Morphing concepts in the field of rotorcraft

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Abstract: *Drawing inspiration from avian creatures, aeronautical engineers strive to create an ideal wing design that can seamlessly perform in various flight conditions. Avian creatures, as well as bats and other flying organisms, exhibit a striking aptitude to adjust the lift produced by their wings, displaying the capacity to repeatedly tailor their wing configurations to match specific environmental conditions. An example of this is when their wings are tightly tucked during dives for hunting, or fully extended during gliding to conserve energy. Moreover, these organisms can manipulate the curvature and twist of their wings to maintain precise control over their aerial maneuvers. In contrast, engineers in the aircraft industry continue to rely on the standard, robust and structured "one-point design" approach, which remains the most practical and feasible method to apply. Nonetheless, advancements in technology have emerged to address long-standing challenges in wing manufacturing that were previously deemed insurmountable. This convergence of different technologies has given significant momentum and recognition to the field of "morphing discipline". When considering an aircraft, shape changes primarily relate to the wing of a fixed-wing aircraft or the blade of a rotorcraft. The concept of achieving a "smooth" shape change stems from the crucial need for drag reduction and improved flow quality, resulting in improved overall performance. The state-of-the-art morphing concepts applied to rotorcrafts comprise a wide range of investigations aimed at improving performance. Looking ahead, the primary challenge for morphing technology will be to persuade the industry of its tangible benefits. This encompasses enhanced aerodynamic efficiency, minimized installation footprint when contrasted with conventional control surface mechanisms, reduced overall weight, and an equivalent standard of safety. This research provides an overview of the current development of different control devices and explores the impact of previous and continuous research endeavors in this field. Numerous ideas for managing airflow have been explored with the aim of enhancing the performance abilities of rotary-wing aircraft. These include active morphing in rotorcraft such as leading edge slats, trailing edge flaps, and passive morphing in rotorcraft such as variable rpm rotorcraft. The aim of these blade modifications is to achieve various desired effects such as increasing the maximum lift coefficient, reducing drag, and minimizing vibratory loads. Convincing the industry of these advantages will play a crucial role in shaping the future of morphing technology.*

Key Words: *morphing, airfoil, wing, rotorcraft, active, passive, skin*

1. INTRODUCTION

Drawing inspiration from avian creatures, aeronautical engineers strive to create an ideal wing design that can seamlessly perform in various flight conditions. Bats, birds, and various other flying creatures possess the remarkable ability to modify the lift generated by their wings. These creatures can repeatedly adjust their wing configurations to match specific conditions. For instance, wings can be tightly folded for diving in pursuit of prey or fully extended for energy-saving gliding. Additionally, these creatures can adjust wing twist and the camber to exert control over their flight maneuvers.

The concept of “morphing” has gained significant prominence in the aeronautical and aerospace field, particularly since 2016. Many scholarly articles have delved deeply into this subject matter and related technologies. In this introductory section, our objective is to assess and lay down the fundamentals of the idea, focusing specifically on its application in aeronautics.

The term “morph” originates from ancient Greek and refers to the shape, figure, or other related aspects of an entity. Therefore, “morphing” pertains to the process of modifying the original form or appearance of a particular object or system. Within the realm of technology, morphing is a subfield of “smart structures”, which involves integrating fully functional devices into a structural framework. This integration bestows the system with supplementary functionalities for accommodating external alterations or evolving demands, all the while upholding its core load-bearing attributes. It is worth noting that smart structures are sometimes mistakenly conflated with terms like “adaptive structures” or “intelligent structures”.

In reality, there are distinctions among these concepts, and a hierarchical relationship can be established. The term “adaptive” is used to describe structures that have the capacity to alter any of their inherent characteristics.

The term “smart” is used to describe structures that incorporate fully integrated actuators and sensor systems. Essentially, it represents the smooth amalgamation of active components within the structural framework. If a structure is furnished with a form of “cognitive function”, it signifies its capability to analyze data from external sensors in addition to its internal knowledge. (whether preprogrammed or acquired), it can be categorized as “intelligent”. The graphical representation of this concept can be seen in Fig. 1.

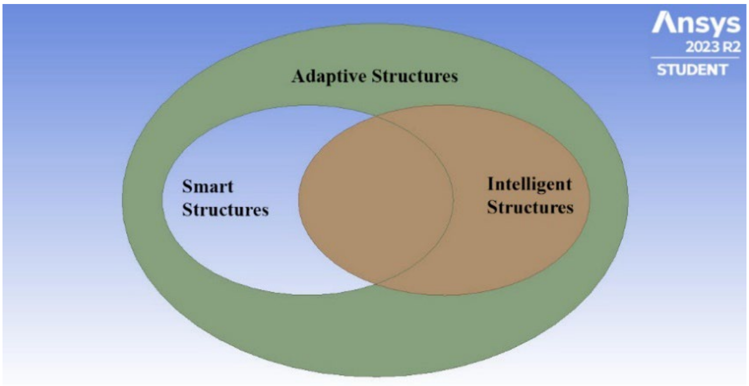

Fig. 1 – Conceptual representation of adaptive, smart, intelligent structures domain

Aircraft designs typically revolve around a solitary condition that is recognized as the design point, which represents the optimal match among all envisioned missions. This design point determines the aircraft's optimal geometric shape, which governs its aerodynamics. It is evident that a wing capable of modifying its shape to a greater extent to accommodate the diverse conditions encountered during its mission could significantly enhance the aircraft's performance.

