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Research on soft actuator model based on COMSOL simulation analysis

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Abstract

In this study, we designed and fabricated a pneumatic soft actuator with winding fibers. We modeled and analyzed its deformation, and simulated the affecting factors. The soft actuator is made of silicone rubber and is pneumatically driven. We wound the fibers around the silicone rubber of the pneumatic soft actuator to enhance intensity and power. The isotropic material of the silicone rubber and anisotropic material of the winding fibers were modeled. The fiber-reinforced pneumatic soft actuator was simulated using COMSOL software. We studied the stress and deformation characteristics of soft actuators using three different designs with different winding fiber densities, offset distances of the air cavity along the center point, and air cavity. Uneven stress distribution and large stress changes can affect the uniformity and stability of the strain layer deformation, thereby affecting the bending characteristics of the soft actuator. The higher the density of the winding fiber, the more uniform is the stress distribution on the surface of the strain and limiting layers.

1. Introduction

The executive parts of a traditional rigid actuator generally adopt a spatial open-chain linkage mechanism, which is connected by kinematic pairs. The driving mode of the actuator is mostly motor-driven, and the structure is not deformed during driving. The advantages of rigid actuators include high control accuracy, large loading capacity, and good rigidity. However, traditional rigid actuators have the disadvantages of high stiffness, poor adaptability in unstructured environments, low flexibility, low degrees of freedom, complicated structures, and a limited working space[0]. Inspired by biology, researchers designed soft actuators, which deform significantly during driving. The structure of a soft actuator directly determines its state of motion. Mostly, soft actuators were made of hyperelastic materials[0]. In absence of moving joints, the degrees of freedom for soft actuators are theoretically infinite. A soft actuator can be deformed at any position, allowing a strong adaptability to the environment[0].

There are many different actuation modes for soft actuators including shape memory alloy, electroactive polymer, and pressurized liquid or pneumatic driving. Pneumatic driving is the most commonly used mode for soft actuators. By applying air pressure to the intracavity, the soft actuator can be deformed in the direction of lower rigidity and deforms by expansion, bending, and torsion, thereby achieving movement[0-]. One type of pneumatic actuator is the fiber-reinforced actuator. Compared with similar actuators without fiber reinforcement, a fiber-reinforced actuator can be subjected to stronger air pressure, generating greater power. The pneumatic soft actuator material is typically silicone rubber, which is a hyperelastic material that deforms significantly during driving. The silicone rubber lumen of the soft actuator is the driving and movement structure. To improve the motion and control precision of the pneumatic soft actuator, it is necessary to establish a mathematical model and perform simulation analysis of the material and structure.

Control accuracy can be improved by establishing mathematical models for soft actuators, which are different from those of rigid actuators. Degrees of freedom in a soft actuator are uncertain, making accurate mathematical models rather difficult and challenging.

In this study, a soft silicone rubber actuator was pneumatically driven. We wound the fibers around the silicone rubber of the pneumatic soft actuator to enhance intensity and power. We consider silicone rubber as an isotropic material and the winding fiber as an anisotropic material, which were both modeled. The fiber–reinforced pneumatic soft actuator was simulated using COMSOL software. Through the fluid–structure coupling dynamic analysis, the factors affecting the mechanical properties of the soft actuator were analyzed.

2. Design and manufacturing of fiber reinforced soft actuator

2.1 Deformation of soft actuator

Compared with other physical driving modes, pneumatic driving mode has the characteristics of fast response speed, high power density and high bearing capacity. The silicone rubber of soft actuator has good flexibility. The pressure is always maintained at a low level when driven by air pressure. While the soft actuator realizes deformation, it also has high safety.

