TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue IV, November, 2024

THE INFLUENCE OF GEOMETRIC PARAMETERS ON THE PERFORMANCES OF PNEUMATIC SOFT ACTUATORS

Ionela-Lenuța POP, Silviu-Dan MÂNDRU

Abstract: *The aim of this work is to highlight the influence of geometric structural parameters of soft pneumatic actuators on their behavior and performance. To achieve this objective, three actuators with different cross-sections were dimensioned and designed, selecting four specific structural parameters for each. The size of each of these parameters was varied three times to observe the differences in the behavior and performance of the actuators. The analysis of these variations was conducted through finite element simulations (Finite Element Method).*
Key words: *soft robotics, soft materials, pneumatic soft actuators, finite element method;*

1. INTRODUCTION

Soft pneumatic actuators play a pivotal role in the rapidly evolving field of soft robotics, offering unique capabilities in adaptability, flexibility, and gentle interaction with complex environments. These actuators are increasingly used in various applications, ranging from medical devices to industrial automation, due to their ability to achieve complex motions and safe interaction with humans and delicate objects. However, the actuators' performance and behavior are influenced by their geometric parameters, which are crucial for optimizing their efficiency and functionality [4, 5].

The design and optimization of soft pneumatic actuators require a knowledge of the influence of various geometric parameters on their performance. Finite Element Method (FEM) analysis has emerged as a key tool in this design process, enabling the identification of optimal geometric configurations that meet specific design criteria [4, 5].

Numerous studies have explored the impact of different parameters on the performance and deformation characteristics of these actuators, revealing the importance of precise geometric control in achieving desired actuation outcomes. For instance, research has shown that the number and arrangement of internal cavities, wall thickness, and the shape of the actuator significantly affect its bending performance. Actuators with multiple cavities, designed to allow omnidirectional bending and extension, demonstrate varying degrees of flexibility and force generation depending on the geometric configuration of their internal structures. The choice of parameters such as the radius of the section, wall thickness, and internal cavity geometry has been shown to directly impact the actuator's stiffness, bending angle, and required input pressure [2, 6, 7].

Also, the cross-sectional shape of the pneumatic chambers plays a crucial role in determining the bending angle and overall performance of the actuator. Studies comparing different cross-sectional shapes, including rectangular, triangular, semicircular, and circular, show significant variations in bending performance under similar pressure conditions. These findings underline the importance of design and optimization of geometric parameters to improve the functionality and efficiency of soft pneumatic actuators [1].

This article aims to delve into the influence of geometric parameters on the characteristics of soft pneumatic actuators. By reviewing recent studies and analyzing the outcomes of FEM

Received: 30.09.24; **Similaritie**s: 31.10.24: **Reviewed**: 24.10./24.10.24: **Accepted**:27.11.24.

simulations, this work seeks to provide a complete understanding of how to optimize actuator design for enhanced performance in soft robotics applications. The insights gained from this research are intended to guide the development of more efficient, reliable, and versatile soft pneumatic actuators, contributing to the advancement of soft robotic systems.

2. 3D Modeling

This project centers on investigating the impact of specific structural and geometric parameters on the behavior of soft pneumatic actuators. The components design was carried out using the SolidWorks software platform.

The primary objective of this study is to achieve a deeper understanding of how geometric variables influence the functionality and performance of soft actuators. To this end, three distinct types of actuators were designed and analyzed: those with rectangular, semicircular, and triangular cross-sections (Fig. 1). Each type featured different configurations and geometric parameters. It is noteworthy that during the design process, the length, width, and height of the actuators were kept constant, allowing the focus to remain on key parameters such as the thickness, height, the spacing between pneumatic chambers, and the thickness of the air channels.

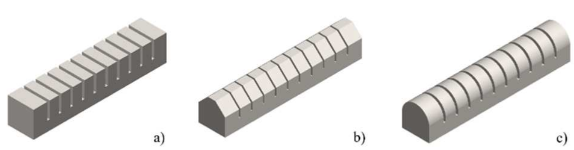


Fig. 1. Structure of the pneumatic actuators: a) rectangular cross section, b) triangular cross section, c) half-round cross section

In these experiments, the actuators were designed to comprise three main components: a structure housing the pneumatic chambers, two base plates, and an intermediate limiting layer made from a thin sheet of paper. The internal structure was configured with pneumatic chambers arranged in series, facilitating the controlled and efficient transmission and amplification of movement. The base plates provide support and stabilization, while the limiting layer functions to restrict excessive expansion of the pneumatic chambers and to regulate movements in specific directions.

The initial phase in actuator design involves the identification of parameters that will be consistently utilized throughout the development process. Defining these parameters as global variables is essential, as it facilitates subsequent modifications and ensures uniformity across the entire design framework. In SolidWorks, global variables are established by accessing the *Tools* menu and selecting the *Equations* option.

