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DESIGN AND ANALYSIS OF BENDING MOTION IN SINGLE AND DUAL CHAMBER BELLOWS STRUCTURED SOFT ACTUATORS

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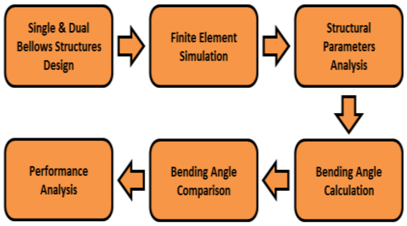
Graphical abstract



Abstract

As one of the most important characteristics of soft actuators, bending motion has been widely used in the field of soft robotics to perform different manipulation and tasks. In this study, we design silicone rubber material based soft actuators consisting of single and dual chambers, and a bellows structure. Several models of bellows soft actuators were designed, simulated and analyzed using finite element analysis (FEA) software MARC®, in order to understand the characteristics of bellows structured soft actuator with single and dual chambers and to optimize the performance of bending motion of bellows soft actuators. The results confirm that the bellows structured pneumatic soft actuator model 4 of single chamber and model 5 of dual chamber produces the best bending motion and bending angles.

Keywords: Pneumatic bending actuator; single chamber bellows actuator; dual chamber bellows actuator; finite element analysis

1.0 INTRODUCTION

In the field of soft robotics, soft actuators are an emerging research area with a wide range of applications. Soft actuators are normally made of soft materials that can provide softer, more deformable and flexible pre-designed motions. Pneumatically actuated and controlled, these actuators have been highlighted and implemented for developing bio-inspired robots to mimic biological locomotion through soft materials. Soft actuators are not like the traditional and conventional actuators such as electric actuators, which are always rigid, heavy, and limited in degrees of freedom. Besides softness, another advantage of the soft actuator is that it can offer multiple degrees of freedom (DoF) that enable it to mimic bio-inspired motions [1] that conventional actuators cannot offer.

However, soft actuators still need to acquire high output force from bending motion as compared to motorized actuators for manipulation and grasping applications. A bidirectional propelling multi-chamber flexible rubber actuator has been designed and fabricated based on the principle of traveling elastic deformation and applied to achieve locomotion and transportation of small objects within narrow gaps and spaces. This principle suits intervention in medical applications, such as to assist colonoscopy to the large intestine [2-5]. Further improvement in soft actuator design confirms that elliptical motion can be produced in response to pneumatic pressure applied sequentially to the air chambers, which cater the issues of mountability and drivability with colonoscopy insertion [6].

One of the studies has combined the bending and twisting motions in the actuators to develop a soft and flexible tip bronchoscope (FOB) that can provide a half spherical bending motion for bronchus intervention [7]. Another study applied soft actuators for a hand rehabilitation glove. The actuator was made up of elastomeric materials with integrated bellows structured design to produce bending motion and force [8]. A tiny bending type soft actuator was designed based on bellows structure to mimic the motion of a nematode. The fabrication of this micro-scaled actuator was made using silicon rubber material (KE-1603-A/B) from Shin-Etsu [9]. Furthermore, the reduction in the dimension of the same soft actuator from 2.0 mm to 400 μm forms a new actuator, which confirmed that a bi-directional bending motion against positive and negative applied pressure [10]. To achieve variable point bending motion through soft actuators, a low melting point alloy was integrated inside a rubber balloon actuator, which becomes solid on cooling, results in shifting of bending point of the actuator [11]. Based on the theory of contraction and extension of artificial muscle, another pneumatic actuator has proven to provide bending motion by involving fiber braiding inside silicon rubber structure, different knitting angles on the left and right sides of a chamber and provided unidirectional bending motion [12].

To attain bi-directional bending motion from soft actuators, two pneumatic chambers are applicable; the bending motion of the actuator depends on the ratio between the outer thickness of the circumference of the actuator and the separator width between two chambers. The ratio between these two quantities must be kept at 2.5 for optimal bending angle [13]. One of the studies has tested soft actuator with dual chambers in terms of chamber separator thickness, actuator thickness, fiber location, fiber materials and rubber materials to analyze the optimal bending angle. Two of the optimal actuators were fabricated and embedded together to form traveling wave generator, applied on fin propeller system to mimic Gymnotiform swimmers [14].

