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Review of Wing-Morphing Technology

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Abstract: This study aims to review wind morphing technology. Wing morphing is a newly emerging field of research in aeronautical engineering, which generally deals with supplanting the traditional wing flight dynamics and making it more efficient. This paper highlights the major advances in the field of research such that an overview of the methodology and findings of the researchers is provided. This is achieved by categorizing wing morphing and defining each of its types and then providing examples from past research. It is a qualitative study, and data were gathered from journal articles, conference papers, reports, and books. This study analyzed various types of wing morphing techniques prevalent now. Three major types of wing morphing technologies, including Planform, Out-of-Plane, and Airfoil morphing, along with their subtypes, have been discussed. This study is relevant in current times as morphing has developed significantly in recent years. It is a concise and comprehensive overview of the types of structural wing morphing for fixed wings. It hence is useful as a beginner's read into the vast world of futuristic-aerodynamic research.

Keywords: *Wing morphing, types of morphing, developments, flight dynamics*

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I. INTRODUCTION

Ever since the Wright Brothers first invented aircraft, they took inspiration from birds to create the machine capable of replicating their flight [1]. This design concept is followed today, and bird flight is deemed the most efficient flight [2]. Hence, to achieve that, mainly two steps [3] are taken: firstly, the airplane body is made as smooth as possible to reduce drag. Secondly, the wings are made as efficient as possible in order for them to deliver lift efficiently at a range of velocities and flight conditions. However, traditional aircraft have not been able to achieve the ideal in both these aspects.

As for the first aspect, aircraft bodies are not smooth enough to minimize interference drag, i.e., drag resulting from discontinuous interfering surfaces. Due to the nature of the materials used, aircraft bodies have imperfections and discontinuities, resulting in flow turbulization and additional drag [4].

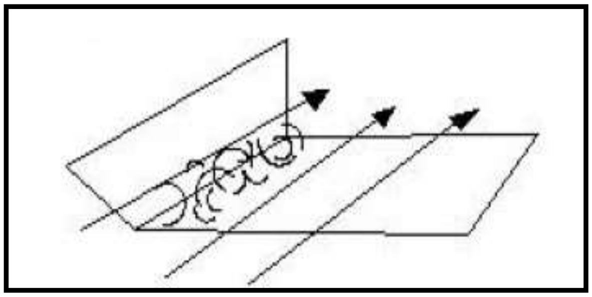
Fig. 1. Interference drag

This effect is further amplified where there are actuating surfaces such as flaps/ailerons on the wings. When these control surfaces are actuated, the resulting shape has gaps and discontinuities that end up deviating it from the established ideal [5].

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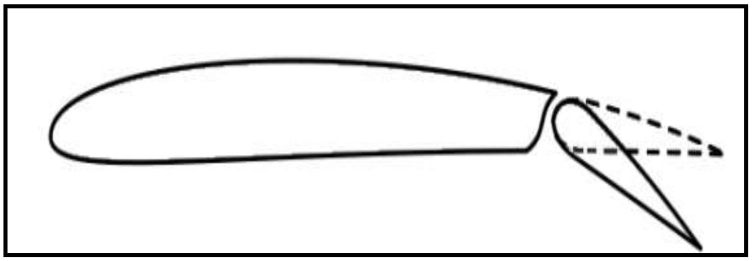

Fig. 2. Traditional flap mechanism

As for the second aspect, even that is imperfect because traditional aircraft wings cannot generate the same amount of lift at every velocity since they are dependent.

$$\text{Lift} = \frac{1}{2}\rho v^2 \times Cl \times \text{Area} \tag{1}$$

where v^2 is velocity

Hence, in order to keep the lift constant, either the Cl or the Area must change. However, traditional aircraft designs do not allow that. In contrast, Morphing technology aims to develop such a wing that can change its shape during flight. The concept is based primarily on the wings of a bird that can be stretched, twisted, turned, and bent by the bird in order to contribute to a flawless flight. Some designs are made especially to cater to this design significance [6]. In this way, the significance of wing morphing becomes the next step towards achieving an ideal flight. If a design is made such that it mitigates the inefficiencies of traditional flight, it will help reduce drag [7], noise [8], fuel consumption [3], etc.

Many developments have been made in wing morphing research recently [9, 10], especially in the past twenty years. Therefore, a review was needed in order to highlight the breakthroughs. Hence, this research aims to review the wing morphing technologies developed in recent times and highlight the characteristics of various types of morphing technologies existing. This study begins with defining morphing in general and then highlights various types and characteristics of morphing technologies. Moreover, this study enlists some recommendations for scholars and practitioners.

