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(Review Article)

Development of a fishbone camber morphing airfoil actuated by SMA wires

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Abstract

This paper investigates the design and aerodynamic efficiency of a bio-inspired variable camber morphing airfoil featuring NACA0012 ribs with a deformable fishbone trailing edge. The deformation mechanism uses smart memory alloy wires arranged on the ribs to deflect the trailing edge upwards or downwards based on the set of wires actuated. Experimental validation of the designed system demonstrates two distinct angles up to 30 degrees. Subsequent aerodynamic investigations were conducted to compare the performance of the morphing trailing edge concept with conventional flap configurations. Results indicate a notable aerodynamic efficiency, surpassing conventional flap designs by more than double at a deflection angle equal to 24 degrees.

Keywords: Morphing wing; Variable camber; Bio-inspired design; Fishbone structure; Shape memory alloy; Computational fluid dynamics

1. Introduction

Morphing wings represent a revolutionary concept in aircraft design, promising unprecedented adaptability and efficiency throughout flight regimes [1]. While traditional fixed-wing aircraft have long dominated aviation, the exploration of morphing wing technology dates back to the early 20th century, with both the United States and Soviet Union focusing on variable spans and variable-sweep in order to decrease take-off and landing distance and optimize performance at both high and low speed. However, early attempts at morphing wings were hampered by inherent limitations: rigid structures required heavy and complex mechanisms, increasing the risk of failure and inflating costs. As a result, progress in morphing aircraft stagnated towards the end of the 20th century [2].

The emergence of intelligent materials, as shape memory alloys (SMAs), has marked a renaissance in morphing wing development [3,4]. Their lightweight and flexibly enable seamless and continuous morphing, allowing unprecedented adaptability and aerodynamic performance. Smart materials have catalyzed the emergence of smart structures, capable of autonomously sensing and responding to environmental changes. By minimizing energy conversions and reducing potential failure points, these structures represent an incredible innovation in aircraft design.

Camber morphing, particularly at the trailing edge, has received significant research focus. By dynamically adjusting the curvature of the airfoil, camber morphing offers a comprehensive approach to low drag aerodynamic control [5,6]. The fishbone concept, developed by NASA's Langley Research Center (LaRC), is at the forefront of camber deformation research. This innovative design, characterized by a multitude of flexible ribs attached to a central spar and enveloped in a latex skin, enables deflections in camber and spanwise direction. While no wind tunnel testing validated this concept, its visionary principles continue to inspire researchers in morphing wing technologies. [7,8]

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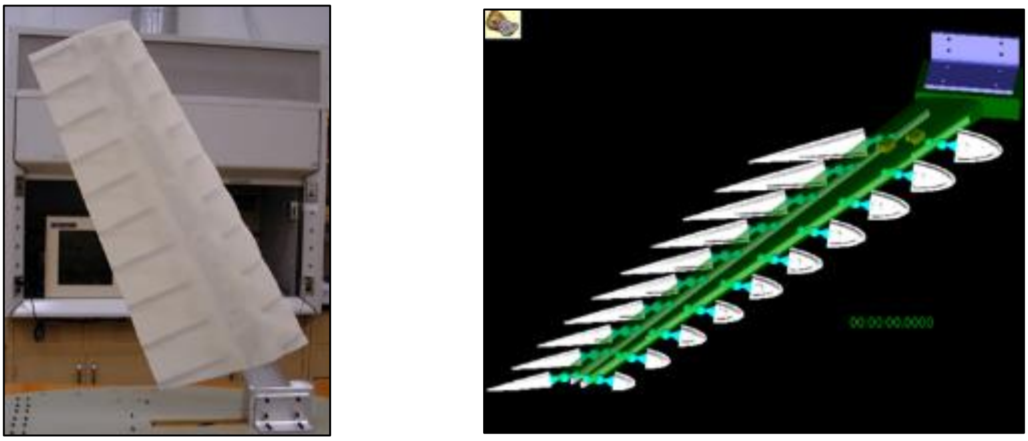
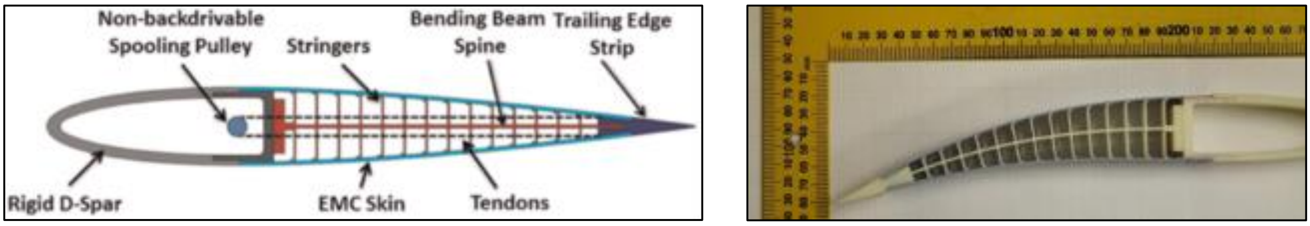