Developing a morphing wing necessitates resolving contradictory demands. On one hand, the wing structure needs to be compliant enough to facilitate configuration changes. On the other hand, it must be sufficiently rigid to mitigate aeroelastic instabilities and bear the loads imposed on it. Balancing these contradictory demands, while also considering weight considerations, becomes a critical aspect of the design process, as depicted in Fig. 2 [1].

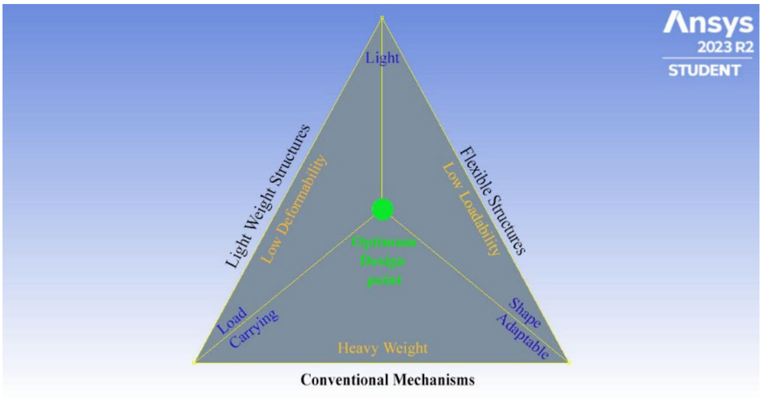

Fig. 2 – Morphing requirements

Looking ahead, the primary challenge for morphing technology will be to persuade the industry of its tangible benefits. These benefits encompass improved aerodynamic performance, reduced installation footprint when compared to conventional control surface systems, weight reduction, and a comparable level of safety. Convincing the industry of these advantages will play a crucial role in shaping the future of morphing technology.

2. ROTORCRAFT-SPECIFIC MORPHING COMPLEXITIES

Contemporary investigations into aircraft morphing encompass rotary-wing aircraft, with a particular emphasis on helicopters. A helicopter is an aircraft that utilizes rotating wings, called rotor blades, to generate lift and propulsion. The rotor, consisting of the hub assembly and rotor blades, provides the necessary forces and moments to control the helicopter's position, altitude, and velocity.

Engineers have confronted a multitude of challenges when it comes to ensuring stable flight for rotary-wing aircraft. These challenges arise from the intricate aerodynamic conditions they operate in, which are notably distinct from those encountered by fixed-wing aircraft. Even in what might seem like a straightforward scenario, such as hover, rotor blades contend with varying flow velocities along their length. These issues are managed through blade designs that incorporate inherent twists. However, during forward flight, the aerodynamic conditions change azimuthally. Traditional control systems rely on a swashplate mechanism to introduce azimuthal alterations in blade pitch, permitting inputs only once per revolution. While this approach has proven effective, it does have its limitations. It rotates the entire blade around its radial axis and it is unable to fully counterbalance periodic and elevated harmonic stimulations. Selecting a fixed blade design entails making a concession, as the ideal configuration varies across different flight conditions.

When contrasting the rotor blade of a helicopter to the static wing of an airplane, it becomes evident that the rotor blade operates within a significantly more dynamic and varied environment. Even during a hover, the blade tips can attain speeds of up to 207 m/s (equivalent to 402 knots) [2], surpassing the never exceed speed (VNE) of many small airplanes. Due to the rotational motion of the blades, there is a linear variation in the relative airflow experienced by different parts of the blade, as shown in Fig. 3.

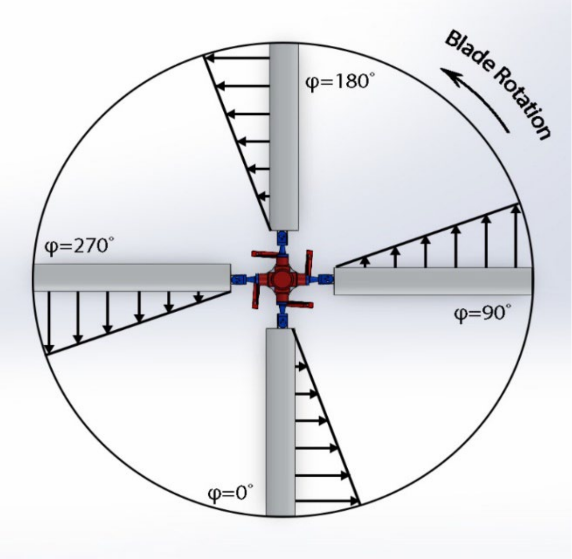

Fig. 3 – The rotor velocities at hover flight

In the context of forward flight, it's important to note that the helicopter's own velocity combines with the blade velocity. On the side that advances, there is an addition of velocities, while on the side that retreats, there is subtraction. This is visually represented in Fig. 4. To provide a practical example, when the helicopter is flying at a speed of 150 knots, the tip on the advancing side encounters an effective airflow of approximately 550 knots, while the retreating side experiences a relatively lower airflow of around 250 knots.