II. METHOD AND MATERIALS

In order to familiarize the reader with the core of morphing, this paper will start by mentioning the different types of morphing possible. The sub-categorization of morphing is more semantic than science. Therefore, the basis for the sub-categorization of morphing and the definitions have been taken from what was proposed by Barbarino et al. [11], as highlighted in the next section. It is a review study that relied on existing literature to gather data and form inferences. The main focus of the study was scholarly work and advancements in the field of morphing in the last two decades. The data for this study was gathered from secondary sources such as journal articles, conference papers, and books. A thorough review of the relevant data has been conducted, and the researchers developed the discussion and inferences based on the gathered data.

Once the structure of the paper was set, a brief definition of each type of morphing is given under the respective section, followed by a novel example of conducted research. There are several researches conducted by researchers under each category. To pick out one or two novel researches from the pool of available literature was a difficult task. However, a conclusion was reached that for this paper, it is more fitting that the examples given in this paper need to be simple to understand such that a beginner can grasp the essence of what each morphing exactly is; so that he does not have trouble finding his way around various in-depth papers. This is why papers with simplicity in concept and eloquence in design were preferred over more recent papers; since not every recent paper needs to be of notable mention.

The applications included in this study are mainly structural shape changes for fixed wings. Therefore, applications such as flight control or those belonging to other fields such as space have been deemed unsuitable for this paper's scope. Due to the absence of available books, the main source of knowledge was other published literature.

III. RESULTS AND DISCUSSION

A. *Morphing*

Wing morphing is generally defined as the changing of the shape of the wings. The wing morphing procedure helps in improving the optimal flight performance by modifying the wing shape, even in-flight conditions in which conventional control surfaces decrease their performance. Explicitly, wing morphing could improve aerodynamic characteristics and reduce aircraft structural weight and acoustic noise [12]. However, how the shape of wings changes due to morphing is a question that needs further investigation. A thorough analysis of existing literature highlighted that wing morphing could be lumped into three main types: Planform, Out-of-Plane, and Airfoil morphing. At the same time, each can be further subdivided as shown [11].

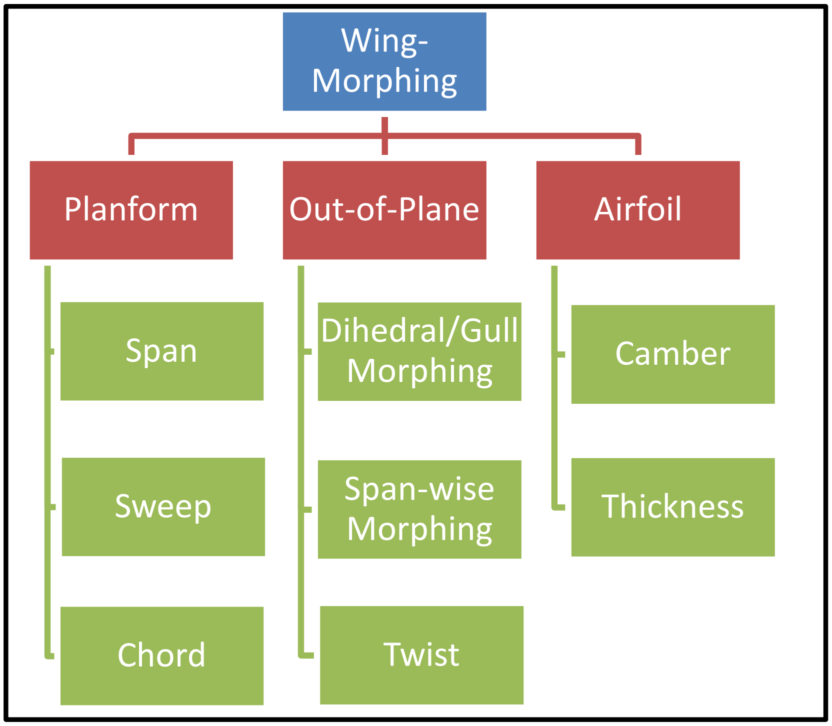

Fig. 3. Classification of wing morphing

Each of the sub-categories is now explained with examples of conducted researches for each type of morphing.