The objective of the paper was to investigate bending motion of bellows structured soft actuators having single and dual chambers. Six models were designed and analysed for each single and dual chamber bellows actuator to identify the models that yield the best bending characteristics. The analysis was carried out as static analysis using numerical solutions from the finite element modelling software MARC® that can handle material's nonlinearity and proved good agreement between experimental and simulation results [2, 9, 13, 15-18].

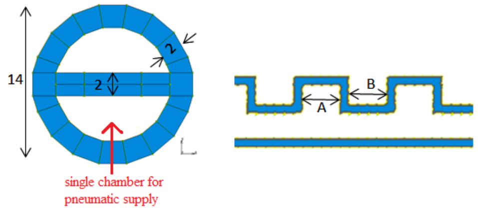
2.0 DESIGN CONCEPT

In this study, bellows structured soft actuators with single and dual chamber are designed and analyzed using Finite Element Analysis (FEA). The intended design specifications of both single and dual bellows actuators focuses on the development of a soft, flexible and bending type actuator for endoscopic application.

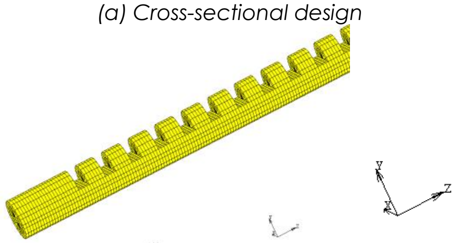
2.1 Single Chamber Bellows Actuator

For a single chamber bellows actuator, we had chosen the proposed design with fixed wall thickness of 2.0 mm and the outer diameter of 14.0 mm. Other parameters, such as actuator length, diaphragm width (A) and diaphragm spacing (B) were varied. By varying these structural parameters, we could design six different models. The basic structural design and parameters for the single chamber actuator are given in Figure 1.

Table 1 shows the design specifications, such as actuator length; diaphragm width (A), and diaphragm spacing (B), to analyze the single chamber bellows actuator shown here. This variation resulted in models 1 to 6. The output displacement in -YZ direction was observed from the six models.



(a) Cross-sectional design



(b) Outer design

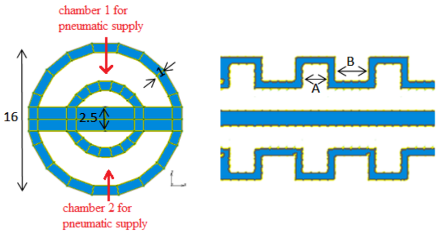
Figure 1 Structural design of single chamber bellows actuator

Table 1 Design Specifications of single chamber bellows

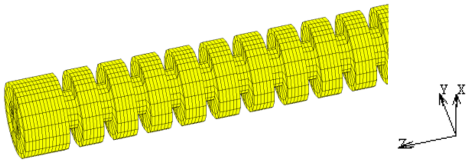
Model	Total length [mm]	Diameter [mm]	Diaphragm Width A [mm]	Diaphragm spacing B [mm]
1	168	14	4	4
2	165	14	3	4
3	166	14	4	3
4	166	14	2	4
5	168	14	4	2
6	168	14	2	2

2.2 Dual Chamber Bellows Actuator

A dual chambered bellows structured pneumatic actuator was also designed and analyzed in this study. For the dual chamber bellows actuator design, it was difficult to achieve bending motion. Therefore, different ratios of circumference thickness to chamber splitter thickness were implemented and simulated using MARC® software to achieve bending motion, but by keeping this ratio equals to 2.5 results in the bending motion [13]. To achieve more optimal results, six different models of dual chamber bellows actuator were designed, keeping this ratio fixed to 2.5 and also, the actuator diameter fixed to 16 mm. Only the diaphragm width (A) and diaphragm spacing (B) of the bellows structure were altered to achieve these six models. Figure 2 shows the structural design of dual chamber bellows actuator.



(a) Cross-sectional design



(b) Outer design

Figure 2 Structural design of dual chamber bellows actuator:

Table 2 represents the parameter variations in the structure of dual chamber bellows actuator in terms of lengths, diaphragms width (A) and diaphragm spacing (B) to obtain the optimal bending angle and displacement from the six designed models.