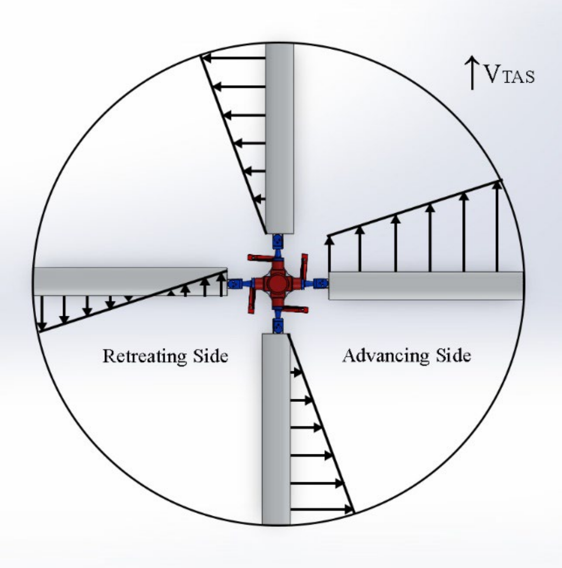

Fig. 4 – The rotor velocities at forward flight

Close to the root of the retreating side, there exists an area where reverse flow occurs, as illustrated in Fig. 5. Additionally, the tip on the advancing side may encounter high Mach numbers, giving rise to compressible effects and the possibility of Mach-divergence drag.

Conversely, the retreating tip may experience stall conditions, resulting in additional drag. These phenomena can contribute to the occurrence of vibrations in the rotor system.

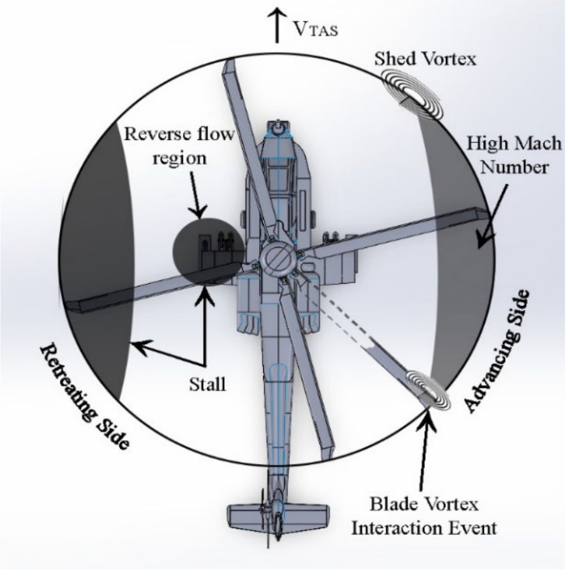

Fig. 5 – Challenges faced by a rotor during forward flight

Rotor blade morphing can be categorized into three primary domains: continuous shape change, discrete shape change, and area change.

Continuous shape change involves conspicuous alterations in the blade's configuration, achieved through blade deformation. This encompasses changes in blade/tip twist and gradual camber adjustments. Variable twist permits the redistribution of lift in various flight conditions.

Discrete shape changes entail evident modifications to the blade's structure, accomplished through the incorporation of distinct components such as plates, flaps, or blade sections.

The discrete shape changes techniques prove effective in elevating the blade's angle of attack, redistributing lift, and mitigating the noise associated with Blade-Vortex Interaction (BVI).

Area change encompasses the extension or adjustment of the blade's planform surface to enhance its overall area. Within this domain, span extension and chord extension represent the morphing techniques.

The utilization of variable diameter rotors permits flexibility in rotor size, resulting in benefits such as enhanced autorotation and hover performance, decreased power requirements due to higher tip speeds, and an increase in rotor thrust.

Given the additional complexities in rotorcraft, it becomes crucial to explore morphing solutions that leverage existing structures and materials, incorporating a morphing perspective. By doing so, morphing benefits can be introduced to rotorcraft without introducing the uncertainties associated with novel materials and components into the design process.

This approach is advantageous not only because of the challenges involved in designing such materials but also due to the extensive material and structural testing required to comply with airworthiness regulations [3], which can be time-consuming and resource-intensive. Conversely, focusing research on designing a morphing system within the conventional domain can lead to a practical solution and significantly reduce the otherwise lengthy development time.

3. RESEARCH GOAL AND OBJECTIVES

In a comprehensive review of morphing aircraft, it is emphasized that camber morphing has emerged as the preferred choice for rotorcraft morphing [4]. I believe that camber morphing offers the potential for achieving smooth aerodynamic flow, as well as enabling primary control and mitigating noise and vibration in rotorcraft. This broadens the scope of morphing solutions and expands the range of potential benefits. Therefore, the current research focuses on implementing rotor blade morphing technology specifically for the IAR PUMA 330 helicopter.

