's deformation behavior. Thus, the performances of 3 kinds of sensor elements with 50, 25, and 16 μm thickness of PET sheets were compared. As a result, the thinnest one, whose flexibility was highest, was selected because of the highest sensitivity.

B. Substrate material and testbed

In this paper, a kind of artificial skin (HITOHADA GEL, EXSEAL Co., Ltd., Japan) with ASKER-C hardness of 0 was utilized as the substrate material. Using this substrate and PVDF film, a testbed inlaying clamps matching films' thickness was manufactured as shown in Fig. 1 (a). All the sensors are supported vertically without being clamped the sensing area, and then electric wiring from the pins for signal transmission is done below the testbed.

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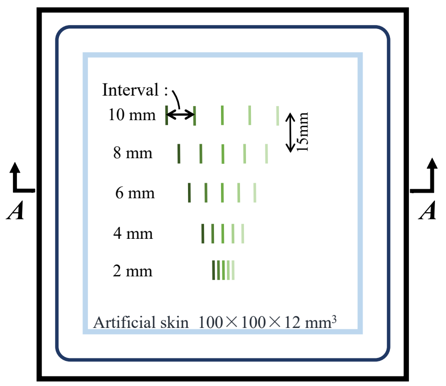
III. Shear Stress Distribution Measurement in Different Underneath Depth

To test whether this system can observe the deformation and stress distribution of substrate, an experiments were conducted. At the same time, the effect of the distance of adjacent PVDF elements in horizontal direction was also evaluated.

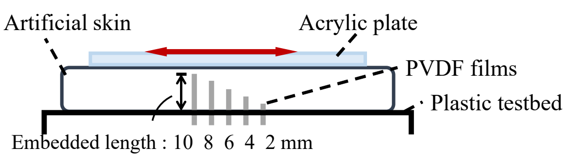
A. Experiment Setup

The artificial skin material was manufactured in a thickness of 12 mm. 25 PVDF films are arranged inside it. They were divided into 5 groups with different intervals from wide to narrow in 10, 8, 6, 4, and 2 mm respectively. In each group, 5 PVDF films are aligned and differ in the embedded lengths of 10, 8, 6, 4, and 2 mm respectively from left to right. The arrangement is schematically illustrated in Fig. 2.

The dynamic simple shear deformation, whose direction was orthogonal to the PVDF film, was applied to the surface of the experimental device. The dynamic simple shear deformation was exerted in sinusoidal pattern with amplitude of 2.5 mm and frequency range of 0.5 to 5 Hz based on the previous study, which measured the interaction force and deformation of skin surface when wearing an physical assistant robot [7]. This surface deformation was applied with a manipulator (MOTOMAN-MH5F, Yaskawa Electric Co., Ltd., Japan) as shown in Fig. 3. The part which contacted to the substrate material surface was designed as a square acrylics board in size of 80 mm$\times$80 mm at the central position, and could cover all the elements. It should be noted that the contact part did not slip on the substrate.



(a) Top view



(b) *A-A* sectional front view

Fig. 2. PVDF films' arrangement

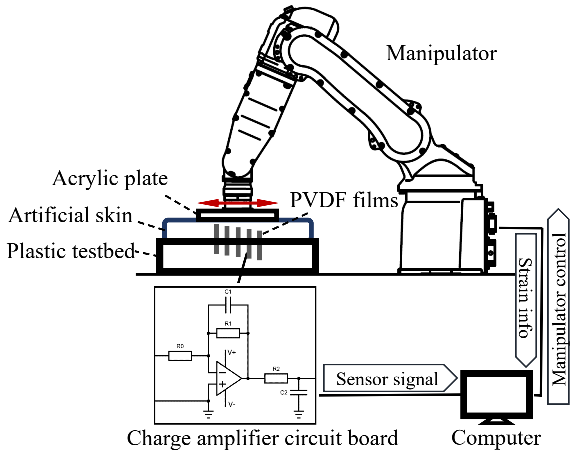


Fig. 3. Experimental system

B. Experimental result

The clear and highly sensitive sinusoidal output signal could be observed. Thus, the peak to peak value of the output signal, which was obtained as the sinusoidal wave, was used as the representative parameter for comparison among conditions. Firstly, the signal differed obviously among embedded lengths as shown in Figs. 4 and 5. The shape of graphs became approximately an exponential form, which reflects the mechanical characteristics of soft material. This trend verifies the feasibility for deep directional force distribution measurement as mentioned below.