Table 2 Design Specifications of dual chamber bellows

Model	Total length [mm]	Diameter [mm]	Diaphragm Width A [mm]	Diaphragm spacing B [mm]
1	145	16	2.9	2.9
2	140.65	16	2.175	2.9
3	141.375	16	2.9	2.175
4	145	16	2.9	1.45
5	143.55	16	1.45	2.9
6	142.1	16	1.45	1.45

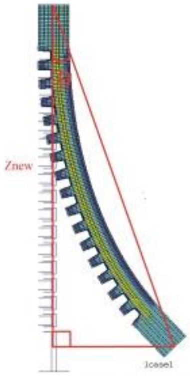
3.0 SIMULATION

In order to analyze the behavior of the silicon rubber in both single and dual bellows structured actuators, MARC® advanced nonlinear simulation software was used. The software is recommended and applied to the simulation of complex and non-linear behaviors of materials, which cannot be handled by conventional computer-aided design (CAD) software.

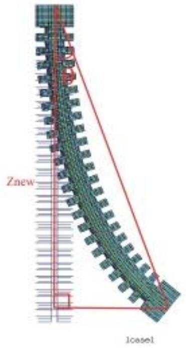
The MARC® software is a powerful, general-purpose, nonlinear FEA tool to simulate the response of products under static, dynamic and multi-physics loading scenarios. This software can also tackle manufacturing and product development problems in a single modeling environment.

3.1 Simulation Setup

The simulation setup for MARC software involves the designing of both single and dual chamber bellows actuator by connecting nodes to form elements of the structure. Single chamber bellows actuator structure contains nodes=7555 and elements=4686 while the structure of dual chamber bellows actuator contains nodes=13035 and elements=8008. For simulating each design; the geometrical and material properties must be inserted with boundary conditions followed by the contact table. The material considered for both bellows actuator was silicon rubber (KE-1603-A/B) from Shin-Etsu. We set the material properties with young modulus=1.7338 and poison ratio=0.3. For the boundary conditions, the maximum applied face load pressure was set to 500 kPa at 1000 increments, which was linearly applied through contact table. For holding the actuator, fixed displacement was applied at one end of the designed actuator, so that the actuator could bend from the other end. By keeping all the above settings constant, six different models were designed, simulated and analyzed separately for each single and dual chamber bellows actuator to characterize the optimal bending motion of each design from both categories. MARC® simulation environment at an applied pressure of 30 kPa to single chamber actuator and 10 kPa to dual chamber bellows actuator is shown in Figure 3(a) and (b) respectively.



(a) Single *chamber bellows actuator (At 30kPa)*



(b) *Dual chamber bellows actuator (At 10kPa)*

Figure 3 MARC® simulation for (a) single chamber bellows actuator and (b) Dual chamber bellows actuator

4.0 RESULTS AND DISCUSSION

Single and dual bellows actuators show the output displacement in -YZ direction due to the axis of the designed models and the axis of the simulation.

For calculating the bending angle from the simulation results, the similar method was adopted for both single and dual chamber bellows actuators. First, the value of Znew was determined using Equation (1)

$$Znew = Actuator\ length - Mod\ Z \tag{1}$$

The value of *Znew* is the difference of total designed length of actuator before the application of pressure and the bending of the actuator in –Z direction due to applied pressure. The bending angle was calculated by using trigonometric function shown in Equations (2) and (3).

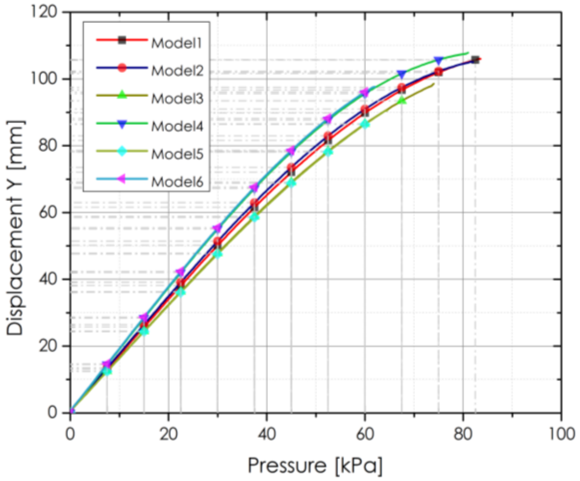
$$tan\theta = \frac{perpendicular}{base} \tag{2}$$