The structural parameter modifications in multi-chamber soft pneumatic actuators exert varying influences on their bending behavior. Thus, for the analysis of these structural parameters, design principles incorporating fixed length, height, and width were employed. Literature reviews, supported by experimental and simulation studies, have established that the thickness of the pneumatic chamber walls, the chamber height, the inter-chamber spacing, and the thickness of the air channels have substantial effects on the bending characteristics of soft pneumatic actuators.

Therefore, the structural parameters of soft pneumatic actuators, specifically, the thickness of the pneumatic chamber walls, the chamber height, the inter-chamber spacing, and the air channel thickness, play a critical role in determining their performance. Adjusting or combining these parameters in different configurations can yield a wide range of responses from the actuator.

Table 1. Variables employed in the simulation process

Parameter	Value [mm]			
Wal thickness	1.5	2	2.5	
Distance between chambers	1	1.5	2	
Height of pneumatic chamber	10	12	13	14
Thickness of center channel	1	1.5	2	

The critical parameters associated with these actuators are designated as outlined in Table 1. This methodology facilitates a comprehensive assessment of each parameter's impact on actuator performance, offering a deeper insight into how structural modifications influence their functional properties.

3. FEM

3.1 Materials

In the design and fabrication of soft pneumatic actuators, the selection of material is a crucial factor influencing both performance and reliability. For the purposes of this study, Ecoflex 00-50, a high-performance silicone elastomer, was chosen due to its exceptional mechanical properties and flexibility. This material is particularly advantageous in soft robotics applications, as it can withstand substantial deformation while preserving its structural integrity, thereby ensuring both durability and elasticity in demanding operational environments [8, 9].

In designing soft actuators, understanding the material properties is crucial due to their significant impact on deformation. Stress-strain data were sourced from existing literature, obtained through uniaxial tensile tests conducted according to ASTM D412 standards [3, 10]. These data were then input into ANSYS, where a second-order Ogden model was applied to accurately characterize the material. This process yielded key material constants, essential for precise simulation and performance prediction [4, 5]:

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} (\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \qquad (1)$$

Where:

- μ_i and α_i are material's constants;
- λ represents the stretches.

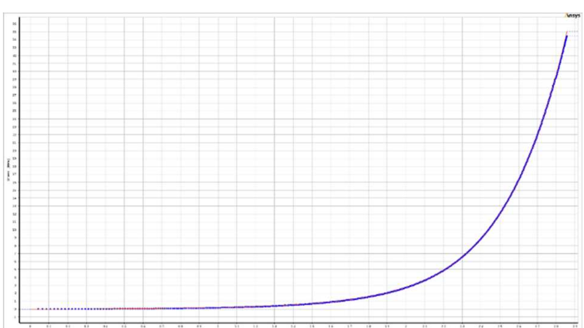


Fig. 2. Graph of uniaxial tensile test for Ecoflex 00-50 and second-order Ogden model.

The Exoflex 00-50 material displays non-linear stress-strain behavior. A curve fitting with a strain energy model provides an accurate mathematical description for simulations. Figure 2 shows uniaxial tensile test data with strain on the x-axis and stress on the y-axis. The blue line represents experimental data, showing stress increases exponentially with strain, while the red line shows the second-order Ogden model, effectively capturing the material's hyperelastic behavior.

Table 2. Values of material constants

Material constants		
μ1	$1.50 \cdot 10^{-6}$	MPa
μ2	0.0054	MPa
A1	13.45	MPa
A2	6.03	MPa
D1	0	MPa^{-1}
D2	0	MPa^{-1}

Following the curve fitting process in ANSYS, we obtained specific parameters μ1, μ2, A1, A2, D1, and D2 for the Ecoflex 00-50 material, as shown in Table 2. These parameters are essential for validating and calibrating the numerical model and understanding the material's behavior under various conditions. They enhance theoretical insights into the material's mechanics and offer a practical tool for accurate predictions in similar applications.

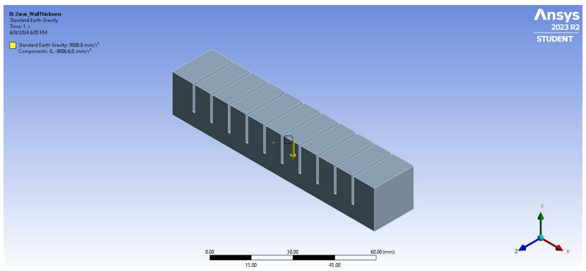
3.2 Simulation

The process began with the implementation of fixed supports at one end of the actuator to constrain its movement. Pressure conditions were then applied to the internal pneumatic chambers according to the loading scenario under analysis. In addition, gravitational forces were incorporated into the model to account for the effects of weight on the structure.

