Characterization Of Soft Bending Actuator For High Bending Angle

Mariam Md Ghazaly, Muhammad Izzat Mohd Jahid

Abstract: In these previous years, it has been reported that machinery has caused injuries and deaths in the industries. Machineries consist of moving mechanical parts that are mostly actuated by hard conventional actuators. Using conventional actuators could result in injuries, leading to complications during human robot interaction. Due to their hard physical features, it is difficult to implement conventional actuators in various environments except in industry. Due to such difficulties, these issues are mitigated by introducing soft actuators. Soft actuators are built out of soft materials similar to silicon and are actuated when air pressure is introduced as well as on inflating the internal fluidic channel. This results in the soft actuator to create a bending motion. Such types of actuators include a broad range of application; however, the issue here would be to control the bending motion pertaining to the soft actuator, and thus this warrants an analysis for such types of actuators. This research aims to design and characterize two classes of soft bending actuator by employing FEM analysis in order to optimize the bending motion pertaining to two classes of soft bending actuator. Two types of soft actuator designs were analyze, i.e. the (i) PneuNets soft bending actuator and (ii) Fibre-reinforced bending actuator. For both designs, optimization was done via Finite Element Method (FEM) analysis using Abaqus software by varying three parameters, i.e.: (i) height of chamber, (ii) length of chamber and (iii) width of chamber/ fiber angle. The FEM analysis shows that the fibre-reinforced soft actuator exhibit higher bending motion, 217.5mm in compared to PneuNets soft bending actuator, 160.9mm respectively. The bending motion can also be controlled direction by varying the fibre angle in the fibre-reinforced actuator. This gives the fibre-reinforced actuator a broader range of motion in compared to PneuNets actuator.

Index Terms: Bending angle, design optimization, FEM analysis, pneumatic actuator, soft actuator, soft robotics, soft pneumatic.

1 INTRODUCTION

Typically, soft actuators are built from fluidic channel structures with compatible materials like shape memory alloys, elastomers, electroactive polymers, hydrogels, or composites that go through a phase transition in a solid-state [1]. There are numerous triggers for the actuation of soft actuator, which include chemical reactions, electrical charges as well as pressure fluids. In particular, the most suitable candidate for robotic applications is pneumatic and hydraulic powered soft actuators because of their low material cost, lightweight, high power-to-weight ratio as well as the associated ease of manufacturing enabled by emerging digital manufacturing techniques [2]. Once pressurised, expansion of the chambers pertaining to the soft actuator occurs in the directions that involve low rigidity, which also leads to twisting, bending and extending or contracting motions. Also, integration of these actuators as actuators as well as structural elements into the soft robotic systems' structure can be done [3-6]. Soft robotics is regarded to be an emerging field that depends on the systems that comprise soft or elastic compatible materials [7]. Key characteristics of such a strategy include soft actuators that allow achieving broad and consistent deformation pertaining to the output as well as the intrinsic adaptability due to component conformity with various environments [8]. Currently, most of the new actuation techniques are being employed for soft robots, for instance, form Electro Active Polymers (EAPs) and Memory Alloys actuators, among others. The most frequently employed soft robotics actuation process is still the fluid pressure (hydraulic and pneumatic) [9]. In this research, we have elaborated on the design and characteristic optimization of two classes of soft bending actuator which exhibit high bending angle.