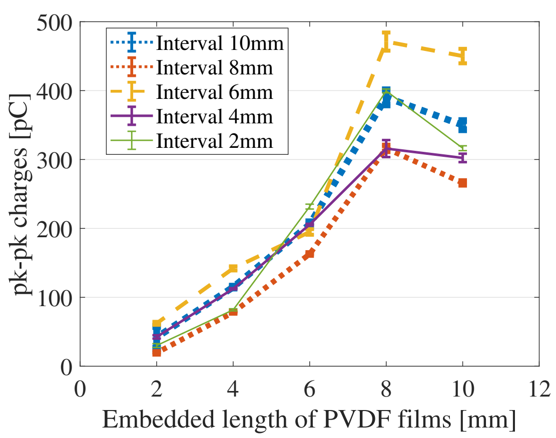


Fig. 4. Signals differ with embedded length among different intervals in 2 Hz

Considering the effect of interval between sensing elements, according to Fig. 4, any bad effect was not observed even in case of interval of 2 mm compared to the condition of 10 mm interval. Instead, Fig. 4 suggested that the group located closer to central area generated larger charges. Furthermore, the output signals of the pairs symmetrically located sideways of 6 mm, the intervals of 10 and 2 mm, 8 and 4 mm, matched each other.

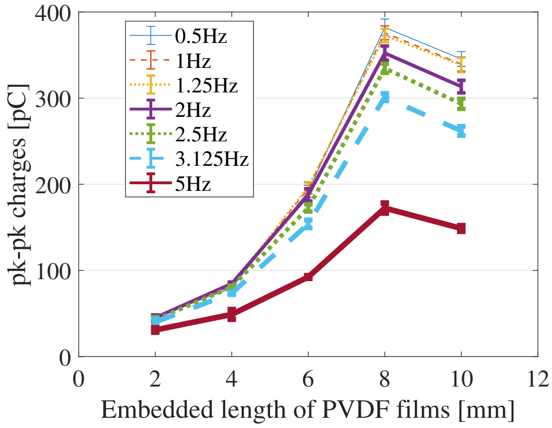


Fig. 5. Signals differ with embedded length among different frequencies of 2 mm interval

Then, the result of signal variation among different frequencies is shown in Fig. 5. The decrease of signal in the deeper section of high frequency condition suggested the attenuation of stress wave propagation from surface through the soft material [8]. This trend coincides with the transmissibility characteristics of viscoelastic soft material.

IV. Discussion

According to Figs. 4 and 5, the signal of sensors, whose embedded length was 10 mm, became lower than that of 8 mm. The top of PVDF film of these sensors was distant from the surface only 2 mm. It seems that this sensor system perhaps cannot measure the force when it was embedded closer to the surface because of the complex deformation of the film.

The tendency that the centered group outputted larger signals in Fig. 4 probably reflected the stress distribution in the perpendicular direction under the contacting area.

Furthermore, because of the individuality of sensors, which probably reflects the installation error of PVDF film occurred in the embed process, calibration is necessary for precise measurement of force distribution.

The arrangement of PVDF sensing elements should be decided considering the practical application. For example, the spatial resolution of measurement can be improved by more intensive arrangement of sensing element. Though this paper concentrated on the shear force sensitivity, the normal stress would be also applied at the same time. Thus, the research about the identification of normal and shear components from output signal will also be expected.

V. Conclusion

In this study, a sensor system which measured the distribution of shear stress and deformation using built-in PVDF films was developed. By using group of PVDF films, whose embedded length differed, force distribution in the depth direction was successfully observed. The frequency response of deformation transmissibility can reflect the viscoelasticity of soft material. These results suggest the feasibility of proposed sensor system.

Acknowledgment

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