Effect of Geometrical Shape on Axial Deformation of Soft Actuator

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Abstract. Soft actuators are the latest trend of research because of their light weight and ease of manufacturing and control. Soft actuators have expanded their fields and taken place in many applications where linear or angular deflection is required. Soft actuators are very useful in the applications where deflection is required with soft touch. Soft Actuators are highly compliant and adaptive to unknown environments. Because of these characteristics, soft actuators are very popular in the field of medical and in the applications where interaction with fragile structure is required. The soft actuators can give required responses mostly depends on their shape. Linear or angular deformation can be achieved by changing the geometrical shape of actuators. This paper presents the effect of geometrical shape on axial deformation of soft pneumatic actuator. Samples of soft actuators are selected with various shapes for finite element analysis. Results are obtained in form of axial and lateral deformation. An attempt is made to achieve good amount of axial deformation with very less or negligible lateral deformation by selecting appropriate shape. Based on the generated results, the shape is identified which gives desired results and more suitable among the selected nine samples. This sample can be useful in the application having space constraint in lateral direction.

Keywords: Finite Element Analysis, Hyperelastic Material, Soft Actuators.

1. Introduction

Soft robotics is a current trend of research because of its flexible nature. The field mainly deals with soft material which plays an important role against unexpected interaction with environments or humans. Many animals use soft structure for the motion and the same concept is used in soft robotics. The key parameter of soft robotics is the soft actuator through which desired motion can be achieved. El-Atab et al. [1] reviewed various soft actuators viz; electrically responsive, magnetic responsive, thermally responsive, photo-responsive and pressure driven. Kang et al. [2] presented pneumatic manipulator inspired by biological structure which works nearly similar as arm of octopus. Mosadegh et al. [3] described a soft actuator in form of pneumatic network called “pneu-net”. Modification in design was also discussed [3] which can increase the actuation time. Tan [4] discussed the soft actuator based on shape memory polymer which can deform with the change in temperature. Kim et al. [5] reviewed the study of soft bodied animals which can move with their muscles and the soft actuators which works similar to the muscles. Martinez et al. [6] discussed the ability of soft pneumatic actuators to resist mechanical damages. Udupa et al. [7] described a novel asymmetric bellow flexible pneumatic actuator (AFPA) which is used to grip the smaller objects with gentle touch.
Alici [8] reported the characteristics of soft actuators with respect to the field of soft robotics. Kulkarni [9] investigated centrifugal forming method to fabricate soft robotic actuator from silicone-based elastomers. Shintake [10] presented a fully edible pneumatic actuator based on gelatin-glycerol composite which can be integrated to form a gripper capable of handling various objects. Yang et al. [11] discussed the concept of eccentric soft bending actuators (ESBAs) and introduced a virtual trajectory based kinematic model to describe the deformation of ESBAs. Cao et al. [12] reviewed various types of soft linear actuators considering their design and deformation. Scalet [13] reviewed soft robots and soft actuators based on shape memory polymers considering materials, manufacturing techniques, and design strategies. Chen [14] discussed a water hydraulic soft actuators which can be used for large size underwater robots. Zhong et al. [15] described an analytical modeling method for pneumatic soft actuator which gives the relationship between the input pressure and bending angle. The analytical model was validated by FEM models and experimental results. Finite element analysis is also very important in design and development pneumatic soft actuator. It can save the time and cost involved in checking the response of actuator against applied pressure. Many researchers developed FEA model of soft actuators and obtained the results. Main challenge in the FEA is the parameters of the hyperelastic material. Behaviour of hyperelastic material is not same as normal material because of its property of large deformation. Lobdell and Croop [16] presented a validation mechanism to compare the simulation results and experiment test results. Elsayed et al. [17] obtained the FEA results of three types of silicone materials (Ecoflex 0030 and 0050 and Dragonskin 0030) and compared with experimental results. Elgström [18] studied hyperelastic material method and implemented Mooney-Rivlin method in FEA software to generate the results. Steck et al. [19] presented the FE analysis of Ecoflex material under large deformation. Xavier et al. [20] reviewed various materials for soft fluidic actuators with their hyperelastic material models. The procedure of using these models for FEA was also discussed. Elkeran et al. [21] discussed the material modeling and FEA of Ecoflex 0030 for soft surgical robot.

2. Materials and Methodology

The material used in pneumatic soft actuator is mostly hyperelastic in nature. Two main factors should be considered for the finite element analysis of hyperelastic material. (i) The behaviour is nonlinear and (ii) the response against pressure is in form of large deformation. Due to these factors, the procedure of FEA of hyperelastic materials is different than normal materials. The overview of key difference in the procedure of FEA of hyperelastic material is shown in figure 1.