Fig. 6 – The NACA 13112 rotor blade sections of the IAR 330 PUMA helicopter

The design process examines the possibilities of incorporating active means to achieve morphing in the trailing edge flap.

Additionally, passive morphing techniques utilizing centrifugal force are also explored. The present research work is primarily focused on the preliminary phase, aiming to design, develop, and assess the feasibility of elementary models for the morphing system.

I have designed the NACA 13112 rotor blade section in the Catia V5 design software, as shown in Fig. 7.

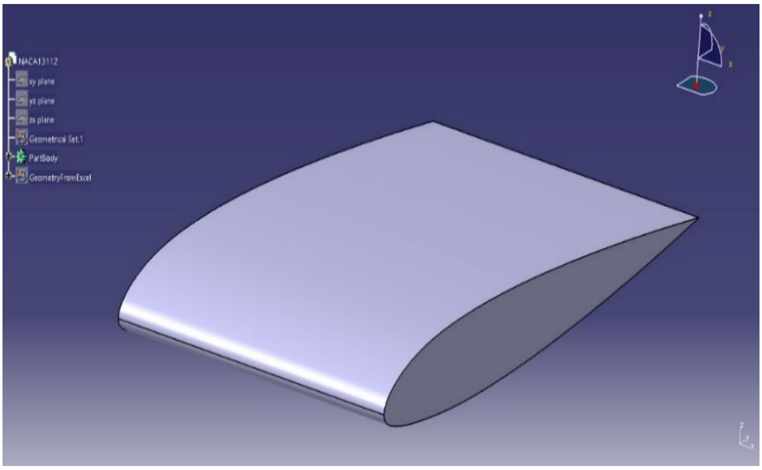

Fig. 7 – The NACA 13112 rotor blade section designed in the Catia V5 software

4. RESEARCH OVERVIEW

The current state of advanced morphing technologies implemented in rotor blades includes a wide range of investigations aimed at improving performance, reducing vibrations, and mitigating noise. These investigations span from theoretical numerical concepts to real flight tests, as well as experiments conducted on whirl stands and wind tunnels. The term "morphing" is used here in a broad sense, encompassing any technology that brings about performance enhancements or addresses issues related to vibrations and noise.

Researchers have explored various morphing techniques to achieve these objectives. Numerical analyses have been carried out to explore the viability and efficiency of various morphing concepts. These studies employ computational models and simulations to evaluate the performance and aerodynamic characteristics of morphing rotor blades.

Wind tunnel testing has been instrumental in validating and refining morphing concepts. Scale models of rotor blades with morphing capabilities are subjected to controlled airflow conditions, allowing researchers to analyze their aerodynamic behavior, load distribution, and overall performance.

Whirl stands, which simulate the dynamic inflow conditions experienced by rotor blades in forward flight, have been used to assess the performance and structural response of morphing rotor blades under realistic operating conditions. These tests help in evaluating the dynamic behavior, stability, and control effectiveness of morphing blades.

Furthermore, flight tests have been conducted to validate the performance and assess the practicality of morphing rotor blades in real-world operating conditions. Flight tests provide valuable data on the integration, functionality, and effectiveness of morphing technologies in operational rotorcraft.

The attainment of morphing capabilities in an aircraft is possible to be accomplished through both dynamic and static methods. Active systems function by utilizing dedicated actuators to regulate the behavior of the morphing mechanism. It's important to mention that active morphing systems might necessitate advanced onboard data processing capabilities, complex multivariable control systems with numerous dimensions, rapid and ongoing actuation mechanisms, alongside substantial computational resources [5].

Conversely, a passive system operates without the need for an additional onboard energy source for actuation. It relies solely on external factors such as aerodynamic loads, temperature variations, or centrifugal forces (particularly in rotorcraft) to induce changes in the wing's shape while maintaining adequate stiffness. Consequently, passive systems are generally lighter and inherently stable, albeit offering slightly less optimized performance.

5. ACTIVE MORPHING IN ROTORCRAFT

In the field of rotorcraft, the conventional use of swashplates for primary flight control has been a reliable method. However, this traditional setup has a negative impact on rotorcraft performance. The mechanical complexity of swashplates, coupled with their exposed bearings, linkages, and hinges, contributes to the aerodynamic weight and drag of the helicopter [6]. To address this issue, researchers have been exploring the integration of control mechanisms directly into the rotor blades, resulting in a field of active research.

Numerous concepts for flow control have been examined to enhance the operational efficiency of rotorcraft. Some of these technologies encompass trailing-edge flaps, leading-edge slats, active blade twisting, and dynamic airfoil morphing.

Trailing edge camber morphing has traditionally been associated with the implementation of flaps controlled by servos in rotorcraft. The idea of servo-operated flap dates back to the early 1920s, a period during which Louis Brennan conceived a helicopter design featuring a sizable, single two-bladed rotor fitted with servo-operated flaps for maneuvering [7]. In 1930, Corradino d'Ascanio from Italy designed a helicopter that incorporated servo tabs, as depicted in Fig. 8.

