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# Characteristics Evaluation of a Pressure Sensitive Rubber – based Tactile Sensor

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***Abstract* –Pressure sensitive rubber has been proposed to be used as the tactile sensor in robotic catheter system for MIS (minimally invasive surgery). The contact area in the blood vessels can not be clearly known within the current technical level. In this paper, supposing there are three different situations when the sensor contacts the blood vessel wall, including the contact area is one point, the contact area is part of the surface and the contact area is entire surface. This paper analyzes the strain based on FEA (finite element analysis) when the force loading area of pressure sensitive rubber is different. The linearity of pressure sensitive rubber is good on condition that the contact area is constant. Then we change the contact area to do more experiments and learn that the strain increases with the increase of the contact area. Keep contact area as a constant value, we can get an accurate calibration curve of pressure sensitive rubber. In this way, we evaluate the characteristics of the pressure sensitive rubber when it is used in robotic catheter system for MIS as a novel tactile sensor.**

***Index Terms – Tactile Sensor, Pressure Sensitive Rubber, FEA (Finite Element Analysis), MIS (Minimally Invasive Surgery).***

## I. INTRODUCTION

Nowadays, the incidence of cardiovascular and cerebrovascular diseases is increasing fast. These diseases threat human life seriously. MIS (minimally invasive surgery) is an effective method to treat these diseases. In order to protect the surgeon from X-ray, Tele-Operation Master-Slave System for Minimal Invasive Brain Surgery has been reported [1]. A Novel Robotic Catheter System with Force and Visual Feedback for Vascular Interventional Surgery has been reported [2]. Then a master-slave catheterization system has been proposed [3], this system has a steerable catheter with positioning function and its insertion mechanism has the function of force feedback. From the previous study we can know that the contact force between the catheter and the vascular wall is very important for the surgeon in minimally invasive surgery. A force sensing system has been proposed to be installed in the front and around the side wall of the catheter. If the catheter collides with the blood vessel wall, this information can be transmitted to the doctor, then, the doctor makes the right judgment to avoid breaking the blood vessel and enhance the safety during endovascular neurosurgery. So it is necessary to measure the contact force accurately using proper tactile sensor.

However, the blood environment, where the tactile sensor will work, is complex. All of these request the sensor to have high precision and high resolution. Recently, various types of techniques have been explored in realizing the tactile sensors based on the resistor, capacitor, piezoelectric, conductive rubber, MEMS, and PVDF materials [4]. Makoto Shimojo [5], a professor comes from Japan, proposed a novel tactile sensor using pressure conductive rubber with electrical-wires stitch method [4]. The sensor is flexible enough to measure the contact force precisely. At the same time, it is able to work normally in the blood. Compared with the other sensors, pressure sensitive rubber has higher precision, and its control system is simpler. So some researchers put forward using it to measure the contact force. Shear the pressure sensitive rubber into appropriate size of block, then fix them on the front and side wall of the catheter. As shown in Fig. 1 [6]. We paste the sensors around the outside wall of the catheter. When catheter contacts the blood vessel wall, the value of the contact force can be measured in this way.