B. *Planform Morphing*

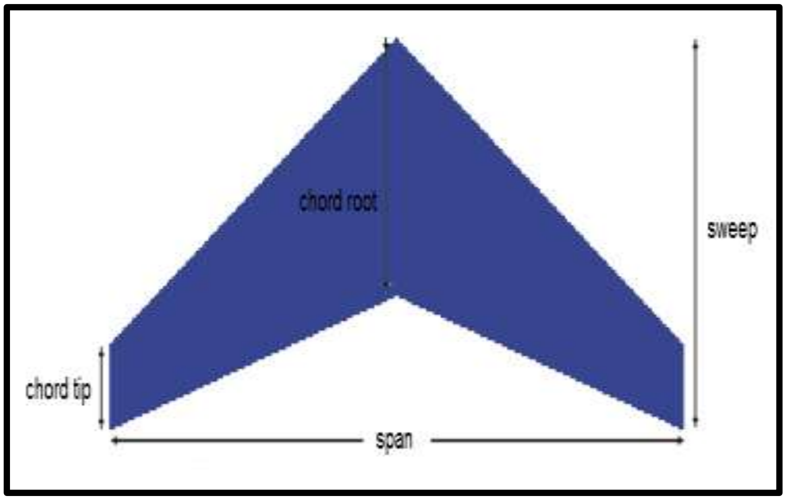

Fig. 4. Wing planform

The wing's planform is defined as the outline of the wing as projected on a horizontal plane. Hence, the dimensions of the wing are reduced to three main aspects: Chord, Span, and Sweep. The chord is the length from the wing leading edge to the trailing edge. The chord will be different at the wing root and tip if the wing is tapered, as shown above. The span is the overall wing length, from tip to tip. Moreover, the sweep of the wing is the angle (usually backward) that the wing is tilted at. Hence, planform morphing deals with the alteration of only the dimensions mentioned above of the wing. The main idea behind changing the span and chord length is to change the wing's aspect ratio, which is directly related to the lift. Hence, if we can change the aspect ratio in-flight, we can get a variable lift.

On the other hand, sweep is not connected to the aspect ratio; hence, changing it will not change lift. However, the sweep is added to wings to improve high-speed performance. In traditional wings, the sweep angle is designed to be ideal for only the optimum operating speed. This means that at speeds below and above this speed, the sweep would be inefficient. Morphing can change such that the sweeping operation becomes dynamic, and hence, it changes with speed to assure peak performance at every speed.

1) Span morphing: Span morphing consists of varying the span of the selected wing, i.e., changing its overall length, as the illustration below shows.

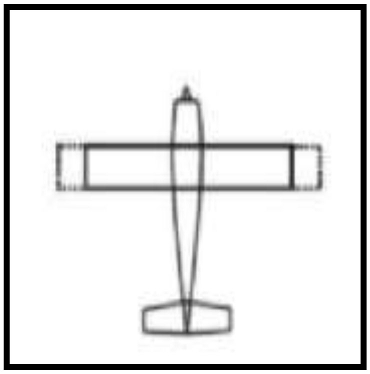

Fig. 5. Span morphing illustration

A sample design of the Variable Span Wing (VSW) as developed by previous researchers [13], is shown below in Fig. 6.

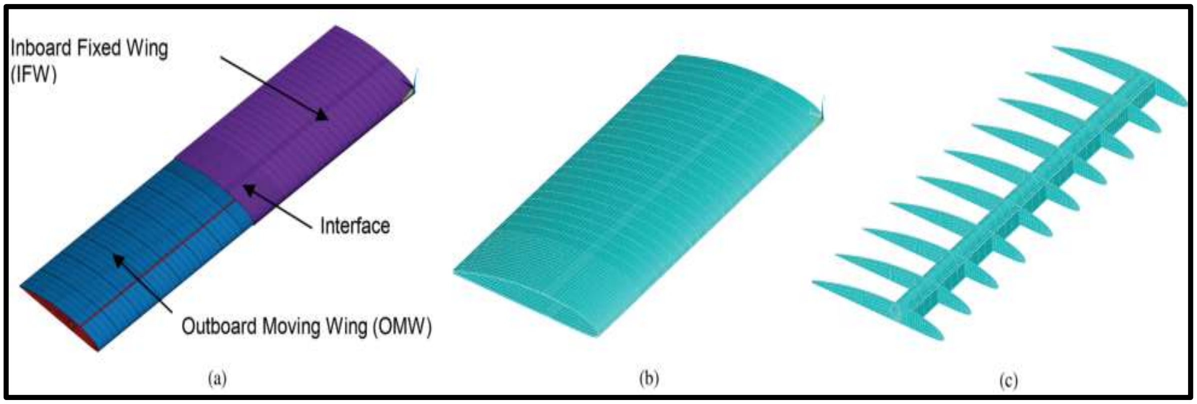

Fig. 6. Variable span wing [14]

The research depended on the decrease in the aircraft's need for lift during stable flight and the subsequent need to decrease drag at higher speeds. The morphing design consisted of a wing that could decrease its span at higher speeds to decrease lift and drag.