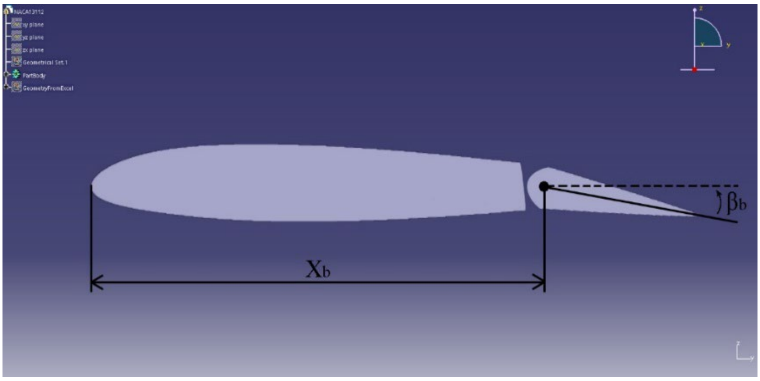

Fig. 8 – Airfoil with active trailing edge flap.

During the 1940s, Charles Kaman of Kaman Helicopters took the concept initially introduced by D'Ascanio a step further by incorporating servo flaps into his helicopter design [8]. The cyclic deflection of these servo flaps generated aerodynamic moments, leading to blade twisting, thereby altering the angle of attack and introducing cyclic rotor control capabilities [7]. In contrast, plain flaps eliminate the gap created by hinges and the supporting structure for the flaps behind the blade's trailing edge. This approach offers advantages like decreased power losses resulting from aerodynamic drag and enhanced flap efficiency. In the realm of rotorcraft, the morphing of the trailing edge camber presents an opportunity to enhance these plain flaps by eliminating the need for hinges and revealing a streamlined, smooth surface [9].

Expanding on this idea, Werter et al. [10] further explored the concept by extending it to include trailing edge and leading edge morphing mechanisms installed on a conventional wing-box framework for fixed-wing aircraft. In this variation, actuation is achieved by using servo motors to reposition the lower skin horizontally. This concept is referred to as Translation Induced Camber (TRIC). Fig. 9 provides an illustration of the TRIC concept, showcasing its application in the wing structure's sections at the trailing edge and the leading edge [11].

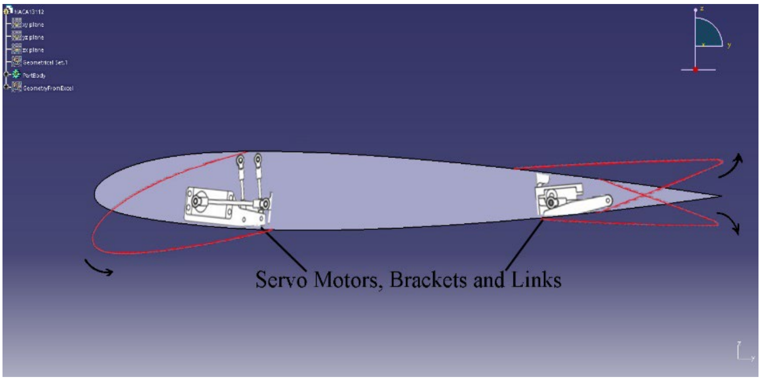

Fig. 9 – Mechanism inside the wing structure showing the full range of deformation

While initially developed for fixed-wing aircraft, the design and feasibility study of this concept for rotorcraft applications could prove highly advantageous. Adapting the TRIC concept to rotorcraft would require careful consideration of the unique aerodynamic and structural requirements of helicopter rotor blades.

6. PASSIVE MORPHING

Passive morphing is a concept that leverages the substantial centrifugal force generated in rotorcraft. This force can vary, with smaller helicopters carrying two to four passengers producing around 6 to 12 tons of force at the blade root, while larger helicopters can generate up to 40 tons of centrifugal force [12]. This centrifugal force can potentially be harnessed to actuate a flap without the need for an active system. If the advantages of utilizing a passively morphing flap are demonstrated in rotorcraft flight operations, developing and testing a passive morphing system could prove beneficial. However, such a system must include proper means to control the flap deployment.

In the context of helicopters, passive morphing has primarily been explored for chord and span morphing using the available centrifugal force. In these concepts, the alteration in shape is accomplished by adjusting the centrifugal force, which is achieved by modifying the rotor's speed. For example, a system for altering the blade's profile using a cellular structure has been developed and subjected to testing [13], demonstrating its effectiveness in mitigating stall occurrences [14].

For span morphing, a prototype rotor has been developed, constructed, and evaluated on a hover platform [15]. This idea is dependent on a spring-based mechanism that adapts to variations in RPM, which leads to a decrease in power consumption of approximately 10% when compared to the standard configuration.

Numerous studies have been conducted to explore the integration of changes in centrifugal force by employing extension-twist coupled composites to induce blade twist.