a) LaRC Fish Bone morphing wing prototype [8]   b) Dynamic Analysis and Design System model [8]

Figure 1 LaRC fish bone morphing wing concept

Woods et al. (2012) [9] developed a novel wing design utilizing a NACA0012 airfoil to facilitate significant and continuous changes in camber at the trailing edge. The Fish Bone Active Camber (FishBAC) concept comprises a fixed section at the leading edge and a flexible section at the trailing edge, consisting of a flexible rod supported by numerous perpendicular stringers beneath the wing skin. The morphing transformation is achieved through tendons, which are tensioned by an actuator positioned in the fixed section of the wing, resulting in the bending of the trailing edge, as depicted in Fig. 2. Aerodynamic analysis conducted in their study revealed an enhanced lift-to-drag ratio compared to the NACA0012 airfoil configurations with and without flaps. Wind tunnels were then conducted to compare the FishBAC concept with a conventional wing equipped with a flap through various angles of deflection and angles of attack [10]. While both wings could generate equivalent lift coefficients, the FishBAC concept exhibited reduced drag and achieved improvements in lift-to-drag ratio ranging from 20 to 25%.



a) FishBAC concept Scheme   b) FishBAC wind tunnel model deflected

Figure 2 FishBAC concept [10]

In 2014, D. Karaguiannis et al. [11] introduced a novel wing design capable of adjusting its curvature through ribs composed of three interconnected sections linked by pivot links. Activation of SMA wires located between these sections induces deflection of the trailing edge. Similar to the FishBAC airfoil, Yokozeki et al. (2014) [12] developed a corrugated structures variable camber morphing airfoil able to achieve trailing edge deflection through wires connected to servomotors. Wind tunnel tests carried out on a prototype demonstrated an increase of lift coefficient compared to traditional hinged wings. Subsequently, Takahashi et al. (2016) [13] utilized a similar approach to propose a variable camber morphing airfoil capable of deflecting both leading and trailing edges using corrugated structures. Joran Driesen (2018) [14] developed a concept employing SMA wires to deflect the trailing edge tip by over 2 mm, connecting the fixed leading edge to the deformable trailing edge via the spar. P. Bishay et al. (2019) [15] proposed a camber morphing horizontal and vertical stabilizers composed of a flexible corrugated trailing edge structure able to deflect upwards and downwards thanks to SMA wires guided by polycarbonate pulleys. F. Rosse (2021) [16] developed a morphing wing design composed of an inner compliant flex core structure and a retractable skin, enabling linear servos to create deflections of up to 50 degrees. Computational Fluid Dynamics (CFD) analysis revealed that this concept generated increased lift over a limited range of drag coefficients compared to conventional wings with flaps. Finally, a kerf bending active camber concept able to deflect the trailing edge was proposed by A. Dharmdas et al. (2023) [17] and demonstrated a 27% improvement in lift-to-drag ratio compared to conventional flap airfoil through CFD analysis.