![Figure 1. Key difference in the procedure of FEA of hyperelastic material [22].](image-url)
FEA of the hyperelastic material does not give you appropriate result considering material properties only. To obtain realistic results, hyperelastic material models are considered in the FEA software. ANSYS software was used to obtain the results discussed in this paper. Parameters of the hyperelastic model can be considered directly from the other literature or it can be obtained separately by curve fitting using test data. Another important factor is nonlinear behaviour of material which can be handled by the advanced technique called “Nonlinear Adaptivity (NLAD)”. Physical preference for NLAD should be “Nonlinear Mechanical”. Auto time setting should be ON and substeps should be selected by user. [22]

There are various hyperelastic materials used in the soft pneumatic actuators. The most popular Ecoflex 0030 was selected to obtain the FEA results. To check the effect of shape on axial expansion, various shapes were selected for soft actuators. Again to make the design simple, involvement of reinforcement and other material was avoided. Thickness of the actuator was kept uniform for the samples as well as the input pressure. The details about selected material, hyperelastic material model and its parameters are indicated in table 1.

Table 1. Details of Selection [21]

| Material       | Ecoflex 0030 |
|----------------|--------------|
| Hyperelastic Material Model | 3rd order Ogden model |
| $\mu_1$        | -35.799 MPa  |
| $\mu_2$        | 15.992 MPa   |
| $\mu_3$        | 21.738 MPa   |
| $\alpha_1$     | 0.899        |
| $\alpha_2$     | 1.061        |
| $\alpha_3$     | 0.704        |

Total 9 samples with various shapes, were selected for the soft actuator to observe the response specifically axial deformation. The main objective of this work was to identify the suitable shape for soft actuator which can give maximum axial deformation with minimum lateral deformation. Dimensions were kept same for all the samples in form of maximum length (60mm), maximum width/diameter (30mm) and thickness (4mm). Applied pressure was also kept same for all the samples i.e. 0.02 MPa.

Figure 2 indicates the basic shape of sample 1 in which air is supplied at pressure of 0.02 Mpa. Other eight samples are selected with different geometrical shape which are indicated in figure 3 and figure 4.
3. Results and Analysis

Figure 5 represents the responses for sample 1 before and after pressure applied. After applying pressure of 0.02 MPa, axial deformation is found as 14.17 mm and single side lateral deformation is 18.722 mm. Figure 6 shows the responses for sample 2 before and after pressure applied. After applying pressure of 0.02 MPa, axial deformation is found as 7.1455 mm and single side lateral deformation is 12.399 mm. Responses of sample 3 are presented in figure 7 before and after applying the pressure. Maximum axial deformation is 13.673 mm and maximum lateral deformation is 17.795 mm.
Figure 5. Responses of sample 1 before and after pressure applied

Figure 6. Responses of sample 2 before and after pressure applied
Figure 7. Responses of sample 3 before and after pressure applied

Figure 8. Responses of sample 4 before and after pressure applied
The figure 8 indicates the FEA results of sample 4 for which axial deformation is 7.1514mm and lateral deformation is 12.202mm. It was observed that soft actuators with flat surfaces are not giving good axial deformation. Due to this reason, changes were made in the shape of soft actuator and results were obtained for sample 5 as shown in figure 9. Sample 5 gives more axial deformation compare to lateral but the amount of axial deformation is very less. Results obtained for five samples were lacking the sufficient amount of axial deformation (at least 50% of the total length). Four new samples were selected to achieve the satisfactory results (figure 4).

Figure 9. Responses of sample 5 before and after pressure applied

Figure 10. Responses of sample 6 before and after pressure applied
To enhance the ratio of axial to lateral deformation, further attempts were made which are shown in figure 10, figure 11, figure 12 and figure 13. These are the responses of sample 6, 7, 8 and 9 respectively.

Figure 11. Responses of sample 7 before and after pressure applied

Figure 12. Responses of sample 8 before and after pressure applied
After obtaining the results, comparison graphs (figure 14 and figure 15) were prepared to compare the axial and lateral deformation of all the samples with respect to same input pressure. It was also observed that generated von-Mises stresses should be in permissible limit (indicated in figure 16). Changes in maximum lateral dimension are shown in figure 17 and figure 18.