For example, Prabhakar introduced a spring-based structure designed to restore the spanwise configuration within a rotor blade, permitting the extension of the blade span to increase rotor RPM and the contraction of the blade span to lower rotor RPM [16].

Similarly, Moser designed a mechanical linkage mechanism that established a connection involving the lateral displacement of a ballast mass, influenced by changing chordwise extension and centrifugal loading. This linkage system functioned using a bistable von Mises truss structure [17].

During the late 1980s and into the early 1990s, a team of researchers at the Langley Research Center, within the US Army Research Laboratory, directed extensive endeavors toward the advancement of rotor blades constructed using extension-twist coupled composite materials [18-20].

This development was accomplished through the inclusion of supplementary ballast weight in the rotor blades, which effectively augmented the centrifugal force, leading to a controlled twist modification. Nonetheless, this approach did entail a modest rise in blade mass, which had repercussions on rotor performance. Although the initial research showcased the considerable potential of composite materials with extension-twist coupling, it yielded only minor adjustments in blade twist across the spectrum of rotational speeds, covering both high-speed cruise and hover.

Confronted with these challenges, this work served as the cornerstone for subsequent investigations and enhancements in this technology, with the ultimate goal of achieving more significant twist adjustments and enhancing the overall performance of high-speed rotorcraft.

In 2005-2006, Nampy and Smith introduced the idea of utilizing composites with a Flexible Matrix (FM) for rotors with extension-twist coupling [21, 22]. These composite materials offer a higher degree of twist flexibility per unit of axial centrifugal force when compared to conventional materials. Nevertheless, a limitation of rotor blades incorporating embedded FM is their insufficient torsional stiffness, rendering them unsuitable for rotorcraft applications.

The state of current research indicates that the development of twist-morphing adaptive rotorcraft structures is still facing several challenges and unresolved issues. Among these, a key challenge lies in achieving substantial twist variation by modifying rotor RPM within a rotor blade made from extension-twist coupled composite materials, while ensuring that material strain limits are not exceeded or sacrificing blade stiffness requirements. This continues to be a major hurdle in the domain of rotorcraft design and engineering. Researchers continue to work towards innovative solutions to overcome these limitations and unlock the full potential of twist-morphing technology for rotorcraft applications.

8. SKIN MATERIALS

To address the challenge of bridging the gaps between mechanism parts in a morphing system, it is necessary to carefully consider the selection of an appropriate skin material or concept. A thorough review of existing literature has been conducted to identify suitable airfoil skin materials capable of both spanning the slotted gaps and delivering a seamless surface.

There are several potential solutions available for creating morphing skin, each offering its own advantages and applications. Here are a few examples:

One potential solution for creating morphing skin is the use of Shape Memory Alloys (SMAs) that can return to their initial form after deformation when subjected to a particular trigger, typically involving heat. They possess excellent shape memory properties and can be utilized to create morphing skin that changes shape based on temperature variations. SMAs are particularly valuable in applications where precise control over shape change is required.

An alternative approach entails employing air pressure to expand a highly pliable elastomeric covering surrounding the morphing mechanism. This idea is represented in a schematic manner in Fig. 10. In this design, it's imperative to ensure that the segment of the blade where the morphing mechanism is integrated is hermetically sealed, and the mechanism itself is entirely enclosed, isolated from the remainder of the blade.

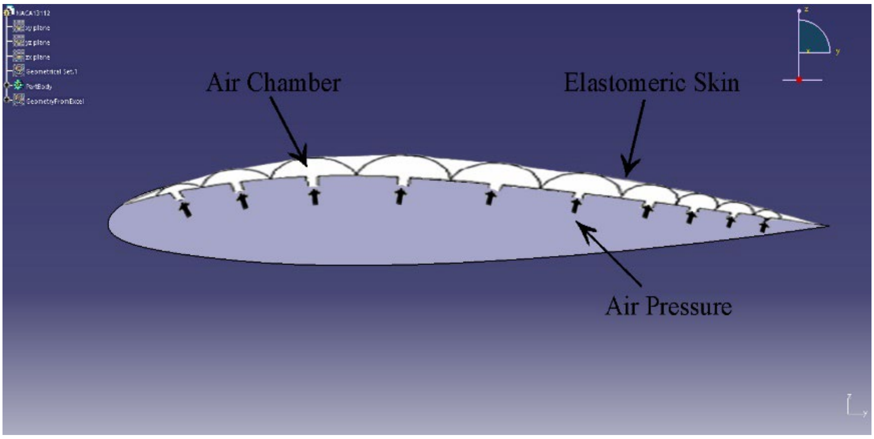

Fig. 10 – Illustration of the configuration of an airfoil featuring an inflatable skin

When the Shape Memory Alloy actuators are activated and the mechanism begins to morph, dedicated channels positioned near the slots of the mechanism open within the airfoil. This opening enables the controlled inflation of the elastomeric skin. This inflation results in the formation of a seamless aerodynamic surface that harmoniously accommodates the movement of the mechanism.

