A BENDING ACTUATOR BASED ON EXTENSILE PAM AND ITS APPLICATIONS FOR SOFT ROBOTICS

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ABSTRACT

In this study, a kind of bending actuator based on extensile Pneumatic Artificial Muscles (PAMs) was proposed. The actuator was built, tested and modeled to characterize its performance and mechanical properties. And its applications for soft robotics were also explored. The bending extensile PAM consists of two 3-D-printed end fittings, an elastic tube, a braid tube and an embedded elastic frame. The free bending tests were conducted to evaluate the bending capability. The tests of output force and moment were implemented to assess its driving capability. Moreover, non-linear quasi-static model was built based on the principle of virtual work to characterize mechanical properties. To demonstrate its potential applications for soft robotics, a three-finger gripper and a soft humanoid hand based on the bending actuator were developed. Their bionic configuration enable them to adapt to diverse working conditions and mitigate unexpected impairment. In this work, the design of this actuator and the results of experiments were depicted and discussed, and the modeling results were compared with testing data and analysed carefully. This paper presents the excellent performance and intriguing prospects of this self-sensing bending actuator in soft robotics.

1 INTRODUCTION

In recent years, soft structures have caught increasing attention in robotic field due to their high flexibility of performing and simplicity of structures, compared with these robotic mechanisms built with diverse rigid structures and components [1]. Traditional rigid robots require complex feedback systems and mechanical structures to avoid accidental damage to objects or operators and adapt to diverse working conditions, while soft robots are able to achieve dexterous motion via simple integrated structures and mitigate unexpected impairment with passive compliance. Pneumatic Artificial Muscles (PAMs) have been used in many robotic designing but generally as contractile PAMs to utilize the high power to weight ratio [2], while another type of PAMs, extensile PAMs, were neglected for a long time due to the much lower output force in the same size. However, with the increasing interest in soft robots, extensile PAMs and other soft actuator have shown promising potential in soft robotics owe to the properties of high deformation ratio and simplicity of structures [3] [4] [5].

In this study, a kind of bending actuator based on extensile PAMs was proposed, built and tested. Moreover, non-linear quasi-static model was built based on the principle of virtual work to characterize mechanical properties of actuators. Meanwhile, its application in soft Robotics was explored. A three-finger gripper and a soft humanoid hand based on the Bending Extensile PAM were developed and tested.

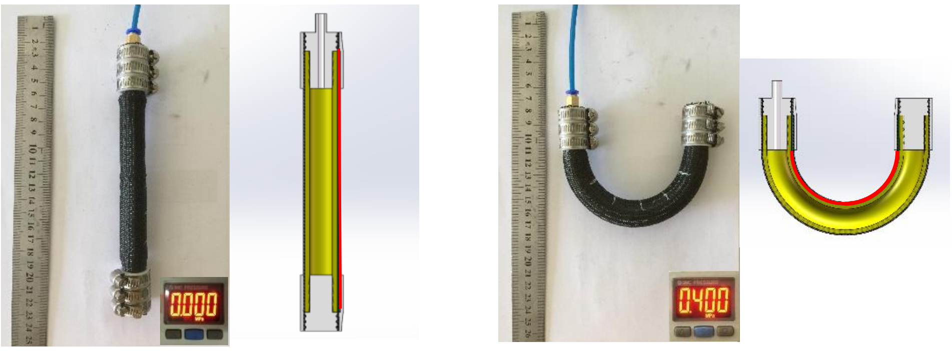
2 EXPERIMENTAL CHARACTERIZATION OF BENDING PAM

Two Bending Extensile PAM (BE-1, BE-2) with different braid angles were fabricated and tested to analysis the effect of braid angle on their mechanical properties and build models, Fig. 1a. The free bending curvature and blocked force were both measured with the two Bending Extensile PAMs of BE-1 and BE-2 under a set of working pressures to characterize their capabilities of deforming and driving.

And another Bending Extensile PAM (BE-3) was also built for a quasi-static test to understand the properties of Bending Extensile PAM more comprehensively, Fig. 1b.

