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FLEXIBLE WING STRUCTURE AND VARIABLE-SWEEP WING MECHANISM

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Abstract - *Aircraft Wings use aerofoil design to create a lift force that leads to flight. Ailerons are used to stabilize the flight and control pitch motion. These are flap-like mechanical devices with lots of components which leads to increased weight and a higher chance of failure. Using flexible wing systems can increase the manoeuvrability of the aircraft significantly. Using compliant mechanisms is the next step as they do not require hinges, bolts, etc., weight can be reduced significantly. Due to the aerofoil design, at higher speeds, the wind over the leading edge may go supersonic. This occurs due to chordwise flow which can lead to the angle of attack being too big which in turn can lead to loss of control. The spanwise flow which is created due to the swept nature of the wing can increase the maximum speed at which this occurs; effectively increasing the maximum speed of the aircraft. Different sweep angles create different spanwise flow. Thus, using a variable swept wing can work in different conditions. In this paper, we discuss what are aerofoils, flexible wing structures and swept wings and how these work.*

Key Words: **Flexible Wing Structures, Aerofoils, Sweep Angles, Ailerons, Compliant Mechanisms, Morphing Wings**

1.INTRODUCTION

The term 'Flexible Wing Structure' refers to the flexibility and morphing capacity of the ailerons to change the camber of the airfoil design instead of the conventional, rigid and multiple part complex designs used today. The aileron flaps are linked to the outboard trailing edge by complex hinges which are carefully designed to tolerate high forces and harsh conditions. These are bulky, hefty and complex due to the use of rigid designs and complicated joints. Instead of using such rigid structures, if flexible ailerons are used, the weight of the wing can be decreased. A smooth continuous surface in place of multiple separate flaps can increase the fuel efficiency of the aircraft [1]. Deflection in the contour of the flexible aileron can be produced by using a compliant frame. Adaptive control on the same has the potential to reduce the fuel burn of the aircraft. This has a huge impact on today's world where rising environmental concerns rule the industry. However, to utilize this technology and benefit from its gains, further design studies are required.

Swept wing designs are commonly used today in commercial aircraft due to their various advantages like a higher Critical Mach Number which results in a delay to the onset of wave drag. Swept designs can be of two types: backward and forward. Backward swept wings are seen in commercial flights where cruising is crucial. Whereas forward-swept wings are used in high-performance aircraft where speed and control are more important. Both of the designs are useful in their respective areas, but one cannot be used in the other situation. An aircraft with a variable-sweep angle is a cross-disciplinary solution that can be used to design an aircraft that can work in multiple situations like cruising, high-G maneuvering and loitering [2]. Therefore, with variable swept wing design and its morphing capabilities mission performance of aircraft can be increased.

Despite there being no established definition of a morphing aircraft, 200% change in wingspan, 50% change in wing area and 20° change in wing sweep are mentioned and generally accepted in the literature [3]. Combining the concepts of flexible wings using compliant structures with variable swept wing design and morphing design, missions requiring several aircraft types to accomplish may be performed with fewer types and with greater efficiencies.

2. FLEXIBLE WING STRUCTURE

2.1 AEROFOIL AND AILERON

Airfoils, shown in Fig. 1 below, are structures that are designed aerodynamically to provide lift. An Aircraft experiences four forces – Lift, Drag, Thrust and Weight. Weight is the force of gravity due to the mass of the aircraft.

Thrust is the force used to move an aircraft through the air. Drag force is generated due to contact between a fluid (air) and a solid body (aircraft). Lift is the force acting perpendicular to the motion of the aircraft.

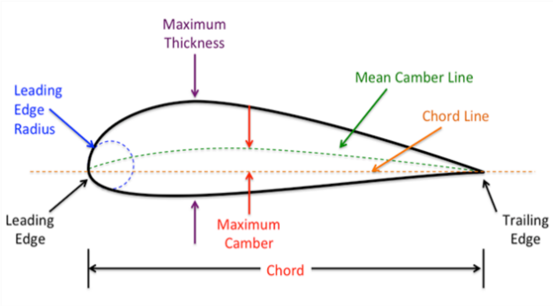

Fig. 1 Airfoil

Airfoils work in part, on Bernoulli's Principle which states that the velocity of the fluid is inversely proportional to its pressure. We design the airfoil such that the air moving over the top surface of the aircraft wing moves at a higher velocity than the air moving over the bottom surface of the aircraft wing. So according to Bernoulli's principle, the pressure of air over the top face is lower than the pressure of air over the bottom surface of the wing. And as fluid flows from higher to lower pressure we can achieve lift force.