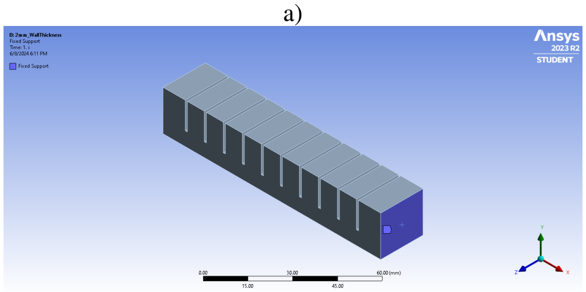
These boundary conditions were essential for replicating real-world behavior and ensuring that the simulation results accurately reflected the actuator's performance.

The accurate application of boundary conditions was crucial for the realism of the simulation, as depicted (Fig. 4). The process began with the application of fixed supports at one end of the actuator.

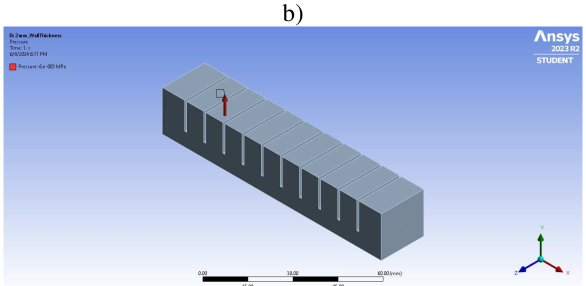
Subsequently, pressure conditions were applied to the internal pneumatic chambers according to the loading scenario studied. Additionally, gravitational forces were incorporated into the model to simulate the effects of weight on the structure.



a)



b)



c)

Fig. 3. Application of boundary conditions: a) application of gravitational field, b) application of fixed support, c) application of internal pressure.

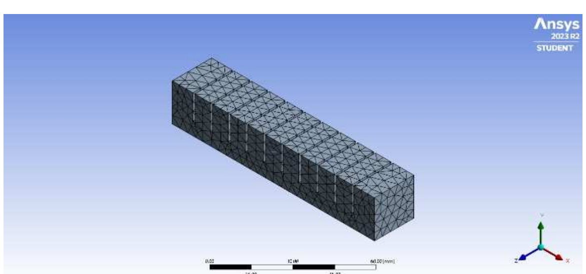


Fig. 4. Finite element generation.

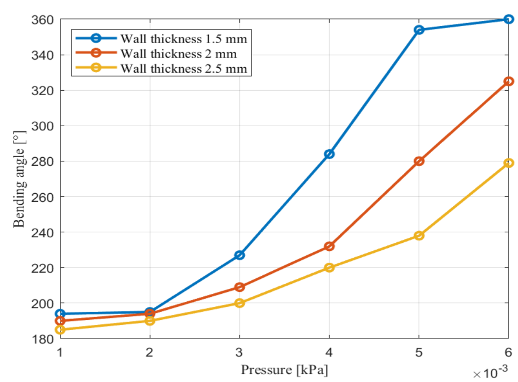
In this study, a finite element mesh refinement analysis (Fig. 4) was conducted to evaluate the sensitivity of results to mesh size. Starting with a coarse mesh, progressively finer meshes were used, and the resulting changes were documented.

Convergence, a critical aspect of finite element analysis, was meticulously monitored and defined as the point where results stabilized, and further mesh refinement produced negligible differences. Consequently, a 4 mm mesh size was determined to be optimal.

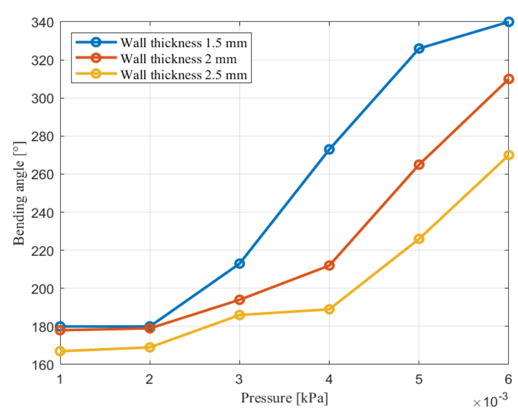
4. RESULTS

4.1 The effect of pneumatic chamber wall thickness

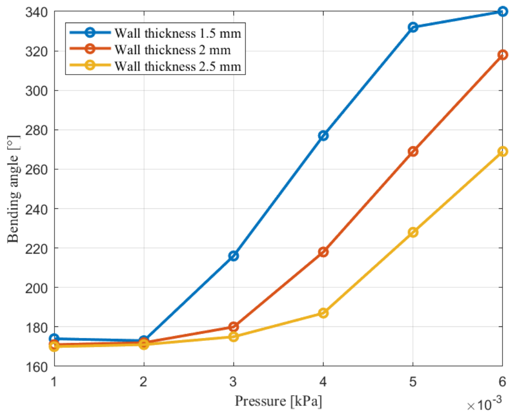
This study examined the bending angles of three types of soft pneumatic actuators with rectangular, semicircular, and triangular cross-sections, under varying pneumatic chamber wall thicknesses of 1.5 mm, 2 mm, and 2.5 mm (Fig. 5), and subjected to applied pressures ranging from 1 kPa to 6 kPa.



a)



b)



c)

Fig. 5. The effect of pneumatic chamber wall thickness for: a) the actuator with a rectangular cross-section, b) the actuator with a semi-circular cross-section, c) the actuator with a triangular cross-section.