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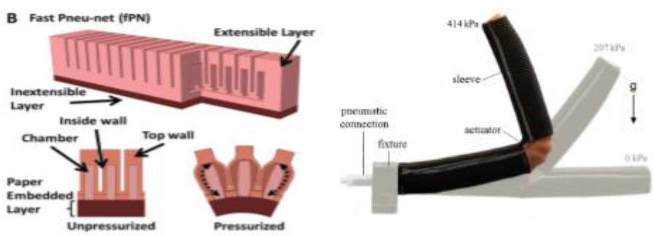
For soft robotics, pneumatically driven elastomeric actuators are noteworthy as these are easy to manufacture, inexpensive, lightweight, and offer basic inputs pertaining to non-linear motion. The soft actuator's motion could differ with regards to the soft actuator's design. Various designs can be used for different tasks i.e. 3D Printed Hydrogel Soft Actuator design, Fibre-Reinforced Actuators design as well as the PneuNets Bending Actuators design. PneuNets bending actuators can be defined as soft actuators that comprise internal fluid channel structures built on extremely stretchable elastomer materials that can readily deform on pressurising the internal channels to produce a predefined movement [10-12]. The reaction pertaining to this type of actuator relies on its morphology, which in turn is based on the inner fluid channels' design as well as the materials' characteristics employed in the manufacturing process [13-16]. At the soft pneumatic actuator's base, insertion of a flexible yet inextensible strain-limiting layer is done in the shape of a paper or cloth to avoid extending as well as create a bending motion that is in proximity to a human finger. In contrast, construction of fibre-reinforced actuators is done by utilising an elastomer bladder that is wrapped with inextensible fibres [1]. Similar to any other normal balloon, the internal bladder also behaves identical since it tries to expand in all directions when under pressurised condition. When bladder is covered with inextensible fibres, then its radially expansion is restricted, while allowing only to expand axially when pressurised. The actuator is prevented from expanding in that sheet area when a sheet of paper is introduced as an inextensible layer, since one side of it expands axially while the other one does not, which also results in bending of the actuator when exposed to pressure. The fibre angle can be changed to vary the motion of the actuators to achieve a broad range of motions, i.e. radial expansion, twisting and axial extension. There is a need to test and ensure variety of design parameters to optimize the soft actuators. Some examples of parameters that will affect the bending characteristic for soft actuators include the fibre arrangement and the chamber's morphology. These parameters greatly affect the actuator's performance and behaviour. Various kinds of soft actuators have varying parameters that affect their behaviour and performance. Table 1 shows the example of parameters that may affect the design performances.

TABLE 1
SOFT ACTUATOR PARAMETERS

PneuNets Bending Actuators	Fibre-Reinforced Actuators
• Gap between chambers [18] • Material used for fabrication [18] • Rate of inflation [18] • Number of chamber [19] • Chamber wall thickness [19] • Chamber length [19]	• Actuator cross sectional shape [1] • Radius of actuator [1] • Length of actuator [1] • Wall thickness [1] • External sleeve [20] • Fibre arrangement (angle of fibre) [20]



2 CONSTRUCTION AND DESIGN OF THE SOFT ACTUATOR

For the analysis and optimization of the soft actuators, two designs were chosen; i.e.: (a) the PneuNets soft actuator design and (b) Fibre-Reinforced soft actuator design. To perform the FEM analysis, the two designs were drawn in the SolidWorks software before being transferred to the Abaqus software for FEM optimization analysis. The parameters for the two designs were then made to vary.

2.1 PneuNets soft actuator design

PneuNets bending actuators are soft actuators with internal fluid channel structures made of extremely stretchable elastomer materials that deform when the internal channels are pressurized to create a predefined movement as shown in Fig. 1. The PneuNets soft actuator design consists of three parts which is the main body, a paper layer and a bottom layer. The materials for the main body and bottom layer parts were set using Elastosil M4601 silicone rubber. Paper served as the strain limiting layer and was positioned between the bottom layer and main body parts. This is done to ensure that only the silicone parts will expand during pressurisation. This also prevents the expansion of the strain limiting layer and the bending of the actuator. Inside the chambers, the forces applied for testing purposes have values of 1 psi until 9 psi. Furthermore, there is a second force applied at the actuator, which is the gravitational force with its value of 9.81m/s^2. The reaction of this type of design depends on its morphology which is determined by the design of the inner fluid channels and the properties of the materials used in the manufacturing process. A flexible yet inextensible strain-limiting layer in the shape of a paper or cloth is inserted at the base the soft pneumatic actuator to keep it from extending and instead produce a bending motion close to that of a human finger. The FEM analysis was performed using the Abaqus software. The Abaqus software can perform finite element analysis, which can then be used to analyse an object's mechanical properties. To conduct FEM analysis, pressure is applied within the PneuNets soft actuator design's internal chambers. Fig. 2 illustrates the steps needed to conduct FEM analysis using Abaqus for the PneuNets design.