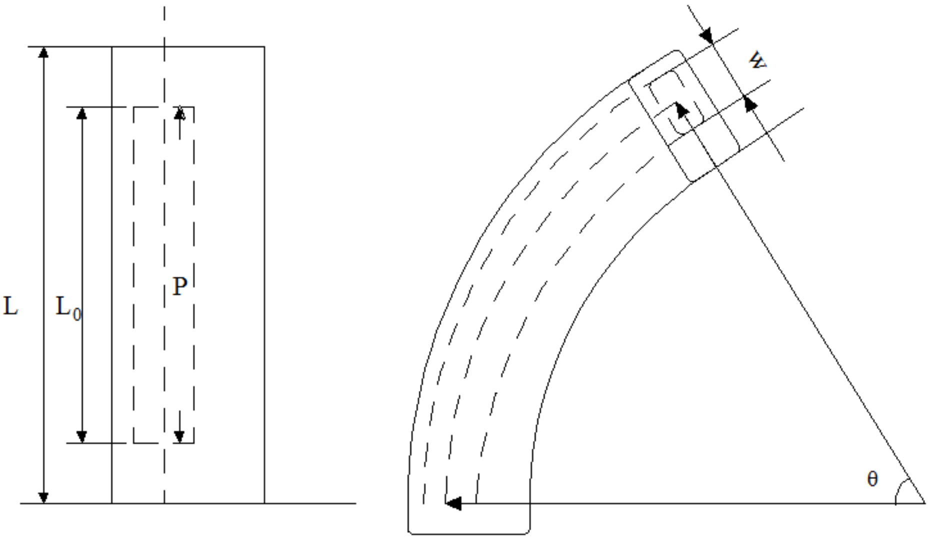


Fig. 1 Deformation principle of pneumatic soft actuator.

The pneumatic soft actuator was made of a hyperelastic material with an air cavity distributed inside. As shown in Fig. 1, the air cavity P expands when pressured air was introduced into it, resulting in movement. Therefore, motion control of the soft actuator can be achieved by controlling the air pressure in the air cavity. Where L is the axial length of the soft actuator, L0 is the axial length of the air cavity. The air cavity structure, material type, and wall thickness of the soft actuator influence its mechanical properties. The motion performance of a soft actuator can be changed by changing its geometric and material properties.

As shown in Fig. 1, the position of the air cavity was offset from the center of the soft actuator. When the pressured air is passed into the air cavity, the region of the soft actuator with the least rigidity expands. In the design of a soft actuator, the desired motion can be achieved by controlling wall thickness.

2.2 Manufacturing of fiber reinforced soft actuation

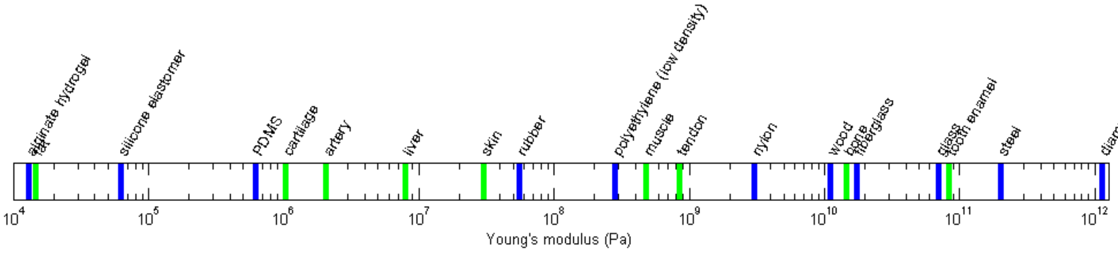


Fig. 2 Approximate tensile modulus (Young's modulus) of selected engineering and biological materials.