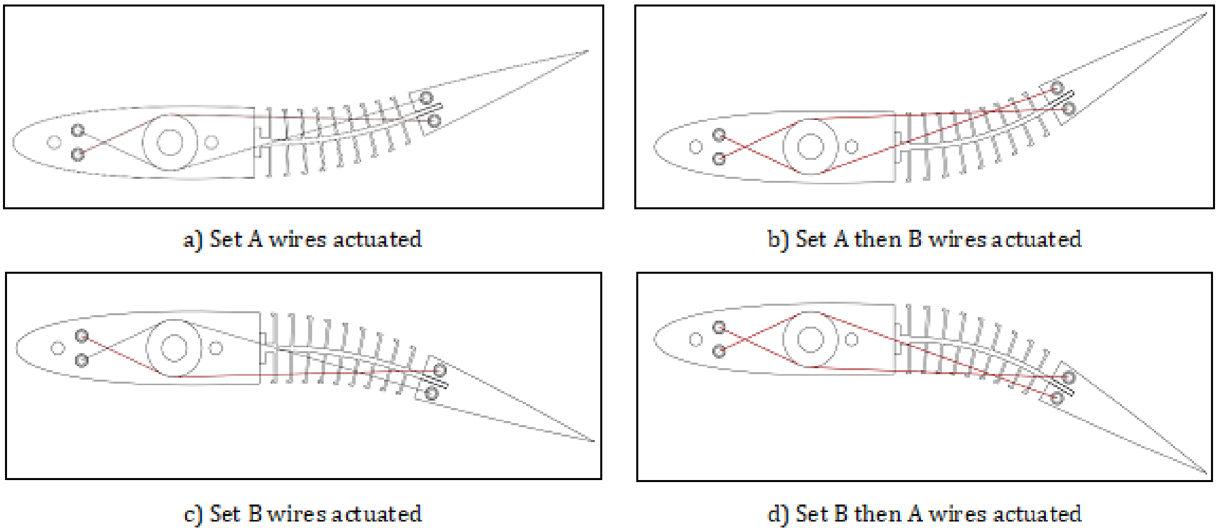
The aim of this research is to introduce and analyze a fishbone camber morphing concept actuated by SMA wires capable of deflecting the trailing edge in both upward and downward directions. A prototype was built and experimented, while CFD simulations using Ansys FLUENT were performed to compare the aerodynamic performance between the morphing design and conventional NACA0012 airfoils equipped with plain flap.

2. SMA wire actuated rib module

The current study aims to develop a fish bone mechanism utilizing SMA wires instead of a servomotor for deflecting the trailing edge. The choice of the well-established NACA0012 profile, known for its symmetry, streamlines mechanism design due to existing research and ease of implementation.

The proposed design is composed of a spar running through the frontal fixed rib section connects ribs, with two SMA wires symmetrically attached to the front and rear of the rib, linking the fixed part to the trailing edge similar to Joran Driesen's concept in Ref. (14). These SMA wires contract upon heating, exerting upward or downward force on the trailing edge, depending on the activated wire set. Unlike the FishBAC airfoil, this design allows independent bending of each rib. To prevent electrical contact between heated wires, they are attached at different levels.

Activation of Set A wires inclines the trailing edge upward, while Set B wires induce a downward inclination, as presented in Fig. 3. Sequential activation of opposing wire sets can achieve a secondary, larger deflection angle, as demonstrated in Fig. 3-b and d.


a) Set A wires actuated

b) Set A then B wires actuated

c) Set B wires actuated

d) Set B then A wires actuated

Figure 3 Mechanism design

The selected SMA wire for the upcoming experiments is the TiNi44 alloy, with diameter of 0.3 mm, a length approximately 20 cm, and a shrinkage rate of 4%. Through experimentation, the wire's maximum pulling force has been measured at around 3.5 N once activated. The rib has been crafted from Polylactic acid (PLA) filament via 3D printing with a span of 30 cm and 8 mm thickness. SMA wires are manually assembled on the rib using small metal regulators screwed to elongated round nuts.

3. Design experiments

Throughout the experiments, the fixed portion of the rib was securely fastened to a workbench as presented in Fig. 4. An electric current of 1.5 A was applied to the SMA wires to raise their temperature to approximately 100 degrees Celsius. Various deflection modes were tested, with the resulting deflection angles meticulously recorded.