Another factor in achieving lift is the angle of attack. An airfoil consists of a leading-edge (which is the front edge) and a trailing edge (which is the rearmost edge). An imaginary line joining these two edges is called a chord line. The angle this chord line makes with the direction of the relative wind is known as the angle of attack. The angle of attack directs the flow of air on the bottom surface of the airfoil down; and following Newton's Third Law, the airfoil experiences an upward Lift force.

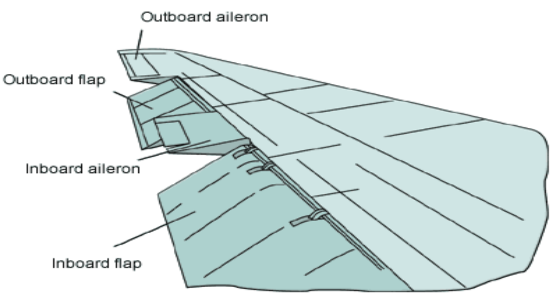

Fig. 2 Aileron

Ailerons as shown in Fig. 2 above, are hinged flight control surfaces, ordinarily forming the trailing edge of a wing. These are flap-like devices used to control the roll movement of the aircraft. Pairs of ailerons work in conjunction so that when the aileron on one wing moves downward, increasing the lift force on its wing; the aileron on the other wing moves upward, decreasing the lift force on its wing. There are various types of ailerons: single-acting, wingtip, Frise and differential.

2.2 MORPHING AILERON

Morphing aileron or Flexible Compliant Aileron (FCL) is a type of aileron that can reconfigure its geometry to suit its current altitude, airspeed, and lift-to-drag ratio requirements by continuously deforming the structure [4]. It has been proven that continuous, morphing airfoils display an aerodynamic advantage over airfoils with conventional, discrete trailing edge control surfaces [5][6][7]. A morphing aileron's smooth surface causes a delayed transition and reduced separation, resulting in reduced drag over the airfoil and improved aerodynamic efficiency. Conventional ailerons are attached to the wing by complex hinges and have sharp corners. These hinges bear which leading to losses which contribute to drag which has a limiting effect on the performance of an aircraft. Morphing ailerons on the other hand do not possess such gaps that give them an aerodynamic advantage [4] [8]. Fig. 3 shows an example of a Flexible Wing Structure.

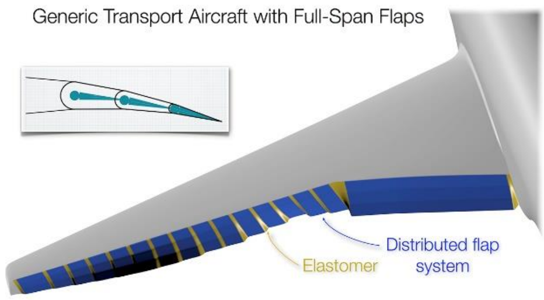

Fig. 3 Flexible Wing Structure

Fig. 4 as shown below, provides an example of a morphing trailing edge [9]. Here shape memory alloy (SMA) wires are used to control the deflection of the ailerons. These wires are attached near the top and bottom of the aileron.

As shown in Fig. 4, position (a) shows an unactuated state; position (b) shows an angular displacement in the counter-clockwise by heating the upper wire; position (c) shows an actuation in the reverse direction by heating the lower SMA wire [9].

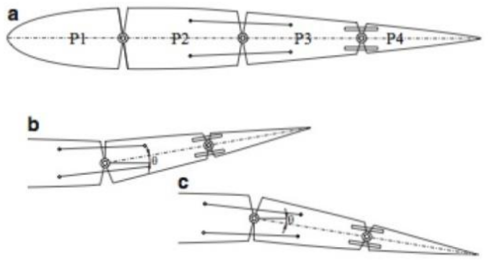

Fig. 4 Morphing Aileron [9]

The Smart Wing Project of the Defense Advanced Research Projects Agency (DARPA) also used a smoothly contoured trailing edge with variable wing twist. The maximum trailing edge deflection allowed by Smart Material was ±25 degrees. The program's associated challenges included severe manufacturing issues, power consumption, and scalability [10].