Figure 1: The Bending Extensile PAM composed of two end fittings, an elastic tube, a braid tube and an embedded elastic frame.

Each BE (Bending Extensile) PAM consists of two end fittings, an elastic tube, a braid tube and an embedded elastic frame. As normal extensile PAMs[3], the braid angle of bending extensile PAMs was under 35.26° degrees approximately, and both of the elastic tube and braid tube were fastened to the end fitting at each end. The difference is that an elastic frame was embedded between the elastic tube and braid tube and also fixed to the end fittings at each end, Fig. 2a. The aim of embedding elastic frame is to generate a bending deformation toward the side where the elastic frame was embedded when the extensile PAM inflated, Fig. 1b. In the experiments, it was found that the elastic frame could also enhance the stability of the configurations and bearing capacity by preventing the collapse under lateral loads. The elastic frame could also be designed to obtain various mechanical property of Bending Extensile PAM. The two Bending Extensile PAMs of the same length of about 12.5cm were both fabricated with a latex bladder with an outer diameter of 17mm and a thickness of 2.5mm, 5mm wide and 0.5mm thick fiber-reinforced epoxy laminates and polyethylene terephthalate (PET) braids. But they have different the braid angles of 21.0° and 29.9°.



(a) The rest state with the elastic frame embedded in right side

(b) The inflated state with the bending angle of 180 degree and the bending radius of about 4.2cm

Figure 2: The Bending Extensile PAM composed of two end fittings, an elastic tube, a braid tube and an embedded elastic frame.

The free bending curvature is the bending curvature of the elastic frame at a certain pressure without outputting any force or moment. The curvature was indirectly measured by capturing the positions of several mark points on the actuator. The BE-2 PAM with the braid angle 21.0° achieved a bending angle of about 175° at 0.35MPa much more than the 116° of the BE-1 PAM with the braid angle 29.9°. From the Fig. 3, it could be draw that the BE PAM fabricated with same materials but smaller braid angle has larger the bending angles at the same working pressure. Fig. 3 depicts the curves of bending curvatures during the whole pressurizing and depressurizing process. The variations of Bending Curvature show hysteresis to working pressures, which is caused by the friction of braid and the viscoelasticity of the Bladder.

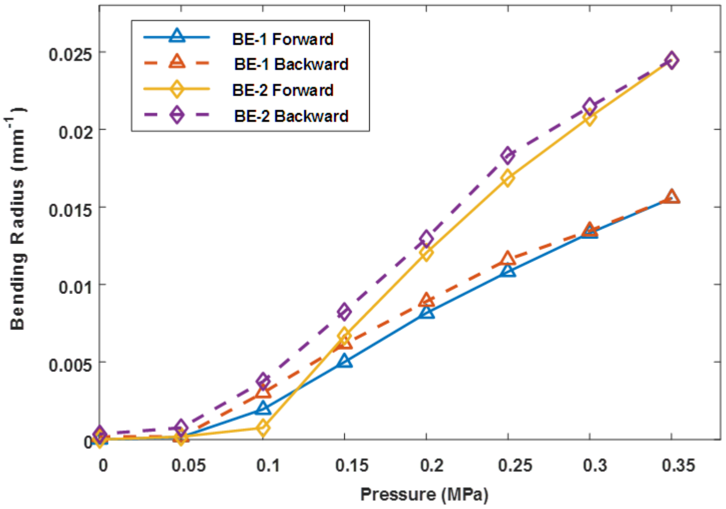


Figure 3: Bending curvatures of BE PAMs under a set of Pressures from 0MPa to 0.35MPa: The curves represent the processes of pressurizing and depressurizing. Solid lines describe changes of Bending Curvature during the pressurizing process; the dashed lines depict variations of Bending Curvature during the depressurizing process

Block force is the force the Bending Extensile PAMs generates when one end clamped on the test frame, and the other contacting with the force sensor, Fig. 4. Block forces were tested with BE-1 and BE-2 Bending Extensile PAMs at a set of pressures from 0MPa to 0.30MPa. The BE-2 Pam generate almost double force of BE-2 PAM which has a larger braid angle, Fig. 5. The linear trend lines of Fig. 5 show the linear relationships between the block force and test pressure. The linear increasing rate of BE-1 PAM to pressure is about twice as that of BE-1 in the linear interval. And it is obvious that there is a deadband of pressure before the actuator start to output forces.