$$\theta = tan^{-1}\frac{\text{Mod } Y}{Znew} \tag{3}$$

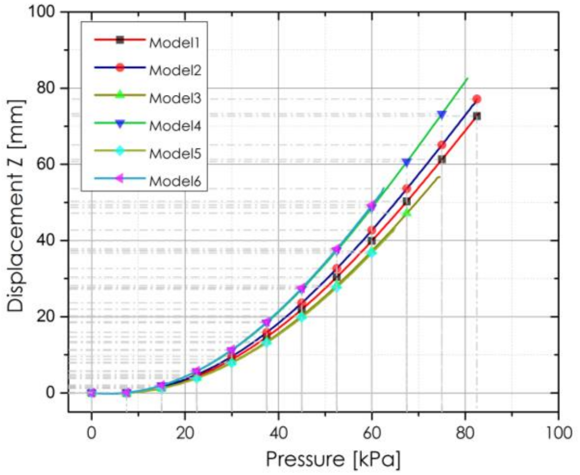
where, θ is the bending angle in radian, which was further converted, to degrees, Y and Z are the directions of displacement for both bellows actuators. The results for both single and dual chamber bellows actuators are presented as follows.

4.1 Single Chamber

For plotting the displacement of single chamber bellows actuator and bending angle calculations, we took the modulus of the values resulted from-YZ direction for all the six models as demonstrated in Figure 4.



(a) *Displacement in -Y direction*



(b) Displacement *in -Z direction*

Figure 4 Results of nonlinear FEM of six models of single chamber bellows actuator, (a) and (b) show displacement of -Y and -Z direction respectively.

From the simulation, we can analyze that Models 1, 2, and 4 followed linear bending motion till the applied pressure reached approximately 80 kPa. For the pressure above 80 kPa, the bending motion of these models resulted in non-linearity due to the bellows structure. Model 3 produced linear bending motion up to 73 kPa of pressure. For pressure above this value, it gave a random increase in bending motion. Model 5 and 6 produced linear bending motion till the applied pressure reached 62 kPa, after a further increase in pressure; the models were unable to continue the linear bending motion. The results of bending motion of single chamber bellows actuator consisting of both linear and nonlinear bending regions of motion are shown below in Figure 5.

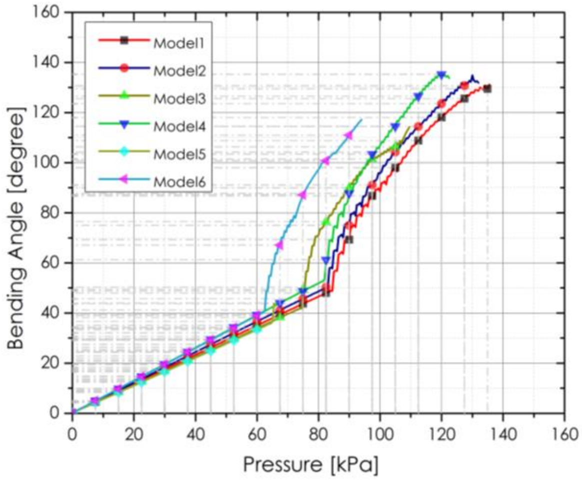


Figure 5 Linear and non-linear regions of bending motion for single chamber bellows actuator

For single chamber bellows actuator, it can be witnessed from Table 3 that out of six models, Model 4 has achieved maximum bending angle in both the linear and nonlinear regions of bending motion.

Table 3 Bending angle of single chamber bellows actuator

Model	Max. Bending Angle in Linear Region(Deg.)	Max. Bending Angle in Nonlinear Region(Deg.)
1	48.48°	131.19°
2	50.32°	131.97°
3	41.97°	114.20°
4	51.89°	133.72°
5	35.79°	43.81°
6	40.18°	117.22°

Figure 6 presents the simulation results of model 4 for bending motion achieved by the single chamber bellows actuator in variation of applied pressure from 0 kPa to 120 kPa.