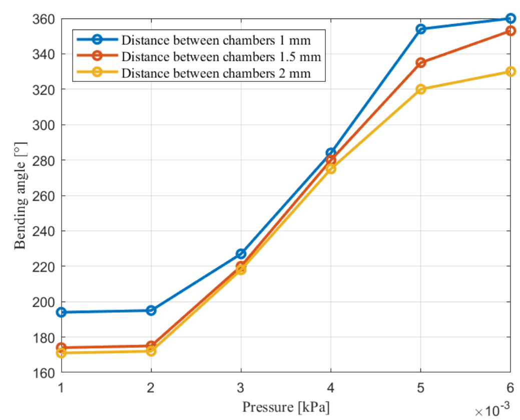
The actuator with a rectangular cross-section and a wall thickness of 1.5 mm exhibits the highest flexibility, reaching a maximum angle of 360° at a pressure of 6 kPa. In comparison, actuators with semicircular and triangular cross-sections of the same wall thickness achieve smaller maximum angles, at 340°. This result suggests that the rectangular cross-section allows for greater deformation due to a uniform distribution of pressure across the wall surface.

For actuators with a wall thickness of 2 mm, a similar trend is observed. The bending angles are smaller than those for a thickness of 1.5 mm, yet the rectangular actuator remains the most flexible, followed by the triangular and then the semicircular one. This indicates a trade-off between wall thickness and cross-sectional shape, where a greater wall thickness reduces flexibility but may offer advantages in terms of durability and structural stability.

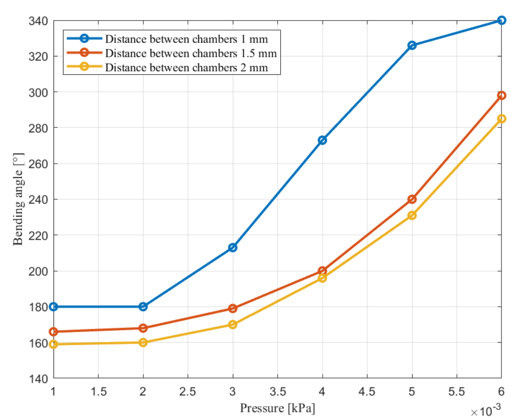
For actuators with a wall thickness of 2.5 mm, the bending angles are the smallest for all cross-section types. The rectangular actuator reaches a maximum angle of 279° at a pressure of 6 kPa, while the semicircular actuator reaches 270°, and the triangular one reaches 269°. This suggests that, at greater wall thicknesses, the differences in cross-sectional shape become less significant, and the increased wall strength limits the overall flexibility of the actuator.

4.2 The effect of distance between pneumatic chambers

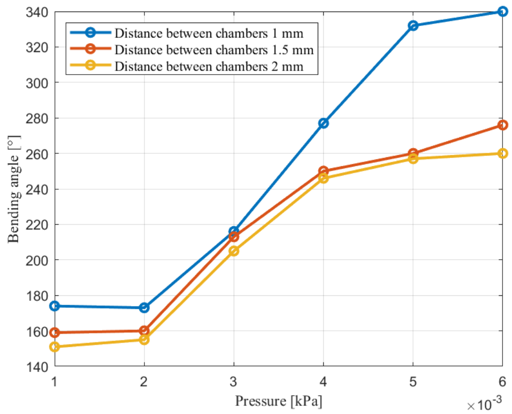
The data analysis reveals the impact of chamber spacing on the bending behavior of soft pneumatic actuators. Across all analyzed cross-sections, an increase in bending angle correlates with higher pressure, though the extent of this increase varies based on chamber spacing and section shape. The rectangular actuator with a 1 mm chamber spacing exhibits the greatest flexibility, achieving a maximum bending angle of 360° at 6 kPa. In contrast, at larger chamber spacings, the maximum bending angle decreases to 353° for 1.5 mm and 330° for 2 mm. Thus, closer chamber spacing promotes more uniform pressure distribution, allowing for greater deformation (Fig. 6).



a)



b)



c)

Fig. 6. The effect of pneumatic chamber spacing for: a) the actuator with a rectangular cross-section, b) the actuator with a semi-circular cross-section, c) the actuator with a triangular cross-section.