Another example is the FlexSys Adaptive Compliant Wing shown in Fig. 5. The use of elasticity in the underlying structure via implementation of a compliant structure is a primary enabling technology for the lightweight, low-power adaptive trailing edge [11].

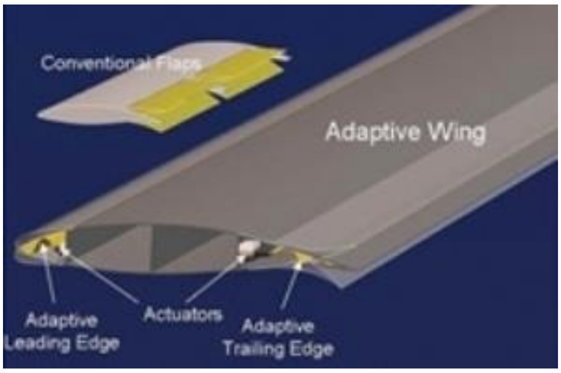

Fig. 5 FlexSys Adaptive Compliant Wing [11]

Here, compliant mechanisms are used to achieve the airfoil bending required to control the motion of the aircraft. It can theoretically provide 65% chord laminar flow on the upper surface and 90% chord laminar flow on the lower surface [11]. As compared to traditional hinged flaps, which can lead to the flow separation of the flap knee, Natural Laminar Flow (NLF) airfoils with long laminar runs have steep pressure gradients in the pressure recovery area. Therefore, the gentle curvature of the compliant flap can minimize or remove the flow separation over the flap surface [11]. Research on various Flexible Wing systems including the ones mentioned above and other such technologies is ongoing at various institutes.

2.3 POTENTIAL BENEFITS

A. DRAG REDUCTION:

As of 2011, jet fuel comprises 86% of the Air Force energy budget and over 8% of the total Air Force budget [12]. One benefit that emerges from the use of Flexible Wing Structures is the reduction in lift-drag ratio. Less drag means less resistance to the motion of the aircraft which means less fuel required to run an aircraft a particular distance. A variable camber wing provides the ability to optimize fuel reduction by changing the wing camber during the flight to the particular flight/mission situation or the desired configuration of the aircraft with a wing contour that gives the best performance under such conditions, which cannot be accomplished by the use of a traditional flapped wing. [4]. It is speculated that 5-6% of the fuel cost can be conserved by using a Smart Adaptive Wing System [11]. Decreases in induced drag could also be realized by actively adjusting wing camber along the span [4]. The Variable Camber Continuous Trailing Edge Flap (VCCTEF) is another design concept which can achieve a drag reduction of up to 6.31% and an improvement in L/D of up to 4.85% when compared to a traditional Wing System [13].

B. NOISE REDUCTION:

Another important benefit of Flexible Wing Structures is the reduction of noise. Traditional hinged ailerons have holes and gaps which creates noise. Flap side edge noise can make a major contribution to the overall airframe noise [14]. Using adaptive morphing wings like Variable Camber Compliant Wing (VCCW) designed by the Air Force Research Laboratory (AFRL) and Variable Camber Continuous Trailing Edge Flap (VCCTEF) can significantly reduce this problem [4] [13].

C. WEIGHT REDUCTION:

Conventional Wing Systems are heavy as they have use complex mechanisms such as flap screw jack actuators to control the movement of the ailerons. Using other mechanisms like SMA torque rod actuators instead can lead to comparatively light Wing Systems [13]. Using Flexible Wing Structures can significantly reduce weight of an aircraft.

D. FUEL BURN REDUCTION:

The effect of morphing on fuel burn occurs as it allows the aircraft to sustain high efficiency despite changing operating conditions and requirements [1]. Given that commercial aircraft fly in a variety of environments, the ability to morph their shape to produce the best possible result in each is a useful function [3]. While adaptive trailing edges with traditional surfaces reduce fuel burn by less than 1% for a typical transport mission, adaptive morphing trailing edge technologies could reduce fuel burn by 3% to 10% [1].