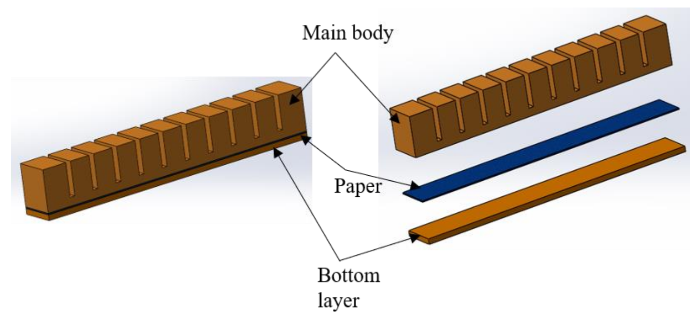


***Fig. 1**. PneuNets soft actuator design.*

2.2 Fibre-reinforced actuator design

For design optimization, the FEM analysis was also performed on the fibre-reinforced actuator design. To conduct FEM analysis, pressure is applied within the fibre-reinforced actuator design's internal chambers. Fig. 3 illustrates the procedures needed to conduct FEM analysis for fibre-reinforced design. The main body is partitioned into 2 segments: the upper and the lower segments. The material for the upper segment is set as Dragon Skin 10 silicone rubber. The material for the lower segment is set as Smooth-Sil 950 silicone rubber. For the cap part, the material used is Smooth-Sil 950 silicon rubber. Compared to the upper segment, the lower segment and caps have stiffer materials. This to ensures that the upper segment can be inflated more easily compared to the lower segment. Kevlar was chosen as the fibre material. The fibre is wrapped around the actuator's main body by following a 3° symmetry arrangement. This is to ensure that during pressurisation, expansion will only take place within the silicone parts and that the actuator will be constrained by the fibre, thereby allowing the actuator to bend. For testing purposes, forces with values of 1 psi until 8 psi were applied inside the chambers.

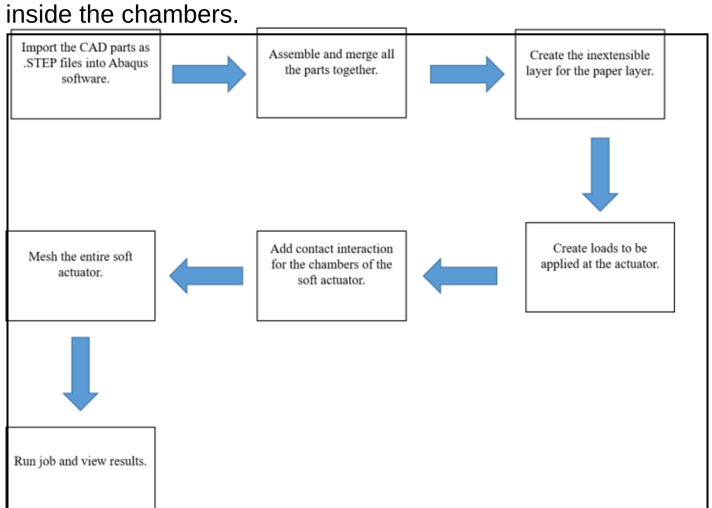


***Fig. 2**. FEM analysis procedure for optimization*

2.3 FEM analysis of soft bending actuator with different parameters

FEM analysis was performed on the two (2) soft actuator designs, specifically the fibre-reinforced soft bending actuator and the PneuNets soft actuator designs. The FEM analyses conducted on the two designs utilised different parameters to analyse and optimize the performances of the two soft bending actuators. The Abaqus software was used to conduct the FEM analysis. In the case of the PneuNets soft bending actuator design, the three (3) varying parameters were the chamber's height, width, and length. The different values are presented in Table 2. Each parameter variation was created using the SolidWorks software before undergoing simulation using the Abaqus software.

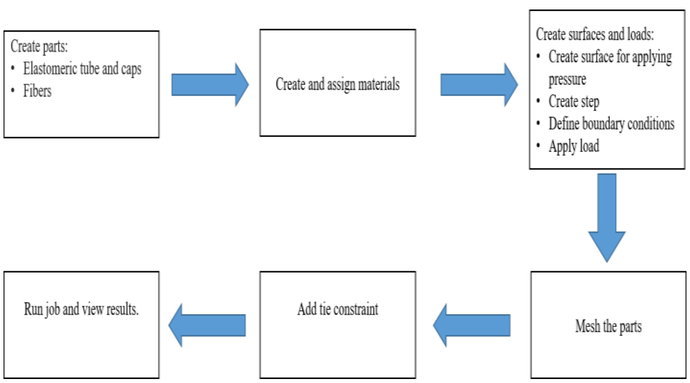
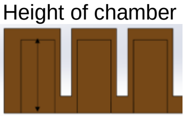
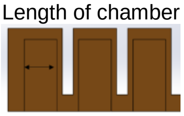
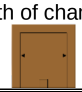