Figure 4: Block Force Test: One end of actuator clamped on the test frame, and the other contacting with the force sensor

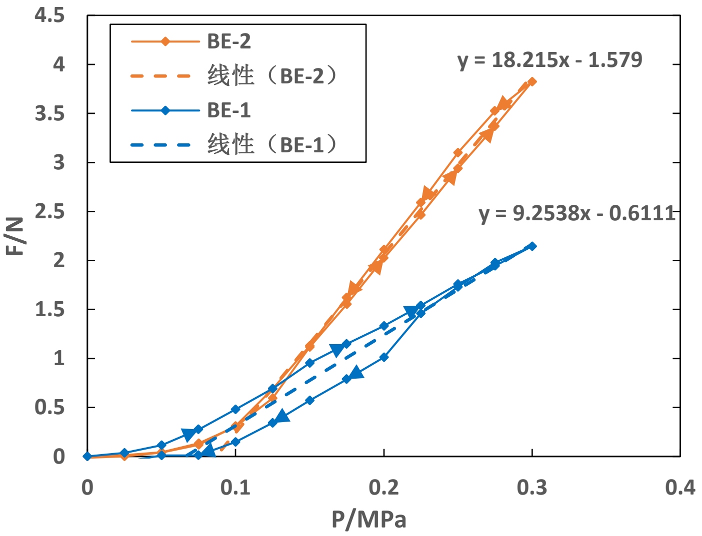


Figure 5: Curves of Block Forces under a set of Pressures from 0MPa to 0.3MPa: The curves represent the whole processes of pressurizing and depressurizing. The dashed lines depict the linear increasing trends of Bending Curvature to test Pressure during the whole process.

To characterize the mechanical properties of Bending Extensile PAM more deeply and thoroughly, another Bending Extensile PAM (BE-3) was also built for a quasi-static test with the similar braid angle of 22.0°. The test was conducted on a Zwick-010 Electro-mechanical Universal Testing Machine between 0.10MPa and 0.20MPa in increments of 0.05MPa. At each pressure, the actuator was test with a load cycle starting from the blocked state to the free-bending state then returning to the blocked state, Fig. 6.

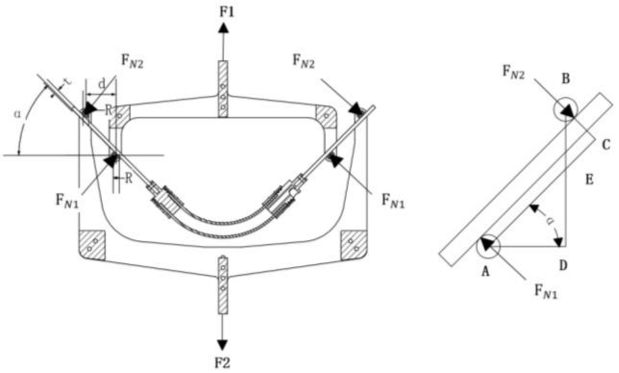


Figure 6: The design of loading frame for quasi-static moment load

The output Moment and bending curvature were calculated as follows.

$$\alpha = \arctan(\Delta s/d) \tag{1}$$

$$M=\frac{F_{load}[d+(2r+t)sin\alpha]}{2cos\alpha^2} \tag{2}$$

$$K=\frac{2\alpha}{L_0} \tag{3}$$

F_{load} is the Load of the Testing Machine, Δs is the stroke of load frame, L_0 is the original length of actuator. Since the original signal contains too much noise, it was smoothed to describe the relationship more explicitly, Fig. 7. For further analysis, the average moments were calculated with the unloading and loading process. The hysteresis are also found in the cyclic loading test. The BE-3 bending extensile PAM achieved about a free-bending curvature of 0.012/mm, a free bending circular radius of about 8cm and the free bending angle of 86° under 0.20MPa. During each cycle, the actuator generated the maximum output moment at the blocked state, and output the moment of around 300N·mm.