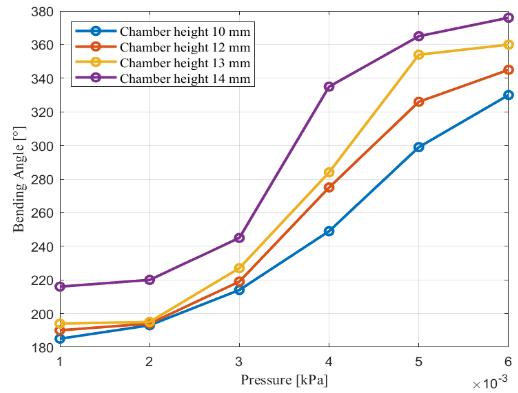
The actuator with a rectangular cross-section and an inter-chamber distance of 1 mm exhibits the highest flexibility, achieving a maximum angle of 360° at a pressure of 6 kPa. In comparison, as the inter-chamber distance increases, the maximum bending angle decreases, reaching 353° for a distance of 1.5 mm and 330° for 2 mm. Therefore, a smaller inter-chamber distance promotes a uniform distribution of pressure, allowing for greater deformation.

For actuators with a semicircular cross-section, a similar trend is observed. The bending angles are smaller than those for the rectangular actuator but follow the same pattern. At an inter-chamber distance of 1 mm, the maximum angle is 340°, decreasing to 298° for 1.5 mm and 285° for 2 mm. This indicates that, although the semicircular cross-section is less flexible than the rectangular one, it also benefits from a smaller inter-chamber distance to achieve a greater bending angle.

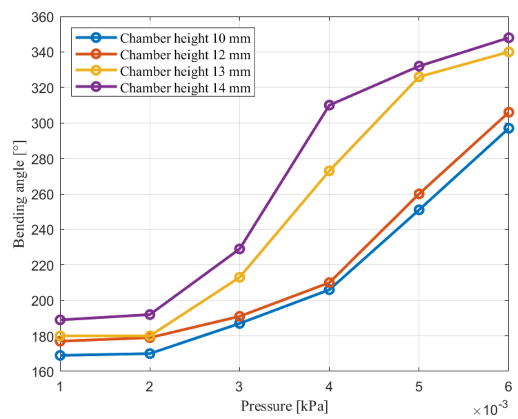
For actuators with a triangular cross-section, the bending angles are the smallest among all the cross-section types analyzed. At an inter-chamber distance of 1 mm, the maximum angle is 340°, decreasing to 276° for 1.5 mm and 260° for 2 mm. This suggests that, for this cross-section, the inter-chamber distance has a more pronounced impact on limiting the flexibility of the actuator.

4.3 The effect of pneumatic chamber height

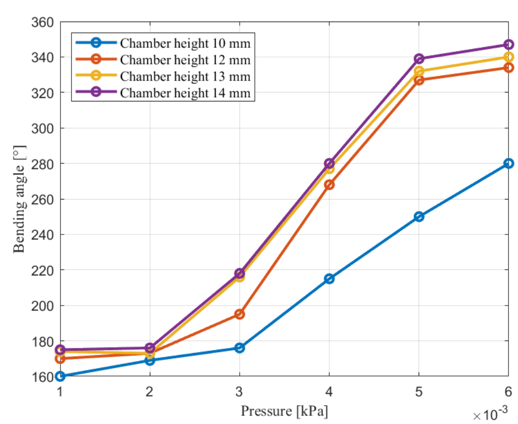
Actuators with varying cross-sections consistently (Fig. 7) show increased bending angles with higher pressure, regardless of chamber height, giving key efficiency insights.



a)



b)



c)

Fig. 7. The effect of pneumatic chamber height for: a) the actuator with a rectangular cross-section, b) the actuator with a semi-circular cross-section, c) the actuator with a triangular cross-section.

For the actuator with a rectangular cross-section, increasing the pressure results in a consistent and significant increase in the bending angle. At a chamber height of 10 mm, the bending angle increases from 185° at a pressure of 1 kPa to 330° at a pressure of 6 kPa. Similarly, at a chamber height of 12 mm, the angle ranges from 190° to 345°, at 13 mm from 194° to 360°, and at 14 mm from 216° to 376°. This substantial variability indicates a high sensitivity to pressure changes, which is advantageous in applications requiring rapid and precise responses.

The actuator with a semicircular cross-section shows a steady and moderate increase in the bending angle as the pressure increases. For a chamber height of 10 mm, the bending angle rises from 169° to 297°. At a height of 12 mm, the angle varies from 177° to 306°, at 13 mm from 180° to 340°, and at 14 mm from 189° to 340°. This moderate and consistent increase indicates stability and predictability, making this actuator suitable for applications where consistency and reliability are essential.