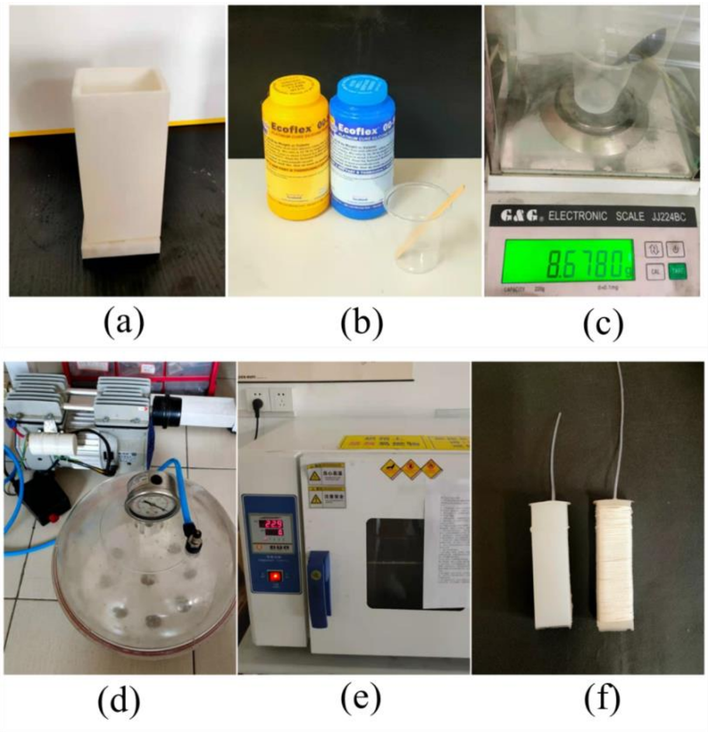
The main feature of soft actuators, which differs from traditional rigid actuators, is the manufacturing material. Young's modulus, also known as tensile modulus, is typically used to describe the hardness of solid materials and the ability of materials to resist deformation. As shown in Fig. 2, with a Young's modulus of 1 GPa as the boundary point, rigid materials such as steel, plastic, and nylon, have Young's moduli higher than 1 GPa0. This type of material is the main manufacturing material of traditional rigid robots. Materials with a Young's modulus of less than 1 GPa are defined as soft materials such as rubber, silicone rubber, and hydrogel. The Young's modulus of these materials is equivalent to that of biomaterials, which is between 104 Pa and 109 Pa. Soft actuators made of these materials have ultrahigh degrees of freedom, good deformation ability, and environmental adaptability.

Table 1. Material parameters of Ecoflex series silicone rubber

Ecoflex series model	Mixing time	Curing time	Elongation at break	Mixed viscosity	Shrinkage
00–10	40 min	4 h	800 %	14000 cps	＜ 0.001 %
00–20	30 min	4 h	845 %	3000 cps	＜ 0.001%
00–30	45 min	4 h	900 %	3000 cps	＜ 0.001%
00–40	18 min	4 h	980 %	8000 cps	＜ 0.001%

Different soft materials directly affect the extension, expansion twist, and bending properties of soft actuators. In this study, we used hyperelastic silicone rubber (Ecoflex 00–30) as the soft actuator material. Ecoflex platinum–catalyzed silicone rubber is a highly active, non-toxic, and odorless chemical material0-0. This series of silicone rubbers was soft after curing and exhibited excellent tensile properties and elasticity. The material parameters of Ecoflex series silicone rubber are presented in Table 1.

As shown in Fig 1, the air cavity is the basic component of the soft actuator, which requires super-extensibility. Silicone rubber can produce large deformations under air pressure and quickly return to its original size after the pressure is removed. The design of a soft actuator can be adjusted by changing the geometric parameters of the air cavity. Those include the wall thickness, cross–sectional shape, and length of the cavity. Modifying these parameters changes the mechanical properties of the soft actuators.



(a) (b) (c)

(d) (e) (f)

Fig. 3 Manufacturing process of soft actuator.

The manufacturing process of soft actuators is described as follows:

1) As shown in Fig. 3(a), based on the designed air cavity structure, the base, inner core, and side cover of the 3D printing mold were assembled. The gap was sealed with a hot–melt glue gun to prevent leakage of liquid silicone.

2) As shown in Fig. 3(b), (c), and (d), we weighed the liquid glues A and B of Ecoflex 00–30 silicone using an electronic scale. Samples A and B were poured into a plastic cup at a ratio of 1:1 and stirred. Then, we placed a plastic cup containing silicone A and B into a vacuum hood to remove air bubbles.

3) As shown in Fig. 3€, the release agent was sprayed on the assembled mold surface. Liquid silicone was slowly poured into the mold, placed in an oven, and cured at 60 °C for 40 min.