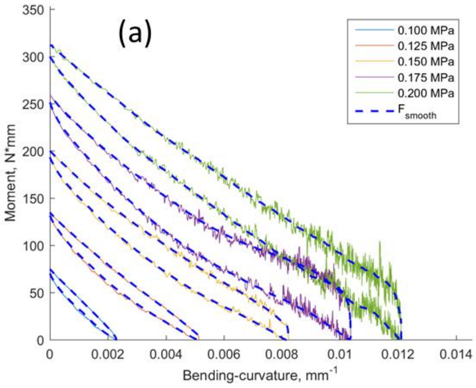


Figure 7: Quasi-static cyclic moment loading test: The lower line of each cycle presents the unloading process from blocked state to free bending state; the upper line of each cycle presents the loading process from free bending state to blocked state.

3 MODELING OF BENDING PAM

Since the Bending Extensile PAMs and Extensile PAM were both developed from the Contractile PAM, the McKibben Actuator [2], the modeling works of these actuators predictably have something in common. However, the Bending Extensile PAMs mainly output bending deformation, while conventionally McKibben Actuators are mainly utilized to Output axial displacement. So for bending PAMs, the distribution of deformation at cross section is uneven which is different from axial actuating PAMs and makes distinction between bending and axial actuating PAMs in mechanical property. And that is also the key point for the modeling work of Bending Extensile PAMs.

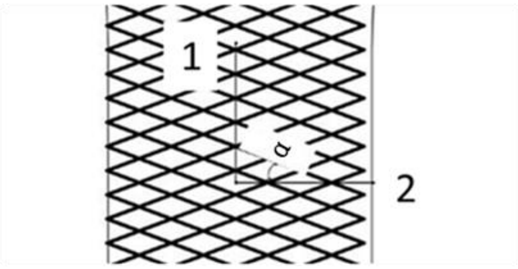


Figure 8: The constraints of braid (Braid Angle α): Direction 1 is the axial direction, and direction 2 is the circular direction.

The modeling results are shown and compared with the test results in Fig. 9a. The error of energy model is about 8.44%. Fig. 9b shows the block moments of test data and the energy model, and the error of energy model is about 2.49%. From the block moments of test data, it can be drawn that the BE PAM has a deadband, and for BE-3 PAM, which is from 0MPa to 0.0678MPa, and the block moment is proportional to the active pressure, which is calculated by subtracting the Dead Pressure of 0.0678MPa from real inner pressure of bladder.