The design was manufactured and tested at various speeds. The results showed that at low speeds, the traditional wing design showed slightly better performance. However, the reverse is true for velocities exceeding 25 m/s. This is because this is the region where the OMW retracts and reduces the overall wing planform area, resulting in a decrease in total drag. This reduction in drag reached about 22% from the original design.

2) Sweep morphing: Sweep morphing consists of varying the sweep angle of the selected wing throughout the flight, as shown in Fig. 7.

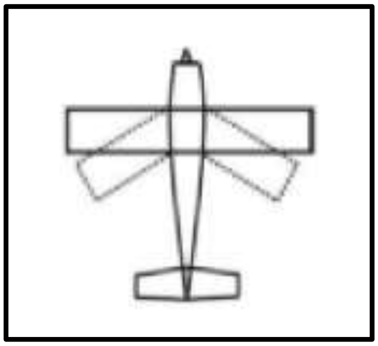

Fig. 7. Sweep morphing illustration [14]

Research indicate that it is ideal for the aircraft to have little to no sweep during take-off, ascent, and landing; and higher sweep angles during high-speed flight [15]. The idea behind sweep morphing is to reduce wave drag, hence reducing total drag, and increase the aircraft's maneuverability [16].

Sweep Morphing has already been incorporated by several military jets, such as the Tornado F3, which allows them to achieve a higher cruise speed and a faster dash speed.

3) Chord morphing: As the name implies, chord morphing involves the variation of the wing chord. The idea behind it is the same as span morphing, where a wing area changes the lift and drag acting on it. This phenomenon is already used in conventional aircraft, but the purpose is achieved using traditional flap mechanisms [17], causing other problems, as explained at the beginning of this paper.

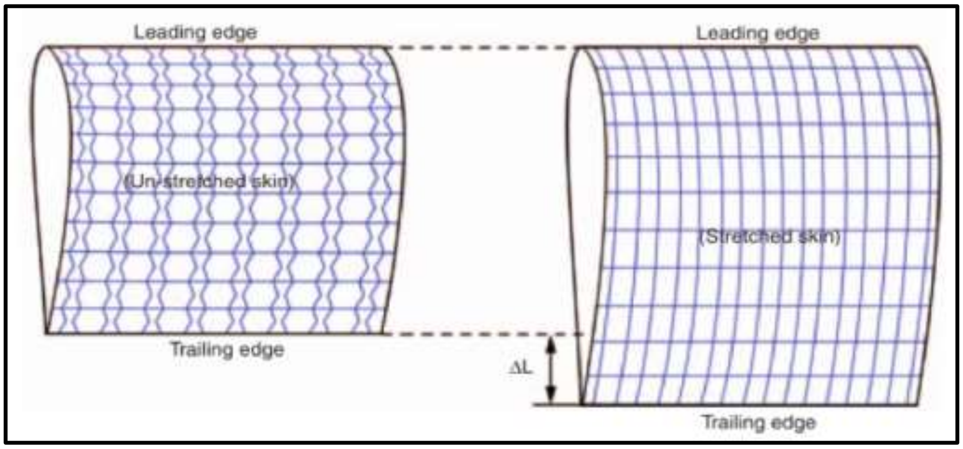

Fig. 8. Chord morphing illustration [18]

Morphing can help achieve the desired result more efficiently. The figure above shows a design used by researchers [18] to test the efficacy of this concept. They used a honeycomb structure to suggest a possible design for increasing chord length. The results showed that the cellular structure could withstand strains over ten times greater than those that would cause the original material of which the score was composed.

4) Out-of-Plane morphing: So far, the morphing types that were considered were within the plane of the wing. Out-of-Plane Morphing, on the other hand, is not restricted to one plane. Rather, the morphing action occurs around either the lateral axis or the longitudinal axis, casting the wing out of the horizontal plane.

5) Dihedral/Gull morphing: Both Dihedral and Gull morphing consists are closely related to rotating the wing around the longitudinal axis. The difference is that Dihedral (or Anhedral [19]) is given to the wing at the root, whereas Gull morphing takes place at the center of the wingspan. The picture shows the work of some individuals [20] who tested a design for Gull morphing, which, consequently, incorporates Dihedral morphing.

