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Unleashing the Potential of Morphing Wings: A Novel Cost Effective Morphing Method for UAV Surfaces, Rear Spar Articulated Wing Camber

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Abstract: The implementation of morphing wing applications in aircraft design has sparked significant interest as it enables the dimensional properties of the aircraft to be modified during flight. By allowing manipulation of the 2D and 3D parameters on the aircraft's wings, tail surfaces, or fuselage, a variety of possibilities have arisen. Two primary schools of thought have emerged in the field of morphing wing applications: the mechanisms school and the smart surfaces approach that uses shape-memory materials and smart actuators. Among the research in this field, the Fishbone Active Camber (FishBAC) approach has emerged as a promising avenue for controlling the deflection of the wing's trailing edge. This study revisits previous research on morphing wings and the FishBAC concept, evaluates the current state of the field, and presents an original design process flow that includes the design of a unique and innovative UAV called the Stingray within the scope of the study. A novel morphing concept developed for the Stingray UAV, Rear Spar Articulated Wing Camber (RSAWC), employs a fishbone-like morphing wing rib design with rear spar articulation in a cost-effective manner. The design process and flight tests of the RSAWC are presented and directly compared with a conventional wing. Results are evaluated based on performance, weight, cost, and complexity. Semi-empirical data from the flight testing of the concept resulted in approximately a 19% flight endurance increment. The study also presents future directions of research on the RSAWC concept to guide the researchers.

Keywords: rear spar articulated wing camber (RSAWC); fishbone active camber (FishBAC); camber; biomimicry; morphing wing

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1. Introduction

1.1. The Motivation behind the Morphing Structures

Aviation history often highlights the inspiration humans drew from the flight of birds, which led to early studies in this field [1]. Today, manned or unmanned aerial vehicles that are heavier than air classify as fixed-wing, rotary-wing, or hybrid aircraft [2]. In this classification, fixed-wing refers to wings that do not undergo any shape changes during flight. However, flying creatures in nature, such as birds, bats, and insects, are known to alter their wing geometries during flight [3]. Research has shown that birds manage the aerodynamic forces created by their wings by changing the shapes of their wing skeletons and feathers [4]. Similarly, bats, which are flying mammals, can create shape changes in their wings by using the membranes between their wings [5]. Even smaller winged insects undergo similar membrane shape changes [6].

Although morphing wing technology has been studied and developed, it has not become a commonly used or widely accepted technology in the aircraft we have developed as a society. To control a flying vehicle during flight, different aerodynamic forces must be generated on its surfaces. For instance, on aircraft wings, ailerons or wing flaps work in opposition to each other. When one aileron moves downward, the other moves upward, resulting in an increase in lift on one wing and a decrease on the other, causing the plane to roll. The standard control surfaces, such as ailerons, rudder, and elevator, allow a flying vehicle to be controlled in its three axes [7]. In addition to these structures, some aircraft configurations use combined control surfaces, such as the ruddervator or elevon [8,9]. Modern passenger aircraft wings often feature three additional structures, namely flap, slat/slot, and spoiler. The purpose of these structures is to manipulate the airflow over the wings to improve the take-off and landing performance of the aircraft. The standard control surfaces and high lift devices are movable surfaces hinged to aircraft structures and moved by hydromechanical or electromechanical actuators that vary according to the size of the aircraft. These surfaces will be referred to as conventional control surfaces for the remainder of the work, to differentiate them from morphing wing structures. The concept of conventional control surface is used to refer to the widely accepted or customary control surface, to distinguish it from morphing wing structures [10].

Upon observing the wing structures and wing deformations of flying creatures in nature, it is evident that significant changes in shape occur compared to the fixed-wing aircraft we have developed [11]. Flying creatures, such as birds, have been observed to achieve considerable performance advantages by changing the two and three-dimensional properties of their wing geometries during flight [12]. Two-dimensional changes involve variations in the thickness and camber of the airfoil. Three-dimensional changes refer to variability in the finite and three-dimensional structure of the wing, such as wing length, wing sweep, wing dihedral angle, and wing twist angle [13].

Although birds can achieve improved flight performance through two and three-dimensional wing modifications, current conventional aircraft designs are optimized for cruise flight and feature hinged conventional additions that enhance capabilities during specific flight phases. Consequently, the structures we model and use in our aircraft designs are much simpler than the wings of birds, as illustrated in Figure 1.

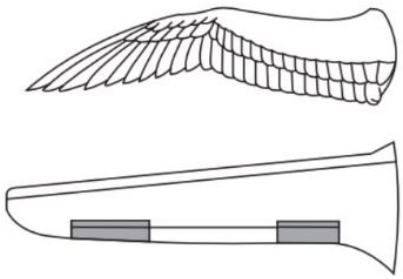

Figure 1. Bird wing versus the conventional fixed-wing aircraft wing. Reprinted with permission from Ref. [14]. Copyright © 2023 Science World.

The situation at hand tells us that there is a performance deficiency in modern conventional aircraft that could be improved by using the biomimicry method [15]. In addition, designing aircraft that can undertake multiple roles requires the development of aircraft that can operate in a wider performance range, which is important for efficiency. For example, a multi-role aircraft design that can perform both low and high-payload missions can be created by changing the wing camber. This situation should remind us that producing modern conventional aircraft for different roles, such as cargo and reconnaissance planes, is also an efficiency problem. Having high-performance aircraft that can perform many roles could provide efficiency advantages in costly areas such as maintenance, production, fuel consumption, and flight training.

Reducing costs in aviation, as in every sector, is important. Multi-role vehicles can accomplish this [16]. When morphing wing technologies are evaluated in this context, it is a key technology that can provide advantages for the multi-role capabilities of modern aircraft [17]. Figure 2 shows how the transition between two different aircraft configurations can be achieved using morphing wings that birds possess.

Figure 2. Morphing of bird wings between two different configurations. Reprinted with permission from Ref. [18]. Copyright © 2023 the Royal Society.

As the aviation industry enters the second century of aircraft design, increasing efficiency through enhanced performance and aerodynamic features has become a prominent issue. Several concerns have emerged as trending topics, including the reduction in fuel consumption, greenhouse gas emissions, and noise, as well as the increased usage of alternative fuels and blending ratios [19].

Efficiency improvements in aircraft performance have typically been achieved through structural lightening and the development of more efficient engines that reduce fuel consumption. However, progress in these technologies has slowed down in the past 20 years [20]. Therefore, it will not be possible to balance the additional environmental impacts and costs resulting from the growth of aviation without improvements in other areas. More development is needed in sustainable aviation research topics such as alternative fuels, more electric and all-electric aircraft, optimized flight plans and airport operations, and the use of new technologies to increase aerodynamic efficiency [21].

Morphing wing technologies should be considered as an important candidate that can open the door to the necessary developments as an area that can provide advantages in increasing aerodynamic efficiency [13,22,23]. Since it is different from conventional aircraft structures and beyond the norm, the idea that morphing wing technology is a new technology is widespread [24]. However, it should be noted that the first functional aircraft, the Wright Flyer, used wires attached to the wingtip to twist the wing for lateral control, which is a form of morphing wing application [25,26]. In summary, morphing wing technologies are as old as aircraft themselves. Some applications of these technologies have been realized for adaptation to passenger aircraft. The most important of these is the folding wingtip design integrated into the Boeing 777X aircraft [27]. This structure increases the wing area by becoming horizontal during take-off and landing and works as a wingtip device that reduces pressure leaks and related inefficiencies by becoming vertical during cruise flight, is an important wingtip design that contributes to increasing aircraft efficiency.

Unmanned aerial vehicles (UAVs) stand out as low-cost test platforms for the implementation of disruptive technologies. Research topics such as fuel cells, solar panels, hybrid energy management systems, and morphing wing technologies can be applied to these vehicles with low risks and costs [28–31]. However, it is not expected that these studies will consist of scalable applications for general aviation or passenger aircraft. The UAV sector is a rapidly growing industry that offers cost-effective solutions for many military and civilian missions [32]. For these reasons, the focus of this study has been determined as morphing wing applications in unmanned aerial vehicles.

1.2. A Literature Survey on Morphing Wings of UAVs

There are questions to be answered: What is a morphing wing? By which aspects do we define a wing as a morphing one? The term used in literature for shape-shifting aircraft structures is "morphing" structures. The word "morphing" comes from the word root "morph" [33], which means shape change. When this origin is considered, it should be understood that all significant shape changes observed from the outside of aircraft can be referred to as "morphing" structures.

One of the most prevalent examples of morphing applications in aviation is the retractable landing gear, which emerged during the World War II era as a part of aviation advancements [34]. The primary purpose of this design is to eliminate drag caused by the landing gear when it is not needed outside of the take-off and landing phases of flight. The landing gear can be retracted into the fuselage or under the wings for widespread use, enabling the aircraft to attain a lower drag coefficient and higher aerodynamic efficiency [35].

Morphing technology is also utilized in the design of the supersonic passenger aircraft Concorde, where the angle-of-attack change was applied to the cockpit [36]. With a delta wing configuration, high angles of attack during take-off and landing presented visibility issues for pilots in the cockpit, prompting the development of this application.

The studies that focus on wings are the most dominant in morphing aircraft component design. Wings are the most dominant components in terms of flight performance, despite other morphing structures previously mentioned. The size and shape of wings determine the aircraft's suitability for a particular task, and designers are interested in morphing structure designs that can be applied to them.

A classification methodology was applied to evaluate and examine the literature on morphing wing applications in unmanned aerial vehicles, categorized according to their goals. Morphing UAV wings in the literature were analyzed in three categories: those targeting planform change, those targeting changes in non-planform parameters, and those targeting changes in wing profile parameters [37]. Figure 3 summarizes this categorization.

