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DESIGN, DEVELOPMENT AND FABRICATION OF WINGS EMBEDDED WITH MORPHING TECHNOLOGY

Tamur Ahmed
Department of Mechanical and Aerospace Engineering
Air University, Islamabad
190573@students.au.edu.pk

Jahanzeb Masud
Department of Mechanical and Aerospace Engineering
Air University, Islamabad
Jahanzeb.Masud@mail.au.edu.pk

Salaar Ahmed
Department of Mechanical and Aerospace Engineering
Air University, Islamabad
190615@students.au.edu.pk

Rija Roy
Department of Mechanical and Aerospace Engineering
Air University, Islamabad
190639@students.au.edu.pk

Syed Irtiza Ali Shah
Department of Mechanical and Aerospace Engineering
Air University, Islamabad
irtiza@mail.au.edu.pk

Abstract

Morphing aircraft and unmanned aerial vehicles (UAVS) are expected to have a multirole capacity, allowing them to adapt to changing mission environments. A UAV model is required to efficiently and quickly calculate the attributes of numerous wing variants. Unmanned Aerial Vehicles (UAVs) are increasingly being used in unconventional and asymmetric military missions, as well as in a variety of civic situations. With dynamic onboard reconfiguration capabilities, UAVs are designed to accommodate conflicting mission objectives. The ability to accomplish a wide range of missions is severely limited by the traditional fixed-wing aircraft configuration. Wing morphing has been offered as a method to modify a flying vehicle's aerodynamic features while it is in flight. A morphing aircraft is a type of aircraft that may morph/ change geometry while in flight to boost efficiency. Traditional aircraft wings are a sacrifice that enables the plane to fly in a wide range of conditions while offering sub-optimal performance in each of those. Morphing shows potential as little more than a future enabler technology for next-generation aircraft. Wing morphing technologies seek to make the aircraft increasingly energy and aerodynamically efficient by actively changing the wing configuration during flight. Morphing offers hope as a future facilitator innovation for next-generation aircraft. Wing morphing technologies strive to make airplanes more power and aerodynamically efficient by actively changing the wing form during flight. These wing and tail form variants may be used to facilitate rapid directional changes, slow flight without crashing, and minimize drag during high-velocity flight. This study's overarching goal is to investigate the effects of readily adjustable wing sweep and wingspan on aerodynamic and flight stability characteristics.

Keywords: Morhphying, UAV, performance, characteristics, wing sweep, wing span

1. INTRODUCTION

The word morphing in the Oxford language dictionary means a smooth gradual transition from one phase to another. In the field of smart structures, the word has a somewhat similar topology meaning gradual transition of structure with respect to externally applied conditions. Wing transforming is the streamlining of the optimal design of an airplane by effectively changing the wing state of the airplane during flight. Not just that transforming gives decrease fuel utilization it additionally further develops mobility, extend the section of ideal flight speeds, decrease in vibrations, and vacillate is likewise accomplished because of the disposal of pivoted control surfaces like ailerons and folds. Advancing optimal design in the field of flight controls has been there from the absolute first day when the Wright siblings presented wing wrapping for the purpose of roll control. Biological mimic is in close proximity to wing morning technology. The observation of flight drove man to fly, and we still have a lot to learn from nature today. Birds can perform Avian morphing even in urban environments, allowing them to efficiently Cruise perform powerful manoeuvres and accurate descents. Each wing arrangement is tailored to a specific flight requirement. A falcon, for example, waits for prey in a high aspect ratio arrangement before scooping down to attack as soon as prey is found. Traditional flaps, slates, and ailerons have compromised geometry that only allow for restricted functions in a wide variety of flight circumstances.

There are primarily three distinct categories of wing morphing. The three types of morphing are called "In plain morphing," "Airfoil morphing," and "Out of plane morphing".

2. LITERATURE REVIEW AND ANALYSIS

Birds have long influenced man's desire to soar. Nature has revolutionized them into this as a result after millions of years. Although an aero plane and a bird appear to be extremely similar at first glance, the morphology of a bird is not as rigid as that of an aero plane. They can fluidly modify the shape of all of their body components to provide optimum performance in a number of flight conditions, such as elevated dash and small hovers, as well as increased maneuverability. Morphing technique attempts to simulate aircraft ability to adapt to various flight conditions by altering the shape of the aircraft at different phases of flight, much like birds do. This allows for a larger flight path, higher flight quality, and numerous operation characteristics to be executed by the same aircraft.

