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Practical Approach Design Piezoresistive Pressure Sensor in Circular Diaphragm

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Abstract: This paper presents a methodology for analytical calculation and computational simulation using the finite element method for piezoresistive graphite sensor element on flexible polymer substrate, A4 paper. The computer simulation aims to find the region of greatest mechanical tension and deflection of the circular diaphragm set in the circumference edges. The steps for simulation are geometry definition, mesh generation, inclusion of material physical properties and simulation execution. The mathematical modeling of maximum mechanical stress and deflection is described analytically and computationally. The analytical calculations were compared with the computer simulation and presented a relative percentage error of 3.38% for the maximum deflection. The results show that the piezoresistor should be positioned at the edges of the circular diaphragm to take advantage of maximum mechanical stress by defining the best location for graphite film deposition for sensor device designs and fabrications.

Key words: Piezoresistivity, sensor element, finite elements and mathematical modeling.

1. Introduction

During the last 20 years piezoresistive pressure sensors have been widely studied and are considered the most popular of MEMS (micro-electro-mechanical system) structure devices. These electronic devices are manufactured with square, rectangular or circular diaphragms [1-3]. Pressure sensors are used in industrial process control, environmental monitoring, audio microphone structures, biomedical systems, and other applications. The different types of sensors have high performance, reliability, are very sensitive, have low cost and are small, important features of these sensors [4-5].

To analyze the distribution of the maximum mechanical stress along the circumference of a circular diaphragm, the finite element analysis (FEA) [6] can be employed and, consequently, an optimized design is obtained. In general, the sensitivity of a piezoresistive sensor is optimized by considering its geometry (width, length and thickness). Otherwise, the electrical and mechanical relations are given by the effect of piezoresistivity, property of the material in which the resistivity is influenced by the mechanical stress applied to the material [7].

In this work we use the theory of pure bending of a circular plate that deflects due to an applied pressure for diaphragm design [8]. In this type of problem the following assumptions are assumed: small deflection model, large deflection model and finite element analysis [9]. Two methods are described for designing efficient circular diaphragms, namely the theory of small deflections and the finite element method. The finite element method is a numerical method used in several areas [10-11].

Ref. [12] shows that new materials, such as carbon

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nanotubes are being used to manufacture pressure sensors because they are flexible and have adequate mechanical, electrical and thermal properties for some applications. In Ref. [10] different polymer substrates were studied and characterized and pencil graphite was used as flexible piezoresistive sensing elements.

Today's technological process requires extensive prototype testing to ensure that requirements specifications are met at a competitive cost. Therefore, numerical models can be used to detect design failures and identify possible defects even before the scale production of sensor devices [13].

2. Materials and Methods

In this work, the software ANSYS AIM Student 18.0 was used to compare the analytical calculation and the computer simulation, aiming to determine the region of greatest mechanical stress for positioning graphite piezoresistors on circular diaphragms. The steps for running the simulation are described in the next sections.

2.1 Circular Diaphragm Geometry

The first step for simulations is to build the circular diaphragm geometry. The measurements used are described in Table 1, where the diaphragm radius ranges from r_1 to r_6 and the thickness is kept fixed.

2.2 Mesh Generation

The second step of the simulation process is the mesh generation. It consists of the decomposition of the total volume into smaller elements where the finite element method is applied to solve the equation systems.

Using the "Global Sizing Fixed" configuration it was possible to obtain the largest number of elements and nodes, described in Table 2. This method increases the number of nodes and elements compared to the previous work [2] (rectangular diaphragm), obtaining a more refined mesh, with an average increase of 58.65% of the number of nodes and 44.25% of the number of elements.

2.3 Physical Properties

The next step for simulations is to determine the boundary conditions of the problem. In this step, the physical properties of the material are defined, as well as the region where the pressure is applied and the crimping region of the circular diaphragm. Table 3 lists the properties of A4 paper used in the manufacture of substrates for piezoresistive sensing elements.

Table 1 Dimensions of circular diaphragm.