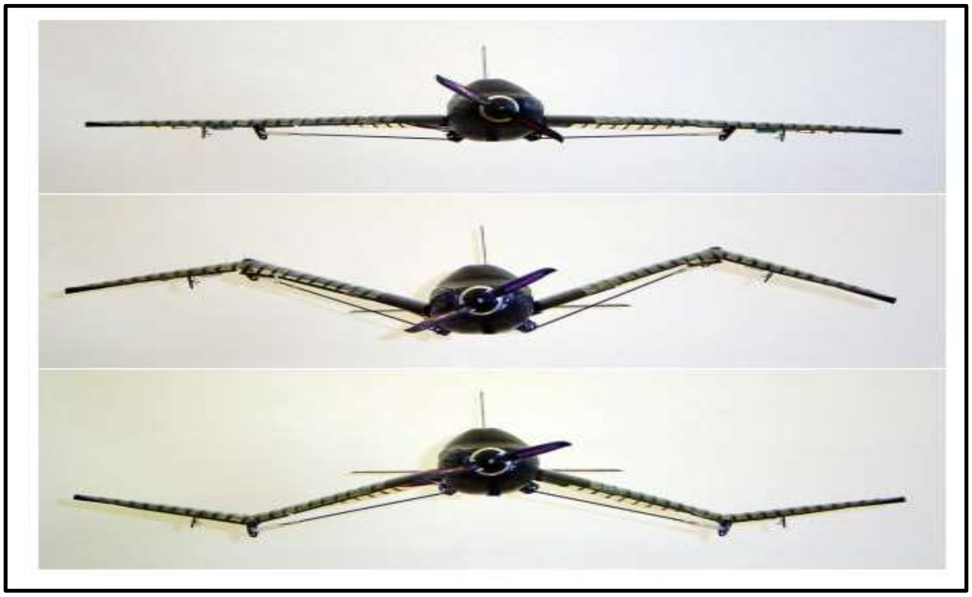

Fig. 9. Gull angle variation [20]

This type of morphing is perhaps the rarest of all due to its limited advantages over traditional wings and the rigorous durability requirements.

Span-wise morphing: Span-wise bending is much the same as Gull morphing, except that a smooth elliptical shape is obtained in the former. This mechanism is a big challenge to design, and its fabrication was not even possible until recently.

Manzo et al. [21] investigated the procedure with two approaches. The first was to use a D.C. motor to activate a spool system that gave the wing a curvature. The second approach was to use SMA. Fig. 11 shows a representation of their model.

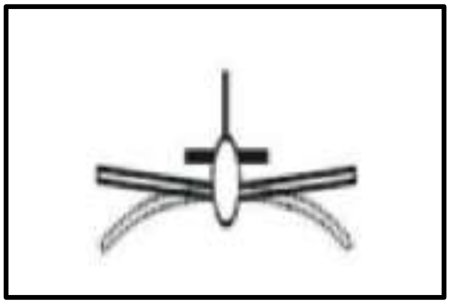

Fig. 10. Span morphing illustration [14]

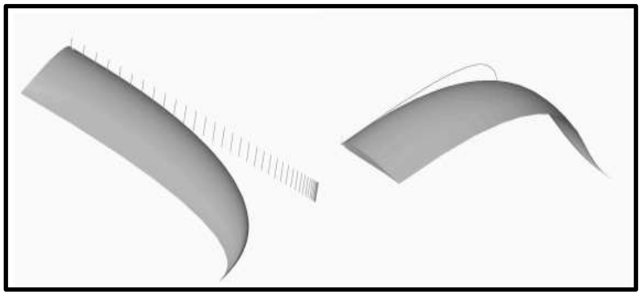

Fig. 11. Span-wise morphing - flat/planar (left) and furled (right) [22]

Just like the previous type of morphing, the benefits of this type are also limited to extremely specific types of flights. Hence, this type of morphing is seldom researched.

6) Twist morphing: Twist morphing incorporates the mechanism of twisting the wing profile in the lateral plane. Most of the time, only the wing tip actuates, and the wing root is kept fixed due to the intense structural requisites required to actuate.

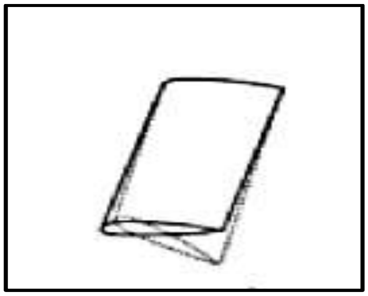

Fig. 12. Twist morphing illustration [14]

Twist morphing is perhaps the most prolific type of morphing. This is due to its relative ease of implementation and the vast range of advantages it offers over traditional wings and other types of morphing.