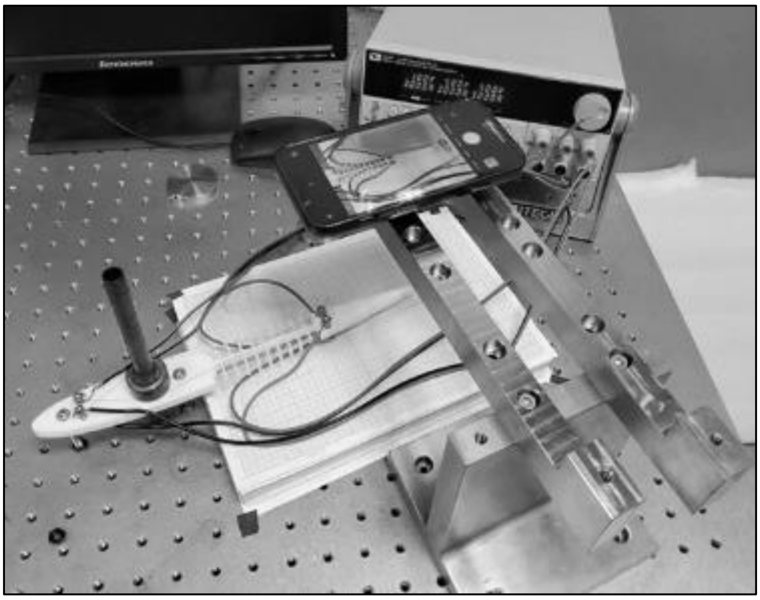
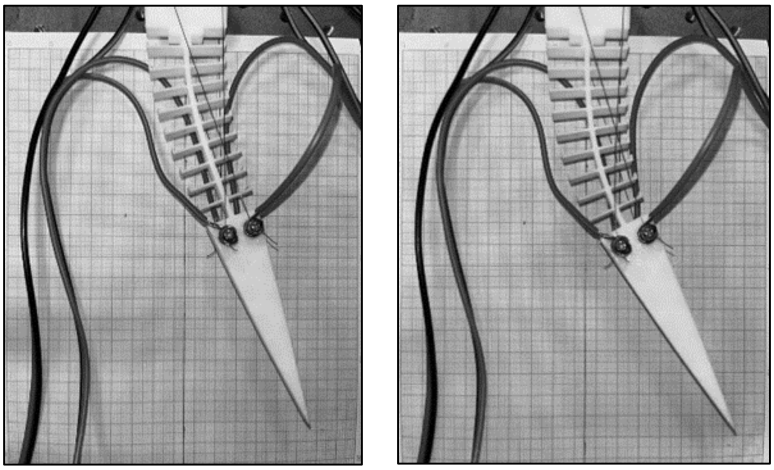


Figure 4 Experiment set-up

Fig. 5 illustrates the resulting deflection modes observed from the experiments. The first deflection mode yielded an angle of approximately 20 degrees, while the second mode achieved a deflection angle of around 30 degrees. Across all deflections, it typically took about 3 seconds after wire activation to stabilize at the desired angle, with approximately 10 seconds required to return to the initial position upon deactivating the SMA wires.



a) First deflection right b) Second deflection right

Figure 5 Results of the two modes of deflection

The experimental findings underscore the design's capacity to enact two distinct trailing edge deflection modes upward and downward, through SMA wire actuation. Although the designs offer the capability to achieve varied deflection angles, they do not afford continuous control over the deflection angle, as proposed in existing literature.

4. Aerodynamic performance analysis

4.1. CFD simulations

To assess the aerodynamic efficiency of this new morphing concept, a series of comparative CFD simulations using Ansys Fluent were performed comparing the morphing profile with airfoils equipped with conventional plain flaps set to the same angle of deflection equal to 24 degrees.