Airplane wings are a concession that allows the plane flying in a wide range of conditions while giving it semi functionality in each. Engineers and designers have long been intrigued by the ability of a wing to change shape during flight, as it reduces the amount of design compromises required. Morphing technology can modify certain geometry parameters such as the shape which includes (chord, sweep and span), morphing out of plane which includes span bending, span twist etc. airfoil modification (camber and thickness). Altering the wing's structure or shape is nothing unusual. Previously, morphing approaches have always cost money, complication, or weight penalty, although these have been somewhat mitigated by system-level advantages.

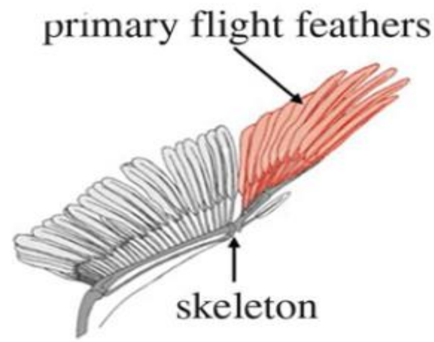

Fig 1: Birds feathers attached to internal skeleton

Fig2: replication of bird feathers

Such compromises are becoming less acceptable with the prevailing situation to exceptionally economical and "ecofriendly" aircraft, forcing the development of revolutionary morphing designs capable of giving greater benefits with fewer drawbacks. Recent advancements in "smart" materials may be capable of overcoming these limitations and enhance the

The manufacture of different aircrafts either civil or military have been done with different flight capabilities. Nevertheless, fuel consumption and distribution change all through the journey, and the aircraft may be compelled to fly in much less conditions due to air controlling traffic constraints. Because airliners are more versatile than military aircraft, the resulting sub-optimal performance is more significant, and fuel efficiency is a far more important performance metric.

The motivation to have airplanes go through transforming is to expand their exhibition at various flight conditions. Quickest speed, energy utilization, taking care of, most extreme burden, perseverance, dependability, and adjustment can be in every way improved with the transforming wing idea. The airplane's overall performance can be improved by increasing some or all of these parameters. For example, altering the wing area and airflow net shapes can help enhance performance measures.

Flights have different stages and the outcome of morphing is to expect better performance by the aircraft at these stages. Top speed, fuel usage, maneuvering, payload capacity, range, durability, and stability can all be improved using the morphing wing concept. Improving one or more of these factors will increase flying efficiency and allow the aircraft to undertake more missions. Changing the design of the wing section and the air net, for instance, can significantly promote performance metrics.

Communier et al [1] have presented a working model for morphing and also have carried out its testing in the wind tunnel. The morning in this mechanism is being achieved by carving slits at the leading and trailing edges of the aero foil which are actuated by the arm rods mechanism. Small angular deformation in each slit produces at large a change in the shape of the airfoil and hence morphing is achieved. The leading and the trailing edge are dealt with as separate systems that are combined to produce the same overall effect. In figure 3 leading and trailing edge, slits are shown along with their actuating mechanisms. Drag reduction is achieved due to a smaller angle of attack in camber morphing as compared to that of ailerons or other control surfaces. Results show that wings morphed by the above-explained mechanism give better aerodynamic performance but the limitation is that only small changes in angle can be achieved.

A double rib sheet (DBS) structure has been proposed by Zhao et fir changing the camber of the wing. The DRS structure constituents are having a semicircular on one end and a circular ear at the other end. The individual constituents are coupled as shown in figure the relative motion of the DRS structure is realized by actuators that are distributed along the chord of the wing. The method presents no other additional weight penalty other than the weight of adhesives and actuators. As a result, the wing's structural weight is well within the limit. Experimental analysis has been carried out on Talon UAV an increase in efficiency of 14.1% is observed in comparison to that of fixed-wing Talon UAV. In addition, the critical angle obtained is 18 degrees and distortion in performance is observed at 4 degrees which is due to the laminar-turbulent transition.