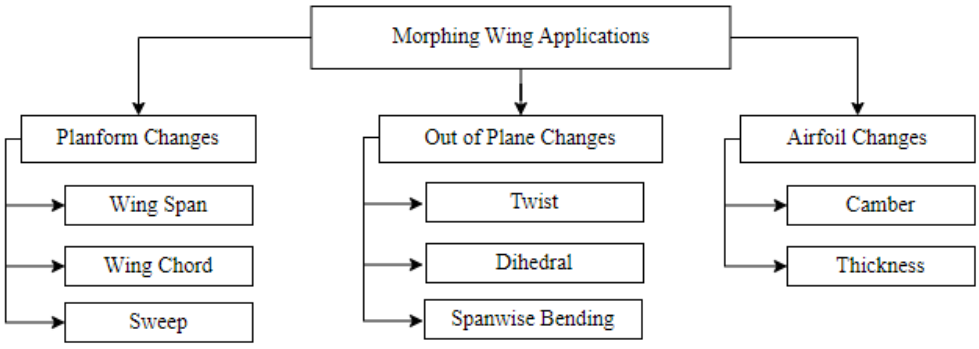

Figure 3. Classification approach used in the literature review.

Planform morphing/wingspan morphing: Planform applications can be described as applications that affect the size and position of the wing. They can also be expressed as three-dimensional parameters. These morphing applications have been categorized into three subgroups: wings with changing wingspan, chord length, or sweep angle.

The wing aspect ratio expresses the ratio between the wingspan and the chord length. An increase in the wingspan reduces the wingtip losses of the aircraft. Aircraft with a higher aspect ratio are aerodynamically efficient and have a high glide ratio. For example, gliders are designed to have a high aspect ratio [38]. However, in such aircraft, the wings are moved outside the body's inertial mass, making it difficult to induce roll. Aircraft with a lower aspect ratio have short and wide wings. These aircraft have higher maneuverability due to their lower inertial factor [39]. In flight acrobatics, aircraft with lower aspect ratios are, therefore, more common. For this reason, efforts are being made to develop morphing techniques that can alter the aspect ratio of aircraft wings. These studies can be viewed

as an effort to pave the way for the design of multi-role aircraft. An increase in the aspect ratio reduces the induced drag by reducing the wingtip losses.

A telescopic wing to increase the wingspan was designed by Samuel and Pines [40]. Three different configurations were tested, and the experimental results were compared with the finite wing theory. Similar analysis results were obtained on a fixed-wing counterpart using the same method. It was stated that the wings would undergo shape changes using pneumatic force. According to wind tunnel tests conducted, the aerodynamic results were positive for the telescopic wing with changing wingspan. The maximum open telescopic wing was found to have a higher drag coefficient and a lower lift-to-drag ratio compared to its fixed-wing counterpart.

In another study conducted by Mestrinho et al. [41], a morphing wing management algorithm was developed for Olharapo, a fixed-wing unmanned aerial vehicle, to fly most efficiently in the speed range of 11 $m.s^{-1}$ to 40 $m.s^{-1}$. Wing span changes were made in the study, and it was found that a 22% reduction in the drag coefficient could be achieved at a speed of 35 $m.s^{-1}$. At the same time, by modeling the roll motion, it was calculated that a control motion equivalent to conventional ailerons could be created by making asymmetric morphing between the aircraft's wings.

Another design study was conducted to achieve a 44% change in wingspan in a project called Zigzag Box [42]. They designed a morphing wing that can provide a 22% increase or decrease in wingspan. It is noted that this wing, designed for a Medium Altitude Long Endurance (MALE) unmanned aerial vehicle, is heavier than conventional wings. The study results suggest that the wing design may provide a 5.5% increase in endurance; however, this ratio may decrease due to the weight increase.

Ajaj et al. [43] conducted a well-recognized wing morphing project. The GNAT Spar stands for Gear Driven Autonomous Twin Spar. In this study, a wing consisting of a gear and rail mechanism capable of increasing wing span by 20% was designed and produced. Wind tunnel tests were conducted, and a decrease in induced drag and an increase in aerodynamic efficiency was observed. The wing's covering was made of latex material, and the required actuation force was reported to be 55 N.

Ajaj and Jankee [44] have designed an unmanned aerial vehicle that can change its wingspan symmetrically and asymmetrically. The design is called "the transformer aircraft". A telescopic morphing wing mechanism that can increase wing span up to 50% using a rack and pinion mechanism has been manufactured. Wind tunnel tests and flight tests were performed, and the study resulted in an increase of 39.1% in the aircraft's endurance and 9.1% in its range for a constant lift coefficient. For asymmetric control, it was noted that the yaw control alone may not be sufficient, whereas it can be combined with conventional ailerons to increase the aircraft's roll control.

Planform morphing/wing chord morphing: Wing chord changing applications provide an alternative to conventional flap systems used in take-off and landing but do not provide a meaningful contribution to other phases of flight. It is, therefore, not a common focus in morphing wing designs for fixed-wing aircraft. However, there are studies on the blades of rotary-wing aircraft.

Perkins et al. [45] included a sled structure and sliding ribs placed next to each other in their design with the aim of achieving a similar goal. Telescopic rib use was also evaluated for the same purpose. The design was intended for air vehicles performing loiter flights in the air. Loiter refers to flights that involve circling in the air before landing or circling above a specific area during certain missions. The study indicated that since the lift distribution on the wing is elliptical, the increase in wind speed at the root of the wing would have a greater effect on increasing lift force.

In another study, Barbarino et al. [46] developed a concept wing flap design for a helicopter main rotor blade. A NACA 0012 airfoil profile was chosen for the design, which could increase the wing flap by up to 30%. An accordion honeycomb structure and aluminum parts were used to provide 40% deformation according to the length of the flap, resulting in a 30% increase in the wing flap. The elastic connections in the

honeycomb structure were designed to withstand low local stresses and sustain large global deformations. The study concluded that helicopters could operate at higher altitudes with this application, and advantages could be gained regarding rotor blade stall conditions.

Planform morphing/wing sweep morphing: The sweep angle is the angle between the wing axis and a line perpendicular to the wing root, drawn from a point 25% back from the leading edge of the wing. Aircraft that feature sweep angles are typically designed for supersonic or near-supersonic flight, which is also known as transonic flight. In this type of flight, the relative airflow over the wing is split into two components, and the flow over the leading edge of the wing is slowed down compared to the normal airflow. This helps to reduce the effects of compressibility but can also lead to a loss of lift at subsonic speeds. Research has shown that the best lift-to-drag ratios are achieved with sweep angles in the range of 40–45 degrees [47].

The sweep angle also affects the stability and control characteristics of an aircraft. Changes in the sweep angle of the wings can alter the position of the aerodynamic center and the center of gravity, thereby affecting the longitudinal stability of the aircraft. This technology has been applied especially in military aircraft to achieve efficient flight in both subsonic and supersonic regimes. Numerous studies have been conducted on the effects of sweep angle on flight stability in this field, particularly in the 1960s and 1970s [48,49].

Unmanned aerial vehicles are typically designed to fly at subsonic speeds, depending on their mission and size [50]. However, targeting unmanned aerial vehicles may be an exception to this.

Greatwood et al. [51] performed modifications on a commercial unmanned aerial vehicle model to add a mechanism that could alter the wing sweep angle. They developed a design that could change the wing sweep angle up to 30 degrees, allowing for lower changes in the angle during flight. The aim of the study was to achieve a landing similar to that of birds, where the aircraft could descend to very low speeds and glide to a stop. The modification was successfully tested on an aircraft with a stall speed of 9 $m.s^{-1}$, where the nose was raised during landing with the mechanism, resulting in a glide to a stop at a speed of 3 $m.s^{-1}$.

Out-of-plane morphing applications refer to the modifications made to an aircraft's wing without causing significant changes to the wing's dimensions and reference area. Examples of these applications include changes in twist angle, changes in dihedral angle, and applications that provide bending along the length of the wing.

Out-of-plane morphing/twist angle morphing: The application of twist on a wing is implemented to reduce and control the aircraft's tendency to stall and spin. Geometric or aerodynamic twist can be applied to a wing. Aerodynamic twist is achieved by altering the wing profile along the span of the wing. Geometric twist is achieved by changing the angle of incidence along the span of the wing. For example, the wing root can have an angle of $+3^\circ$ while the wing tip has an angle of -2°. This way, the root of the wing experiences a loss of lift first, giving the pilot more time to respond. Since ailerons are located at the wing tips, it is not desirable for the flow to separate there first. It is preferred that the loss of lift starts at the root of the wing in aircraft [52].

Garcia et al. [26] developed a morphing wing design to improve the control abilities of a micro-class UAV. The study involved implementing a change in twist angle along the length of the wing of a micro UAV with a 24-inch wingspan. The coating on the wing of the micro UAV was produced as a thin, semi-transparent plastic membrane. While the spars inside the wing provided the necessary support for the aerodynamic surface, the membrane created the aerodynamic surface. To enable the twisting motion, a torque rod was added to each wing.

Schlup et al. [53] designed an unmanned aerial vehicle with morphing wings that can alter its twist angle and the curvature of its horizontal tail, called the Matamorph-2. The XM-2 UAV, featured in the study, was reported to require no control surfaces due to the morphing capabilities of its wings and tail. The wing structure consists of balsa wood and composite layers, with polyurethane foam and a flexible coating material used in the

twist sections. This allows the wings to achieve a twist angle of up to ±15°. The morphing movement is achieved through a servo motor-driven gearbox located within the fuselage. As shown in Figure 4, the necessary twist changes were observed in the wings.

Figure 4. Matamorp-2 UAV with the wing twist capability. Reprinted with permission from Ref. [53]. Copyright © 2023 the American Institute of Aeronautics and Astronautics, Inc.