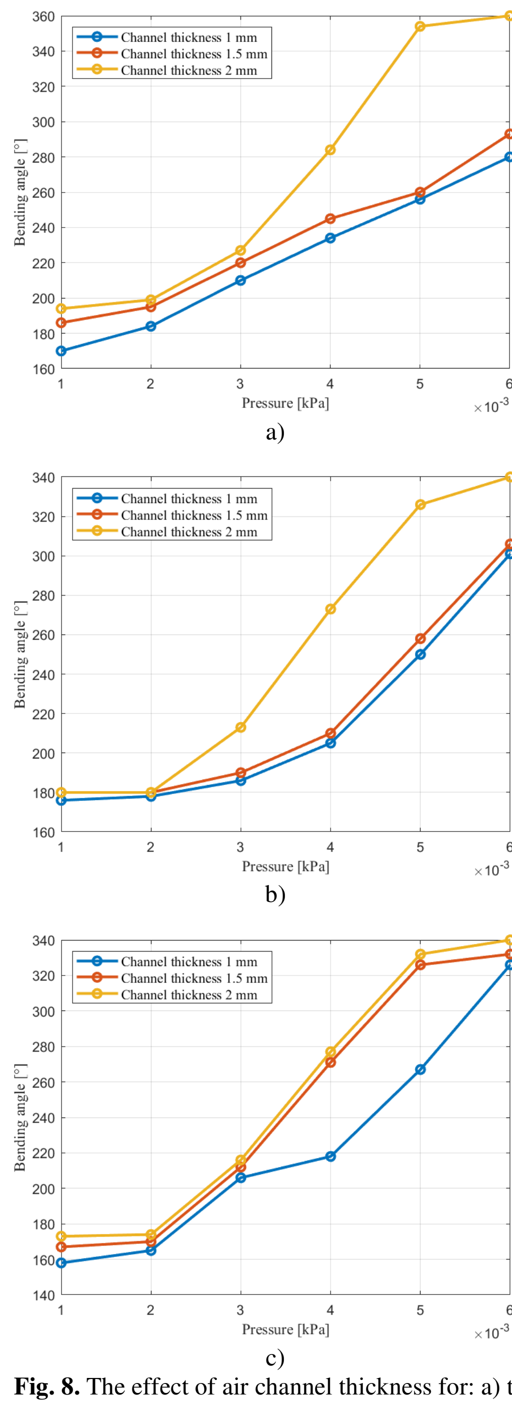
The actuator with a triangular cross-section also exhibits an increase in the bending angle with pressure, but at a slower rate compared to the rectangular actuator. At a chamber height of 10 mm, the bending angle increases from 160° to 280°. At a height of 12 mm, the angle varies from 170° to 334°, at 13 mm from 174° to 340°, and at 14 mm from 175° to 347°. This suggests that the triangular actuator offers balanced performance, combining stability with flexibility, making it ideal for applications that require a compromise between rapid response and stability.

4.4 The effect of central channel thickness

The study analyzes channel thickness for three types of actuators: rectangular, semi-circular, and triangular cross-sections.

The actuator with a rectangular cross-section shows the greatest increase in thickness angle with pressure, indicating high sensitivity to pressure changes. At a thickness of 2 mm, the angle varies significantly, reaching a maximum of 360° at 6 kPa. This adaptability makes it suitable for applications requiring a quick and precise response to pressure variations.

The actuator with a semicircular cross-section demonstrates a steady, moderate increase in thickness angle with pressure. At 2 mm thickness, the maximum angle is 340° at 6 kPa, reflecting stable and predictable performance, ideal for applications needing consistent reliability among pressure levels.



a) b) c)

Fig. 8. The effect of air channel thickness for: a) the actuator with a rectangular cross-section, b) the actuator with a semi-circular cross-section, c) the actuator with a triangular cross-section.

The actuator with a triangular cross-section also shows a consistent increase in thickness angle with pressure but to a lesser extent than the other types. At 2 mm thickness, the maximum angle is 340° at 6 kPa. This indicates that the triangular actuator provides a balanced response, making it suitable for applications that require both stability and flexibility.

Channel thickness is evaluated at three distinct dimensions (1 mm, 1.5 mm, and 2 mm) under various applied pressures. The objective is to understand how channel thickness varies with these parameters and to compare the behavior of different cross-sectional geometries (Fig. 8).

4.5 The effect of cross-sectional geometries

Figure 9 shows the variation of the bending angle with respect to the three types of actuators with different cross-sections: rectangular, semi-circular, and triangular.

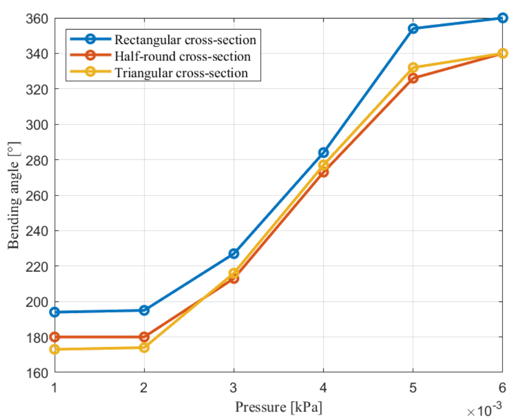


Fig. 9. Influence of cross-sectional geometry.