Chanzy et al. have shown a 15 kg load bearing capacity morphing UAV wing. The morphing wing's supports are made of carbon fibre bracings and glass fibre covering, styrofoam covering, and SLS nylon inlays. SLS fabric male and female sliders, as shown in Figure 5, enable the wing's top and lower surfaces to slide over each other. To complement the experimental verification, we used the highest capability CFD code with MATLAB and ABAQUS for mathematical modelling. The servo motor is attached to an SLS nylon rib in the actuation mechanism. The fully autonomous thread is another crucial factor that allows the wingspan to maintain its shape while consuming no energy. The aforesaid technique produces slowly but enough roll control for the UAV learner, according to experimental data.

Multi-unit flexible rib mechanism has been presented by Meguid et al. the overall assembly consists of basic subunits that are connected by revolute joints attached over a flexible rib system driven by onboard servo motors. A functional prototype has been designed which is cranked by a flexible servo motor actuated mechanism or simply rocker slider system. The design can alternate between two distinct states indefinitely. The aero foil leading edge and trailing are capable of changing shape independently while the central point has a constant geometry. The structural integrity of the flexible rib system has been analyzed by finite animal element analysis by discretizing with quadratic hexahedron elements along with quadratic wedge elements. Aerodynamics of the maximum Camber has been analyzed for a velocity value of 20 m per second and results for lift coefficient to drag coefficient have been calculated. At the conclusion of the design stage perimeters for the maximum lift to drag ratio were recorded by repetitive alterations.

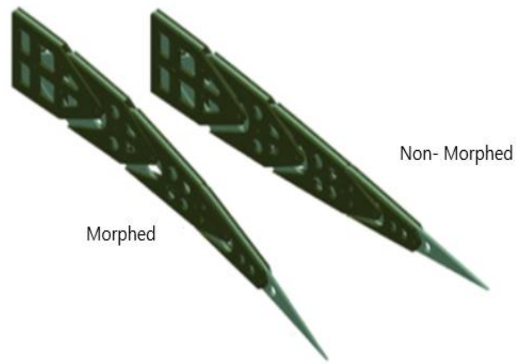

Fig 3 multi-unit flexible rib structure [4]

Morphing mechanism by the application of corrugated structures at the core of wing has been proposed by Yokozeki et al [5] which fosters the an-isotropic character of corrugated geometry. The corrugated structure is composed of identical C-shaped round portions and identical transverse sections. Chord-wise tension is created via a strain wire coupled to a servo motor assembly, which can achieve the requisite morphing ability by varying the pressure in the line. The proposed design is only capable of producing downward motion because of design restrictions tension wire is attached to the lower wing surface only. The corrugated structure along with tension wires as shown in Figure 7 has been only applied to the trailing edge while the Leading edge has a constant geometry. A prototype has been manufactured from carbon-reinforced plastics and results show that the proposed design can be used in place of flaps for low-speed maneuvers such as landing and take-off but high-speed maneuvers such as role motion are not possible.

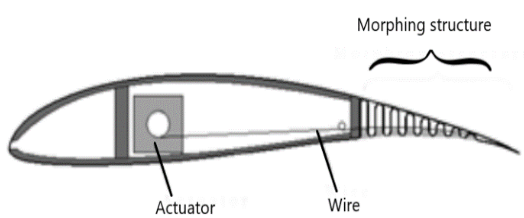

Fig 4 Corrugated structure at trailing edge [5].

A camber morphing technique based on a compliant composite structure and an electromechanical actuator is presented by Yokozeki [6]. Recent progress in material engineering material topology optimization is becoming increasingly popular to exploit material anisotropy in the best favor of required features. Continuous fiber composite materials are one such example where the manufacturing of complex structural members can be done. The concept design as shown in figure 8 consists of a structural morphing rib in combination with an actuating mechanism. The global actuation system is a motor speed control actuator in conjunction with an activator tube attached towards the wing skin. The rib is made of nylon polymer and polyester 12 sequentially created morphing structure. Pushing and pulling of the actuator rod by the servo motor produces morphing in the trailing edge of the wing. The study shows that rib structure exploiting anisotropy and strength of composite material provides superior maneuverability and plays an instrumental role in achieving maximum control.

Kota et al [7], who use a mission adaptable compliant wing, address adjustable curvature trailering at cruising elevation on protracted aircraft (MACW). The flap system's topology has been optimized by taking into account the actuation force, morphing movement error, transforming shape error, system external circumstances, buckling forces, fatigue damage, and lift capability. During flow acceleration, while maneuvers the trailing edge gets affected by flow separation which has a strong adverse effect on the pressure gradient of the wing. To increase the aircraft's durability in different types of manure, an optimization was performed to achieve minimal flow separation and a maximum laminar boundary layer throughout a broad range of lift coefficients. Possible provision of differential deflections along span provides better load distribution and mean wing bending moment to give efficient lift force distribution hence providing fuel savings and better structural stability. Experiment set up showed that energy required to elasticity deform the wing in the case of MECW is 33% less than the actuation force in a conventional wing flap.