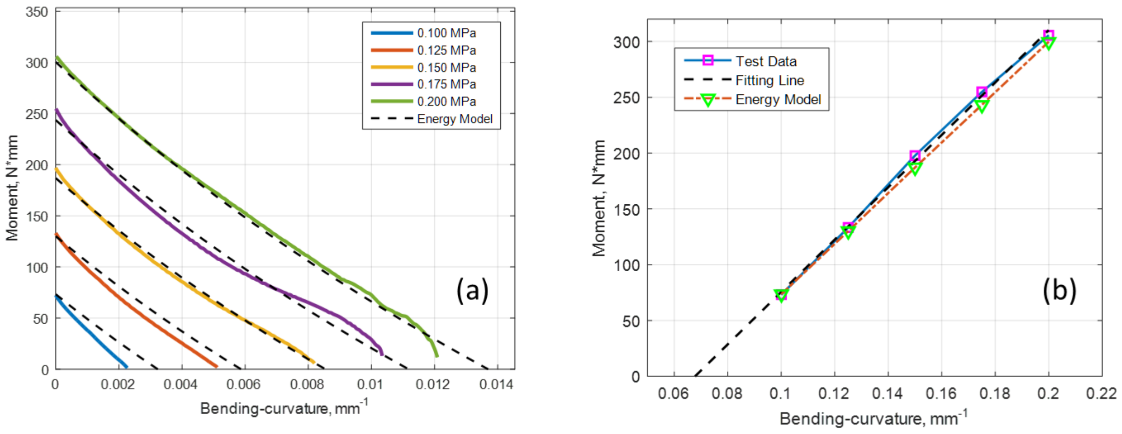
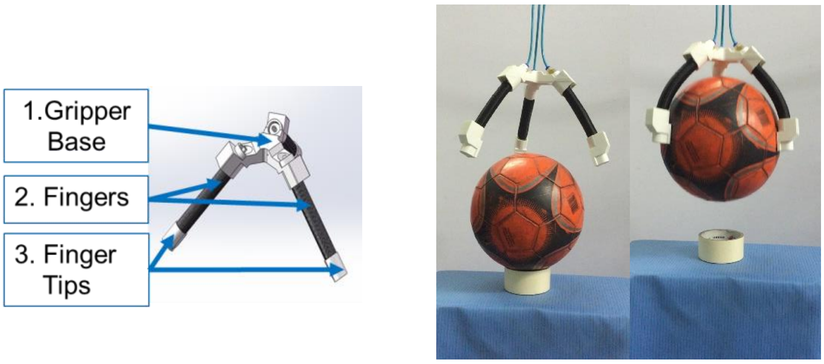


Figure 9: Modeling results of Energy model: (a) Test data and modeling results of Quasi-static cyclic moment loading test; (b) Test data and modeling results of Block moment.

4 THE APPLICATION OF THE BENDING EXTENSILE PAMS

To demonstrate the usability of the Bending Extensile Pam , we also developed a three-finger gripper and a soft humanoid hand. The soft gripper and humanoid hand were both composed of three parts, including a hand base, soft fingers and their fingertips. Each finger was built with a Bending-Extensile PAM. One end of each Bending Extensile PAM was fastened to the hand base and their grasper tips were also respectively installed on the other end of each Bending Extensile PAMs, Fig. 10 and Fig. 11. Larger strokes of bending motion, soft but stable configurations and bionic profile enable them to adapt to diverse objects and mitigate unexpected impairment.



(a) The rest state

(b) The process of Grasping

Figure 10: A Soft Three-finger Gripper

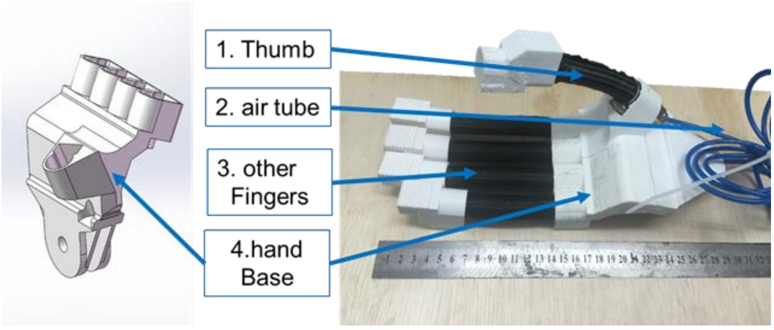


Figure 11: A Soft Humanoid Hand Based on B-E PAMs.

5 CONCLUSIONS

In this work, three Bending Extensile PAMs were built and test. Two of them were built with different braid angle to study the effect of the braid angle on motion and force output capabilities of BE PAM. The BE PAMs with the larger braid angle achieve larger bending angles and generate more output forces with the same working pressures. Another Bending Extensile PAM was also built for a cyclic moment loading test to study the mechanical properties more thoroughly and deeply. A nonlinear quasi-static model was built based on the Mooney-Rivlin hyperelastic model and principle of virtual work. The modelling results were compared with the test data to demonstrate the validity of the model. The soft gripper and humanoid hand have shown the usability and potential of the Bending Extensile Pam in soft robotic. The larger stroke of bending motion, soft but stable configurations have made Bending Extensile PAMs good candidates for soft robotic and wearable device.

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