**Figure 13.** Responses of sample 9 before and after pressure applied

**Figure 14.** Comparison of axial deformations of samples
Figure 15. Comparison of lateral deformations of samples

Figure 16. Comparison of von-Mises stresses of samples
Figure 17. Change in maximum lateral dimension (single side)
Table 2. Overall comparison of samples

| Sample | A: Axial Deformation (mm) | B: Change in maximum lateral dimension (mm) | C: (Ratio of A to B) | D: von-Mises stress (MPa) |
|--------|---------------------------|--------------------------------------------|---------------------|--------------------------|
| 1      | 14.17                      | 32.828                                     | 0.431643719         | 0.29822                  |
| 2      | 7.1455                     | 20.802                                     | 0.343500625         | 0.19489                  |
| 3      | 13.673                     | 31.044                                     | 0.440439376         | 0.4384                   |
| 4      | 7.1514                     | 20.47                                      | 0.349360039         | 0.19746                  |
| 5      | 10.717                     | 4.7388                                     | 2.261543007         | 0.16947                  |
| 6      | 41.038                     | 5.9748                                     | 6.868514427         | 0.18083                  |
| 7      | 34.269                     | 3.3966                                     | 10.08920685         | 0.18669                  |
| 8      | 28.271                     | 2.291                                      | 12.34002619         | 0.25742                  |
| 9      | 30.876                     | 0.68734                                    | 44.9209998          | 0.1513                   |

Table 2 indicates the overall comparison of all the samples considering all the results which were obtained through finite element analysis. It can be seen that von-Mises stresses for all the samples are in permissible limit (1.37 MPa). Sample 6 gives the largest value for axial deformation due to its geometrical shape. As shown in figure 4 and figure 10, the sample 6 has more flat surfaces to be acted upon by the pressurised air hence more force is applied in axial direction to deform the actuator. However sample 6 shows considerable lateral deformation also due to which it is not desirable in context to the application of the actuator for constrained lateral space. The sample 9 has the smallest value for change in maximum lateral dimension with satisfactory axial deformation. To compare all the samples, the ratio of axial deformation to the change in the maximum lateral dimension is obtained.
as shown in Table 2. It is observed that sample 9 gives the largest value for the said ratio and hence more suitable when more axial deformation is required with minimum lateral deformation. Further comparison was made between sample 6 and 9 considering various cases (Table 3). Case 1 is the state when sample 9 achieves axial deformation similar to sample 6. Case 2 is the state when sample 6 achieves axial deformation similar to sample 9. The value of ratio C is more for sample 9 in the both the cases. It can be observed that sample 9 gives good results against sample 6 in the cases considered for comparison.

Table 3. Comparison of sample 6 and 9

| Case  | Parameter | Sample 6       | Sample 9       |
|-------|-----------|----------------|----------------|
|       | A         | 41.038mm at 0.02MPa | 41.356mm at 0.03MPa |
| Case 1| B         | 5.9748mm        | 4.7mm          |
|       | C         | 6.868514427     | 8.799148936    |
|       | A         | 33.833mm at 0.015MPa | 30.876mm at 0.02MPa |
| Case 2| B         | 3.58mm          | 0.68734mm      |
|       | C         | 9.450558659     | 44.9209998     |

(Refer Table 2 for A, B and C)

4. Conclusion

Linear actuators are used where linear deflection is required. Soft linear actuators are specifically used to provide soft touch because of its soft material. They are highly compliant and good for the applications in unknown environments. Shape of soft pneumatic actuators affects its responses and so one can achieve the desired output by changing the geometrical shape. The main energy source for the soft pneumatic actuators are the pressurised air mostly obtained from air pump due to which deformation can be achieved. An attempt is made here to obtain the suitable shape which can give good amount of axial deformation with very less or negligible lateral deformation. Manufacturing aspects were also considered and thus reinforcement and involvement of other materials was avoided. Various geometrical shapes of soft actuators were considered and results were obtain through finite element analysis. Results show that the requirement of only axial deformation can be fulfilled by selecting proper shape (sample 6) which also offers lateral deformation. Sample 6 gives 68.39% more axial deformation at 0.02MPa with respect to its original size. Sample 6 also gives 19.91% deformation in the lateral direction. When the space limitation is the problem in the lateral direction, one should have to take care about axial changes as well as lateral changes in the dimensions and accordingly select the geometrical shape. Among the nine selected samples, sample 9 gives good results as per the requirement. Sample 9 gives 51.46% more axial deformation at 0.02MPa with respect to its original size. The change in maximum lateral dimension is lowest of sample 9 i.e. only 2.29%. Comparison of sample 6 and sample 9 concludes that 45.82% working space volume can be saved in case of sample 9 against sample 6. Geometrical shapes of actuators are not limited to only these nine samples. The obtained output is helpful in form of working space optimization. After obtaining the suitable geometrical shape, soft actuators can be manufactured by pouring the liquid silicon rubber in to the mould mostly generated by 3D printing. Next step is to leave the rubber as it is for a few hours so that it can be cured properly. Cure time may vary based on the selection of materials. Future work may include the experimental analysis to obtain more realistic result for the soft pneumatic actuator made from hyperelastic material. Further research can be done on the geometrical shapes of soft pneumatic actuators to achieve better results.
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