Hybrid camber morphing concept has been presented by Zheng et al [8] which fosters the benefits from both the worlds of material and structural sciences. A monolithic compliant mechanism has been introduced for the transmission of forces from the actuator to the morphing mechanism. To achieve massive deformations, hyper-elastic topology optimization has been utilized, while a combination of the meshless approach in the leading and trailing edges of the wing has been used to decrease computing resources. A spring steel plate manufactured using electron discharge machining EDM and fiberglass-reinforced skin, aluminium stringers with a lead screw, and an actuator are all parts of the Assembly. Lead screwed actuator with linear stepper motor converts rotational inputs to a straight-line movement. Polylactic acid was used to 3D print additional mechanisms (PLA). A maximum of 27 degrees can be achieved at the leading edge which is a result of 48 mm displacement of complaint mechanism whereas at the trailing edge minus 8 degrees to 40 degrees can be achieved for minus 9.74 mm and 37.83 mm displacements respectively. Aerodynamic load testing simulation was carried and the load-carrying capability of the wing was found to be permissible. Analysis needs to be tested or cross-checked with experimental results the setup for which has been explained in the research paper.

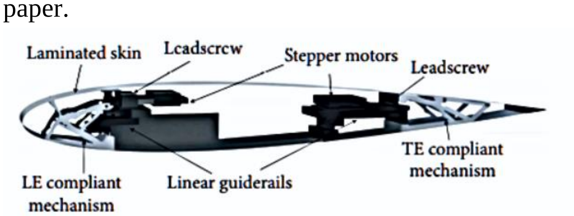

Fig. 5 Laminated skin and variable camber morphing wing [8]

To increase fighter aircraft capabilities, this article concentrated on their stability. The dissymmetric varied span system, or VSMW, was used to do this (Variable Span Morphing Wing). This technology is advantageous not only while the plane is cruising, but also during flight operations procedures [17].

Now the plane can be made to undergo two types of stabilities.

a) Static stability: When the aircraft is in the air while it is cruising its net forces acting on it are zero neglecting the thrust i.e. at constant acceleration. In this state the plane is in equilibrium. The static stability focuses on the planes equilibrium position that if the plane withdraws this equilibrium state it helps it return to the equilibrium. For this to happen it requires some counter forces or moments which help it stabilize back. Static stability deals with this stabilization.

b) Dynamic stability: The dynamic stability focuses more on the plane's motion when it undergoes disturbances which can be done either by damped or un-damped oscillations or non-oscillatory motions Nonetheless, it is important to note that even if an aircraft is constant, it can be dynamic unstable; Static consistency, on the other hand, is essential if a plane is dynamically stable.

Therefore the aircraft's lateral and longitudinal stability is comprised of the control surfaces constituting the forces and moments that help it stabilize during in flight conditions.

Fig 6 Variable Sweep Morphing in a Bell X-5 [17]

Table 1: Summary

Authors	Year	Findings	Type
Q. Chanzy	2018	Experimental verification and analysis of morphing UAV wings	Camber
Dan Xu	2019	Deep Reinforcement Learning for the Control of a Bionic Morphing Unmanned Aircraft System	Camber
Tuba Majid	2021	Modular Camber Transformation Mechanisms: Design and Construction	Camber
David Communier	2020	Conception and Verification of a Subsonic Wind Tunnel-Based Morphing Camber System	Camber
Anmin Zhao	2019	Structure development and validation of a novel entire adaptive variable camber wing	Camber
Tomohiro Yokozeki	2019	Creation of a Corrugated-Structure, Variable-Camber Airfoil	Camber
U. Fasel	2019	Aerospace composite additive fabrication for form-shifting structures	Camber
Yaqing Zhang	2019	Incorporating nonlinear big deformation into the design of a variable camber morphing wing using a compliant mechanism	Camber
C. Soutis	2016	An adaptable aerofoil whose aerodynamic properties may be fine-tuned	Camber
Matthew G. Good	2003	Structural Optimization for the Development of a Tail for a Variable-Camber Aircraft	Camber
Chawki Abdessemed	2018	3D Stability Analysis of a Transforming Wing's Continuous Side-to-Side Edge Transition	Trailing Edge Flap
Sérgio João Monteiro	2016	Analysis of an Aeronautical Morphing Structure	leading edge
Hafiz Muhammad Umer	2020	Wing Span and Sweep Morphing for Small Unmanned Air Vehicle	Span and Sweep
Frédéric Moens	2019	The Effects of Morphing Technology on the Flight Performance of a Turboprop Regional Aircraft Wing	Span and Sweep
Luis P. Ruiz-Calavera	2021	The advantages of a semi-morphing wing idea are investigated	Semi-Morphing
Amit Geva	2019	An Investigation into a Morphing Wing That Can Adjust Both Its Airfoil and Its Span Using a Folding Mechanism That Can Be Retracted	Span