***Fig.** 3. Fibre-reinforced actuator FEM analysis step*

TABLE 2
SOFT ACTUATOR PARAMETERS PNEUNETS SOFT BENDING ACTUATOR DESIGN PARAMETERS

Parameters	Dimensions (mm) (original)	Dimensions (mm)	Dimensions (mm)
Height of chamber 	13	13.5	12.5
Length of chamber 	6	6.1	5.9
Width of chamber 	11	11.1	10.9

In the case of the PneuNets soft bending actuator design, the three (3) varying parameters were the chamber's height, width, and length. The different values are presented in Table 3. Each parameter variation was created using the SolidWorks software before undergoing simulation using the Abaqus software.

3 RESULTS AND DISCUSSIONS

3.1 PneuNets soft bending actuator design optimization analysis

Table 4 shows the optimized bending and stress and comparisons for the three (3) parameter for the PneuNets design. Table 4 shows that of the three (3) parameters, the chamber height generated the least amount of stress at a value of 33.04 N/m^2. Table 4 also shows that the chamber height exerted the largest influence on the stress generated by the actuator. To lessen the quantity of stress generated by the actuator, there is a need to reduce the height of the chamber to have a thicker chamber roof. The parameters: height=12.5mm, length=6mm, and width=11mm were chosen to be the optimized parameter for the optimized value of the generated stress. As shown in Table 4, the chamber length parameter exhibited the largest bending out of the three (3) parameters, with a value of 160.9mm. This signifies that chamber length has the largest influence in the bending generated by the actuator. To achieve increased bending of the actuator, one must increase the chamber length and achieve a thinner chamber wall. This makes the chamber easier to inflate even with decreased pressure. The parameter values height=13mm, length=6.1mm, and width=11mm were chosen as the optimized parameters for achieving optimized bending values.

TABLE 3
FIBRE-REINFORCED SOFT ACTUATOR PARAMETERS

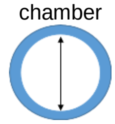
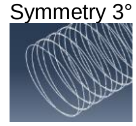
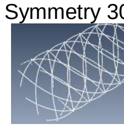
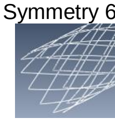
Parameters	Dimensions (mm) (original)	Dimensions (mm)	Dimensions (mm)
Diameter of chamber 	12.7	12.5	12.9
Length of chamber 	155	154	156
Fibre arrangement 	Symmetry 3° 	Symmetry 30° 	Symmetry 60° 

TABLE 4
STRESS AND DISPLACEMENT RESULTS COMPARISON BETWEEN THE THREE (3) PARAMETERS

Parameter	Optimized value (min stress & max bending)			
	Stress		Bending (displacement)	
	Optimized parameter	Optimized stress	Optimized parameter	Optimized bending
Height of chamber	Height=12.5mm Length=6mm Width=11mm	33.04 N/m^2	Height=13.5mm Length=6mm Width=11mm	160.6mm
Length of chamber	Height=13mm Length=5.9mm Width=11mm	33.1 N/m^2	Height=13mm Length=6.1mm Width=11mm	160.9mm
Width of chamber	Height=13mm Length=6mm Width=10.9mm	33.1 N/m^2	Height=13mm Length=6mm Width=11.1mm	160.8mm

3.2 Fibre-reinforced soft bending actuator design optimization analysis

Table 5 presents the optimized bending and stress comparison for the three (3) parameters. As shown by the data from Table 5, chamber length produced the lowest stress value among the three (3) parameters, at 284.2 N/m^2. This signifies that chamber length has the strongest influence in the stress generated by the actuator. The chamber length must be decreased to lessen the level of stress generated by the actuator. The parameter values diameter=12.7mm, length=156mm, and angle of fibre=3° were chosen as the optimized parameters for determining the optimized value of the generated stress. Table 5 also shows that the chamber diameter generated the largest bending out of the three (3) parameters, with its value of 217.5mm. This signifies that chamber diameter has the biggest influence in the bending generated by the actuator. To increase the bending of the actuator, one must increase the chamber diameter and achieve a thinner chamber wall. This makes the chamber easier to inflate even with lower pressures. The parameter values diameter=12.9mm, length=156mm, and angle of fibre=3° were chosen as the optimized parameters for achieving an optimized bending value. The fibre angle of fibre has no influence on the stress produced by the actuator. However, it influences the direction of the actuator's bending motion. The fibre angle value of 60° resulted in an upwards bending motion which is the opposite direction from the two (2) other fibre angles. This also signifies that one can control the direction of the bending motion by varying the fibre angle.