Symbol	Radius (r)	Thickness (t)
r_1	0.005 m	0.0001 m
r_2	0.00555 m	0.0001 m
r_3	0.00625 m	0.0001 m
r_4	0.00714 m	0.0001 m
r_5	0.00833 m	0.0001 m
r_6	0.01 m	0.0001 m

Table 2 Number of elements and nodes.

Radius	Number of nodes	Number of elements
r_1	72,610	14,349
r_2	52,427	9,412
r_3	53,197	9,552
r_4	53,085	9,520
r_5	53,440	9,602
r_6	53,242	9,566

Table 3 Physical properties of paper.

Property	Value	Reference
Young's modulus	2.60 E + 09 Pa	[2]
Poison's ratio	0.26	[2]
Density	852.27 kg/m^3	*

* It is the ratio of the weight to the thickness of the paper, 75 g/m^2 per 0.000088 m.

Table 4 Mass applied to generate a pressure.

Symbol	Mass (kg)
m_1	1.04E-04
m_2	1.42E-04
m_3	2.80E-04
m_4	3.59E-04
m_5	3.92E-04
m_6	4.09E-04
m_7	4.48E-04
m_8	6.39E-04
m_9	8.34E-04
m_{10}	1.23E-03

The masses, described in Table 4, vary from m_1 to m_{10} and represent the loads that are used in the simulation step in each of the six studied rays.

2.4 Mathematical Modeling

The mechanical stress required by ANSYS is converted to pressure by the equation:

$$P = \frac{F}{A} = \frac{mg}{A} = \frac{mg}{\pi \cdot r^2} \tag{1}$$

where F is the applied force and A is the area of the circular region of the radius diaphragm, r.

Eq. (1) is used to calculate the pressure for the ten masses and six circular diaphragms.

Small deflection theory is often used for deflections less than 1/5 of diaphragm thickness [14]. The maximum deflection in the crimped circular diaphragm is given by:

$$y_{\text{máx}} = \frac{Pr^2}{64D} \tag{2}$$

where r is the radius of the diaphragm as shown in Fig. 1 and D is the flexural stiffness given by the equation:

$$D = \frac{E\,t^3}{12(1-\vartheta)} \tag{3}$$

where, t is the thickness, E is Young's modulus and ϑ is the Poisson's ratio of the material.

Replacing Eq. (3) in Eq. (2), you will find:

$$y_{\text{máx}} = \frac{3(1-\vartheta^2)pr^4}{16Et^3} \tag{4}$$

In a crimped circular diaphragm at the ends the maximum, radial and tangential mechanical stress is given by Eqs. (5) and (6).

$$T_{r_{\text{máx}}} = \frac{3pr^2}{4t^2} \tag{5}$$

$$T_{t_{\text{máx}}} = \vartheta T_r \tag{6}$$

Thus, the radial mechanical deformations, ε_r, at the center of the diaphragm are given by the equation:

$$\varepsilon_r = \frac{3pr^2(1-\vartheta^2)}{8Et^2} \tag{7}$$

3. Results and Discussion

One of the results of the computational simulation, in ANSYS, is presented in Fig. 2. It is verified that the distribution of the mechanical tension on the circular diaphragm, after the pressure application, given by the theoretical model of Fig. 1 and simulated Fig. 2 has a good relationship.

Using Eq. (6) the maximum mechanical stresses are determined as a function of the applied pressure. The distribution of Von Mises mechanical stress for a mass

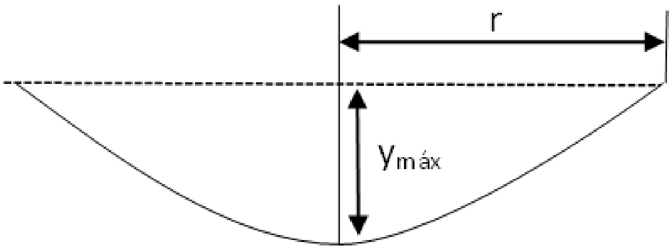

Fig. 1 Distribution of mechanical stress on a circular diaphragm.