The influence of the cross-sectional shape on the bending angle of the pneumatic actuators was investigated. For this analysis, all structural parameters of the actuators were kept constant.

According to the graph in Figure 10, the actuator with a rectangular cross-section, depicted by a blue line, shows that at lower pressures up to 2 [kPa], the bending angle remains relatively constant around 180°. As the pressure increases, the bending angle rises significantly, reaching nearly 360° at 6 [kPa].

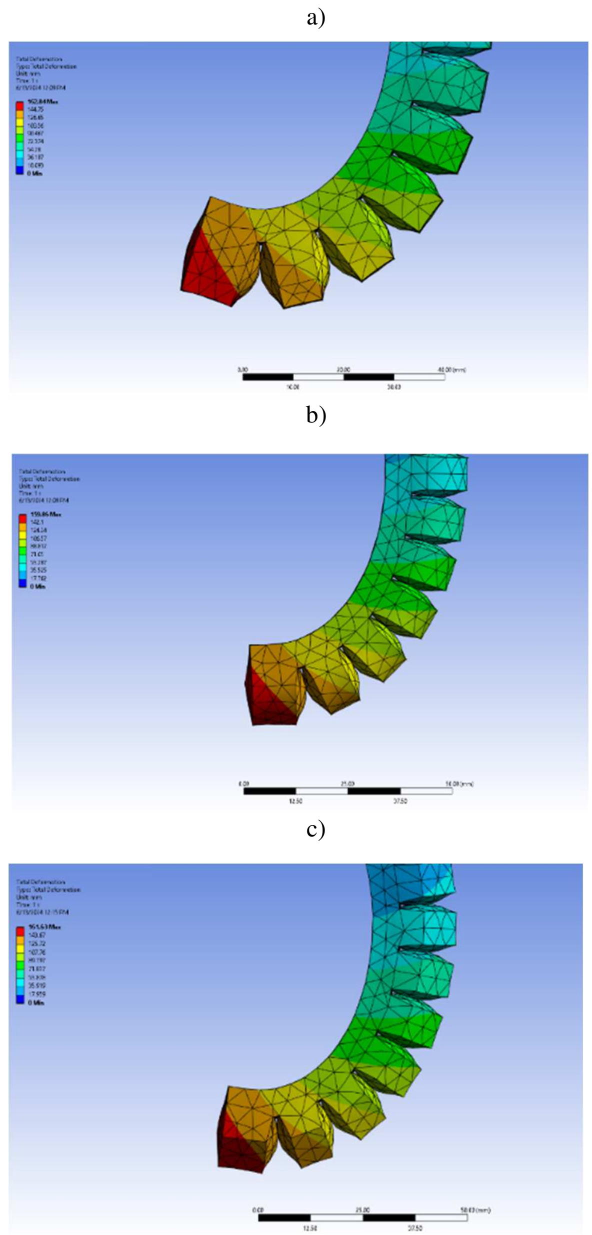


Fig. 10. Interaction between channels: a) actuator with a rectangular cross-section, b) actuator with a semi-circular cross-section, c) actuator with a triangular cross-section

The semi-circular section, represented by the red line, exhibits similar behavior. At low pressures, the bending angle remains nearly constant. Between 2 [kPa] and 3 [kPa], the angle begins to increase, reaching approximately 340° at 6 [kPa].

The triangular section, shown in yellow, demonstrates comparable behavior. At low pressures, the bending angle is constant around

160°. As the pressure increases, the angle also rises, reaching about 340° at 6 [kPa].

5. CONCLUSIONS

Effect of Wall Thickness of Pneumatic Chambers. The results indicate that wall thickness and cross-sectional shape significantly influence the bending behavior of soft pneumatic actuators. Actuators with thinner walls and a rectangular cross-section exhibit the greatest flexibility, suitable for applications requiring large deformations. Conversely, actuators with thicker walls provide increased structural stability, beneficial for applications needing controlled deformation and durability. The optimal choice of wall thickness and cross-sectional shape should be based on specific application requirements, balancing flexibility and structural strength.

Effect of Distance Between Pneumatic Chambers. Among the three cross-sectional types, the rectangular actuator is the most flexible, followed by the semi-circular and triangular ones. A smaller distance between chambers allows for greater deformation at lower pressures for all cross-sections, indicating that this geometric feature plays a crucial role in optimizing the performance of soft pneumatic actuators. The choice of optimal chamber spacing, and cross-sectional shape should be based on application needs, balancing flexibility and structural stability.