To avoid the elastic deformation of an aircraft wing its wing structure is designed such as to be semi morphed i.e. deflecting a large number of redundant and complementary control surfaces. The most modern transport aircraft's wing dynamics can be still improved by two methods. First is to reduce induced drag by increasing aspect ratio of the wing area while the second is to reduce the friction drag by using the laminarity. Now both these methods are effective but hard to achieve. Wing Morphing is an additional possibility alternate to these in modifying the design of the wing. This area is under a lot of research but practically it has not been achieved most of the work has only been simulated and performed in laboratories. This particular paper [18] focused on the morphing wing and its effects on the improvements in drag, aircraft control and load alleviation.

3. RECOMMENDED APPROACH

We have already discussed the basic idea about using corrugated structures inside the core of morphing sections which provide flexibility to the airfoil in the morphing direction while maintaining the ability of carrying dynamic loads along the span. The concept defined by Yokozeki et al can be classified as structure-based camber morphing. The overall assembly consists of a corrugated structure at the leading and trailing of the airfoil while there is a fixed section in the center. The central fixed section is used for placing servo motors and pulleys that are meant for controlled activation of morphing sections.
FX03-137 airfoil has been taken as the reference shape the parameters for morphing where parameters to range a value of maximum thickness ratio 13.7% and a maximum camber ratio of 5.97%. The chord length of the airfoil understudy is 800 mm and the corrugated structure responsible for morphing is present at 69% of the chord length position while the corresponding equivalent system aileron hinge is present at 77% of the portion. There has been some thought given to using tension wire attached to the underside of the wing and a servo motor to shape uniform C-sections of the corrugated structure.

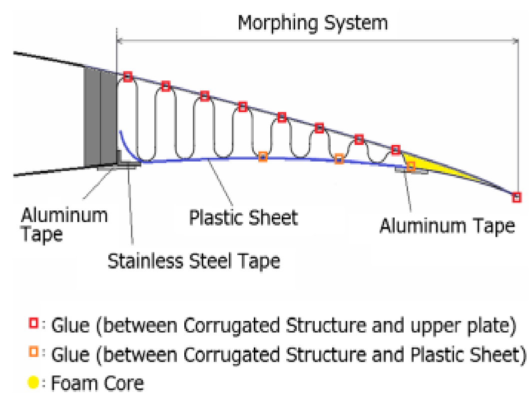

Fig 7 Perspective of the morphing section as seen via a cross-section [5].

Figure 7 shows the take up length of the wire and tension on the vertical axis against the morphing angle of the wing taken on the horizontal axis. A linear trend between the set of variables is observed where take up length and tension in the wire increases linearly with the applied angle of morphing. The relationship developed here plays an important role towards defining fabrication parameters.

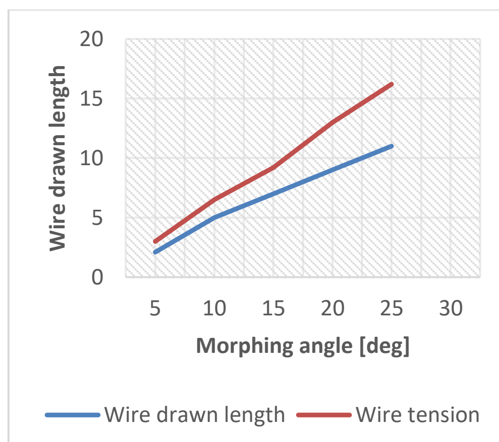

Fig 8 Wire tension as a function of morphing [5].
The FEM analysis for corrugated structure has been carried out on MSC Marc which is a commercial software for structure analysis. MSC marc has its specialty in dealing which situations where a large amount of deformations are to be analyzed and used in applications involving nonlinear material behavior with crack propagation. Now because wire penetrates through the corridor structure and so its motion is constrained along with the thickness of the airfoil so sliding contact is assumed for the FEM analysis. The material of the corrugated structure has been