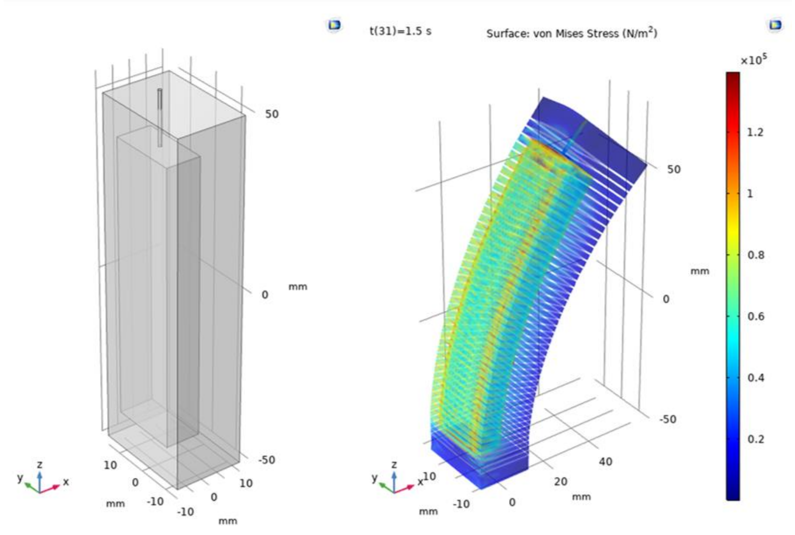
4) The solidified silicone rubber and the inner core mold were removed. As shown in Fig. 3(f), the end cap of the air cavity was solidified and sealed with liquid silicone. We opened a small hole in the end cap of the soft actuator and inserted an air tube into it. The gap between the air tube and the small hole was then glued with the sealant.

The fiber thread was evenly wound on the surface of the soft actuator at equal intervals. The air cavity of the soft actuator was inflated to expand and deform. The fiber can limit radial deformation and improve the axial deformation and strength of the soft actuator. The air cavity of a soft actuator can be designed with a geometrically asymmetric structure. Utilizing the isotropy of the air cavity and the anisotropy of the winding fiber, the actuator bends in a given direction during expansion.

3. Dynamic simulation of soft actuator based on COMSOL

3.1 Modeling of soft actuator based on COMSOL

COMSOL Multiphysics is a finite element simulation software that can solve mechanical, fluid, electrical, and many other problems0. The bending deformation of a soft actuator is the joint action of isotropic (silicone rubber) and anisotropic (winding fiber) materials. In experiments, it was difficult to accurately detect the stress and deformation of the silicone rubber and winding fibers. The stress and deformation of the soft actuator were simulated using the COMSOL Multiphysics software.



(a) (b)

Fig. 4 (a) Soft actuator model with COMSOL, (b) Bending stress distribution of soft actuator model.

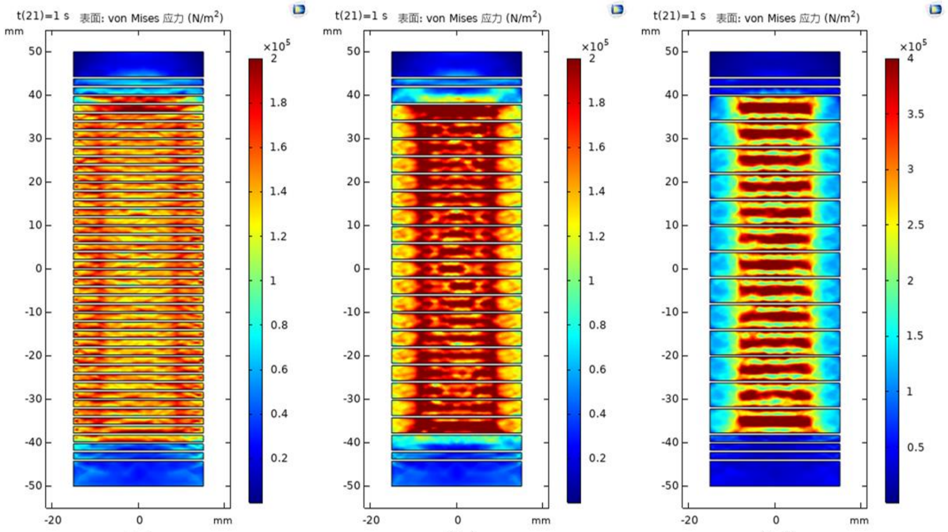
As shown in Fig. 4(a), the solid mechanics module (solid) and fluid mechanics (spf) modules were added. We studied the deformation characteristics of silicone rubber. Using the optimization interface in COMSOL Multiphysics, we fitted the silicone rubber measured data against the Neo–Hookean constitutive model0. Owing to the anisotropic characteristics of the winding fibers, the radial expansion deformation of the soft actuator is limited. We studied the stress and deformation characteristics of soft actuators using three different designs.