2.4 COMPLIANT MECHANISMS

Compliant mechanisms are structures that generate motion and force through elastic deformation. Essentially, these are mechanisms that bend to produce the desired output. Compliant mechanisms can achieve complex motion from simple topologies because their motion is derived from the constrained bending of flexible parts [15]. Fig. 6 shows a scissor made of compliant mechanism. Some of the advantages [15] of Compliant Mechanisms are-

- No Assembly Required
- Compact
- Friction-Free Motion
- Wear-Free Motion
- High Precision
- High Reliability
- Integrated Functions

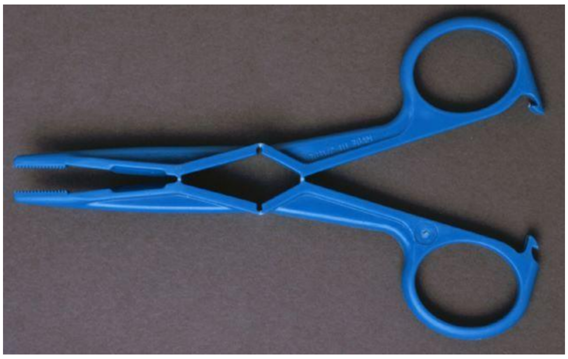

Fig. 6 A Compliant Scissor

Using Compliant Mechanisms instead of conventional hinged ailerons can lead to reduction in weight of the wing and other advantages mentioned above.

3. VARIABLE-SWEEP WING SYSTEMS

3.1 WINGS AND ITS TYPES

Wings on an aircraft are of a swept nature today because straight wings pose a number of drawbacks like being unstable at transonic and supersonic speeds and yaw instability. Using swept wing designs can partially or completely negate such shortcomings.

An aircraft's wing is an essential component that provides lift force. So, a lot of research has been conducted in this domain. Wings are of various types, each with its particular characteristic advantage. Types of wings-

- Rectangular Wings
- Elliptical Wings
- Tapered Wings
- Delta Wings
- Trapezoidal Wings
- Ogive Wings
- Swept Back Wings
- Forward Swept Wings
- Variable Sweep Wings

The aircraft wings whose leading edges are swept back are called swept back wings. When an aircraft is flying at transonic speeds, swept back wings minimize drag. This is the case with the vast majority of commercial aircraft.

Swept forward wings are aircraft wings with their leading edges swept forward. The main problem with this type of wing configuration was that it caused wing twisting when bent under load, placing more stress on the wing roots.

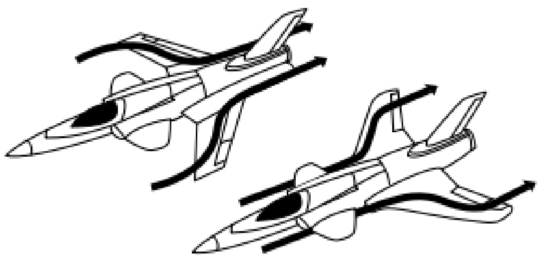

Fig. 7 Swept Back and Forward Swept Wings

Variable Sweep Wings are used as a middle ground between Swept Back Wings, Delta Wings, Trapezoidal Wings and Forward Swept Wings. Variable Sweep Wings can perform in almost all conditions like low speed loiter or supersonic cruise.

3.2 Variable Sweep Wings

Due to the airfoil design, at higher speeds, the wind just over the leading edge may go supersonic. It happens due to chordwise (which is depicted Fig. 8 below alongside with spanwise flow) flow which can lead to the angle of attack being too big which in turn can lead to loss of control. The spanwise flow, created due to the swept nature of the wing can increase the maximum speed at which this occurs; effectively increasing the top speed of the aircraft. Different sweep angles create disparate spanwise flow. Thus, using a variable swept wing can work in various conditions.

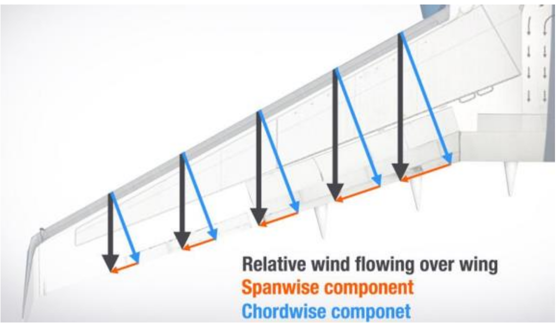

Fig.8 Chordwise and Spanwise Airflow

Variable Sweep Wings, as the name suggests are aircraft wings that can change the sweep angle of their wings. Variable Sweep Wings can act like straight wings, swept back wings and forward swept wings according to the requirement. The air speed that travels over the top side of the can wings approaches the speed of sound as airliners fly faster and faster. Because of the resulting shock waves, this induces vibration in the plane body.

