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Study of the Motion Behavior of Soft Fiber Reinforced Actuators Based on Fiber Angle

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ABSTRACT: The increasing tendency to soft robots in various applications justifies the reason for studying the behavior of such actuators. The present study investigates the effect of fiber angle on the motion behavior of elastomeric fiber-reinforced actuators with two circular and semicircular sections. Unlike previous researches, this study takes into account the elastomer material used in actuator construction. Furthermore, unlike previous researches in which phase angle variation was studied just in linear actuators, phase angle variation in linear-twisting actuators is also considered. The simulation results showed that the phase change angle is 54.2° in silicone linear actuator and 30° in linear-twisting silicon actuator. The results also showed that the maximum bending in the semi-cylindrical bending actuators occurs at a 90-degree angle of twisting fibers. To verify this behavior, experiments were done. Silicone linear actuators were made with four different fiber angles including 30, 54.2, 54.3, 75, and 85 degrees. Moreover, Linear-twisting actuators were made with two different fiber angles including 30, 55, 65, and 85 degrees clockwise and 45 degrees counterclockwise. At last, one bending actuator with fibers at the angle of 88 degrees was made. All these actuators were evaluated after actuation. The experimental results confirmed the simulation results with a maximum calculated error of 14%.

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1. INTRODUCTION

Soft robotics is a branch of robotics dealing with modeling, designing, and fabricating robots which have soft materials and soft actuators in their structure. Among all kinds of soft robots, soft pneumatic fiber-reinforced actuators are very attractive for scientists as they are lightweight, easy fabricated, inexpensive, and also inherently safe. All these characteristics, make these soft actuators applicable in the rehabilitation field. Pneumatic artificial muscles are a particular type of fiber-reinforced elastomeric actuator that the fiber angle is less than 54.7. The artificial muscles were first employed in 1958 by Gaylord [1]. Colony et al. [2] showed that by changing the angle of the thread, a wide range of motions could be achieved and also showed that the actuator has an extension at angles higher than 54.7 degrees and contraction at angles less than 54.7 degrees. Polygrinus et al. [3] investigated the bending actuator of semi-circular cross-section fiber-reinforced and a mathematical model for signifying the relationship between the air pressure and the curvature.

Unlike previous studies in which only the phase shift angle of linear actuators was examined, this study also examines the phase shift angle of linear-torsional actuators. For this purpose, the effect of fiber twist angle on the motion of linear, linear-torsional, and flexural silicon actuators was investigated. Here, first, the motion behavior of the actuator was investigated with the help of simulation, then the accuracy of the simulation results was measured with the help of experimental evaluations.

2. METHODOLOGY

This study was conducted in two main parts including simulation and experiment. In order to simulate actuators' behavior during torsion, linear and linear-torsional motions, each of these actuators was first modeled in Abacus. Their body was considered as cylindrical (for linear and linear-torsional actuators) and semi-cylindrical (for bending actuators) channels and fiber modeled with scripting python in Abacus. For instance, Fig. 1 depicts the linear motion cylindrical actuator model.

The type of analysis must be nonlinear and quasi-static. But, the excitation speed is low, so the analysis was considered static. For simulation, the body geometry was performed with Table 1 dimensions.

The fiber angle was varied from 0 to 90 degrees. The actuator behavior was then examined. Torsional linear actuators are wrapped only clockwise or counter-clockwise. As shown in the figure. In this type of actuator, the fiber angle was also changed from 0-90 degrees. In the bending actuator, the surface of the actuator cross-section is semicircular, and

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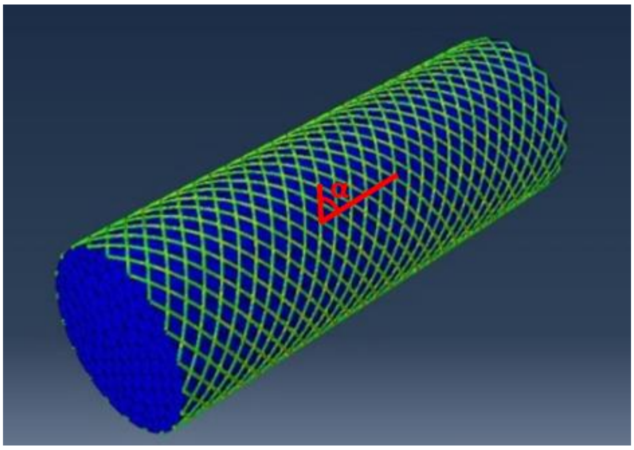

Fig. 1. Linear motion cylindrical actuator model

an inextensible layer is placed on the part of its surface. To simulation verifying, several samples were made. The molds were designed with CATIA software. And then it was built with a 3D printer. Silicone with shore 25 was used for molding. And the ratio of silicon to hardener was 5 to 1. To degassing the silicon-hardener mixture, it was placed in a vacuum chamber and then placed in the oven to dry. The presence of a little bubble in the actuator body will cause the actuator to fail when pressurized. After wrapping fiber, the actuator was covered with a second layer of silicon.

3. RESULTS AND DISCUSSION

In this paper, three types of the actuator are investigated. In the first type, the cross-sectional area of the actuators is circular. The fibers are wrapped bilaterally (clockwise and counterclockwise) around them. The actuators whose fiber angle is higher than 54.2 have an extension, and their fiber angles lower than 54.2 have a contraction. Angle 54.2 is the angle of change of actuator motion. At this angle, the actuator will have no contraction and extension. This angle

Table 1. Dimension of the actuator

Outer radius	Outer radius	Length actuator
20mm	16mm	60mm

is obtained in theory 54.7. The difference between the angles in the simulation and the theory is 0.9%. The simulation and experimental results can be seen in Fig. 2.