Out-of-plane morphing/dihedral angle morphing: Dihedral angle refers to the angle at which aircraft lifting surfaces are inclined to the horizontal plane. The use of dihedral angles in aircraft wings is related to roll stability and control. When planes enter a rolling motion onto one wing, different amounts of force are generated between the lower and upper wings depending on the direction of the relative airflow. Roll stability is also influenced by mounting configurations of the wing to the fuselage: such as upper wing, mid-wing, and parasol wing configurations. In low-wing aircraft, a positive angle may be preferred to increase roll stability, while in some high-wing aircraft, a negative angle may be used to increase roll control. In situations particularly encountered in cargo planes, this angle is referred to as anhedral [54].

Abdulrahim and Lind [55] presented a mechanism for changing the wing dihedral angle of an unmanned aerial vehicle inspired by seagull wings. The UAV was equipped with sensors and data recording devices, and flight tests were conducted to obtain data on its flight characteristics and maneuverability. By using a linear actuator, the inner and outer parts of the wing were made to have different angles with respect to the fuselage. A ±40° angle change was achieved.

Variable dihedral angles have emerged as another area of use for solar-powered unmanned aerial vehicles. Wing designs with dihedral angles that can change, such as the Z and N shapes as shown in Figure 5. These dihedral changes have been implemented to gather the changing angles of sunlight during the flight in the most effective manner [56]. Flight tests have been conducted, and the results indicate that longer flight times can be achieved and that the change in wing angle can be tolerated by control surfaces. Furthermore, it has been demonstrated that solar-powered flights can be efficiently conducted over a wider range of latitudes [57].

Figure 5. Wing dihedral change of solar powered UAV. Reprinted with permission from Ref. [57]. Copyright © 2023 the American Institute of Aeronautics and Astronautics, Inc.

Out-of-plane morphing/spanwise bending: The purpose of bending and changing the shape along the wing is to mimic the flight mechanics behavior of bird species that have the ability to 'wrap' their wings by continuously bending them along the transverse direction during the flight. This movement aims to reduce induced drag and increase the lift-to-drag ratio. These types of designs are called hyperelliptical cambered span (HECS) wings [58]. They can be expressed as inclined wing tip structures that continuously vary during flight.

Manzo and Garcia [59] have presented a HECS wing design that can change its shape during flight. The design includes wires made of shape-memory alloys, which enable the wing to undergo shape changes. Latex material was used to fill the gaps created by the morphing HECS wing design. Figure 6 shows the bending of the wing along the span and the compartment that contains the wires made of shape-memory alloys. Wind tunnel tests comparing the HECS wing and a conventional elliptical wing showed a drag coefficient reduction of up to 50% at angles of attack greater than 5°.

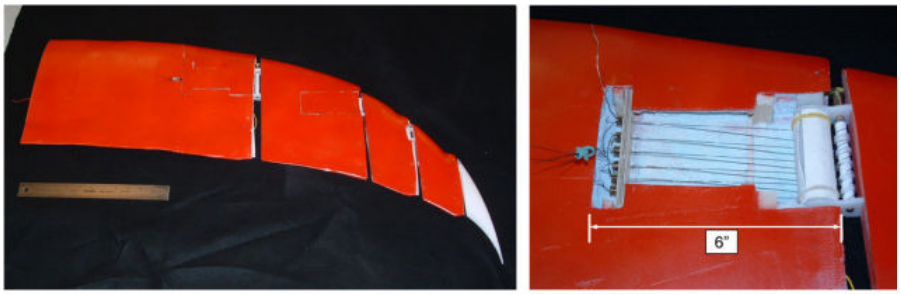

Figure 6. HECS wing design. Reprinted with permission from Ref. [59]. Copyright © 2023 IOP Publishing.

Airfoil morphing/thickness morphing: One of the most frequently studied topics in morphing wing applications is airfoil-focused morphing applications. Especially, the sub-topic of camber change shows the feature of being one of the most interesting issues. In addition to camber change, another two-dimensional morphing application that affects the profile of the wing is the one that changes the airfoil thickness. As the focus of this study, the applications with changing airfoil camber are given the latest and most detailed place in the literature survey.

Airfoils can be classified into two main categories: thin and thick airfoils. While thin airfoils have an advantage in terms of drag coefficient at high speeds, they suffer from lift loss compared to thick airfoils [60]. Hence, changing the thickness of the airfoil during flight can be considered a morphing application that increases the adaptability of the aircraft to different speed regimes and maneuvers.

Secanell et al. [61] studied the required airfoil parameters for a lightweight unmanned aerial vehicle to perform optimally throughout all flight phases. Their analysis demonstrated that a morphing mechanism capable of altering the camber and leading edge thickness can be used to create an optimal wing profile for all flight phases. They suggested that by changing the wing profile for all flight phases, the power required for flight decreases, and operational flexibility is achieved.

Airfoil morphing/camber morphing: Airfoils are selected for a specific speed regime and a specific mission. This selection determines the forces and moments that the wing will generate, giving the aircraft its character. Therefore, the choice of an airfoil and its camber distribution directly affects the aircraft's characteristics. When considering the motivation behind morphing wing applications, which allow aircraft to be designed for multiple roles, the importance of being able to change the airfoil camber during flight becomes apparent.

Ailerons and flaps, which are control surfaces located on the wing, are hinged structures that provide camber change [62]. Although trailing edge flaps are generally preferred for flap positioning, there are also applications called leading edge flaps [63,64].

In unmanned aerial vehicle wings, a component called a plain flap is usually preferred due to its simplicity [65]. Although the gaps in the hinge areas where flaps and ailerons are attached to the fixed part of the wing contribute positively to the performance of the

unmanned aerial vehicle during takeoff and landing, they create inefficiency by increasing drag during cruise flight [66]. Flap and control surface gaps are also a source of noise [67]. These gaps can also be eliminated by wing morphing.

The NOVEMOR (Novel Air Vehicles Configurations: From Fluttering Wings to Morphing Flight) project funded by European Commission with grant agreement number 285395 explored various strategies for wing planform and sweep angle modifications. The project evaluated the effects of these morphing approaches on performance, stability, control, and aeroelastic behavior. The drooping morphing leading edge concept was applied to a full-scale model of a wing tip of the reference regional jet aircraft, whereas the other concepts were applied to a half-size model of the wing tip of the joined wing UAV that was flight tested as part of the NOVEMOR project. According to the researchers, the tests conducted provided a significant result by experimentally demonstrating the feasibility of utilizing the morphing concepts. However, they highlighted the need for additional efforts to advance the development of these morphing concepts further.

In a recent study, Jo and Majid [68] performed an analysis of the effects of camber morphing for an existing aircraft, RQ-7a Shadow . Computational fluid dynamics analysis was applied for both the fixed wing and the morphing wing. NACA 4410, NACA 6410, and NACA 8410 airfoil geometries were used for the same wing chord during the analysis in the study. With the NACA 6410 airfoil, an expectation of a 17% improved flight endurance and flight range was presented as the result of the study.

Cheng et al. [69] designed a seamless morphing wing application. Their study focused on load bearing capability of the morphing trailing edge. Researchers applied 2D and 3D finite element method analyses and the results were compared to test results applied on an experimental prototype. The resulting design withstood 0.015 MPa aerodynamic load and realize 15% camber change.

Cadogan et al. [70] aimed to reduce wing weight and change the lift and drag coefficients of the wing by producing inflatable wings that are actuated by piezoelectric actuators and can switch between three different wing profiles by changing the camber line during flight. The wings shown in Figure 7 were produced and tested in the study. It was stated that the lift force obtained from the wing increased by providing morphing in inflatable wings.

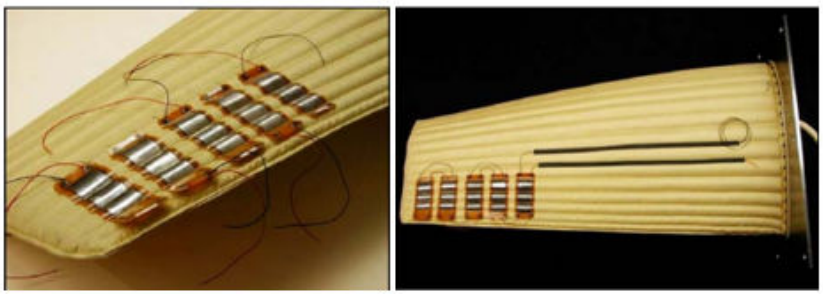

Figure 7. Inflatable morphing wing design. Reprinted with permission from Ref. [70]. Copyright © 2023 the American Institute of Aeronautics and Astronautics, Inc.

Zhao et al. [71] presented a design that can change the wing camber by using a rigid interconnected sliced wing rib structure. Flight tests were carried out with the wing produced for Talon UAV, a commercial unmanned aerial vehicle. It was stated that a flight efficiency of 14.1% was achieved compared to the conventional wing of Talon UAV. It was reported that there was a difference of 40 g in the weight of the produced wing due to the actuator and 4 g due to the adhesive weight. The wings were produced using balsa wood as the structural material and electromechanical units, namely servomotors, as the actuator units, as shown in Figure 8.

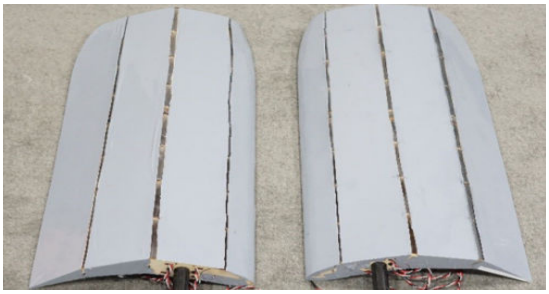

Figure 8. Inflatable morphing wing design. Reprinted with permission from Ref. [71]. Copyright © 2023 Elsevier.