As a result of air friction on the wings, turbulence and drag rise as speed increases. To address this instability and turbulence in supersonic jets at high speeds, swept back wings technology was introduced. The wings are pointed towards the back end, giving the appearance of increased wing length.

With a variable-sweep wing, the pilot can pick the best sweep angle for the aircraft's current speed, whether it's slow or fast. The more effective sweep angles available compensate for the wing's mechanical sweep mechanisms' weight and volume penalties. Because of its greater complexity and cost, it is only suitable for military aircraft.

Wing sweep, whether forward or aft, delays the drag increase associated with travel above the speed of sound aerodynamically. The forward swept wing (FSW), on the other hand, has shown benefits in terms of transonic drag and low-speed characteristics [16].

More lateral stability, less turbulence when speed suddenly changes, and less air friction are all advantages of swept back wings, which are thin and finely built.

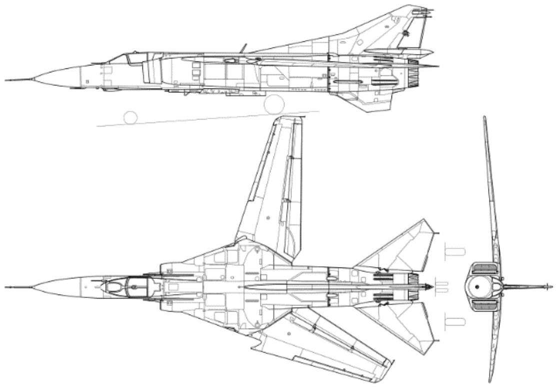

Fig. 9 Variable Geometry Wing, MiG-23

Fig. 9 shows an example of Variable Sweep Wings that is widely used by countries such as Russia, India, Egypt, etc. Other examples of aircrafts having Variable Sweep Wings are Bell X-5, Grumman XF10F Jaguar, MiG-27 among others.

At the transonic maneuvering design stage, the FSW principle can give lower wing profile drag than an equivalent aft swept wing (ASW). At transonic maneuvering conditions, lower profile drag results in higher sustained lift coefficients [16].

Various methods are used to achieve Variable Sweep Wings using complex machineries and smart materials like by C.L. Johnson [17] and Shigeru Horinouchi [18].

Lockheed-Martin's 'folding wings' concept uses shape memory polymer that softens and morphs within seconds after heating while NextGen's 'variable chord, variable sweep' concept uses small hydraulic motors with silicon skin reinforced by metal that produces morphing [3].

Variable Sweep Wings pose various drawbacks like sweeping the wing at an angle, whether backwards or forwards, slows the onset of their impact and decreases overall drag. However, it reduces a wing's overall span, resulting in low cruise efficiency and fast take-off and landing speeds. Using Variable Sweep Angles also produces another issue- weight. The complex mechanism of Changing the sweep angle of the wing can add significant weight when compared to conventional rigid wings.

3.3 USING VARIABLE SWEEP WINGS WITH FLEXIBLE WING STRUCTURES

Using Variable Sweep Wings (VSW) alone has few drawbacks as discussed earlier. Therefore, using VSW with Flexible Wing Structures (FWS) is an option worth considering. It can lead to a symbiotic relationship where the problems posed by VSW can be addressed by FWS and vice versa. For Example, the weight issue posed by VSW can be negated by using FWS and its light-weight properties. Thus, using flexible wing systems in conjunction with variable-sweep angle and active control can increase the manoeuvrability of the aircraft while also increasing the stability and maximum velocity.

4. CONCLUSION

Flexible Wing Structures and Variable-Sweep Wings are discussed in this article. A brief overview of both is given, along with relevant examples. Both technologies are currently being investigated and have some clear candidates for long-term use. It is suggested that both technologies be used together to reduce the disadvantages of each.

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