The structure of the SARISTU ATED morphing skin comprises three primary elements. Within the gaps between the aluminum profiles, there is an infill of low-temperature foam. Both the foam area and the aluminum profiles are shielded by a thin, 1 mm layer of protective low-temperature silicone elastomer. The flexible sections are positioned both above and below the hinge points of the rib framework and play a crucial role in enabling the skin to undergo movement. Both the upper and lower skins are equipped with three foam segments each, as illustrated in Fig. 11 [23]. This solution can be representative of our research.

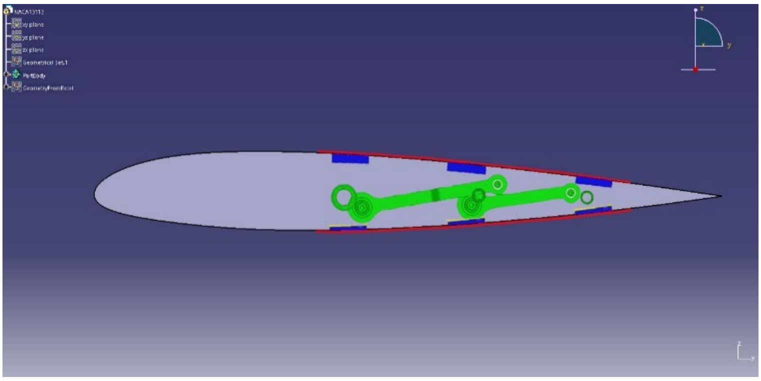

Fig. 11 – The configuration of the lower and upper morphing skins, including the actuation mechanism

It is important to recognize that the development and implementation of morphing skin materials and technologies are active areas of research, with ongoing advancements and discoveries. While the examples provided highlight some current approaches, there may be additional materials and technologies that also exhibit shape-changing behavior for morphing skin applications. Further exploration and innovation in this domain are expected to result in additional progress and fresh opportunities.

9. CONCLUSIONS

Implementation of morphing solutions in aircraft, especially rotorcraft, poses significant challenges due to the need for new materials with specific properties and the development of efficient actuation methods. Morphing aims to enhance overall performance by improving flow quality and reducing weight, which is crucial for aircraft efficiency. However, the physical realization and testing of morphing concepts have been limited, partly due to these challenges.

Among the various morphing techniques, camber morphing has shown promise for rotorcraft applications, particularly trailing edge morphing flaps. These flaps offer localized changes, which are well-suited for rotorcraft blades with limited internal volume. The TRIC morphing concept introduces the possibility of employing conventional materials for morphing applications, which can help simplify the system's complexity.

By utilizing the TRIC concept, researchers can leverage existing materials and conventional design methodologies to implement morphing solutions in rotorcraft. This approach can reduce the need for specialized materials and potentially make the implementation of morphing concepts more feasible for rotorcraft applications. Furthermore, localized morphing can be particularly advantageous for rotorcraft, as it allows for specific control and optimization without affecting the entire blade structure.

Overall, the TRIC morphing concept represents a promising avenue to explore morphing solutions in rotorcraft while addressing the challenges associated with materials and actuation methods. As research progresses, the feasibility of morphing concepts for rotorcraft may become more attainable, opening new possibilities for enhanced rotorcraft performance and capabilities.

Indeed, the actuation scheme is a critical aspect of implementing morphing solutions in rotorcraft, especially when considering the required flap deflections at various frequencies for different applications, like the reduction of vibrations and noise and primary flight control.

Although the examination of the current state of the art has supplied insights into passive systems that use centrifugal forces for chord and span morphing, a significant void exists in the literature regarding the utilization of centrifugal forces for camber morphing purposes. Camber morphing, which involves altering the airfoil's curvature, has the potential to significantly enhance rotorcraft performance by reducing collective pitch requirements and increasing pilot control authority. The development of a morphing system that utilizes centrifugal forces for camber morphing is, therefore, an important area of research. Such a system could provide the required flap deflections at the frequencies needed for effective control and performance improvements in rotorcraft. By using the aerodynamic forces generated by the rotating rotor, this type of morphing system may offer a passive and efficient means of achieving camber morphing without the need for complex and heavy actuators.

Exploring the feasibility and implementation of such a centrifugal-based camber morphing system could lead to valuable advancements in rotorcraft design and performance. The potential benefits of reduced pilot workload, improved control authority, and enhanced overall efficiency make this an area worth further investigation and research. Additionally, successful development and validation of such a system could pave the way for more widespread adoption of morphing technologies in rotorcraft and other aircraft applications.

The literature review reveals that controlling rotor RPM has established advantages. However, it is noteworthy that there is a lack of studies relating RPM variation to camber morphing, despite camber morphing being a popular choice for active morphing in rotorcraft. Integrating camber morphing schemes that utilize centrifugal forces on slowed rotors could offer significant performance improvements for rotorcraft.

It is crucial to acknowledge that the progress and utilization of morphing skin materials and technologies are dynamic fields of study, continually advancing and revealing new insights.