Generally, the non-threaded actuator will increase the length and diameter as the air enters the channel. A cylindrical actuator is twisted at a 0-degree angle. By stimulating the actuator, the fiber force will be higher than the pressure force inside the channel. The direction of the fiber force is the opposite of increasing the length of the actuator. As the fiber angle increases, the fiber force will not be in line with the actuator length, so the amount of force that the fiber exerts in the opposite direction will decrease. By decreasing the fiber force, at a specific angle, the fiber force and air pressure will be equal, which the actuator will have no longitudinal change.

In the second type, the actuator is wrapped only in one direction (clockwise or counterclockwise). Hence it will also have a twisting motion. In this type, in addition to the twisting motion, there is also a change in length. But the angle that the actuator has no change in length is less than that of the first type.

The third type is the semicircular cross-section fiber-rained force actuator. This actuator will bend as the air enters the actuator channel. The higher the fiber angle, the higher the bending of motion (Fig. 3). The maximum bending motion occurs at the angle of fiber 90 degrees. It is difficult to achieve 90 degrees in the fabrication process so that the bending actuator is fabricated and tested at 88 degrees of fiber angles as shown in Fig. 4. On the one hand, several samples with different fiber angles were fabricated and tested to verify the simulation results. The repeatability of the test was also repeated five times. The results of the simulation show that as the cross-section changes (the angle of the fibers and the air pressure is kept constant), the closer to the semicircle it becomes, the higher the bending angle is achieved.

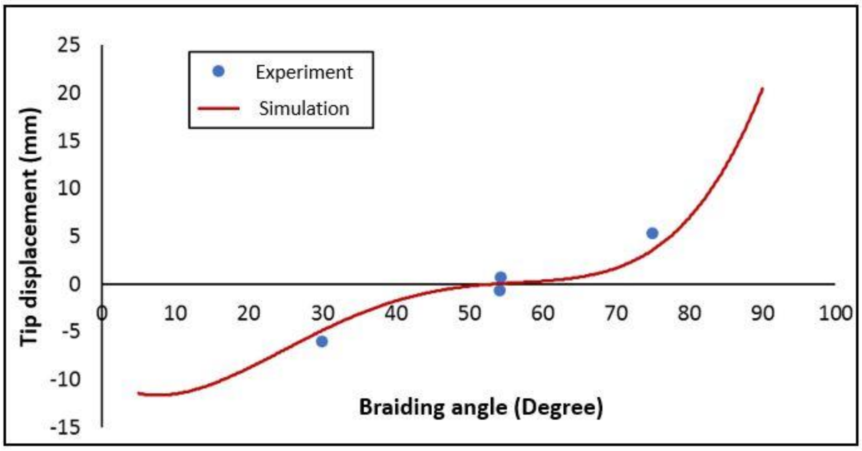

Fig. 2. Comparison of practical results and simulation results for linear actuator at 100 kPa inlet pressure.

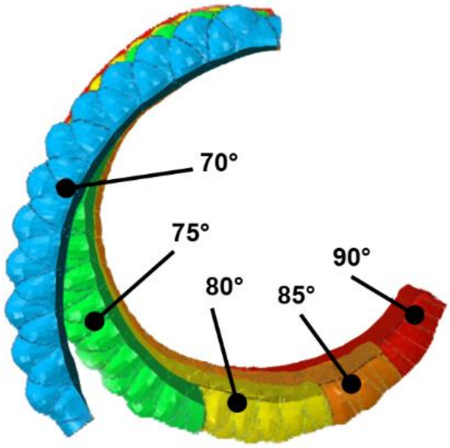

Fig. 3. Influence of the fiber angle on bending motion at constant pressure (70kPa)

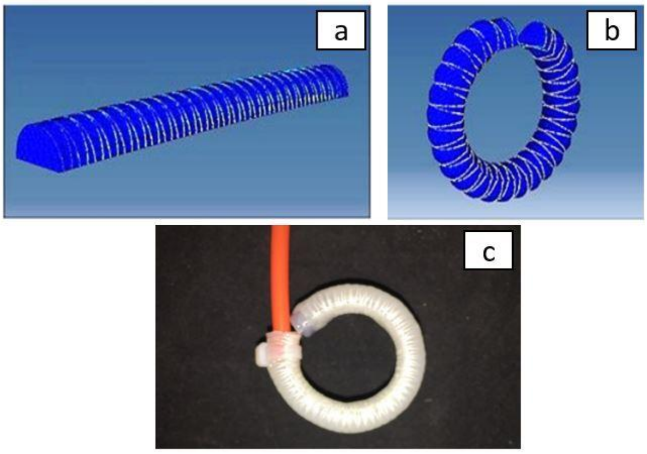

Fig. 4. Semi-cylinder bending actuator with 88-degree fiber angle a) Before applying air pressure. b) After applying 100 kPa air pressure. c) the experimental result and verification

4. CONCLUSION

Fiber-reinforced soft actuators are very popular due to their unique features such as lightweight, easy fabrication, inherent safety, and low price. These actuators have a high potential for application in a variety of fields such as surgery, rehabilitation, transportation. Therefore, the behavioral study of such actuators seems necessary. In this paper, three types of the actuator are investigated. The linear actuators that their fiber angle is higher than 54.2 have an extension, and their fiber angles lower than 54.2 have a contraction. In linear-torsional mode, the actuators have extension and contraction but the angle that the actuator has no change in length is less than that of the first type. In a bending actuator, the maximum bending motion is at the angle of fiber 90 degrees.

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