The morphing action generally takes place at the wingtip, with the actuation region being small. This is because a larger actuation region could lead to larger morph angles, decreasing overall efficiency.

[23] incorporated twist morphing in a fixed-wing design that used piezoelectric actuators to induce torque in the ribs of the wing profile, as shown below.

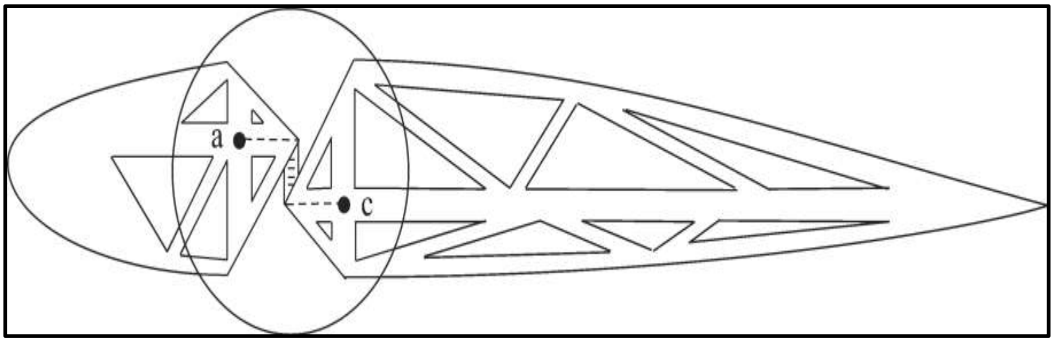

Fig. 13. Rib with piezoelectric actuator [23]

The results have shown that this type of morphing facilitates higher rolling moments than traditional wings. However, the main hurdle is analyzing the support structure; since the studies are usually conducted on a small scale.

C. *Airfoil Morphing*

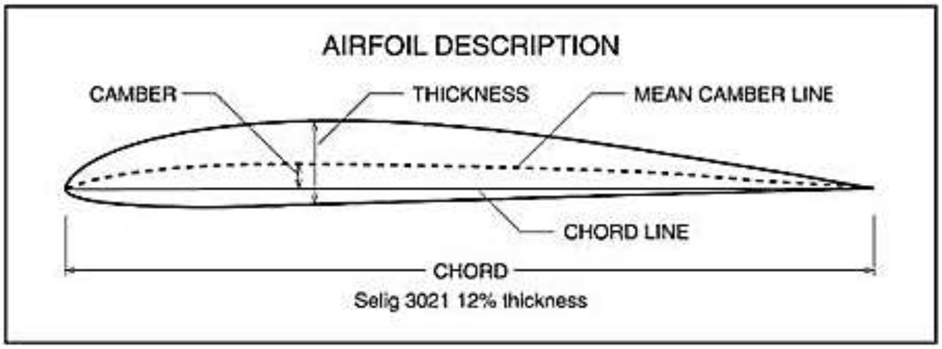

Fig. 14. Airfoil profile [24]

Airfoil morphing, in general, is the changing of the wing cross-sectional profile inflight. The airfoil profile is mainly defined by two main parameters: the camber and thickness.

1) Camber morphing: The camber is the overall curvature of the airfoil [25]. Morphing in the camber takes place by curving the profile to a larger or smaller angle. Smaller angles generally result in the profile becoming more symmetric. Symmetric airfoils are good for higher-speed flights due to less drag and fewer lift requirements. Asymmetric airfoils generate more lift (but also induce more drag). Hence, this shape is useful for take-offs, ascents, and landings.