Following the methodology outlined in Ref. (9), the airfoils were adjusted with a flap positioned at 25% of the chord. However, CFD simulations were also carried out on airfoils featuring a flap positioned at 50% of the chord, as they closely resembled the shape achieved through morphing and exhibited a comparable maximum lift coefficient. Fig. 6 presents a visual comparison of deformations between the morphing profile and profiles outfitted with flaps.

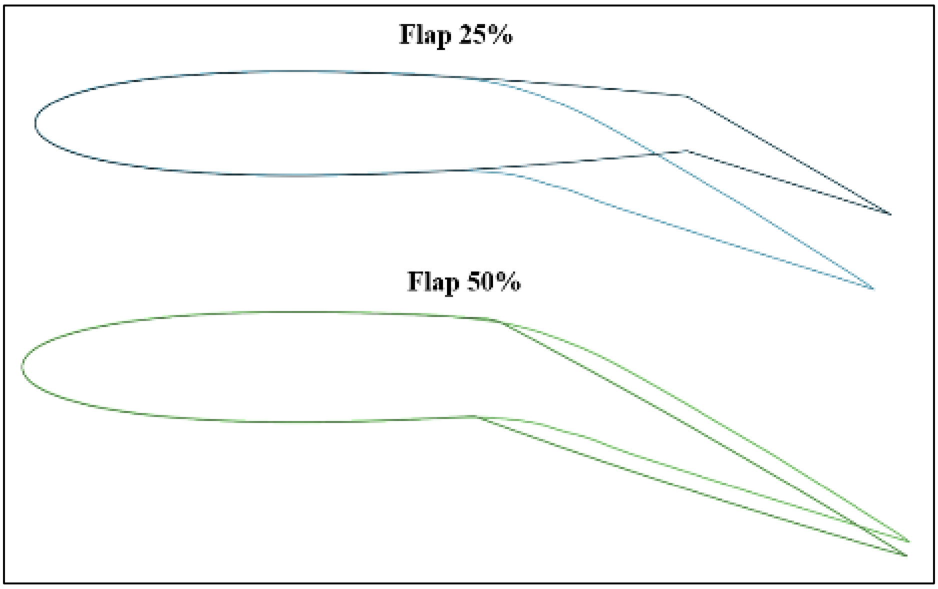


Figure 6 Morphing vs flap shape with a deflection of 24 degrees downward

The flow field velocity was set at 45 m/s, resulting in a Reynolds number of 3,000,000. Given that the freestream velocity remains below 0.3 Mach, the flow is considered incompressible, leading to the selection of a pressure-based solver. The Spalart-Allmaaras Eddy turbulent viscosity model was selected.

Structured mesh domains, depicted in Fig. 7, were utilized for the simulations, ensuring a y^+ value below 1 by setting the distance of the first grid point off the wall to $1 * 10^{-5}$mm.

