Design Optimization and Analysis of External Corrugation and Geometry of Asymmetrical Bellow Flexible Pneumatic Actuator

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Abstract. Pneumatic soft actuators are a highly researched topic in soft robotics. The paper discusses the design and analysis of an Asymmetric Flexible Pneumatic bellow Actuator (AFPBA). This kind of actuator is cheap, easy to produce, reliable and durable. Soft grippers commonly use this actuator to pick fragile objects. The objective is to design an actuator which produced the maximum bending and study the effect of external corrugation and eccentricity on the actuator to select the optimal design. Optimum eccentricity has been determined by two factors – bending and stability. The model has also been tested at different pressures. Nitrile rubber was used as the material to design and analyze the actuator. Finite element analysis was employed to conduct the structural analysis of the actuator. In conclusion, an actuator with a semicircular cross-section and semi-circular corrugation for the bellows gave the maximum bending. For the particular design selected with an eccentricity of 0.87 provided the maximum bending of 30.764 degrees at working pressure (5 bar).

1. Introduction

Soft robotics is a field of robotics which has been at the spotlight in recent years. Robots are used by humans to do tasks they find dull, dirty and dangerous. These environments require the robot to pick or interact with fragile objects and bodies that deform on application of force. The field of soft robotics aims at making special grippers and manipulators from highly compliant materials to aid the robots with these tasks. Soft actuators or robots are usually actuated using electric fields, shape memory alloys (thermally actuated) or pneumatic actuation. A soft robot can interact with complex environments and objects more effectively than a hard robot [1, 2] such as picking up fragile objects like eggs and assistance in surgeries [3]. The tradeoff here is that soft robots are harder to control due to their high compliance.

The benefits to using a pneumatic soft actuator are that they are usually safe, cost effective and easy to maintain. Asymmetric pneumatic actuators are tubes made of compliant material in which the tube chamber is slightly shifted from the center. When pressure is supplied into the chamber, a bending moment is created due to the force acting on the wall due to the pressure and the difference between the center of pressure and centroid of the actuator. This difference is known as eccentricity. This actuator works in a way opposite to how a bourdon tube works [6]. Providing bellows to the tube increases the amount of bending and force which makes them a good candidate for use in soft grippers [4 - 7]. This paper describes how the design configurations like the cross section of the actuator, the
corrugation of the bellows and eccentricity affect the deflection angle and how to select the optimal design to be used in soft grippers.

2. Material selection
Acrylonitrile butadiene rubber (Table 1) also known as nitrile rubber was selected as the material for actuator fabrication. The selection was based on factors such as availability, abrasion resistance, tear resistance and ease of manufacture. Although nitrile rubber has poor temperature resistance which limits its use in high temperature zones, it was found suitable to be for building the prototype [6-8].

| PROPERTY         | VALUE          |
|------------------|----------------|
| Density          | 1000 kg/m³     |
| Shear Modulus    | 2.9 MPa        |
| Poisson Ratio    | 0.49           |
| Ultimate tensile strength | 13.787 MPa     |

3. Design of actuator
The actuator is an asymmetric tube that functions in a way opposite to how a bourdon tube works. The axis of the chamber is slightly shifted to one side of the tube. This shift, known as eccentricity, along with the force exerted on the walls due to the air pressure in the chamber creates a bending moment which causes the tube to bend [6]. The objective of the design should be to maximize bending and stability all the while providing a good surface for better grasping. For this purpose we have to take into account the cross section of the tube, the corrugation of the bellows and the eccentricity of the chamber. A decent amount of wall thickness should be provided to prevent bursting of the actuator. Also, since the tube is to be connected to the air supply, it should be able to fit into a pneumatic connector. The use of an extension rod without bellows helps to connect the actuator to the connector.

3.1. Cross section determination
Initially, 3 different cross sections were taken into consideration for the actuator – circular, semi-circular(Figure 1) and square(Figure 2). Square cross section provided less amount of bending compared to circular cross sections. But the lack of a good gripping surface makes circular cross section a poor choice. In the end, half square semi-circular cross section was selected as it provided good deflection as well as a good gripping surface [9].

3.2. Corrugation shape determination
Four different corrugation designs were considered for analysis – trapezoidal, semi-circular, triangular and square (Figure 3, 4, 5 and 6). These four designs would be tested to select the optimal design which provides the best bending and stability.
Figure 5. Trapezoidal corrugation.