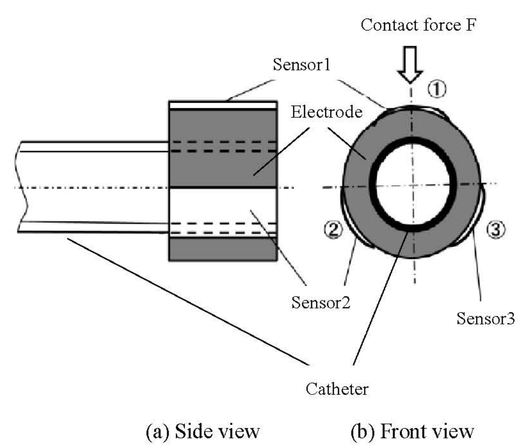


Fig. 1 Position of the input force

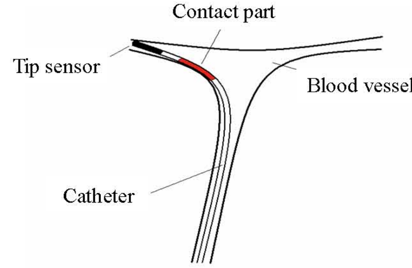


Fig. 2 The catheter in the blood vessel

The size of the sensor is a certain value. As is shown in Fig. 2 [7], when the sensor contacts the vascular wall, the contact area is different; there are many situations, such as one point, part of the surface, the entire surface. In this paper, the FEA (finite element analysis) method is applied to build a simple geometric model to analyze the strain in different situations. The geometric model is endowed with proper parameters corresponding to the properties of a pressure sensitive rubber. We change the contact area and achieve different strain curves based on FEA. In this way, the conclusion that when the contact area is a certain value, the strain increases with the increase of the contact area is obtained. In order to get the accurate calibration curve, the contact area must be a constant value. From this point of view, the paper evaluates the characteristics that using pressure sensitive rubber as the tactile sensor to measure the contact force between the catheter and the vascular wall in the robotic catheter system for MIS (minimally invasive surgery).

## II. The Application Platform of the Sensor

MIS (minimally invasive surgery) is an important method to treat cardiovascular and cerebrovascular diseases. In the process of the operation, the surgeon is exposed to X-ray. In order to protect the surgeon from the X-ray, master-slave robotic catheter operating system is proposed. Fig. 3 is the conceptual diagram of the robotic catheter system [2]. The whole system is composed of two sides. On the master side, the surgeon operates the master manipulator to move along the axial and radial directions [6]. Meanwhile, the control commands are transmitted to the PC of the slave side through the Internet communication. Then the controller of the slave side controls the slave manipulator to insert and rotate the catheter, as if the surgeon operates the catheter just beside the patient. On the slave side, a force sensing system is fixed on the catheter, which can transmit the force feedback information to the master side, when the catheter contacts the blood vessel. Through the master manipulator, the surgeon feels the force actually. The monitoring image gained by the IP camera will be transmitted to the surgeon through the Internet.

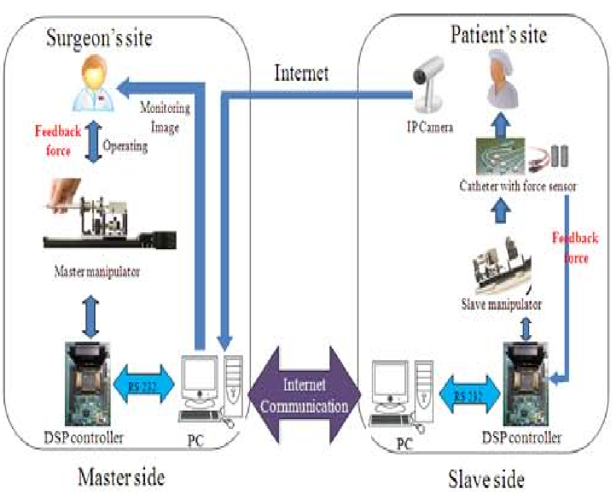


**Fig. 3 Conceptual diagram of the novel robotic catheter operating system**

The more accurate the feedback information is, the safer the surgery will be. The tactile sensor is an important part of the force feedback system. In our research, the pressure sensitive rubber is used as the tactile sensor in the robotic catheter system. It is fixed on the front end and outside wall of the catheter to measure the contact force accurately. Then the force feedback information will be transmitted to the surgeon.

## III. The Composition and Conductive Mechanism of the Conductive Rubber

In order to get the accurate force feedback information, this system selects pressure sensitive rubber as the tactile sensor. Pressure sensitive conductive rubber is made from natural rubber or synthetic rubber, such as epdm, nitrile rubber, neoprene rubber, silicone rubber, etc. Then these materials are vulcanized after mixed with conductive particle. The conductive particles can use carbon black [8], [9], metal particles, graphite, fibrous conductive filler, etc. The polymer matrix of the conductive rubber is not conductive, and its conductivity relies on various adding conductive fillers. In general, the conductive rate of the conductive rubber relies on the dopant concentration of the conductive filler.