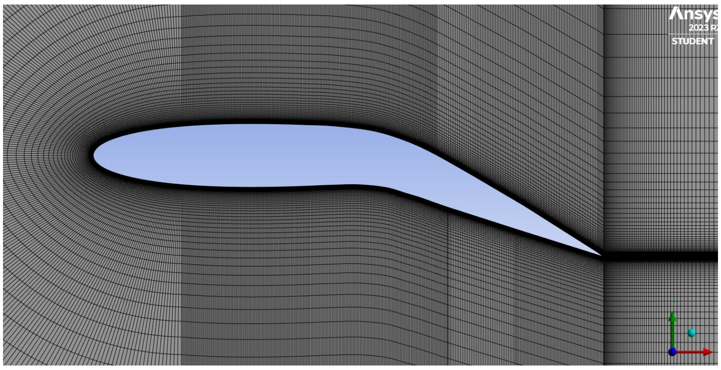
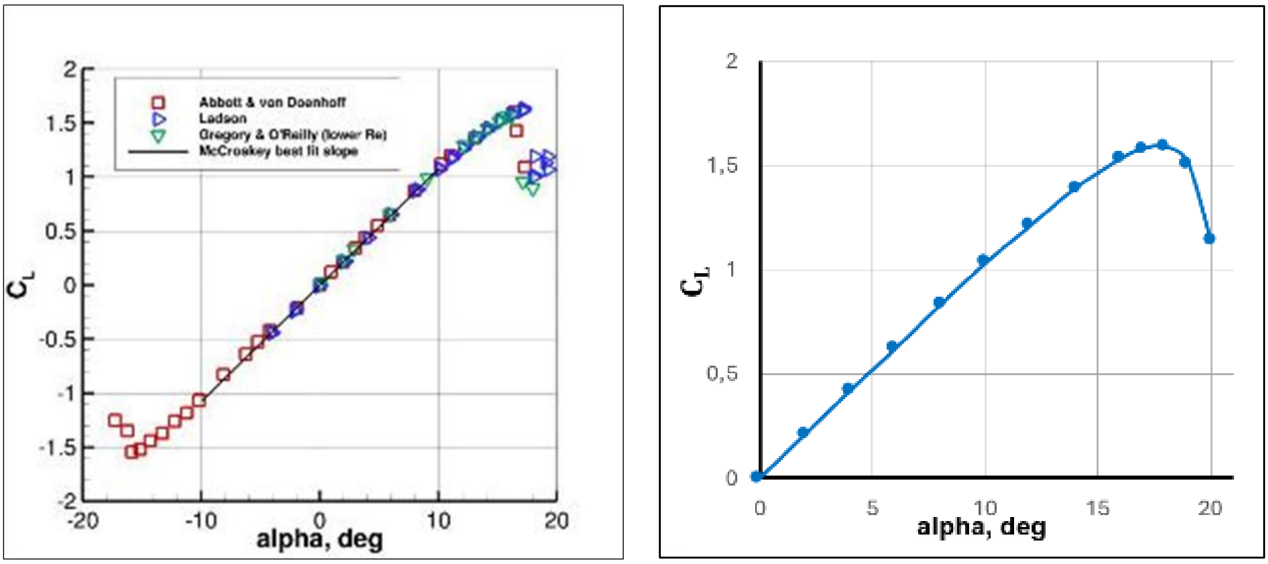


Figure 7 Structured mesh used for simulations

Initial CFD simulations focused on the NACA0012 airfoil, with results compared to those obtained from a NASA study [18]. The similarity between the results illustrated in Fig. 8 validates the simulation approach.



a) Lift polar NASA results

b) Lift polar Ansys Fluent results

Figure 8 Comparison of the NACA0012 lift polar with NASA results [18]

4.2. CFD results

Multiple curves have been graphed to facilitate a comparison of the aerodynamic characteristics between the morphing and flap-equipped profiles. Fig. 9 shows the lift coefficient in relation to the attack angle and the lift efficiency plotted against the lift coefficient.

4.2.1. Comparison between flap 25% and morphing profiles

At high angle of attack, the flap profile demonstrates a higher maximum lift coefficient and a lower drag coefficient at high angles of attack. However, the morphing profile consistently maintains a superior lift coefficient for lower angle of attack. While the flap profiles exhibit considerable drops in aerodynamic efficiency, with a Cl/Cd max equal to 25, the morphing profile maintains excellent aerodynamics up to 66.