considered linearly elastic. The Locus for the trailing edge and deformed shape of upper and lower surfaces have been simulated for deformation angles of 10 and 20°. A slight discrepancy between simulated results and experimental prototypes was found but morphing was still efficiently possible. The models discussed till now have been fabricated to demonstrate aerodynamic forces for morphing motion. The test was acted in Japan investigation organization and the air stream was of Gottingen type. Engine and pulley get together for initiation of the transforming segments were associated with a regulator that was please outside the air stream. Since the viewpoint proportion of the wings was low so mind boggling airstream was normal at the edges of the wing, to alleviate this impact ellipsoid wingtip boards were connected to the two edges of the fundamental wing. The model was upheld by three structs out of which two are associated with the forward portion and another was associated with the intriguing streamlined powers saw by balance under the swaggers. The general test arrangement for a particular transforming point and a speed should be visible in figure 16 where we can see two swaggers connected to the forward portion and one joined to the back piece of the wing.

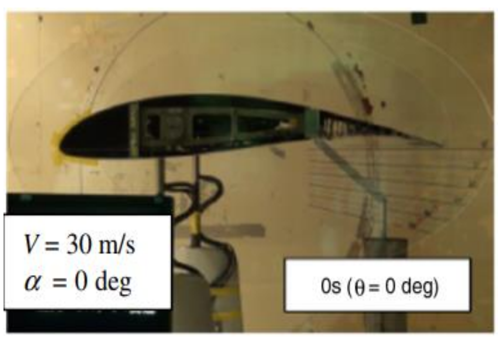

Fig 9 Test setup in wind tunnel [5]

Corrugated structure and upper skin have been fabricated from carbon fiber reinforced polymer along with a layer of fabric and epoxy.

Following formulation has been adopted to find the lift and drag coefficients for morphing wing:

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 * S} \quad (3)$$

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 * S} \quad (4)$$

In the above equations, lift force L and drag force D.

The known geometrical parameter that is 0.64 m square.

Figure 18 shows the relationship of lift coefficient with the flap or morphing angle. Solid lines in the graph show lift coefficient behavior for our morphed wing while the dotted lines are for reference geometry it can be seen that for lower values of angle of attack alpha and intermediate values of morphing angle best results are obtained.

The figure also shows that our initial observation about a discrepancy in the shape of morphing wings at higher morphing angles is playing the role here and is causing deterioration of wing Lift performance.

4. CONCLUSIONS

Aero elastic behavior is one of the areas that need to be explored in more depth. While designing of morphing wings we come across a paradox between rigidity and flexibility where on one hand we want a wing to be augmented with elasticity and on the other, the load-bearing capacity of the wing shouldn't suffer as well. Embedded servo motors in case of pure mechanical solutions are sensitive to aero elastic issues has caused many failures as discussed in the literature review where in some cases slight discrepancy was observed whereas in others deformation angles were totally disturbed.

Because of its benefits, the morphing idea has been popular research topic in the aerospace industry. The slider crank mechanism was discovered to be the best mechanism for achieving the wing sweep motion in this study. Wing actuation kinematics is investigated. For in plane wing shape, the mechanism alters the span and wing area change.

In the third technique, the twisting happens on a specific area of the wing and is accomplished on a UAV-sized wing, the concept for twist morphs has already been illustrated. This is the first model to exhibit a twisting distortion limited to a single wing section. This was accomplished by combining an SSC framework with SMA wires for actuation. This type of notion is beneficial in instances when maintaining flying at low speeds is required.

5. RECOMMENDATION

The main error in the approach of corrugated structures appeared due to the surface shape of morphing wing not being able to match up with the reference shape. The error is partially coming from fabrication of the corrugated geometry and in addition there can be some error from the modeling part as well because the authors were dealing with non-linear geometry. The results can be improved by modifying and optimizing corrugation geometry to achieve more smooth and seamless morphing. One of the approaches to mitigate the above problem is to introduce calculated eccentricity about the central line of the corrugated structure.