Communıer et al. [72] presented a wing design with hollow ribs that can change the wing camber. The NACA 0012 airfoil was used in the study. Servomotors were used as actuators and the wing ribs with hollow designs were deformed through a lever arm as shown in Figure 9. Wood materials were used in the wing ribs and constructed with attention to the direction of the wood fibers for anisotropy. Wind tunnel tests showed that the prototype with the designed wing achieved higher aerodynamic efficiency compared to conventional wings with ailerons, and this was related to the reduction in drag. The weight of the designed wings was reported to be 725 g and the study results showed that there was no increase in weight compared to conventional wings.

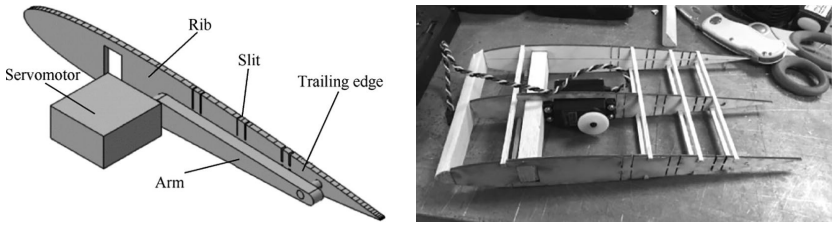

Figure 9. Morphing with hollowed wooden rib design. Reprinted with permission from Ref. [72]. Copyright © 2023 ELSEVIER.

Meguid et al. [73] designed a flexible rib structure that can interlock similar to Lego blocks in their study. The design aimed to be used in unmanned aerial vehicles weighing less than 10 kg. NACA 0012 airfoil profile was used as the basic structure, and a transition from this profile to NACA 6412 airfoil profile was intended. While the ailerons were conventionally kept at the outer part of the wing, a morphing region was created. The movement of the morphing region was provided by a servomotor-rocker mechanism. As a result of not using a flexible material in the outer covering of the wing, gaps formed in the area outside the morphing region (Figure 10). At the end of the study, it was stated that a successful and safe flight was performed with the morphing wing, and thus the design cycle was concluded.

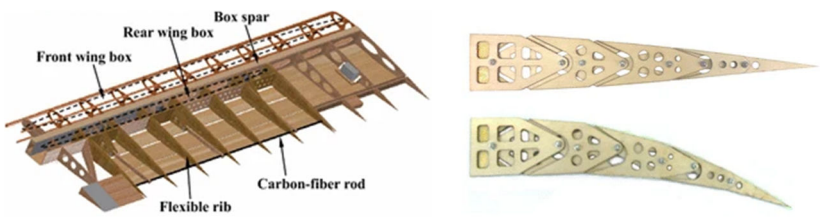

Figure 10. Sliced flexible morphing rib design. Reprinted with permission from Ref. [73]. Copyright © 2023 Springer Nature.

1.3. Fish Bone Articulated Camber Morphing Concept

The literature on fishbone-inspired morphing wings with adjustable camber distribution is presented as an additional section, as it is the main focal point of the study. The aim

of these applications, like other trailing-edge applications, is to increase aerodynamic efficiency by changing the camber of the airfoil, providing multifunctionality, and producing more efficient gapless and seamless alternatives to conventional control surfaces.

The first study in this field was a conference paper published by Woods and Friswell [74]. The abbreviation "FishBAC" was used for the first time. This abbreviation stands for fishbone articulated wing camber, meaning a wing camber that moves in a fishbone-like manner. The researchers introduced the FishBAC concept, which they believed had the potential to provide a nature-inspired approach that could enable continuous camber changes. As shown in Figure 11, a wing rib design with ribs and tendons consisting of rib and tendon voids was presented. These tendons were bonded to a pre-stressed wing skin. An elastomeric matrix composite was used as the wing's skin. A rigid leading edge was placed inside a D-box, and a rotating shaft was positioned for each rib along with a pulley to provide the capability of up and down movement for the trailing edge.

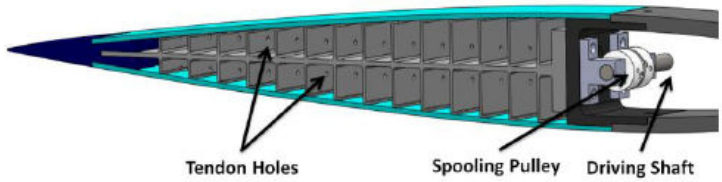

Figure 11. First FishBAC concept. Reprinted with permission from Ref. [74]. Copyright © 2023 the American Society of Mechanical Engineers.

The focus of this research was helicopter rotor blades. Thus, NACA 0012 airfoil was selected, and Xfoil analyses were performed with flapped and unflapped settings to understand the aerodynamic features of the resultant geometry. However, the authors noted that the concept could be modified and developed from small-scale UAVs to airliners and wind turbines.

As the developers of this concept, researchers defined three design criteria for guidance:

- Control Authority;
- Simplicity;
- Reliability.

Their research has employed a highly anisotropic and compliant structure with EMC skin. The fishbone-inspired spine provided the required anisotropy for the core. Pre-tensioning of the EMC was performed to eliminate buckling that may cause over the wing skin. Apart from the previous school of using smart materials as actuators and skin, they have excluded the smart structure approach in their concept. Maintainability, vulnerability to fatigue, and the cost basis of smart structures were provided as the main reasons for exclusion. In the research, analysis performed by the researchers brought promising results with an increase in lift coefficient.

Woods and Friswell [75] developed a new prototype for the FishBAC concept. The new test model was based on an OA212 airfoil. The tendon-shaped area has been moved rearward and narrowed to a 75–90 percent chord that differs from their first proposed concept, as shown in Figure 12. A series of benchtop tests and laser displacement sensor scans were performed to validate the analytical results. Tendon-shaped core coupled with the proposed mechanism and the intended concept was experimentally validated for the first time.

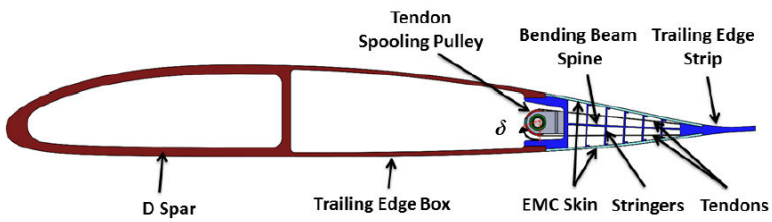

Figure 12. Second FishBAC concept with OA212 airfoil. Reprinted with permission from Ref. [75]. Copyright © 2023 the American Institute of Aeronautics and Astronautics, Inc.

The FishBAC concept was experimentally investigated using wind tunnel testing methods [76]. The study directly compared wind tunnel test results of the FishBAC wing and a conventionally flapped wing with the same airfoil—NACA 0012. The FishBAC test article did not employ an articulation mechanism since the aim was only to evaluate the aerodynamic performance. The test article had a 150 mm span and a 305 mm chord length with morphing that starts at 0.35 c and ends at 0.85 c. The flapped airfoil also had NACA 0012 airfoil and employed a conventional hinged plain flap with a 25% chord length. Figure 13 shows test articles side by side, FishBAC on the left and conventional on the right.

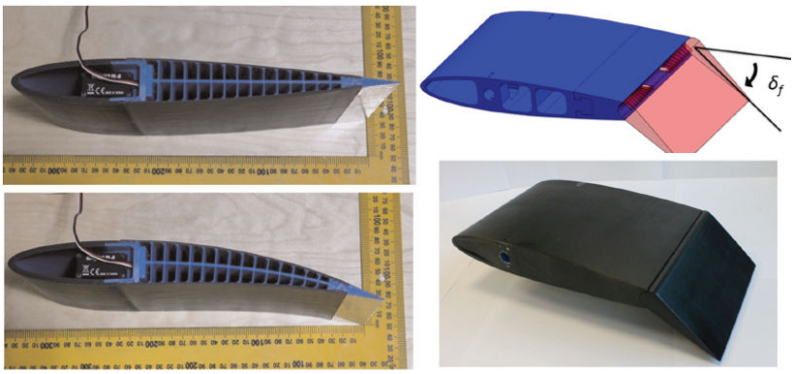

Figure 13. Test articles: FishBAC on the left and conventional on the right. Reprinted with permission from Ref. [76]. Copyright © 2023 SAGE Publications.

The wind tunnel testing results of the conventional and FishBAC test article proved that both wing articles could provide the same lift coefficient increment. However, the deflection of the conventionally flapped wing resulted in more drag force than the FishBAC article. Thus, the lift-to-drag ratio of the FishBAC wing article was higher. To be concise, the increase in lift-to-drag ratio was outlined as 20% to 25% with the FishBAC application [76].

A composite FishBAC prototype was developed by Rivero et al. [77]. In previous designs, isotropic polymers were used, and advantages can be achieved from anisotropic were not utilized. A composite spine for FishBAC has been designed and manufactured for wind tunnel testing. A modular leading edge and trailing edge model approach was embraced, and the FishBAC section was adopted from the previous design, as shown in Figure 14.

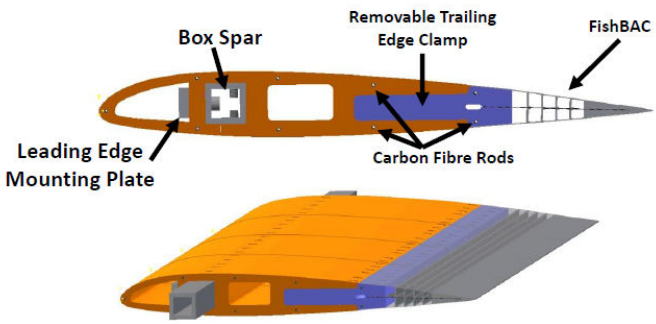

Figure 14. Modular FishBAC design CAD. Reprinted with permission from Ref. [77]. Copyright © 2023 Rivero, A.E.; Weaver, P.M.; Cooper, J.E.; Wood, B.K.S.

