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Modeling and Analysis of the Bending Behavior of Soft Pneumatic Network Actuator with Hyperelastic Models

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ABSTRACT: Soft robots made of hyperelastic materials are widely used in medicine. Designing and analyzing the behavior of soft actuators is challenging due to the nonlinear nature of hyperelastic materials. This study examines the effects of geometrical parameters including the wall thickness, the distance between the chambers, the layer's thickness, the side walls thickness, the cross-section shape, the material of the actuator on the bending behavior, the created stresses in the inner walls and the resulting tip force to obtain the optimal geometry and material to create the maximum bending angle and tip force of the actuator. For modeling the common materials behavior of soft actuators such as Dragon Skin 30, TPU, Ecoflex30, and RTV2, five Hyperelastic model predictions are compared with the uniaxial stress-strain test on these materials, and the best model is selected to simulate each material. The results show that, by reducing the thickness of the walls, the distance between the chambers, and the lower layer's thickness, and using the square cross-section with RTV2, the actuator's maximum bending angle was achieved. However, by increasing the thickness of the walls, the number of chambers, and the thickness of the lower layers, and using DS30, the maximum tip force was achieved.

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1- Introduction

Soft robots are known for their features such as low cost of manufacturing materials, ease of construction, lightweight, and quick and easy control1]], and are widely used in industries and medicine[2]. These robots are used as surgeons and tools for rehabilitating human body organs. In this study, an effective method to investigate the effect of geometrical parameters such as the number of chambers, the thickness of the walls, the thickness of the first and second lower layers, the distance between the two chambers, the thickness of the upper wall of the chamber and the shape of the cross-section and the materials of the actuator are defined in its optimal performance. The materials used in modeling this actuator are Dragon Skin 30, TPU, Ecoflex30, and RTV2. Then, by using 5 Neo-Hookean hyperelastic models, three-parameter Yeoh, Ogden1, Ogden2, and Moony-Rivlin, the accurate model for predicting the coefficients of these materials is selected. Initially, the results of the finite element model are compared with the results of the analytical method and the experimental results. Then the effects of geometrical parameters and different materials on the bending angle, the tip force of the actuator and the stresses on the inner surface of the chambers are investigated. In the end, the optimal geometric state and the best material are obtained to create the highest bending angle and the highest tip force of the actuator.

2- Hyperelastic Models

The parameters of the hyperelastic model are usually obtained by performing a uniaxial tensile test on standard samples and fitting the resulting stress-strain diagram.

Stress equations in terms of principal stresses for different hyperelastic models are as follows:

For Ogden's hyperelastic model, the stress relation is in the form of relation (1)[3]:

$$\sigma_{uni} = \sum_{p=1}^{n} \frac{2\mu_p}{\alpha_p^2}\left(\lambda^{\alpha_p - 1} - \lambda^{-\frac{\alpha_p}{2} - 1}\right) \tag{1}$$

In the 2-parameter Moony-Rivlin model, the following relation is obtained [3] :

$$\sigma_{uni} = 2C_1\left(\lambda - \lambda^{-2}\right) + 2C_2\left(1 - \lambda^{-3}\right) \tag{2}$$

The relation between stress and strain for incompressible material is obtained with the Neo-Hookean model[3] :

$$\sigma_{uni} = 2C_1\left(\lambda - \lambda^{-2}\right) \tag{3}$$

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Table. 1. Geometric dimensions (mm) of the actuator

Parameter	b	a	h	t_b	l	l_g	t	s	N
Value	10	13	1	2	8	2	2	3	5

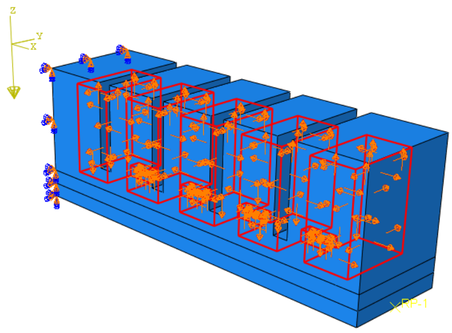

Fig. 1. Applying air pressure to the inner wall of the actuator

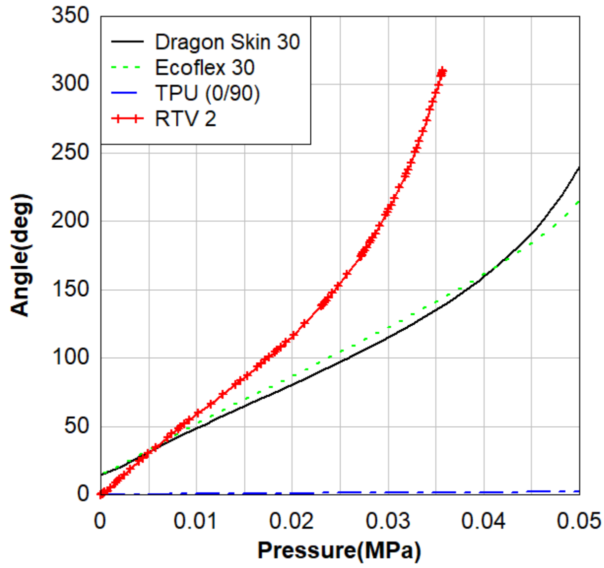

Fig. 2. The effect of different materials on the bending of the actuator

Also, for the Yeoh model, the relationship between stress and strain with the condition that the material is incompressible is as follows [4] :

$$\sigma_{uni} = \sum_{i=0}^{n} 2iC_i\left(\lambda - \lambda^{-2}\right)\left(\lambda^2 + 2\lambda^{-1} - 3\right)^{i-1} \quad (4)$$

3- FEM Modeling

To parametrically check the performance of the actuator, a three-dimensional model of a network pneumatic actuator with a distance of l_g equal to 2 mm, a square cross-section, and geometric dimensions shown in Table 1 have been created.