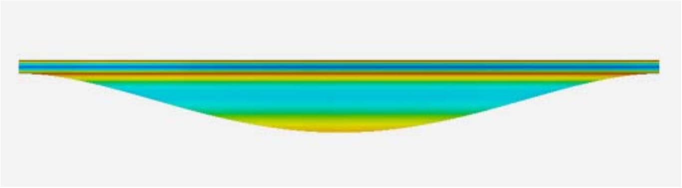

Fig. 2 Computer simulation of mechanical stress distribution over a circular diaphragm.

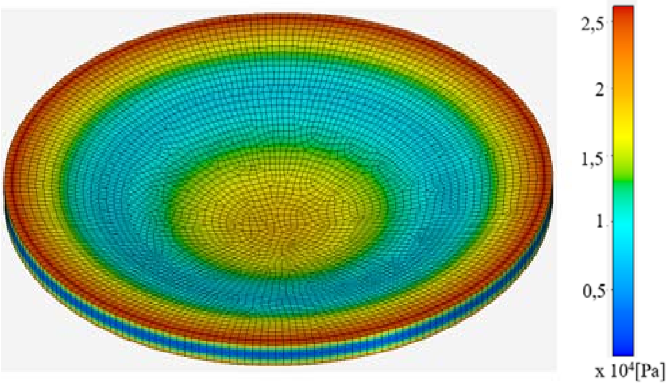

Fig. 3 3D distribution of Von Mises stress.

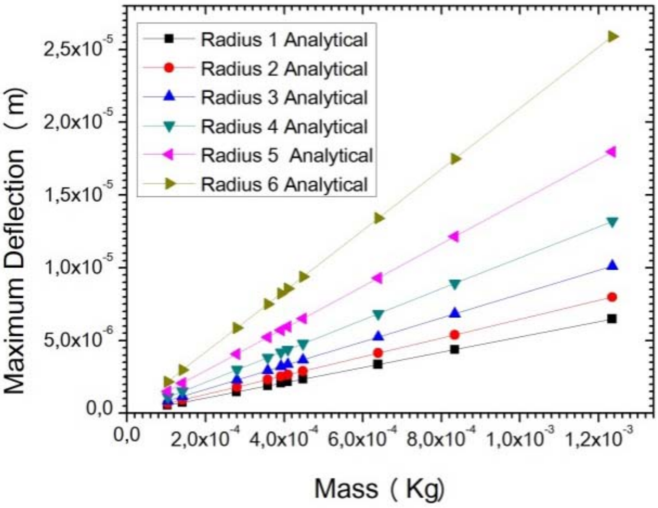

Fig. 4 Variation of maximum deflection as a function of mass.

of 1.04E-04 kg is shown in Fig. 3. In the crimping region of the diaphragm, in red color, there is a higher mechanical tension, while in the center of the circular diaphragm the lowest mechanical tension is obtained, in yellow.

The deflection curve of a circular diaphragm set at the edges as a function of the applied mass is shown in Fig. 4 using Eq. (2). This figure shows that the larger the radius, the greater the maximum deflection of the diaphragm.

Fig. 5 shows the computer simulation and compares all the types of circular diaphragms designed in this work. The geometry of radius 6 has the highest maximum deflection, while the diaphragm of radius 1

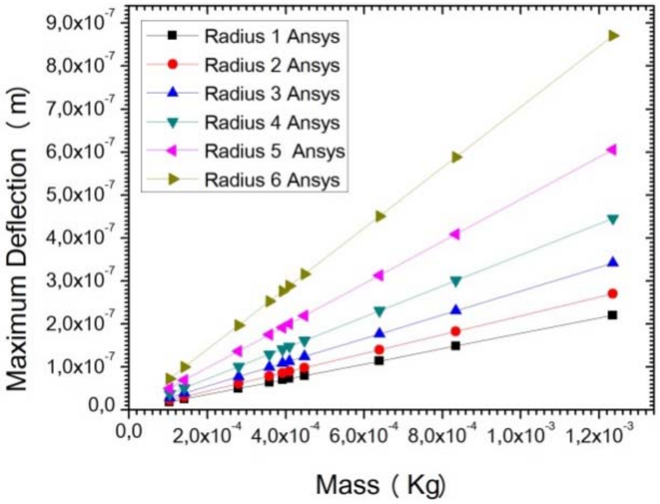

Fig. 5 Variation of maximum deflection as a function of mass.