NOMENCLATURE

- UAV: Unmanned Aerial Vehicle
- DRS: Double Rib Structure
- CFD: Computational Fluid Dynamics
- EDM: Electron Discharge Machining
- VSMW: Variable Span Morphing Wing
- FEM: Finite Element Modelling.
- FDM = Fused Deposition Modelling
- CNF = Carbon nano fibers
- RP = Rapid Prototyping
- TLCP = Thermoplastic Liquid Crystal Polymer
- CNF = Carbon nano fibers
- E = Modulus of elasticity

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REFERENCES

[1] D. Communier, R. M. Botez, and T. Wong, "Design and vali?dation of a new morphing camber system by testing in the price-Païdoussis subsonic wind tunnel," *Aerospace*, vol. 7, no. 3, p. 23, 2020.

[2] A. Zhao, H. Zou, H. Jin, and D. Wen, "Structural design and verification of an innovative whole adaptive variable camber wing," *Aerospace Science and Technology*, vol. 89, pp. 11–18, 2019.

[3] Q. Chanzy and A. Keane, "Analysis and experimental validation of morphing UAV wings," *The Aeronautical Journal*, vol. 122, no. 1249, pp. 390–408, 2018.

[4] S. Meguid, Y. Su, and Y. Wang, "Complete morphing wing design using flexible-rib system," *International Journal of Mechanics and Materials in Design*, vol. 13, no. 1, pp. 159– 171, 2017

[5] T. Yokozeki, A. Sugiura, and Y. Hirano, "Development of var?iable camber morphing airfoil using corrugated structure," *Journal of Aircraft*, vol. 51, no. 3, pp. 1023–1029, 2014.

[6] U. Fasel, D. Keidel, L. Baumann, G. Cavolina, M. Eichenhofer, and P. Ermanni, "Composite additive manufacturing of morphing aerospace structures," *Manufacturing Letters*, vol. 23, pp. 85–88, 2020.

[7] S. Kota, R. Osborn, G. Ervin, D. Maric, P. Flick, and D. Paul, "Mission adaptive compliant wing-design, fabrication and flight test," in *RTO Applied Vehicle Technology Panel (AVT) Symposium*, 2009: RTO-MP-AVT-168, pp. 1–18, Evora, Portu?gal, 2009.

[8] Y. Zhang, W. Ge, Z. Zhang, X. Mo, and Y. Zhang, "Design of compliant mechanism-based variable camber morphing wing with nonlinear large deformation," *International Journal of Advanced Robotic Systems*, vol. 16, no. 6, 2019.

[9] R. Wu, C. Soutis, S. Zhong, and A. Filippone, "A morphing aerofoil with highly controllable aerodynamic performance," *The Aeronautical Journal*, vol. 121, no. 1235, pp. 54–72, 2017.

[10] Bioinspired morphing wings for extended flight envelope and roll control of small drones M. Di Luca1, S. Mintchev 2, G. Heitz 2, F. Noca 3 and D. Floreano

[11] S. Ameduri and A. Concilio, Morphing wings review: Aims, challenges, and current open issues of a technology. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 0954406220944423, 2020.

[12] T. Majid and B.W. Jo, Status and Challenges on Design and Implementation of Camber Morphing Mechanisms. *International Journal of Aerospace Engineering*, *2021*.

[13] M.G. Good, Development of a Variable Camber Compliant Aircraft Tail using Structural Optimization (*Doctoral dissertation, Virginia Tech*) 2004.

[14] Morphing Aircraft Systems: Historical Perspectives and Future Challenges Terrence A. Weisshaar∗ Purdue University, West Lafayette, Indiana 2009

[15] S.Barbarino, OBilgen, R. Ajaj, M. I. Friswell and D. Inman, A review of morphing aircraft, *J Intelligent Material Systems and Structures*, 2011

[16] S. J. Moreira, Analysis of an Aeronautical morphing structure. 2016.

[17] T. N. Sanches, Longitudinal flight control with a variable span morphing wing. 2012.

[18] L.P. Ruiz-Calavera, S.D. Lucas-Bodas, and D.E. Funes-Sebastian. Study Of The Benefits Of A Semi-Morphing Wing Concept. 2021.