A conference proceeding paper was written by Martinez et al. [78]. Although the paper was entitled "Design, Analysis and Experimental Testing of a Morphing Wing" and did not mention the FishBAC concept, the resemblance should be noted in this survey. An original morphing wing concept was proposed to replace the radio-controlled Precedent T240 aircraft's wing, which was conventionally made within the construction methods with a fixed wing section and hinged aileron control surfaces. Unlike the previous FishBAC designs, this design combined spine and stringers and added a torsion rod for actuation.

The wing sections were manufactured from low-cost and available materials such as balsa wood, aluminum, and three-dimensional printer thermoplastics such as PLA and ABS. Figure 15 shows the slotted wing rib structure and wing skeleton. CFD analyses and structural computations were also presented in the paper with promising results. Additionally, by employing a Scanning Laser Doppler Vibrometer, an electrodynamic shaker, fixing support, and scanning vibrometer software, the main wing structure dynamic characteristics were obtained and presented.

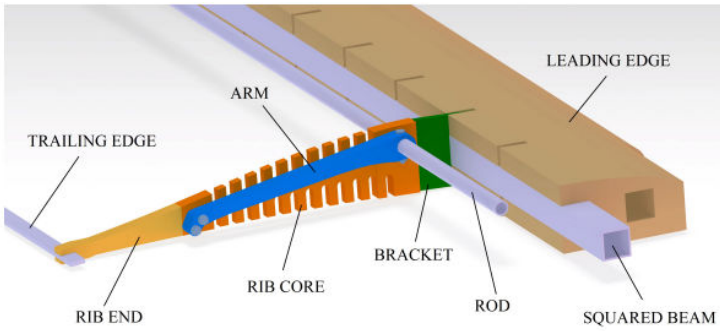

Figure 15. Morphing wing CAD model. Reprinted with permission from Ref. [78]. Copyright © 2023 the American Institute of Aeronautics and Astronautics, Inc.

The wing skin was composed of 80% cotton and 20% spandex resulting in a fabric like that of swimming suits, hence it provided the required elasticity of the skin, and the skin was attached using Velcro strips mounted onto ribs and the wing.

A FishBAC wing section that utilizes the RC aircraft Precedent T240's wing properties was developed. The morphing wing was designed to have the same geometry as the conventional counterpart for precise comparisons of the airfoil. XFLR5 software that uses Xfoil code was used to evaluate the aerodynamic performance of the conventional flapped version and the FishBAC version of the wing section. Additionally, a MATLAB-based solver, TORNADO, was used similarly for analyses. A compliant FishBAC prototype was developed for wind tunnel testing, as shown in Figure 16 [79]. As in previous designs, FMC skin was employed in this design, but without the bottom side of the wing cover. On the bottom part, a thin aluminum plate was preferred. A compliant morphing skin using the FMC concept with silicone and carbon fiber was designed, manufactured, and tested. However, apart from the first and second-generation FishBACs, a torsion rod was employed to perform the articulation. In the conclusions, as expected, given the same lift coefficient, the morphing wing had a higher lift-drag ratio than the conventional T240 wing.

Figure 16. FishBAC design. Reprinted with permission from Ref. [79]. Copyright © 2023 RMIT University.

A novel 3D-printed skin was used in a FishBAC design [80]. These skin panels were manufactured using two different thermoplastic polyurethanes. Additionally, modularity between actuation and installation was employed in this design. A wing part with a 1-m

span, 0.27 m chord, and 25% FishBAC area was built and used for experiments. Benchtop-proof load tests were also performed to provide robustness to the design. The new design also provided a change in pitching moment, and the lift coefficient increased around 0.55, thus showing potential for FishBAC technology as a promising control surface substitute.

1.4. Conclusions from the FishBAC Concept Literature Survey

In the examined FishBAC applications, different movable area percentages, and materials have been selected for application and design, but it has been observed that each FishBAC application consists of four parts: the rigid/fixed part, the movable part, the actuation element, and the wing cover that gives the wing its aerodynamic shape.

The integration of these four parts creates a successful FishBAC wing component. From a systems engineering perspective, all of these parts should be designed using the design philosophy used for the component's design. In other words, the control authority, simplicity, and reliability principles that are expressed as the fundamental approach of FishBAC wing components, and should also be applied in the design of these parts and material selections.

When investigating FishBAC applications, an increase in the use of 3D printing techniques can be observed in recent studies; 3D printers are advantageous in prototyping because they allow users to print final products with high precision. In addition, their fast-printing capabilities make them another advantage in integrating these devices into the design process. The wide range of 3D printing materials that have emerged with the development of thermoplastics and additive filaments provide designers with advantages.

Future research on this subject should offer different approaches regarding additional weight and production costs. In addition to aerodynamic and structural comparisons between conventional and FishBAC designs, data such as weight and cost should be added to reports and articles to provide the reader with a feasibility understanding. Design principles such as aiming for low operating energy requirements and considering lightness in the designed structures will be important. To overcome biases based on weight and complexity against morphing wing designs, extra mechanisms and parts should also be avoided in FishBAC designs.

1.5. Novelty of This Research

This research presents pioneering research on the Rear Spar Articulated Wing Camber (RSAWC), making a significant and original contribution to the realm of morphing wing applications. The RSAWC represents an unprecedented and innovative design approach, utilizing a fishbone-like morphing wing rib with rear spar articulation in a cost-effective manner. Notably, this concept has remained unexplored until now, and findings unlock fresh avenues for future investigations within the domain of morphing wing applications. The distinctiveness of work lies in the successful development and rigorous flight testing of the RSAWC, implemented on the specially designed UAV known as the Stingray, which serves as a testament to the novelty and potential impact of research.

The contribution of this study lies in the direct comparison conducted between a conventional wing and a morphing wing, both subjected to extensive flight testing. Moreover, the article addresses critical aspects such as weight, cost, and complexity, which have been notably underrepresented in the existing literature. Notably, the blended wing-body configuration of the Stingray UAV necessitated the adoption of elevon hybrid control surfaces in lieu of traditional ailerons or flaps on the wings. As a result, the RSAWC wing successfully underwent comprehensive testing and flight evaluations, encompassing both symmetric and asymmetric conditions. In light of these accomplishments, the flight of the Stingray UAV emerges as a remarkable milestone in aviation history, constituting the pioneering flight of a fixed-wing aircraft devoid of any control surfaces, as confirmed through meticulous literature research conducted by esteemed researchers.

2. The Design Process of Rear Spar Articulated Wing Camber (RSAWC)

The methodology found in the FishBAC literature was adopted for RSAWC. It is aimed to change the wing trailing edge camber to be maintained continuously throughout the flight. The approach of keeping the cost of the application low was adopted and developed as a cost-effective concept. In addition, it was considered important that the concept does not bring dramatic effects that increase the weight and complexity of the system.

An unmanned aerial vehicle design has been carried out to implement the concept. An unmanned aerial vehicle design has been carried out to implement the concept. For this purpose, the Stingray unmanned aerial vehicle was designed and produced. The Stingray UAV is designed as an innovative UAV with a blended wing-body and flying wing design and an electric ducted fan. It is aimed to produce all possible parts of the Stingray UAV with the 3D printing method, thus minimizing time costs.

2.1. Test Platform: The Stingray UAV

In the study, a test platform for a UAV was needed for the experimental implementation of the morphing wing design. In previous studies, two approaches were applied in this regard: modifying the wing of a ready-made model aircraft or examining wing structures that do not belong to any UAV as if they were a UAV wing. A different approach was used. An unmanned aerial vehicle was designed specifically, and two different variants were produced with both fixed and RSAWC concepts.

The Stingray UAV is so named because it takes inspiration from the unique features of the Stingray fish, known for its slim and flat body with butterfly-like wing structures. The UAV is designed as a flying wing, and its iconic appearance is reminiscent of the Stingray fish. Furthermore, the application of fishbone-inspired morphing wings in the design of this unmanned aerial vehicle has also influenced its naming after a fish species (Figure 17).

Figure 17. The Stingray UAV with conventional wings.

For the manufacture of conventional wings, the core section was produced from white insulation foam with a density of 16, using a computer numerical control hot wire. Carbon fiber tubes were cut to the appropriate size and placed in the core to support the front and rear spars using epoxy adhesive. Conventional elevons were supported from above and below with 1 mm balsa wood, covered and hinged to the wing. The wing was coated with a thermoplastic radio-controlled aircraft covering, using an iron and a heat gun during the coating process. The technical specifications of the Stingray UAV are presented in Table 1.

Table 1. Stingray UAV Technical Specifications.

Wingspan	**1.36 m**	**Take-Off Weight**	**1.4 kg**
Wing chord	0.264 m	Wing loading	3.256 kg.m^2
Ref. wing area	0.436 m^2	Airfoil	PW-51
Dihedral	5°	Aspect ratio	4.291

A reflex-type airfoil, the PW-51, was utilized in the Stingray UAV. This airfoil shown in Figure 18 developed by Peter Wick, is commonly employed in "plank" class flying wings. The rationale for adopting the flying wing configuration with a plank and reflex airfoil in the design of the Stingray UAV stems from the application of morphing wings.

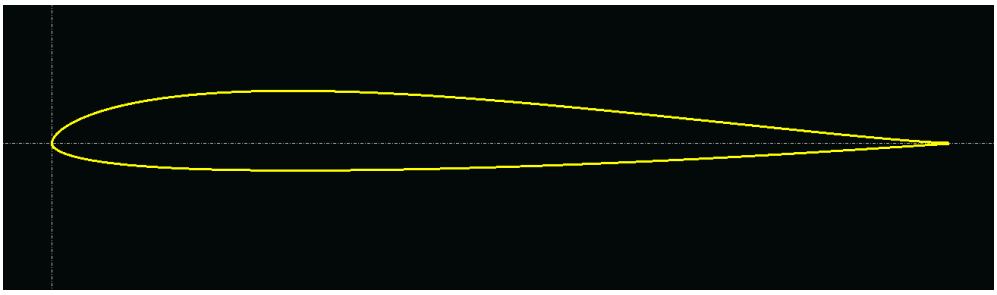

Figure 18. PW-51 airfoil.