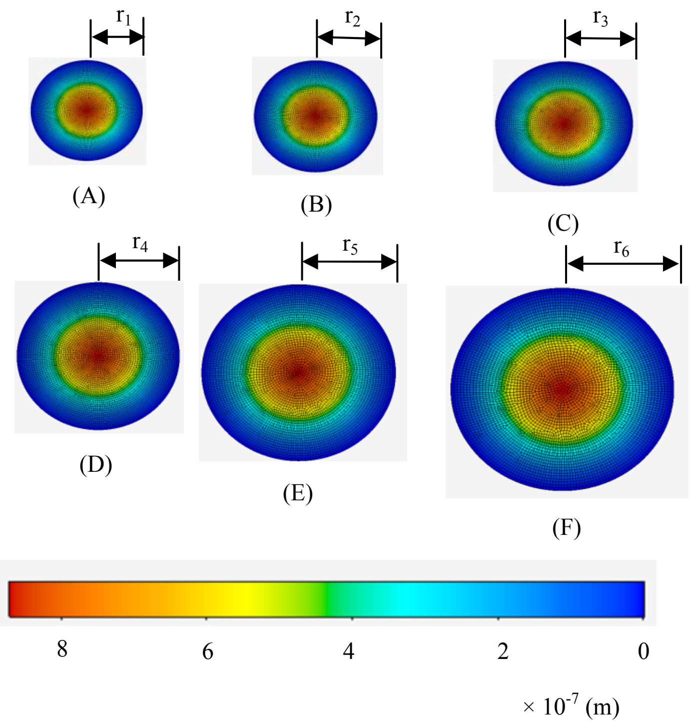

Fig. 6 Maximum deflection distribution.

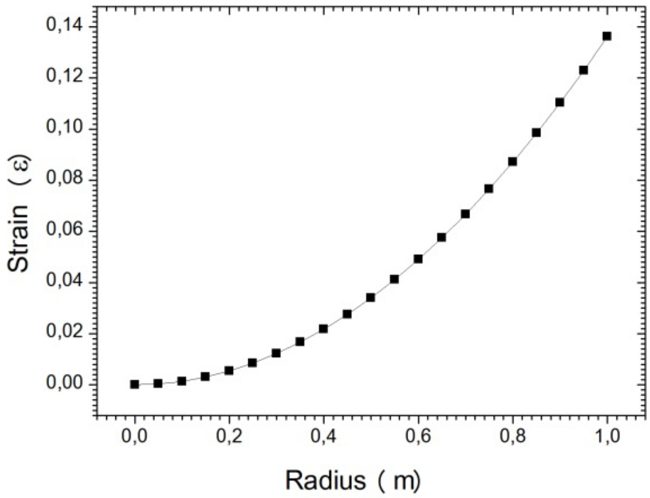

Fig. 7 Strain as a function of diaphragm radius.

has the lowest deflection. The difference between the analytical calculation shown in Fig. 4 and simulated in Fig. 5 is small, on the order of 3.38%.

Fig. 6 shows a comparison between the studied rays. In this simulation, in the center of the diaphragm, the largest red deflection is obtained, while in the circumference edges, in blue, the smallest deflection of the order of 10^{-7} m is obtained.

Mechanical deformation as a function of radius of the circular diaphragm was determined using Eq. (7). The results shown in Fig. 7 indicate an exponential behavior of mechanical deformation with increasing radius.

4. Conclusions

This paper describes a methodology for analytical calculation and computational simulation for choosing the best positioning of the piezoresistive graphite sensor element in regions of maximum mechanical stress. These results are important for sensor device manufacturing processes that use the piezoresistive effect. The difference between the analytical and simulated calculation is small on the order of 3.38%.

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