1) Stress and deformation analysis of soft actuator with different winding fiber density.

2) Stress and deformation analysis of soft actuator with different offset distances of air cavity along the center point of actuator.

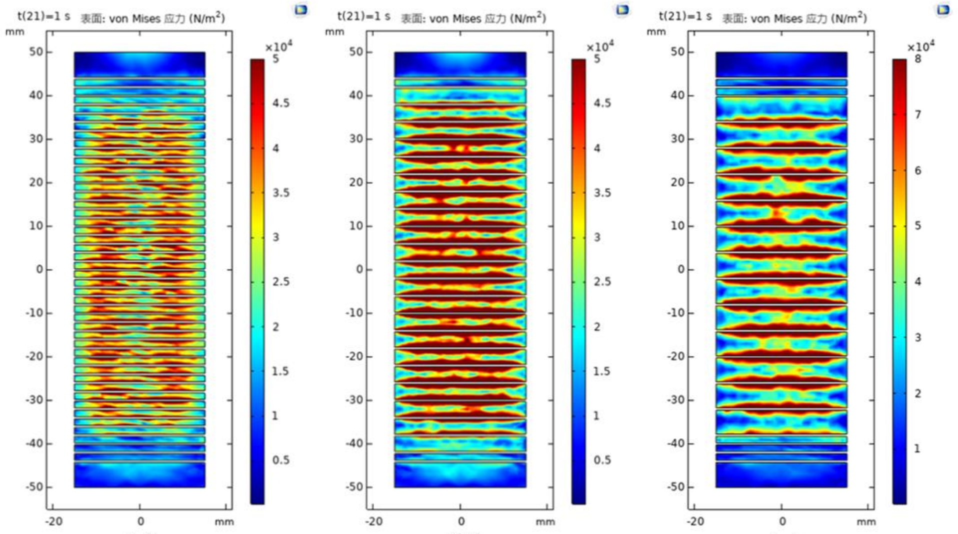
Fig. 4(b) shows the deformation of the soft actuator after inflation. In the following analysis, we used the stress of the silicone rubber to reflect the deformation characteristics. We analyzed the stress and deformation of different surfaces in the bending direction of the soft actuator. The surface of the soft actuator, which is close to the air cavity and has a large tensile deformation, is the strain layer. The surface of the soft actuator, far from the air cavity and with a small tensile deformation, was the limiting layer.

3.2 Simulation of different winding fiber density with COMSOL



(a) (b) (c)

Fig. 5 The stress distributions on the surface of the strain layer of the soft actuator with (a) high winding fiber density, (b) medium winding fiber density and (c) low winding fiber density.



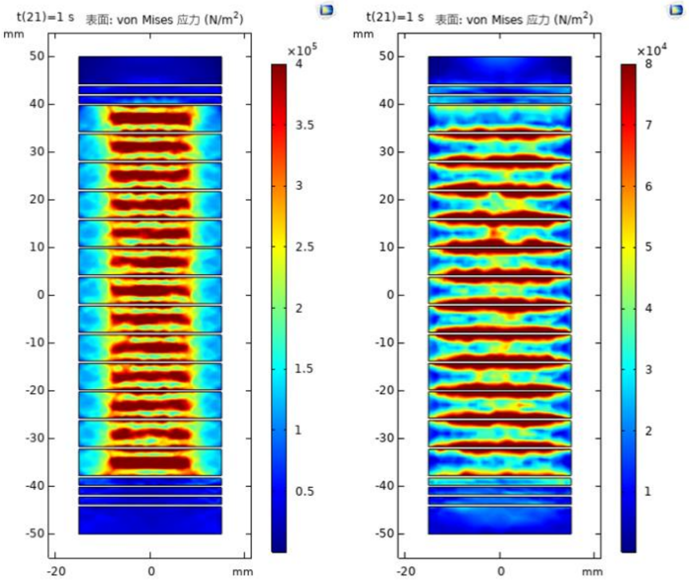
(a) (b) (c)