It is anticipated that incorporating a sweptback wing design might introduce complexities in the design and implementation of morphing wings. Thus, the plank layout for the Stingray UAV was selected, as shown in Figure 19.

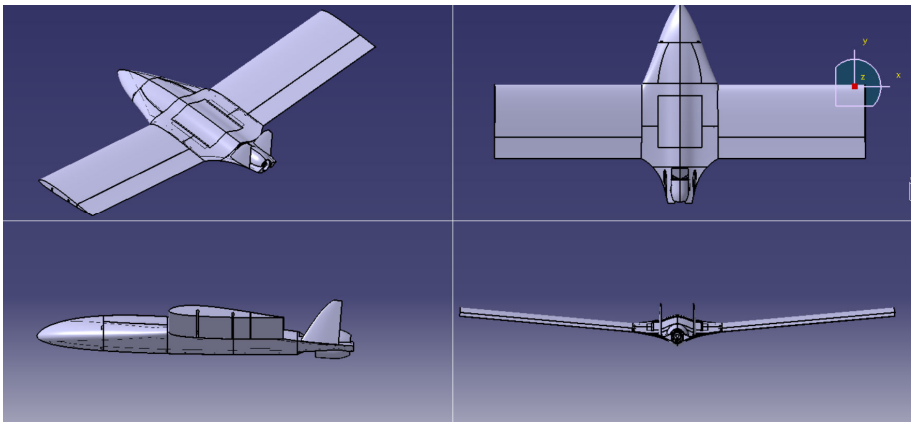

Figure 19. Solid model of the Stingray UAV.

The first flight test of the Stingray UAV prototype was conducted on 7 July 2022. The aircraft was piloted by Yavuz Dal. The flight was initiated by hand launch as Figure 20 shows, and the aircraft flew in a pattern of 300 m in length and 100 m in width after reaching an altitude of 30 m. No trim was given to the aircraft and a cruising flight at 45% throttle was performed.

Figure 20. Flight testing of the Stingray UAV with conventional wings.

After the test platform successfully performed its flight testing, the development process of RSAWC morphing wings for the Stingray UAV started.

2.2. RSAWC Wing Development for the Stingray UAV

After the design, analysis, and flight tests of the Stingray UAV were completed, the design process of the RSAWC wing has begun. The RSAWC wing was designed to have the same dimensions as the conventionally produced wing.

The RSAWC wing is designed to have the same dimensions as a wing produced with conventional methods. The design aims to provide uninterrupted camber changes during flight and to target a higher lift-to-drag ratio compared to conventional control surfaces. While pursuing these objectives, the design adhered to the principles of control authority, simplicity, and reliability.

In the scope of this work, weight and complexity objectives were also set for the RSAWC wing design. To respond to prejudices against morphing wing technologies, minimizing weight increase and not increasing system complexity were targeted. Previous studies have shown the use of electromechanical units called servomotors for the activation of morphing wings, with machine elements such as pulleys sometimes added to these systems. In addition to these, structures that provide activation energy such as shape memory composites and piezoelectric materials have also been used.

The most unique aspect of the design performed in this study is that the wing articulation for the morphing wing is achieved by rotating a structural component called the rear spar. In the Stingray UAV's conventional wings, the movement of control surfaces is accomplished with servomotors located on the wings. In the RSAWC wings of the Stingray UAV, these servos are placed inside the fuselage to rotate the rear spar, allowing the rotation of the wing ribs with the fishbone form around this rear spar.

A destructive move has been made toward the "weight penalty of morphing structures" myth by using a structural component as the activation mechanism of the RSAWC wing. In terms of complexity, when evaluated, it is revealed that the technique does not increase complexity since there is no additional component or machine element added; only the servomotor located on the wing is positioned inside the fuselage with an addition of a basic bearing with a 6 mm diameter.

A modification was made to the previous FishBAC technique by designing a structure where there is no clear distinction between the rigid part and the moving part. In this design, the focus of elastic deformation is on a point where the articulation capability is achieved not through a joint point around which a rotational movement is made, but rather in a way that it will be a point where elastic deformation will be concentrated. Figure 21 shows the location of the servomotor located inside the fuselage.

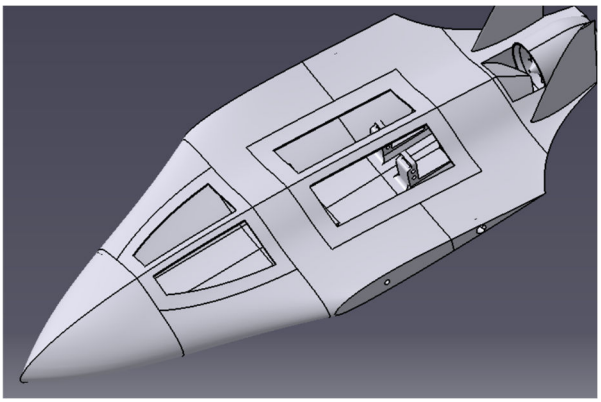

Figure 21. Stingray UAV fuselage.

To ensure that the RSAWC wing is identical to a wing produced by conventional methods, rib design was performed with a wing chord of 0.264 m. During this process, 11 different rib models, were drawn and tested. On the 11th rib where the design was frozen, aileron movements were able to be carried out within the limits of elastic deformation, just like in the conventional wing. A rib thickness of 1.618 mm was selected, and nine ribs were

placed in a half wing with a spacing of 66 mm between them. After the rib design, the three-dimensional modeling of the wing was carried out as shown in Figure 22. Support surfaces were drawn on the leading and trailing edges of the wing for the integration of the selected coating.

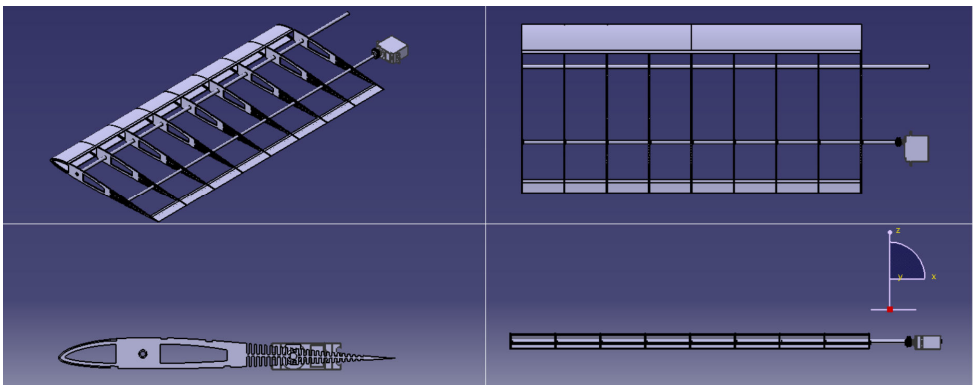

Figure 22. Stingray UAV wing solid model.

After creating the 3D model of the wing, a static analysis was carried out using the finite element method to calculate the required servo torque and examine the functionality of the system. The servo moment values used in the analysis were given a 15% tolerance, taking into account that the wing is without a covering and devoid of aerodynamic loads. Figure 23 shows the upward and downward deformation of the wing in its static analysis.

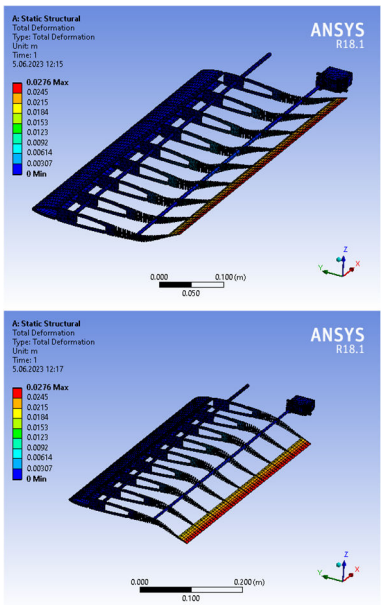

Figure 23. RSAWC wing FEM analysis.

Finite element analysis (FEA) is a method that can be employed to investigate the structural optimization and design enhancements of UAVs [81,82]. In Figure 23, the finite element analysis method was utilized to determine the maximum deformation and displacement. After examining the deformation of the wing, differences in deformation between ribs were observed due to the absence of covering material. However, it was evaluated that these differences would disappear after the wing was covered. A Tower Pro mg946r metal gear servo with a torque value of 10.5 kg.cm^{-1} was used as the electromechanical unit to provide articulation of the rear spar in the morphing wing. After the servo selection was completed, a first prototype was produced, and the functionality of the system was tested.

2.3. RSAWC Wing Manufacture of the Stingray UAV

Following the completion of 3D printing of the nine wing ribs in a wing, cyanoacrylate adhesive was used to bond the wing ribs and spars together. Then, the rear spar-servo motor connection was also provided using the same bonding method. Figure 24 demonstrates the functionality of the first RSAWC concept prototype test with upward and downward elevon movements.