Effect of Pneumatic Chamber Height. All types of actuators analyzed show an increase in bending angle with increased pressure, each offering specific advantages depending on application requirements. Rectangular actuators are recommended for applications needing quick and variable responses, semicircular actuators for consistency and reliability, and triangular actuators for a balance between stability and flexibility. This analysis provides a solid basis for selecting the optimal actuator type based on operating conditions and specific application requirements, enhancing system efficiency and performance.

Effect of Air Channel Thickness. Although all actuator types demonstrate an increase in thickness angle with rising pressure, the rectangular actuator shows the greatest variations in angle depending on channel thickness and pressure. This analysis can guide the optimal actuator selection based on specific applications and desired operating conditions. Proper actuator choice can enhance system efficiency and performance, ensuring reliable and adaptable operation to meet varying application demands.

Influence of Cross-Section Geometry. All actuator types exhibit an increase in thickness angle with increasing pressure, with the rectangular actuator showing the largest variations depending on channel thickness and pressure. This analysis provides a foundation for selecting the optimal actuator type based on specific application needs and operating conditions. Choosing the right actuator can improve system efficiency and performance, ensuring reliable and adaptable operation to meet varying application requirements.

For future work, the proposed design will be further developed through the fabrication of the pneumatic soft actuators. Initially, the molds will be modeled and 3D-printed. Following the fabrication process, experimental testing will be conducted to validate the simulation results, ensuring consistency between the theoretical models and the actuator's real-world performance. This iterative approach will provide deeper insights into the optimization of geometric parameters, enhancing the accuracy of performance predictions.

6. REFERENCES

[1] Hu, W. et al. *A Structural Optimisation Method for a Soft Pneumatic Actuator*. Robotics. Jun, 2018, DOI:https://doi.org/10.3390/robotics7020024.

[2] Lei, J. et al. *Design and Manufacture of a Flexible Pneumatic Soft Gripper*. Applied Sciences. Jun, 2022, 6306, DOI:https://doi.org/10.3390/app12136306.

[3] Marechal, L. et al. *Toward a Common Framework and Database of Materials for Soft Robotics*. Soft Robotics, Jun 2021, 284–297.

DOI:https://doi.org/10.1089/soro.2019.0115.

[4] Pagoli, A. et al. *Review of soft fluidic actuators: classification and materials modeling analysis*. Smart Materials and Structures, Jan, 2022, DOI:https://doi.org/10.1088/1361-665X/ac383a.

[5] Walker, J. et al. *Soft Robotics: A Review of Recent Developments of Pneumatic Soft Actuators*. Jan, 2020, DOI:https://doi.org/10.3390/act9010003

[6] Xavier, M.S. et al. *3D-printed omnidirectional soft pneumatic actuators: Design, modeling and characterization*. Sensors and Actuators A: Physical. 332, Dec. 2021. DOI:https://doi.org/10.1016/j.sna.2021.113199.

[7] Zhang, X. and Oseyemi, A.E. *A herringbone soft pneu-net actuator for enhanced conformal gripping*. Robotica. May 2022, 1345–1360. DOI:https://doi.org/10.1017/S0263574721001144.

[8] ****EcoflexTM 00-50 Product Information* https://www.smooth-on.com/products/ecoflex-00-50/ Accessed: 2024-05-26.

[9] ****Mold Making & Casting Materials Rubbers, Plastics, Foams & More* https://www.smooth-on.com/. Accessed: 2024-04-30.

[10] ****Setup and Characterisation* https://github.com/LucMarechal/Soft-Robotics-Materials-Database/wiki/Setup-and-Characterisation. Accessed: 2024-06-01.

Influența parametrilor geometrici asupra performanțelor actuatorilor pneumatici „soft”

Rezumat: Scopul acestei lucrări este de a evidenția influența parametrilor geometrici ai actuatorilor pneumatici „soft” asupra comportamentului și performanței acestora. Pentru atingerea acestui obiectiv, au fost dimensionați și concepuți trei actuatori cu secțiuni transversale diferite, selectând patru parametri structurali specifici pentru fiecare. Dimensiunea fiecăruia dintre acești parametri a fost variată de trei respectiv patru ori pentru a observa diferențele în comportamentul și performanța actuatorilor. Analiza acestor variații s-a realizat prin simulări cu elemente finite.

Ionela-Lenuța POP, Eng., Ph.D Student, Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanical Engineering, Department of Mechatronics and Machine Dynamics, 103-105 Muncii Blvd., 400641, Cluj-Napoca, ionelapop31@yahoo.com, (+40) 770276013

Silviu-Dan MÂNDRU, Prof., Ph.D., Technical University of Cluj-Napoca, Faculty of Automotive Engineering, Mechatronics and Mechanical Engineering, Department of Mechatronics and Machine Dynamics, 103-105 Muncii Blvd., 400641, Cluj-Napoca, dan.mandru@mdm.utcluj.ro, (+40) 264 401645