Fig. 6 The stress distributions on the surface of the limiting layer of the soft actuator with (a) high winding fiber density, (b) medium winding fiber density and (c) low winding fiber density.

As shown in Fig. 5, the stress on the surface of the strain layer of the soft actuator varies significantly with different winding fiber densities. When the winding fiber density was high, the stress distribution on the surface of the strain layer was relatively uniform. Some stress was concentrated at the edge of the air cavity, following its shape.

With a decrease in the winding fiber density, the stress is concentrated at the winding fibers and the interval of the winding fiber. The "bulge" is formed on the surface of the strain layer of the soft actuator. The deformation of the strain layer of the soft actuator was uneven and the tensile deformation of the strain layer decreased.

As shown in Fig. 6, the stress on the surface of the limiting layer of the soft actuator also varies significantly with different winding fiber densities. With a decrease in the winding fiber density, the stress concentrates at the winding fibers. The tensile deformation of the limiting layer decreased.



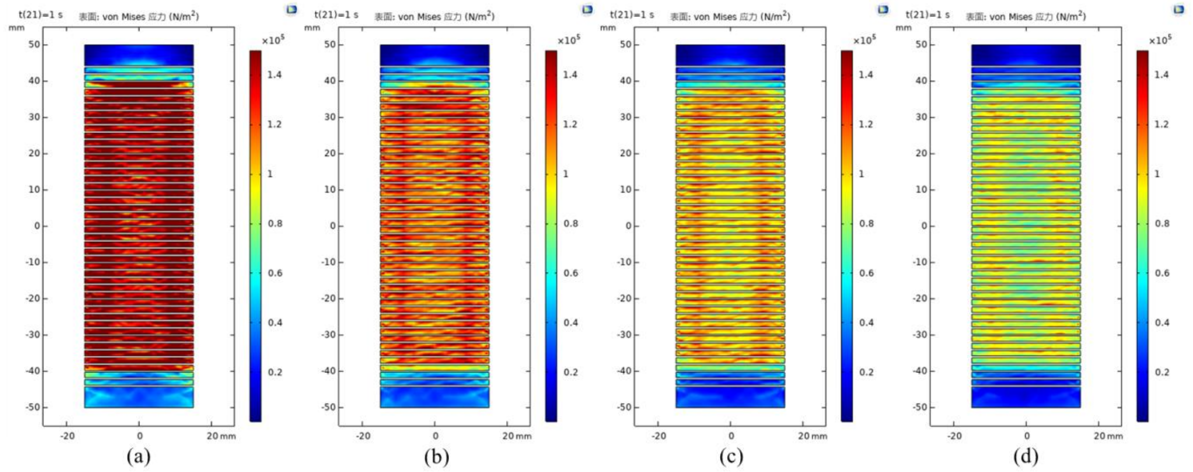
(a) (b)

Fig. 7 The stress distributions on the surface of (a) strain layer and (b) limiting layer with low density of winding fiber.

As shown in Fig. 7, both the strain layer and limiting layer of the soft actuator exhibited tensile deformation, but the positions of the stress concentrations were different. The stress concentration of the strain layer was mainly caused by the axial expansion of the soft actuator along the centerline and the axial tension of the silicone rubber material at the winding fiber spacing. The stress concentration of the limiting layer was mainly caused by the radial expansion of the soft actuator along the centerline, and the stress caused by the winding fiber hindered the radial expansion of the limiting layer.