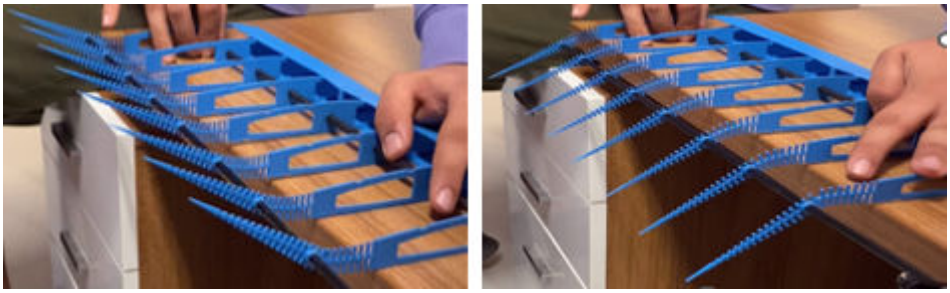

Figure 24. RSAWC wing concept functionality test.

During the functionality test, the following observations were made:

- The torque of the selected servo is appropriate when considering the tolerance value applied to the wing without cover.
- Continuous control authority has been achieved during upward and downward movements, as well as during transitions between movements.
- The differences between the rib deformations observed in the analysis performed by the finite element method were also observed in this functional test. It is anticipated that the deformation differences between the ribs will be eliminated with the addition of the cover.

After conducting a functionality test on the first prototype that was produced successfully, a wing cover was needed to be applied to validate the design. Thus, second prototype manufacture was performed.

There has not been a radical change in the materials used in the production of the second prototype compared to the first prototype. Lightweight PLA material was used for the 3D printing of the wing ribs, carbon fiber material for the wing spars, and cyanoacrylate for the bonding process. The most significant difference between the first and second prototypes is the presence of a coating. In the second prototype, a thermoplastic Oracover coating has been integrated. Additionally, longitudinally cut balsa wood supports produced using laser cutting have been used to enable adhesion of the coating. This ensures that there is no deformation in the coating and that the shape change of the wing is transmitted continuously in the lateral axis. For the leading edge of the wing, a D-box part made of lightweight PLA material was produced using the vase mode. Figure 25 shows the parts used to produce the second prototype.

Figure 25. FishBAC wing second prototype materials.

After the assembly of the RSAWC wing was completed, it was attached to the same fuselage as the conventional right half-wing, and the size and angle controls of the wings were performed. Thus, it was verified that the wing frame was constructed with the correct dimensions and without any warping between the ribs, as shown in Figure 26.

Figure 26. RSAWC wing equality test.

After quality validations were performed, the covering process of the second prototype of the RSAWC wing was carried out. During the covering process, cyanoacrylate adhesive, covering iron, and a heat gun were used. After the covering process was completed, an improvised desktop test rig was prepared, as shown in Figure 27, and the wing's morphing capability was tested.

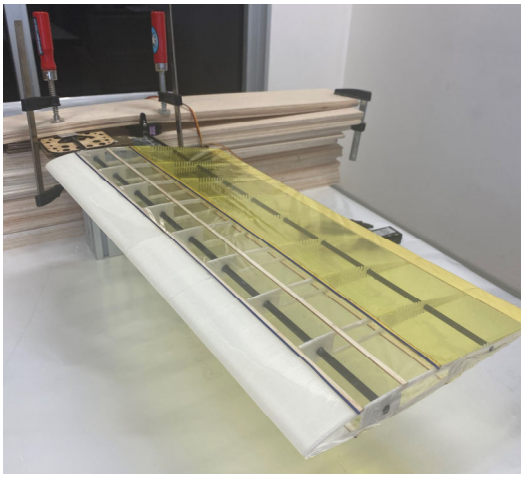

Figure 27. RSAWC with wing cover.

3. Desktop Testing of RSAWC Wing Concept

The mechanism tests were carried out in two stages. In the first stage, the morphing capability of the second prototype of the RSAWC wing was examined in a desktop test setup as seen in Figure 27. In this first testing stage it was observed as in Figure 28, that the desired up and down elevon morphing capacity in the design was achieved with the applied method and provided electromechanical torque.

Figure 28. Desktop testing of RSAWC wing.

In the second stage, conventional and morphing wing prototypes were installed on the same Stingray UAV body, and their movements were compared. The symmetric and asymmetric movements that the elevon control surface should have were performed, and the motion displacements were examined. Figure 29 shows the result of these tests.

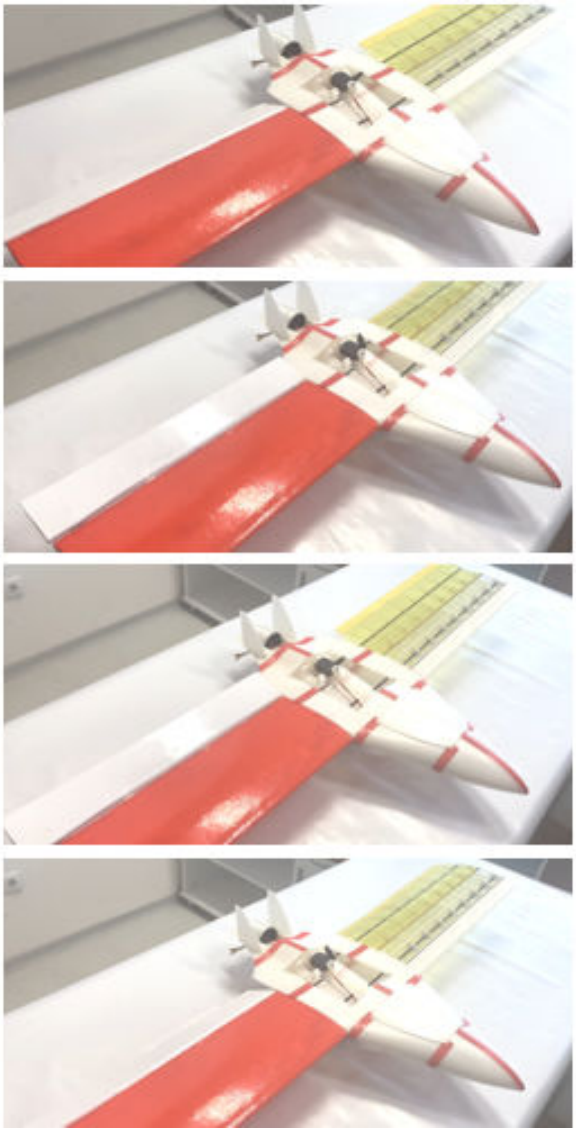

Figure 29. Elevon movements using conventional and RSAWC wings.

4. Flight Testing of RSAWC Wing Concept

During the literature review of morphing wing studies, it was observed that only a few studies have progressed to the flight-testing stage. The scope of these studies is

generally focused on giving a shelf-bought UAV wing the ability to change its shape and conducting tests on it. RSAWC wings with completely equivalent morphing capabilities to conventional wings were produced for the UAV, and flight tests were carried out.

As expressed in Section 2.1, experience had already been gained regarding the flight characteristics and piloting of the Stingray UAV platform with conventional wings. The biggest problem ahead of this flight, which was to be carried out for the completion of this study, was seen as the human factors that could occur during the hand launch. In addition to the unmanned aerial vehicle having sufficient thrust and being able to fly during the hand launch process, it is also very important for the hand launcher to apply enough force at the correct attack angle and with the plane's wing parallel to the ground axis. During the flights carried out by the researcher with the Anatolia Aero Design UAV research team, it was experienced several times that these factors, which can be expressed as human factors, came into play during the hand launch.

In the Stingray UAV, the hand-launching method was employed due to the associated weight and drag penalties. This take-off method brings forth considerations related to human factors. Alternatively, a three-wheeled tricycle landing gear configuration could have been utilized, offering improved ground control and handling capabilities instead of hand launching. The use of three-wheeled landing gear configurations and taxi control has been an area of research emphasis for defense and surveillance UAVs [83].

In order to ensure the safety of the Stingray UAV with morphing wings during its initial flight, a unique approach was taken due to the time required for the aircraft's morphing capabilities. Rather than launching the UAV by hand, it was determined that taking off from a moving platform would reduce risk. After considering both a car and a motorcycle, it was decided that the motorcycle was the more suitable option. However, due to the potential for human factors if the launcher were to release the UAV from their hand while seated behind the motorcycle, a mechanism was constructed. The mechanism was made from cardboard rolls wrapped in thermoplastic aircraft covering films and pieces of fabric. It was positioned at the center of the Stingray UAV and was designed to provide a 5° attack angle, as shown in Figure 30.

Figure 30. Launching mechanism built for the Stingray UAV.

The flight test of the Stingray UAV with its RSAWC wing was conducted on 11 December 2022, under the piloting of Dr. Yavuz Dal. The aircraft was launched from a moving motorcycle. The flight test was performed with a wind speed of 6 m.s^{-1}. After reaching an altitude of 30 m, a flight pattern of 200 m in length and 100 m in width was flown.

During the flight, no trim was given, and the cruising flight was performed at approximately 40% throttle. There were no handling difficulties or control problems experienced compared to conventional wing flight. The RSAWC wing successfully executed both symmetric and asymmetric movements of the elevons, and the flight characteristics were similar to the conventional wing flight in terms of handling. Figures 31–33 show photographs taken during the flight.

Figure 31. Take-off of the Stingray UAV with RSAWC wings.

Figure 32. A photo of the Stingray UAV with RSAWC wings during flight.

Figure 33. A photo of the Stingray UAV with RSAWC wings at approach.

The test flight, which lasted approximately 3 min and 36 s, was successfully completed with a landing, and the aircraft was stored. The flight video can be accessed online at the link "https://youtu.be/qO4vxypVH04" (accessed on 5 June 2023).

5. Results and Discussion

5.1. Complexity Evaluation

A unique articulation method called RSAWC has been developed for the Stingray UAV. This method enabled articulation without adding an extra rotating part, electromechanical unit, or machine element that would increase complexity. This design, which is also the subject of a patent application, involves the servomotor in the wing being retracted into the body and the rear spar, which is normally a structural element, being rotated from the body.