Static air pressure in the form of pressure of 0.05 MPa is entered into the walls of the internal chambers of the actuator and the end part of the actuator is completely bound by ENCASTER. Fig. 1).

Also, to simulate the tip force of the actuator, a rigid object was used as a dynamometer.

4- Results and Discussion

In this section, to obtain the optimal geometric state, the effect of changes in important geometric parameters on the bending behavior of the actuator made with Dragon Skin 30 has been investigated, the results of which are as follows: by reducing the distance between the chambers, the collision of the outer walls of the chambers with each other is increased, so the maximum bending angle of the actuator also increases. At high pressures, changing the distance between the chambers does not have such an effect on the amount of bending of the actuator. The comparison of the results obtained from the examination of the changes in the thickness of the first and second layers and the number of chambers shows that by reducing the thickness of the first and second layers and increasing the number of chambers, the actuator is bent at a greater angle. It can be seen that the bending angle increases with the reduction of the thickness of the side walls of the chambers. According to the results obtained from the examination of two cross-sections of a square and a triangle, the greater area of the inner surface of the chambers results in a greater bending angle. To study the effect of the actuator material on bending behavior, four types of hyper-elastic materials: Dragon Skin 30, TPU(0,90), Ecoflex30, and RTV2 are considered as materials for the main body of the actuator and its first and second layers. RTV2 has less stiffness compared to the other three materials, as a result, by reducing the stiffness of the hyperelastic material, a greater bending angle is obtained (Fig.2).

Also, the observations show that the maximum stress caused by applying air pressure and bending of the actuator has increased non-linearly. The maximum stress occurred on the side walls of the chambers and the place where the air passes between the two chambers (Fig. 3).

Finally, according to the results, the actuator made with TPU produces the least bending and tip force of the actuator. In the following, the force created at the tip of the actuator reaches 1.5, 1.38, and 1.34 N for Dragon Skin 30, Ecoflex30, and RTV2 actuators at a pressure of 50 KPa respectively (Fig. 4).

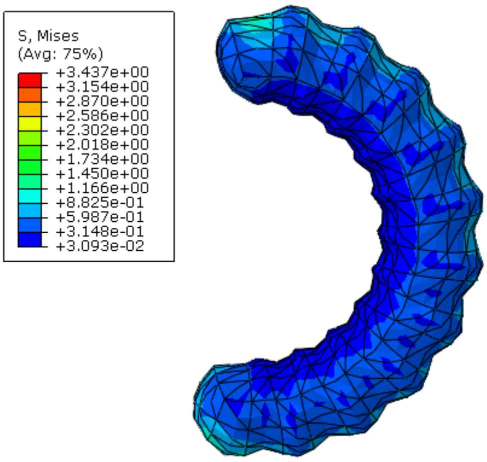

Fig. 3. The stress created on the inner surface of the actuator chambers

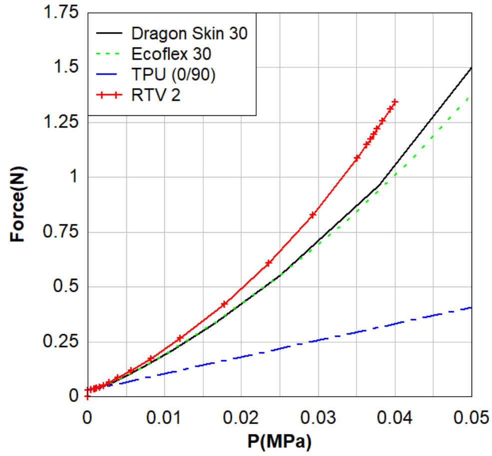

Fig. 4. Actuator tip force according to different materials

5- Conclusions

In this study, the bending behavior of the network soft actuator with pneumatic excitation was investigated. The created finite element model was compared and validated with the help of previous experimental and analytical results. Then, with the help of this model, the effect of geometrical parameters such as the thickness of the walls of the chambers, the distance between the chambers, the thickness of the first and second lower layers, and the number of chambers on the bending angle and the resulting tip force of the actuator is investigated.

To investigate the effect of the actuator materials, the tensile test diagram of Dragon Skin 30, TPU, Ecoflex30, and RTV2 was obtained using an uniaxial tensile test based on the ASTM D412 C standard. In the following, 5 hyperelastic models Neo-Hookean, 3-parameter Yeoh, Ogden1, Ogden2, and Moony Rivlin were fitted on these diagrams to obtain the best model for predicting the behavior of these materials. According to the results, reducing the thickness of the walls, the distance between the chambers, and the thickness of the lower layers increases the bending angle, while increasing the thickness of the lower layers increases the tip force of the actuator. It was also observed the stiffness of the hyperelastic material has an inverse relationship with its bending angle. In the end, the best state of the bending angle of the actuator was 311.48° at 38 KPa and the maximum tip force was 1.5 N at 50 KPa.

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