The pressure sensitive rubber is a sensitive material with piezoresisitive effect. When there is no external force, the resistance value of the pressure sensitive rubber is very high, and when external force is applied, the resistance value reduced significantly, and shows conductive properties. The value of the external force changes in a certain range, the resistance value of the pressure sensitive rubber will change correspondingly.

The relationship of the external force and thickness is as follows:

$$F = k_1(h_0 - h) \tag{1}$$

Where F is the external force applied on the conductive rubber, $k_1$ is the elastic coefficient of the silicon rubber matrix, $h_0$ is the initial thickness of the conductive rubber, h is the thickness when external force is applied.

Assuming the statistic average value of the conductive particle space is $\omega$ [10]-[12], then:

$$\omega = k_2 \cdot h \tag{2}$$

where $k_2$ is proportion coefficient.

According to quantum tunnel effect theory, and bring equation (1) and (2) to resistance equation, the resistance of the pressure sensitive rubber and the external force approximate into quadratic relationship [13]. It can be described as:

$$R(F) = R_0 - AF + BF^2 \tag{3}$$

where $R(F)$ is the resistance value, F is the external pressure force, A= $R_0 / k_1 h_0$ , B=($\pi\chi k_2 R_0$)/(2 $h_0 k_1^2$). $\chi$ is a constant value related to the conductive filler, so A and B are both constant.

## IV. Establishing Geometric Model of the Pressure Sensitive Rubber Based on FEA

This paper establishes a simple three-dimensional geometric model with ANSYS software.

As is shown in Fig. 4, the model is set into a cuboid. The size of the model is X×Y×Z: 1.5mm×3mm×0.5mm, it is equal to the actual size. The value of Z axis represents the thickness of the conductive rubber. The length of each unit is set into 0.05 when meshing. The SOLID45 unit is chosen in this paper. It is three-dimensional structure entity unit [14], [15], which is defined by eight nodes, and each node has three degrees of freedom. It has the functions of plastic, creep, expansion, stress tempered, large deformation and strain. The other parameters are set as follows: The Young's modulus is 2.08e5N/ $mm^2$ ; Poisson's ratio is 0.499; the density is 1e-9t/ $mm^3$ .

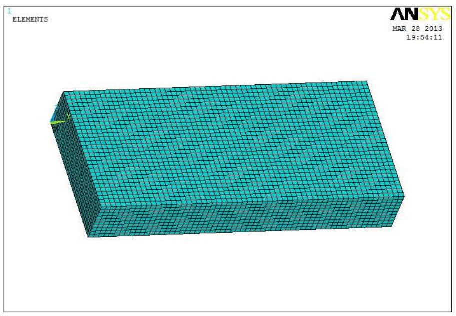


Fig. 4 The model and mesh of the sensor

## V. STRAIN ANALYSIS UNDER DIFFERENT CONTACT AREA

There are three different situations are assumed: the contact area is one point; the contact area is part of the surface; the contact area is entire surface. The model is applied by a same pressure in the same direction under these three situations. The value of the pressure is set as 0.01N, in consideration of the actual contact force when the catheter contacts the vascular wall. The direction of the force is along the negative Z axis.

From the equation (1), we can learn that the external force and the change of the thickness are related linearly. We make the external force changes linearly with the method of load step, ideally, the change of the strain is linearly. As is shown in Fig. 5, Fig. 6 and Fig. 7, the model is applied by a same pressure under the three situations, the figure shows the cloud chart of von mises stress.