In addition, a bearing has been added only to the point where the wing rear spar is connected to the fuselage. Considering that the hinges used in conventional control surfaces and the pull-push rod structures that transmit servomotor movement are eliminated, it can be said that this bearing compensates for its weight. When evaluated in terms of complexity, it can be claimed with a qualitative view that complexity is reduced since the possibility of coming out of the sockets of hinges and pull-push rods is eliminated.

5.2. Weight Evaluation

The weights of the conventional wing and morphing wing of the Stingray UAV were measured as 150 g and 186 g, respectively, after both wings completed flights. This 36 g weight increase corresponds to a 24% increase in wing weight. The main factor in the weight increase was the replacement of the servomotor. A servomotor with higher torque than the one used in the conventional wing was placed inside the fuselage.

Considering the torque of the servomotor used both during testing and flight, it is understood that a more precise study could have been conducted in the selection of a lighter servomotor. The servomotor used in the conventional Stingray UAV wing weighed 138.5 g when weighed together with the morphing wing. Figure 34 shows the weighing process of both wings with the same servomotor.

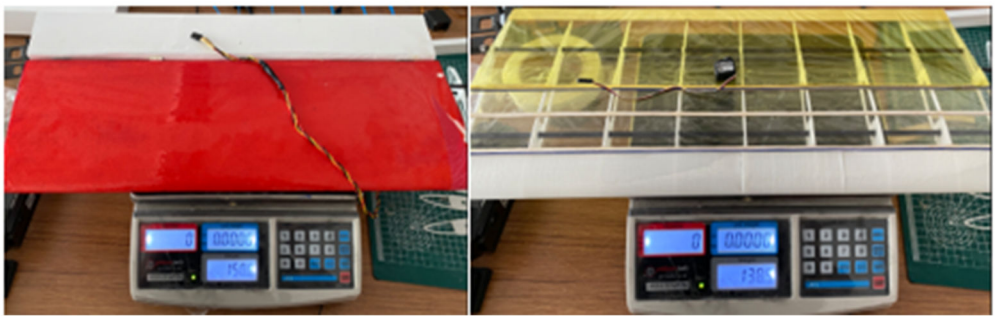

Figure 34. Weighing process for both wings.

As a result of the torque of the servomotor used during both the testing process and flight, it has been understood that a more sensitive study in terms of servomotor selection could lead to the selection of a lighter servomotor. As shown in Figure 34, the servomotor used in the conventional Stingray UAV wing weighs 138.5 g when weighed together with the RSAWC wing. However, if a servomotor with an intermediate value between these two servomotors is selected specifically for this study and used, a value of 150–155 g will be obtained. This indicates that the conventional wing and the RSAWC wing can be produced with equal weights or within a 10% weight margin.

5.3. Cost Evaluation

From the design stage of the study, a cost-effective design approach has been adopted. This perspective was to design and develop a low-cost and accessible design and produc-

tion process, as opposed to studies that implement using shape memory composites and piezoelectric materials.

In the construction of the Stingray UAV, Lightweight PLA printing material, which is now used in 3D printers that most consumers even have in their homes, was used as the main structural material. This material and production method were chosen while also considering the time cost.

In the RSAWC wings of the Stingray UAV, ribs and leading-edge D-boxes were 3D printed using PLA. Balsa wood plates were cut with a laser cutter to support the wing covering. Carbon fiber tubes were used for the wing spars. A thermoplastic model aircraft covering was used for the wing surface. There is no material or production method among these materials that a model aircraft enthusiast cannot access. In addition, there is no structure that will create a big cost difference when compared to the materials used in conventional wings. In light of these evaluations, it can be stated that the objectives of the study have been achieved in terms of cost.

5.4. Performance Evaluation

In the process of wind tunnel analyses performed between Stingray UAV's RSAWC wing and the conventional wing, a 15.2% increase in lift-to-drag ratio was observed in zero angle of attack—unflapped cruise condition. This increase in L/D is mainly sourced from the control surface gap. In a zero angle attack 30 deg flapped state, L/D increased 37.8% for the morphing wing. Thus, the RSAWC wing provides increased efficiency in cruise flight by preventing gaps in the hinge line on conventional control surfaces. As a footnote, a comparison between the gap-sealed conventional control surface and the RSAWC wing should also be implemented as a future study to provide a direct result of geometry change.

Although there are differences in wind conditions between the flight tests performed with the two wings, the throttle arm was used at a lower level of 5% in the RSAWC wing flight. This means that a lower drag force is observed to be encountered. The conventional wing cruise flight was sustained with a 45% throttle arm. The RSAWC wing cruise flight sustained with a 40% throttle arm.

According to the statical thrust tests, current drawn from the electric motor decreases by 2.6 A in between these throttle positions, indicating a higher flight endurance with the same battery capacity. The battery used in both flights was a 4-cell LiPo battery with a 1300 mAh capacity. With the semi-empirical results, a calculation for flight endurance was performed and an 18.75% increase in cruise flight duration was found. Figure 35 shows the change in battery capacity in two wing configurations.

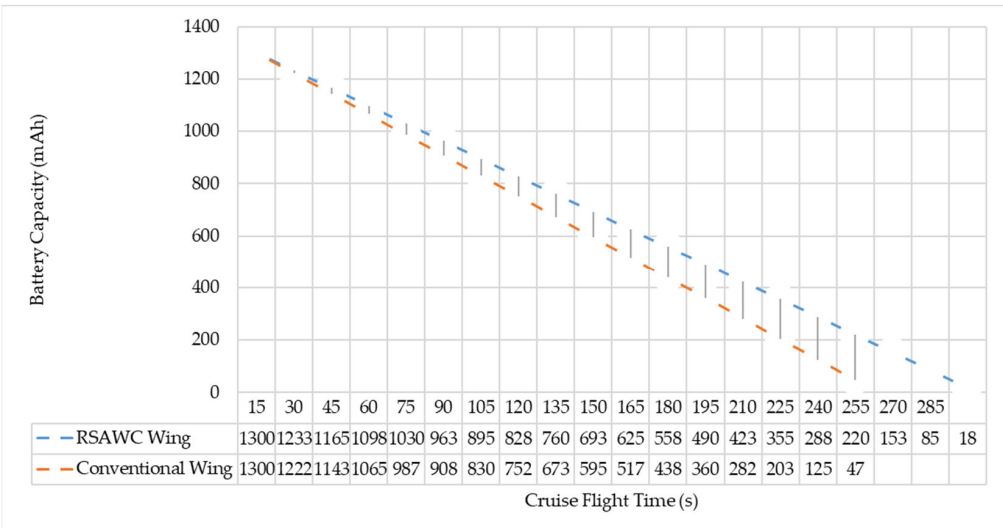

Figure 35. Flight endurance calculation for conventional and RSAWC wing.

Both the theoretical and practical studies on the performance of the RSAWC concept will be detailed in future studies by performing instrumental flights. However, an earlier performance evaluation provides performance advantages compared to conventional control surfaces without penalties on weight, complexity, or cost.

6. Conclusions

A special and innovative unmanned aerial vehicle has been designed within the scope of the study, which includes boundary layer ingestion, ducted electric motor, and blended wing-body structure. Designing this UAV has enabled the direct comparison between a conventional wing and a morphing wing, both of which were flight tested in the study. Instead of a generic process for designing, producing, and analyzing a morphing wing, a more detailed process was preferred. This allowed for concrete results to be presented regarding flight tests with a morphing wing, which is still a rare occurrence in the literature. Detailed assessments were made on topics such as weight, cost, and complexity, which were found to be lacking in the literature.

Due to the blended wing-body structure of the Stingray UAV design, elevon hybrid control surface movement was required instead of ailerons or flaps on the wings. Therefore, the RSAWC wing was able to achieve testing and flight in both symmetric and asymmetric conditions. In this context, it can be stated that the flight of the Stingray UAV is among the aviation firsts, as it is also the first flight of a fixed-wing aircraft without any control surfaces, according to the researchers' literature queries.

Future Directions on RSAWC Concept Research

PLA 3D printing material was used both in Stingray UAV's fuselage and wing parts. Using another 3D printing material with a longer lifespan and higher temperature resistance would be suitable for the RSAWC wing application. Many 3D printing consumables that can be an alternative to PLA are being developed. The printing of these materials and the identification of more suitable materials with 3D printing devices and the supply of these consumables should be included in future studies.

For covering the RSAWC wing, thermoplastic model aircraft covering film was used. This covering film caused problems in adhering to the ribs and resulted in wrinkles in some areas. In order to adhere to the weight and cost targets, future studies should focus on researching new types of covers. Developing more suitable techniques for the connection of covers and the wing frame could also emerge as another direction.

Except for qualitative observations and feedback from the pilot in flight tests conducted in the study, no data could be collected. By integrating a flight card and placing various sensors, roll movement can be measured in degrees/seconds, changes in stall speed and cruising speed can be observed, and current values drawn by the engine can be measured. Flying the same flight pattern with both wings and collecting these data under autopilot control will provide valuable information to the literature.

Reducing the magnitude of movement towards the wing tip in a controlled movement that extends along the span of the wing will provide the opportunity to reduce the formation of wing tip vortices. Using a rear spar with an increasing diameter from the wing root to the wing tip and changing the magnitude of the morphing movement regionally to examine its results have been determined as another route that future studies can focus on.

The potential applicability of the RSAWC wing design to larger UAVs, general aviation aircraft, and even passenger aircraft is a key area of interest. Scaling the design is an important consideration in this regard and will require further examination. This could involve evaluating the strength and durability of the materials used in the design when applied to larger aircraft, as well as potential modifications to the design itself. In addition, factors such as weight and cost may need to be taken into account when considering the viability of using this design on larger aircraft. Overall, while there is potential for the RSAWC wing design to be applied to larger aircraft, further research and analysis will be necessary to determine its feasibility and potential benefits.

7. Patents

A patent application has been realized. It is at the decision stage.

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