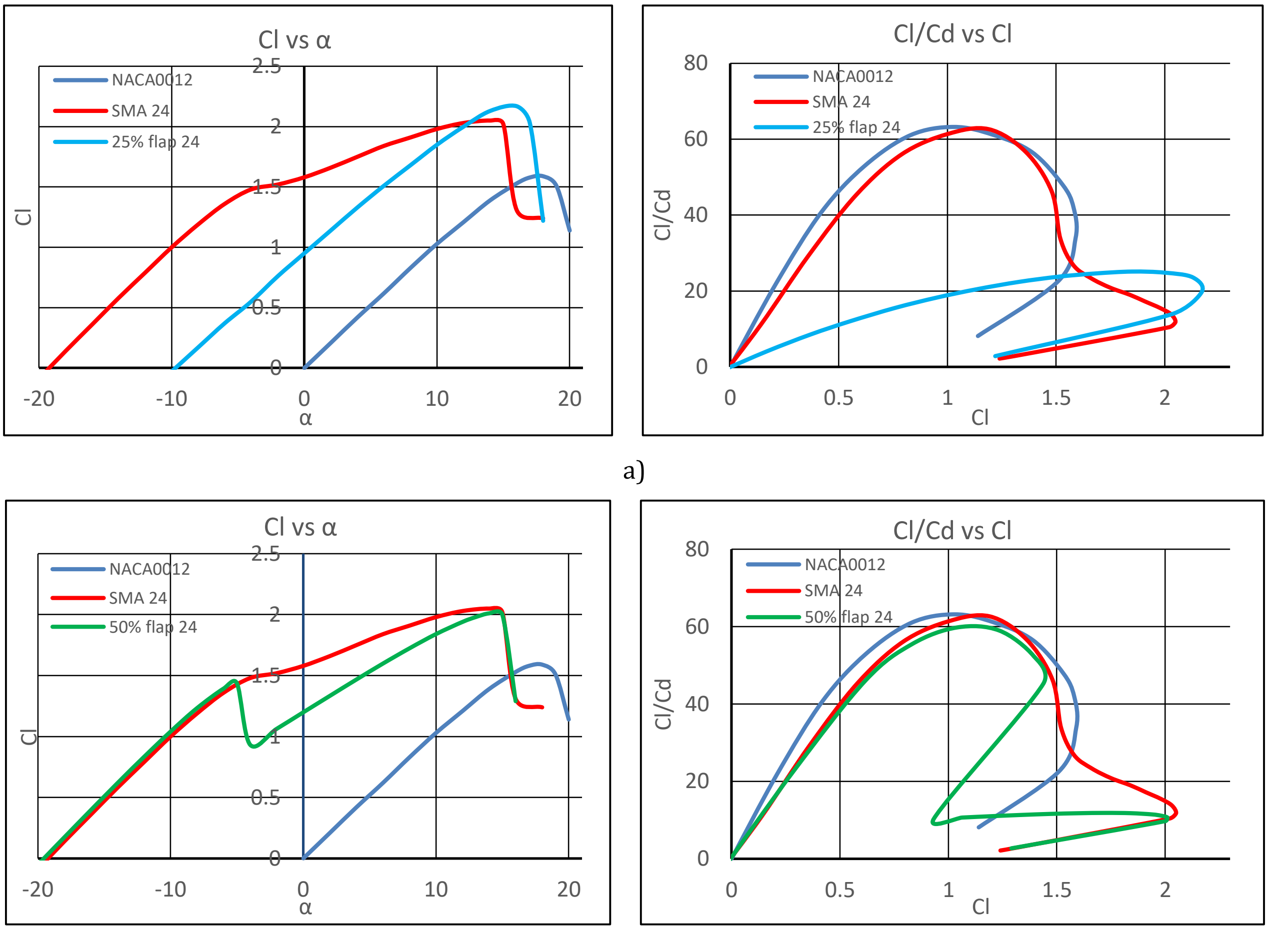
Despite a maximum lift coefficient between 6 and 7% higher for 25% flap profile, the morphing profile offers significantly enhanced lift coefficients and aerodynamics at lower angles of attack and provides a positive lift coefficient across a wide range of angles of attack.

4.2.2. Comparison between flap 50% and morphing profiles

Both profiles have similar aerodynamic characteristics at low angles of attack. However, stating from angle of attack equal to -5 a significant drop in lift coefficient and increase of drag are observed. As illustrated in Figure 93-b, lift efficiency decrease from 45 to 10 between -5 and -4 degrees.

In Fig. 10, the flow velocity contours around the wing at angles of attack equal to -5 and -4 are depicted. It's clear that while the flow separates completely from the trailing edge for the flap profile at -4 degrees, such separation doesn't occur for the morphing profile. This phenomenon occurs due to the sudden change in angle characteristic of the flap profile and explains the drop in the lift coefficient between -5 and -4 degrees.