REFERENCES

[1] L. F. Campanile, Initial thoughts on weight penalty effects in shape-adaptable systems, *Journal of Intelligent Material Systems and Structures*, vol. **16**, pp. 47–56, 2005, ISSN: 1045389X.

[2] J. G. Leishman, *Principles of Helicopter Aerodynamics*, Cambridge University Press, 2006.

[3] F. D. Florio, Airworthiness: An Introduction to Aircraft Certification and Operations, *Elsevier Ltd.*, 2016, ISBN: 9780081009406.

[4] S. Barbarino, O. Bilgen, R. M. Ajaj, M. I. Friswell, and D. J. Inman, A review of morphing aircraft, *Journal of Intelligent Material Systems and Structures*, vol. **22**, pp. 823–877, 2011, ISSN: 1045389X.

[5] M. Mihir, *Quasi-Static Rotor Morphing Concepts for Rotorcraft Performance Improvements*, December 2012.

[6] A. Saxena and I. Chopra, *Development and testing of a swashplate less rotor with compact brushless motor actuated flaps for primary control*, 2011.

[7] J. G. Leishman, *A History of Helicopter Flight*.

[8] M. V. Hoagland, Development of a Low-Cost Product: The K-max Story, in *19th Congress of the International Council of the Aeronautical Sciences and the American Institute of Aeronautics Aircraft Systems Conference*, Anaheim, CA: AIAA, 1994.

[9] J. Milgram, I. Chopra, and F. Straub, Rotors with trailing edge flaps: Analysis and comparison with experimental data, *Journal of the American Helicopter Society*, vol. **43**, pp. 319–332, 1998, ISSN: 00028711.

[10] N. Werter, J. Sodja, G. Spirlet, and R. De Breuker, Design and Experiments of a Warp Induced Camber and Twist Morphing Leading and Trailing Edge Device, *24th AIAA/AHS Adaptive Structures Conference*, pp. 1–20, 2016.

[11] G. B. Spirlet, *Design of Morphing Leading and Trailing Edge Surfaces for Camber and Twist Control*, June 2015.

[12] * * * U.S. Army, *Rotary Wing Flight - Flight Manual 1-51*, United States, Department of the Army, 1979.

[13] S. Barbarino, F. Gandhi, and S. D. Webster, Design of extendable chord sections for morphing helicopter rotor blades, *Journal of Intelligent Material Systems and Structures*, vol. **22**, pp. 891905, 2011, ISSN: 1045389X.

[14] M. Khoshlahjeh and F. Gandhi, Extendable chord rotors for helicopter envelope expansion and performance improvement, *Journal of the American Helicopter Society*, vol. **59**, pp. 1–10, 2014, ISSN: 00028711.

[15] T. Prabhakar, F. Gandhi, J. Steiner, and D. McLaughlin, A centrifugal force actuated variable span morphing helicopter rotor, *Annual Forum Proceedings – AHS International*, vol. **1**, pp. 710–724, 2007, ISSN: 15522938.

[16] T. Prabhakar, F. Gandhi, J. Steiner, and D. McLaughlin, A centrifugal force actuated variable span morphing helicopter rotor, *Sixty-Third Annual American Helicopter Society Forum*, Paper 2007-32, May 2007.

[17] P. Moser, S. Barbarino, and F. Gandhi, Helicopter Rotor-Blade Chord Extension Morphing Using a Centrifugally Actuated Von Mises Truss, *Journal of Aircraft*, Vol. **51**, No. 5, 2014, pp. 1422{1431.

[18] M. W. Nixon, Improvements to Tilt Rotor Performance through Passive Blade Twist Control, *NASA TM-100583*, April 1988.

[19] R. C. Lake, M. W. Nixon, M. L. Wilbur, J. D. Singleton, and P. H. Mirick, A Demonstration of Passive Blade Twist Control Using Extension-Twist Coupling, *AIAA Paper 1992-2468*, April 1992.

[20] M.W. Nixon, Aeroelastic Response and Stability of Tilt Rotors with Elastically Coupled Composite Rotor Blades, *NASA TM-108758*, January 1993.

[21] S. Nampy, and E. Smith, Extension-Twist Coupled Tiltrotor Blades Using Flexible Matrix Composites, *AIAA Paper 2005-2182*, April 2005.

[22] S. Nampy, and E. Smith, Design Evaluation of Model and Full-scale Flexible Matrix Composites Tiltrotor Blades with Extension-twist Coupling, *Sixty-Second Annual American Helicopter Society Forum*, Paper 2006-116, May 2006.

[23] Concilio, Antonio Dimino, Ignazio Lecce, Leonardo Pecora, Rosario, *Morphing wing technologies, large commercial aircraft and civil helicopters*, 2018.

[24] A. A. Karakalas, T. Machairas, A. Solomou, D. A. Saravanos, X. Lachenal, P. M. Weaver, P. Berring, K. Branner, & D. J. (Ed.) Lekou, New morphing blade section designs and structural solutions for smart blades, *INNWIND.EU*, Deliverable 2.23, 2015.