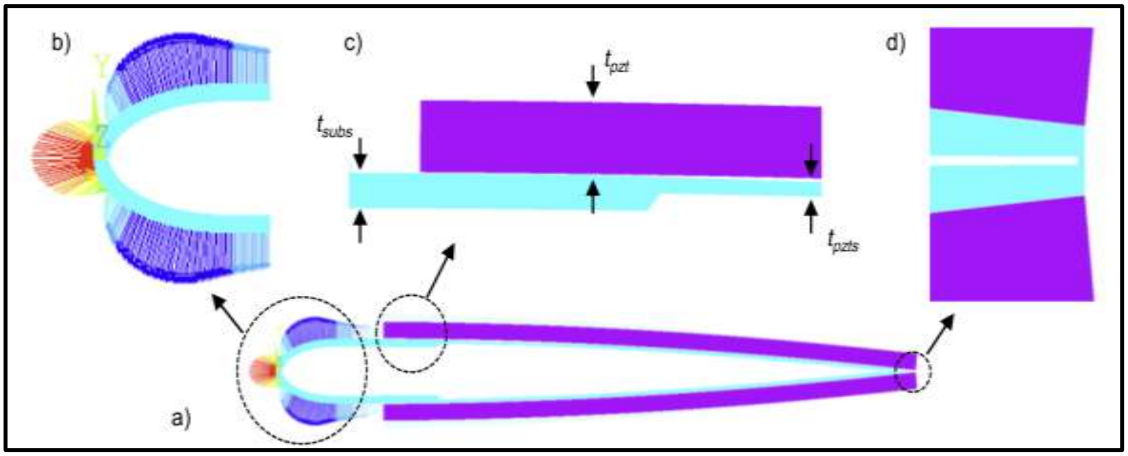

Fig. 15. Example of the finite element model used in the parametric study. a) Complete model. b) Zoomed image of the leading edge and pressure distribution. c) Transition from the passive leading section to the active trailing section. d) Zoomed image of the live hinge that connects the cascading active surfaces at the T.E. [26]

An example of this morphing is that shown above, where researchers [26] used Piezoelectric bending actuators to move the plate inside the wing to change its curvature. Experiments showed that this design was more efficient in terms of performance and power, and weight. The results showed a 99.6% decrease in power consumption and an 87% decrease in the weight of the actuation system.

2) Thickness morphing: Most of the studies conducted on airfoil profiles have to do with airfoil camber rather than thickness. This is because varying thickness has limited advantages to varying camber [22].

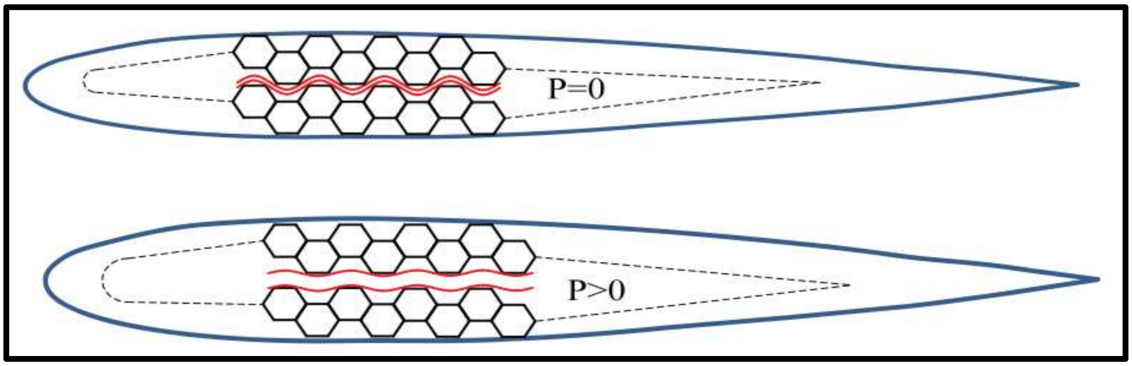

Fig. 16. Pneumatic tubes in honeycomb structure [27]

Interesting research on this part was that by Jian sun et al. [27], as shown above. The researchers used pneumatic tubes to increase the thickness of the overall foil through pneumatic pressure. The tubes were placed within a honeycomb structure, and when pressure was applied to them, the honeycomb structure parted to increase the foil thickness. They presented the results in the form of a working model of the wing and analytical formulae that could help calculate the pressure-thickness relations.

D. *Limitations*

The fact that morphing, despite being under the microscope for over two decades, has not yet been made commercial attests to its major limitations. Perhaps the simplest one to notice is the lack of scalability. Most of the researches considered have been on the UAV scale and have used materials with questionable strength [28] on full-sized airplanes. This is because conventional materials cannot be used due to the aero-elastic requirements demanded by most morphing concepts.

Furthermore, the whole morphing mechanism often needs to be shrouded with a skin or membrane. The flexibility requirements [29] of this membrane cause similar concerns to be shared regarding its material.

Lastly, even if these problems were solved, we must find a way to solve the tricky paradox resulting from our demand for a flexible material that exhibits rigidity during actuation! Many of the solutions found for this paradox are utterly inapplicable on full-scale.