Figure 6. Triangular corrugation.

3.3. Pneumatic chamber and extension rod
The pneumatic chamber passes through one end of the actuator and has a length of 97mm. This length provides a wall thickness of 3mm. An extension rod of 15mm length and 12mm diameter is additionally added to the design to connect the pneumatic connector (Figure 7a). The final design has a total length of 115mm including the extension rod and 12 corrugations. Air at pressure of 5 bar is supplied into the pneumatic chamber (Figure 7b) which exerts a force on the walls of the chamber. This force and the eccentricity provided causes a bending moment in the actuator.

Figure 7. Sectional view of pneumatic chamber(a) and finalized design with extension rod(b).

4. Analysis of actuator.
Finite element analysis using Ansys 18.0 has been used for the analysis of the gripper [8] with nitrile rubber selected as the actuator material and medium level span angle center meshing. This divides the mesh in curved boundaries till each element span an angle of 24 to 75 degrees. The initial analysis is done to select the optimal corrugation for maximum bending. Since one end of the actuator will be connected to a pneumatic connector, we keep one end fixed. A pressure of 5 bar is given to the pneumatic chamber to simulate the actuator at working pressure. All models were subjected to 5 bar pressure with one end fixed (Figure 8, 9, 10 and 11).
Figure 8. Structural analysis of semi-circular corrugation.

Figure 9. Structural analysis of rectangular corrugation.

Figure 10. Structural analysis of trapezoidal corrugation.

Figure 11. Structural analysis of triangular corrugation.

From the graph showing the deflection of all four corrugations at different pressures, we can see that semi-circular corrugation provides the maximum bending (Figure 12). Hence, semi-circular corrugation was selected to conduct other analyses.

The selection of optimal eccentricity was crucial in obtaining better bending. The analysis of the design with different eccentricities is done and their maximum deflection is noted. The eccentricity values between 0.11 and 2.14 are considered for the analysis. This was done because any value of eccentricity below 0.11 provided a very low amount of bending and any values above 2.14 caused failure of the actuator at 5 bar. The graph of the eccentricity versus deflection angle is plotted (Figure 13).
Figure 12. Graph showing deflection angle vs pressure for square, trapezoidal, triangular and semi-circular corrugation.

Figure 13. Graph showing deflection angle vs eccentricity for semi-circular corrugation.

The models were also tested at different pressures to check stability and although the eccentricities greater than 1 gave better deflection, they also led to instabilities in the model at higher pressures. Therefore 0.87 is selected as the optimal peak. The best model is then tested at different pressures to obtain the deflection angle and deflection length and their graphs are plotted (Figure 14).

Figure 14. Deflection angle vs pressure graph of the final design.
5. Results
Semi-circular corrugation provided optimal bending and stability and was used to decide on the eccentricity required for maximum stable bending. Optimal eccentricity value was found to be 0.87. The best model produced a maximum deflection angle of 55.769 degrees. The model can withstand a pressure of up to 8 bar after which the model fails. At a working pressure of 5 bar, the deflection length is 0.0267cm and the deflection angle is 30.764 degrees. The final dimensions of the optimal model selected are given in Table 2.

| Parameters                               | Value  |
|------------------------------------------|--------|
| Total length                             | 115mm  |
| Diameter of actuator chamber             | 4.5mm  |
| Total height                             | 12mm   |
| Length of actuator                       | 100mm  |
| Number of corrugations                   | 12mm   |
| Corrugation Diameter                     | 4mm    |
| Width                                    | 12mm   |
| Crest to Crest diameter                  | 8mm    |
| Actuator chamber length(Without extension)| 97mm   |
| Length of extension rod                  | 15mm   |
| Diameter of extension rod                | 12mm   |
| Minimum wall thickness                   | 2mm    |
| Maximum wall thickness                   | 4.5mm  |
| Cross-sectional semicircle diameter      | 12mm   |

6. Conclusion
Different designs were tested systematically to decide on the optimal model to be used as an end effector. Semi-circular cross section was chosen as the best cross section out of the ones in consideration. Semi-circular corrugations proved to be the most effective external corrugation as it gave the maximum bending and stability. After further analysis optimal eccentricity is decided. With the finalized design, the variation in deflection length and deflection angle with change in pressure along with the maximum deflection for the given specifications is measured and plotted.

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