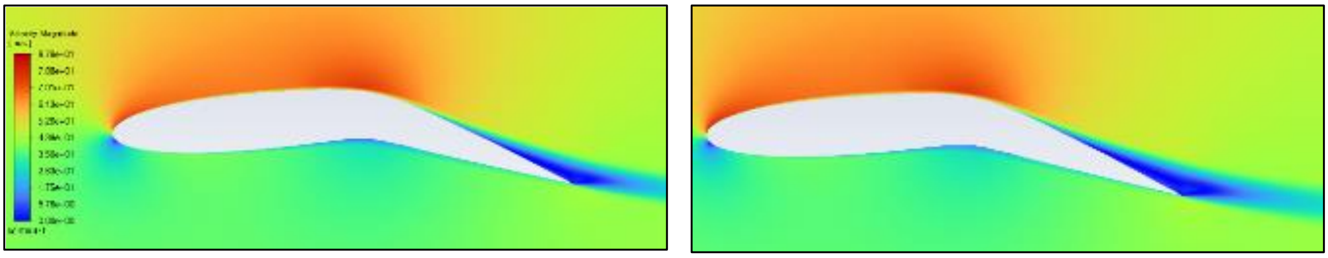
Therefore, morphing profiles offer better aerodynamic performances than flap profiles, thanks to better flow attachment around the airfoil profile.



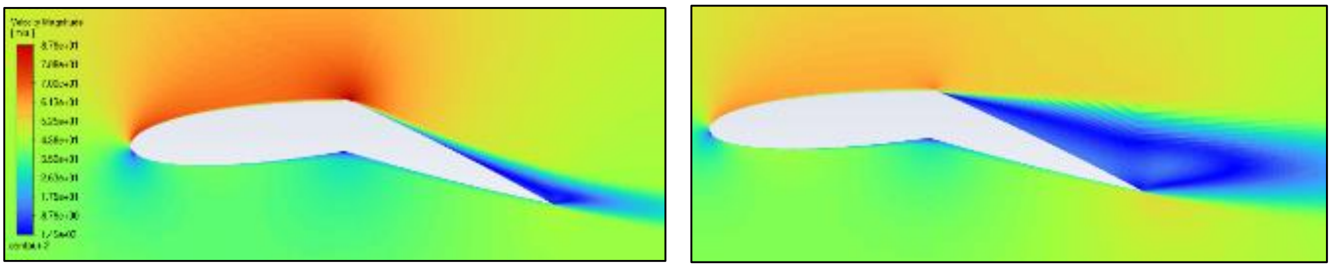
a)

b)

Figure 9 Lift polar (left) and lift efficiency vs lift (right) a) morphing vs flap 25% b) morphing vs flap 50%



a) morphing airfoil



b) flap 50% airfoil

Figure 10 Comparison of contours of the flow velocity at an angle of attack of -5 degrees (left) and -4 degrees (right) between and a) morphing airfoil b) flap 50 %

5. Conclusion

This paper presents a fishbone structured camber morphing airfoil actuated by SMA wires able to perform large and continuous trailing edge deflection. A 3D-printed prototype was built, and experiments demonstrated the mechanism's capacity to deflect the trailing edge in two distinct angles up to 30 degrees in both upward and downward directions.

A comprehensive aerodynamic analysis was conducted to showcase the advantages of this morphing wing compared to conventional flap systems. The results revealed significantly improved flow adherence along the entire trailing edge of the airfoil, allowing the airfoil to keep very high lift efficiency in contrast to flap profiles. Therefore, the morphing airfoil was able to maintain positive lift coefficients across a wider range of angles of attack compared to traditional hinged flap wings thanks to its uniformly curved profile.

However, the design still presents certain limitations. The current morphing concept lacks continuous control of the deflection angle, potentially necessitating an increase in the number of achievable deflection angles.

This study only focused on a single rib without considering the complete wing including additional ribs and flexible skin. Since each rib operates independently in terms of deflection, there exists an opportunity to investigate and experiment twist morphing.

Nomenclature

- SMA = Smart Memory Alloy
- CFD = Computational Fluid Dynamics
- Cl = Coefficient of Lift
- Cd = Coefficient of Drag
- α = Angle of attack
- y^+= Dimensionless wall distance

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflict of interest.

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Authors Short Biography

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