E. *Future Research directions*

After discussing the limitations of morphing, highlighting the prospects of research in this field becomes much clearer. We saw in the previous section how the material selection was the prime limiting factor in advancement in this field. Researchers must find a way to tackle this problem head-on and not completely rely on material scientists to develop suitable materials. Of course, an alternative to this could be to develop a simpler morphing concept that does not require such paradoxical materials. This, however, is easier said than done.

Other than this, there is another direction that wing morphing could be heading which is rarely mentioned. Most of the research in this regard has been regarding the lift and drag capabilities of the morphed wing, but this is not the only advantage to morphing. Other than changing shape to develop a more efficient flight, sometimes we might need to do the opposite. For certain situations, it may be better to develop a morphing wing model that marginally sacrifices efficiency in favor of convenience.

A simple non-morphing example, to drive the point home, is that of the folding aircraft wings commonly utilized by planes used on naval aircraft carriers [30], as shown in the figure below. These wings minimize the space taken by the aircraft aboard the carrier ship. In the morphing industry, studies [31, 32] have been conducted on the control and stability dynamics of such wings. However, no suitable model has been suggested with detailed analysis.

Fig. 17. An S-3B Viking with folding wings [30]

[33] explored the control dynamics of such folding wings on solar-powered UAVs. For the UAV to absorb as much sunlight as possible, its solar panels must be oriented towards the sun. Since the UAV will most likely be changing orientation concerning the sun, re-orientation will only be possible using morphing wings.

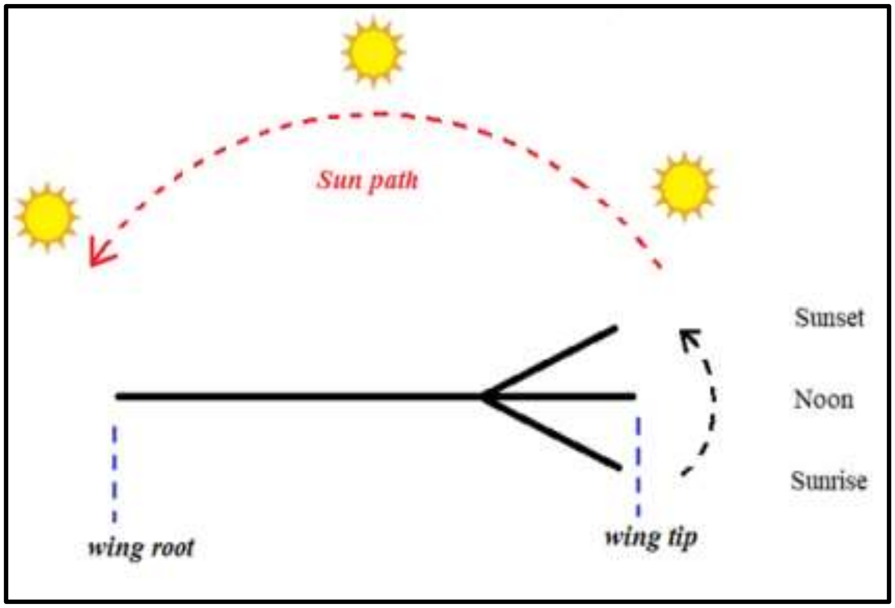

Fig. 18. The wing of a solar-powered plane oriented towards the sun [33]

From what has been seen in this review, it can be noted that each type of morphing has a unique advantage to offer. Hence, another aspect that many researchers have chosen to ignore is to combine different types of morphing. Muhammad [33] has developed a working model of a UAV with a wing that exhibits a mixture of chord and camber morphing. Similar ingenuity is needed in order to discover the vast benefits that wing morphing has to offer.

IV. CONCLUSION AND RECOMMENDATIONS

Despite sounding futuristic, morphing is, in fact, as old as the Wright Brothers [34]. In their first airborne plane, they employed the use of soft wings so that they could be bent with the help of ropes during a flight to create a moment. This allowed the aircraft to perform roll motion. Much development has been made in wing morphing research recently, especially in the past twenty years. Therefore, a review was needed in order to highlight the breakthroughs. In the end, it can be said that morphing has come a long way from where it was a century ago; however, still, more work is needed before fully bringing the technology into the commercial phase. So far, the studies considered have all been on a smaller UAV scale. There is a need to expand the research onto full-scale aircraft. This, however, is a difficult task because of the heavy-grade materials required to retrofit an aircraft with morphing technology and the large amounts of funding required.

Declaration of Conflicting Interests

There is no known conflict of interest in this work.

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