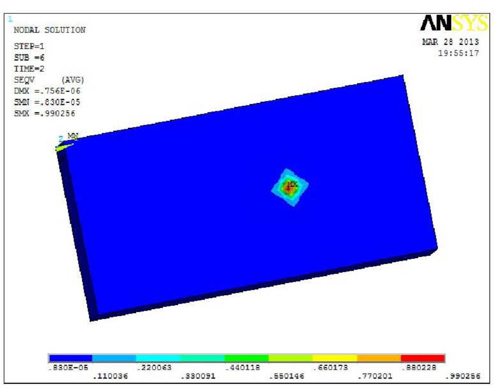


Fig. 5 The von mises stress cloud chart when one point contact

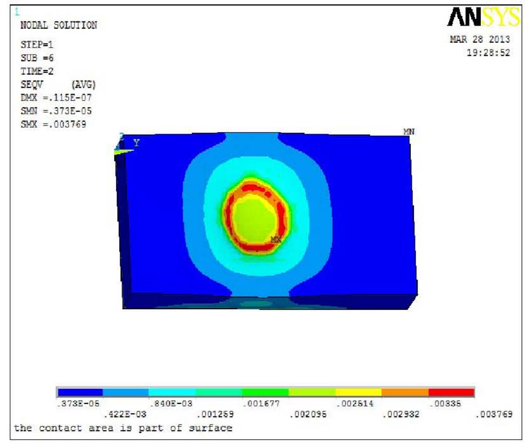


Fig. 6 The von mises stress cloud chart when part of surface contact

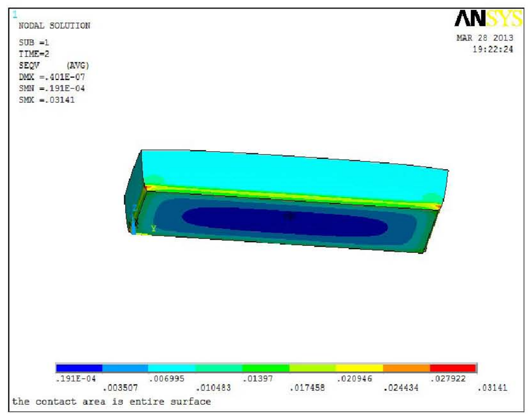


Fig. 7 The von mises stress cloud chart when entire surface contact

Among all the nodes applied pressure, selecting one node to draw its linear curve of the strain and the force. As is shown in Fig.8, Fig.9 and Fig.10, X axis represents time, Y axis represents Z-component of elastic strain. The strain is the percentage of the variation and initial value. With the method of load step we can make the force change according to the law of slope. In finite element analysis we set the number of substeps as ten. That is, the ten force values change linearly in two seconds time. So these figures show how the strain changes at the ten time points. The figures show the linear relationship of the strain and force, which is based on FEA (finite element analysis).

Viewing the three curves in Fig. 8, Fig. 9 and Fig. 10, we can know that the force and strain are linearly related separately in these three cases. However, when the contact situation is one point the strain differs from the ones when the contact area is a certain value in a large degree, the slopes of the straight line are different in a large degree. We consider the situation when the contact area is one point as point contact, that is to say the value of the contact area is zero. This is a special situation. In reality, this kind of situation does not exist. In this case, we can learn that the contact area affects the conductivity of the pressure sensitive rubber in a certain degree.