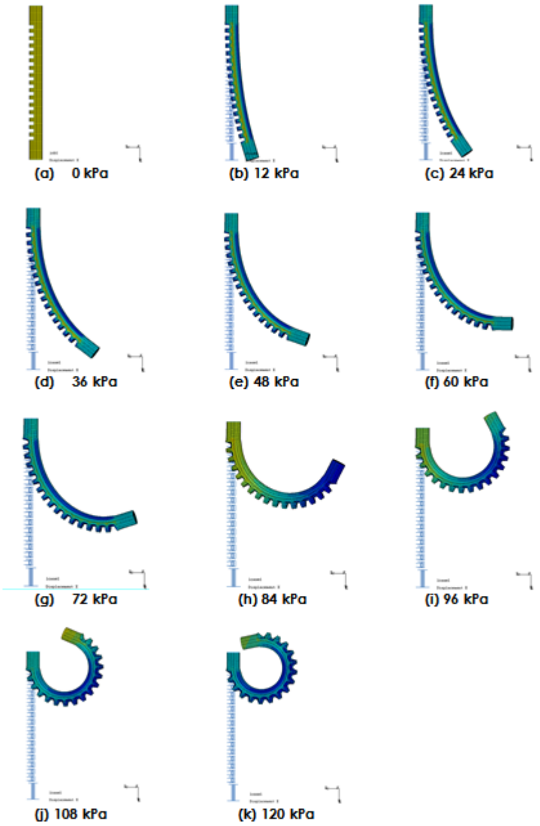
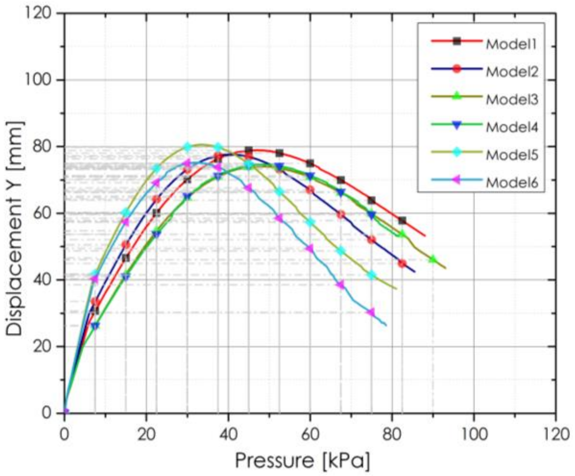


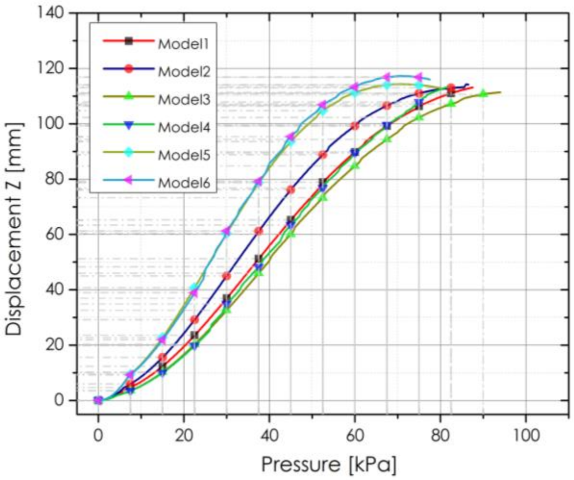
Figure 6 MARC® simulation results for single chamber bellows actuator.(a) 0 kPa, (b) 12 kPa, (c) 24 kPa, (d) 36 kPa, (e) 48 kPa,(f) 60 kPa, (g) 72 kPa, (h) 84 kPa, (i) 96 kPa, (j) 108 kPa, (k) 120 kPa

4.2 Dual Chamber

Similarly, for dual chamber bellows actuator, six models were designed and simulated on MARC® software. All the models produced good bending motion. As the displacement was observed in negative -YZ direction, the modulus of values was considered for -YZ directional for plotting the displacements as shown in Figure 7.



(a) *Displacement in -Y direction*



(b) Displacement in -Z direction

Figure 7 Results of nonlinear FEM of six models of dual chamber bellows actuator, (a) and (b) show displacement of -Y and -Z direction respectively.

The analysis shows that dual chamber bellows actuator resulted in both bending and curling motion. For the applied pressure range from 0 to 80 kPa, the dual chamber bellows actuator performed bending motion, while increasing the pressure above this range resulted in a curling motion. For the graphical analysis and calculation of bending angle of dual chamber bellows actuator, only the linear region of bending motion was considered as shown below in Figure 8.