TABLE 5

STRESS AND DISPLACEMENT RESULTS COMPARISON BETWEEN THE THREE (3) PARAMETERS

Parameter	Optimized value (min stress & max bending)			
	Stress		Bending (displacement)	
	Optimized parameter	Optimized stress	Optimized parameter	Optimized bending
Diameter of chamber	Diameter=12.5 mm Length=155mm Fiber angle=3°	383.6 N/m^2	Diameter=12.9 mm Length=155mm Fiber angle=3°	217.5mm
Length of chamber	Diameter=12.7 mm Length=156mm Fiber angle=3°	284.2 N/m^2	Diameter=12.7 mm Length=156mm Fiber angle=3°	214mm
Fiber angle	Diameter=12.7 mm Length=155mm Fiber angle=30°	341.5 N/m^2	Diameter=12.7 mm Length=155mm Fiber angle=3°	213.1mm

3.3 Comparisan between PneuNets design and fibre-design

Table 6 presents each design's optimized parameters as well as their respective displacement and stress values. Of the two designs, the PneuNets soft bending actuator produced the least amount of stress at 33.76 N/m^2. On the other hand, the fibre- reinforced with higher design produced higher stress values (434 N/m^2), which signifies that it is capable of handling more stress. In terms of the bending motion, a larger bending was achieved by the fibre-reinforced actuator compared to the PneuNets soft actuator with lower levels of pressure. The fibre-reinforced actuator achieved 217.5mm. One can also control the direction of the fibre-reinforced actuator's bending motion by varying the angle of the fibre. This gives the actuator a broader range of motion. To bending motion, the fibre-reinforced actuator was chosen as the optimized soft actuator.

TABLE 6

PNEUNETS SOFT BENDING ACTUATOR AND FIBRE-REINFORCED SOFT ACTUATOR COMPARISON

Parameter	Optimized value (min stress & max bending)			
	Stress		Stress	
	Optimized parameter	Optimized parameter	Optimized parameter	Optimized parameter
PneuNets actuator	Height=13.5mm Length=6mm Width=11mm	33.76	Height=13.5mm Length=6mm Width=11mm	160.9mm
Fiber-Reinforced Actuators	Diameter=6.45 mm Length=155mm Fiber angle=3°	434	Diameter=6.45 mm Length=155mm Fiber angle=3°	217.5mm

4 CONCLUSION

As a conclusion, based on the results of the FEM analysis for the two designs, it can be summarize that for the PneuNets bending actuator, one can increase the bending motion by increasing the chamber length. Increasing the chamber length will lower the wall thickness, which eases the process of inflating the chamber. To lessen the stress of the actuator, there is a need to reduce the height of the chamber. Lowering the chamber height increases the thickness of the chamber roof, which in turn increases the stiffness of the actuator and allows it to endure more stress. For the fibre-reinforced actuator, one can increase the bending motion by increasing the chamber diameter. An increase in the chamber diameter will lead to a decrease in the wall thickness, which eases the inflation of the chamber. To lessen the actuator's stress, the chamber length must be reduced. Lower chamber lengths will lead to higher thickness of the caps. As a result, one can apply higher pressure to the actuator. Furthermore, the fibre angle has a vital part in controlling the ending motion direction of the actuator. One can control and vary the direction of bending motion by varying the angle of the fibre. For purposes of bending motion, the fibre-reinforced soft actuator served as the optimized actuator since it achieved higher bending motion results in comparison to the PneuNets soft bending actuator. One can also control the bending motion direction by varying the fibre angle. This gives the actuator a broader range of motion. The fibre- reinforced actuator was also found to be capable of handling higher stress levels compared to the PneuNets soft bending actuator. For future studies, other parameters for PneuNets bending actuator can be simulated, such as chamber orientation, number of chambers, and type of material to vary the bending motion direction. There is also a need to increase the amount of varied data to achieve more accurate FEM results. For fibre-reinforced actuators, other parameters like the external sleeve and shape of chamber can be simulated so that the direction of bending motion can be varied. Moreover, there is a need to simulate the fibre arrangement angle and the type of fibre arrangement to find new bending motions. Future studies can also fabricate both designs of soft bending actuator to analyse and optimize the force produced by the actuator.

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