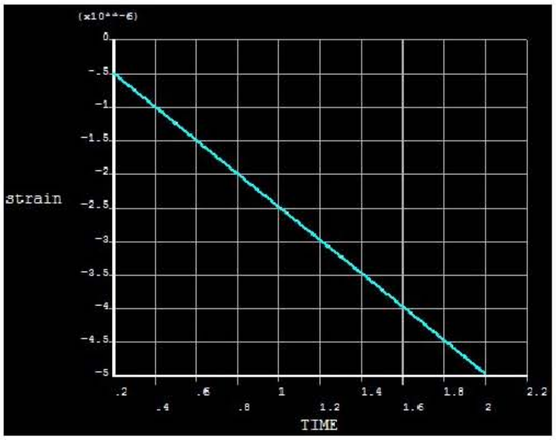


Fig. 8 The curve when one point contact

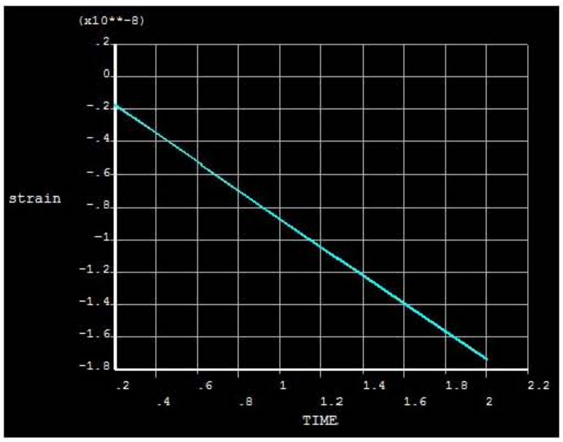


Fig. 9 The curve when part of surface contact

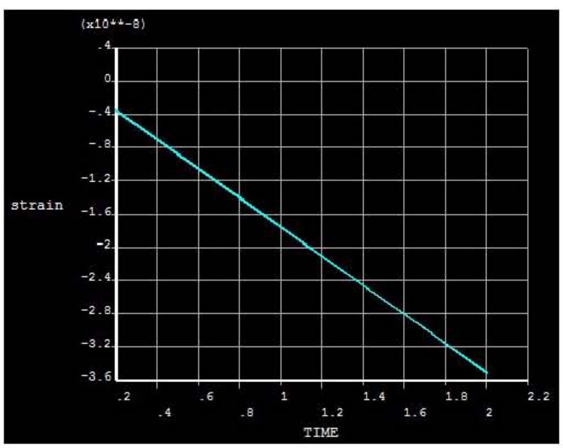


Fig. 10 The curve when entire surface contact

Then, more experiments are carried out. We change the contact area to get more data, and compare the strains at the same time point. In finite element analysis, the external force is applied on the nodes of the contact area. The larger the contact area is, the more nodes are loaded. So, the increasing number of the nodes represents the increasing contact area. As shown in TABLE. I, the strain increases with the increase of the contact area. As the strain increases, the resistance of the pressure sensitive rubber will change, the voltage signal exported from the tactile sensor also changes. This requests the researchers to ensure the contact area keeps the same when we want to get the calibration curve of the pressure sensitive rubber. In general, keeping the contact area the same, we can get the calibration accurately. In master-slave robotic catheter operating system, the voltage signal will be transmitted from the tactile sensor to the computer. Then according to the curve of the external force value and the voltage value, the value of the external force can be obtained.

TABLE. I

THE STRAIN IS INCREASING WITH THE INCREASE OF THE CONTACT AREA

| The number of the nodes | 534 | 1595 | 2430 | 3953 | 5062 |
|---|---|---|---|---|---|
| Strain | 0.532713 E-08 | 0.121972 E-07 | 0.168839 E-07 | 0.235888 E-07 | 0.273573 E-07 |

## VI. CONCLUSIONS AND FUTURE WORK

In this paper, the linearity of pressure sensitive rubber is analyzed on condition that the contact area is a constant value. From this point of view, this paper evaluates the characteristics of the pressure sensitive rubber .Then the relationship between the contact area and the conductivity is researched, using finite element analysis method and comparison experiments with ANSYS software. The result that the contact area affects conductivity is obtained. When the contact area value is not zero, the strain increases with the increase of the contact area. This conclusion provides a new reference for the calibration of the tactile sensor, that is to say, when we want to achieve the calibration curve, the contact area must be a constant value.

It should be noted that in this analysis we ignore the nonlinearity of this material. At every node there are stresses and strains along (X axis, Y axis, Z axis) every axis, however, in this paper we only take one direction (Z axis) into consideration according to quantum tunnel effect theory. This case could affect the result probably. The simulation created by ANSYS software is different from the actual environment in a certain degree. It is also one influent element. At the same time, through the analysis of ANSYS we can not get an actual formulation between contact area value and conductivity. There is still a lot of work to do to complete the relationship formulation of the contact area value and conductivity of pressure sensitive rubber.

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