The winding fiber density of the soft actuator has a significant influence on the bending deformation. The higher the density of the winding fiber, the more uniform is the stress distribution on the surface of the strain and limiting layers. Uneven stress distribution and large stress changes can affect the uniformity and stability of the strain layer deformation, thereby affecting the bending characteristics of the soft actuator.

3.3 Simulation of different air cavity offset distance with COMSOL



(a) (b) (c) (d)

Fig. 8 The stress distributions on the surface of the strain layer of the soft actuator under the condition of different air cavity offset distance (a) 4 mm, (b) 3 mm, (c) 2 mm and (d) 1 mm along the center point.

As shown in Fig. 8, the shorter the offset distance between the air cavity at the center point of the soft actuator, the smaller is the strain layer stress. The shorter the offset distance between the air cavity of the soft actuator and the center point, the larger is the stress on the surface of the limiting layer, which hinders the bending deformation of the actuator.

The offset distance of the air cavity along the center point of the actuator has a significant influence on the bending deformation. The stress on the surface of the strain and limiting layers increased significantly with the offset distance of the air cavity along the center point of the soft actuator.

4 Conclusion

We designed and fabricated a pneumatic actuator based on a silicone rubber. We wound fibers around the soft actuator to enhance its strength and power. The isotropic (silicone rubber) and anisotropic (winding fiber) material of the soft actuator were modelled. The soft actuator was simulated using COMSOL software. The factors affecting the bending deformation of the soft actuators were analyzed. The following conclusions were drawn from the results of this study:

1) Winding fibers around the soft actuator enhances the strength and deformation efficiency of the actuator.

2) The fiber–reinforced soft actuator was simulated using COMSOL. We simulated and analyzed the stress distribution and deformation of soft actuators with different winding fiber densities, air cavity offset distances, and air cavity structures.

3) The higher the density of the winding fiber, the more uniform is the stress distribution on the surface of the strain and limiting layers. Uneven stress distribution and large stress changes can affect the uniformity and stability of the strain layer deformation, thereby affecting the bending characteristics of the soft actuator. The larger the offset distance of the air cavity, the larger the bending angle and the higher the deformation efficiency of the soft actuator.

Список литературы:

Cho KJ, Koh JS, Kim S, Chu WS, Hong Y, Ahn SH. Review of manufacturing processes for soft biomimetic robots[J]. International Journal of Precision Engineering and Manufacturing, 2009, 10(3):171-181.

Majidi C, Shepherd R F, Kramer R K, et al. Influence of surface traction on soft robot undulation[J]. International Journal of Robotics Research, 2013, 32 (13):1577-1584.

Wang J, Xu F, Yan S, et al. Experimental investagation of electrothermal driving mechanism of SMA spring actuators[J]. Journal of Tsinghua University (Natural Science Edition), 2003, 43(2):188-191.

Davis S, Tsagarakis N G, Canderle j, et al. Enhanced modelling and performance in braided pneumatic muscle actuators[J]. International Journal of Robotics Research, 2003, 22(3-4):213-228.

Lilly j H. Adaptive tracking for pneumatic muscle actuators in bicep and tricep configurations[J]. IEEE Transactions on Neural Systems & Rehabilitation Engineering A Publication of the IEEE Engineering in Medicine＆Biology Society, 2003, 11(3):333-339.

Rus, Daniela, Tolley, et al. Design, fabrication and control of soft robots[J]. Nature, 2015, 521(May 28 TN.7553):467-475.

Jiang C Y. Vulcanization system technical analysis and application technology of single-component condensation RTV silicone rubber[J]. Fine and Specialty Chemicals, 2011.

Zhao C F, Fang S J, Luo J L, et al. Effect of fillers on the properties of two-component RTV silicone rubber[J]. Silicone Material, 2006.

Comsol AB, Burlington MA. COMSOL Multiphysics User's Guide, version 3.4, 2007.

Fan R, Chen G, Pei Z. Piecewise fitting of silicone rubber for soft robot based on the Neo-Hookean constitutive model[C]. In2021 3rd International Symposium on Robotics & Intelligent Manufacturing Technology (ISRIMT). IEEE, 2021: 328-332.