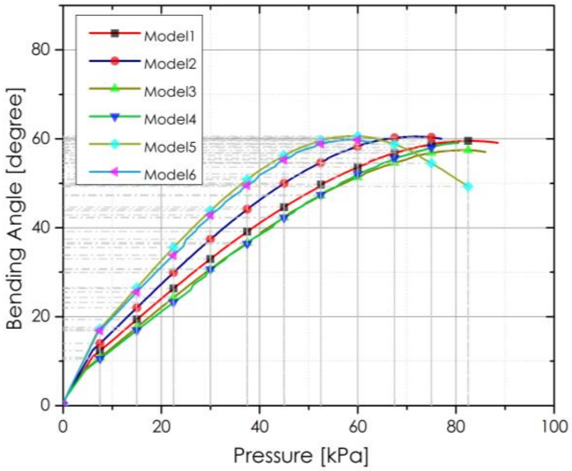


Figure 8 Linear region of bending motion for dual chamber bellows actuator

For calculating the bending angle of dual chamber bellows actuator, the –YZ direction displacements were considered positive and similar method was applied using Equations (1) to (3). The results for bending angles of the dual chamber bellows actuator are shown in Table 4.

Table 4 Bending Angle for dual chamber bellows actuator

Model	Bending Angle(Degree)
1	59.1°
2	60.0°
3	57.0°
4	59.1°
5	60.1°
6	59.1°

From Table 4, it can be witnessed that out of all six models designed for dual chamber bellows actuator. Models 2 and 5 resulted in approximately similar bending motion and bending angle. Some of the simulations results of model 5 for dual chamber bellows actuator are presented against the applied pressure, ranges from 0 kPa to 80 kPa In Figure 9.

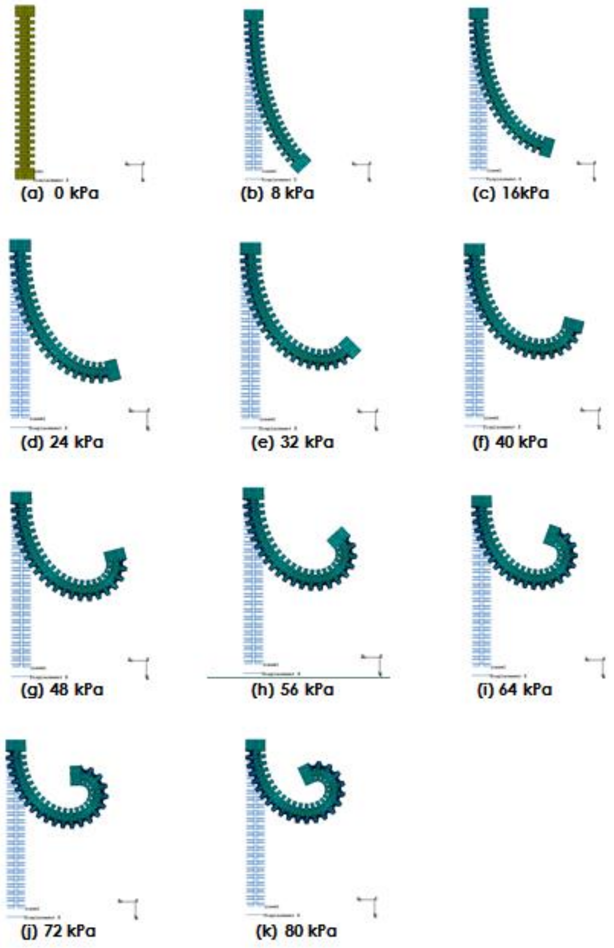

(a) 0 kPa
(b) 8 kPa
(c) 16kPa
(d) 24 kPa
(e) 32 kPa
(f) 40 kPa
(g) 48 kPa
(h) 56 kPa
(i) 64 kPa
(j) 72 kPa
(k) 80 kPa

Figure 9 MARC® simulation results for dual chamber bellows actuator.(a) 0 kPa, (b) 8 kPa, (c) 16 kPa, (d) 24 kPa, (e) 32 kPa,(f) 40 kPa, (g) 48 kPa, (h) 56 kPa, (i) 64 kPa, (j) 72 kPa, (k) 80 kPa

5.0 CONCLUSION

From the simulation analysis, it is demonstrated that for single chamber bellows actuator, model 4 has the most optimal design. In the linear region of bending motion, model 4 gives the angle of 51.9° and in nonlinear region of bending motion, an angle 133.7° was observed. Similarly, in dual chamber bellows actuator, model 5 shows a smooth bending motion in the linear region with a bending angle of 60.1°. Finally, the proposed bellows structured pneumatic soft actuators can produce good bending motion and bending angles in both single chamber and dual chamber bellows actuators. For future direction, fabrication of the most optimal design will be conducted from the proposed single and dual chamber bellows actuators.

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