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Design and Vibration Analysis of Morphing Wing

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Abstract- Traditional control surfaces on aircraft have been based on rigidly hinged flap sections that create unavoidable geometric discontinuities. These generate early flow separation and parasite drag, hindering aerodynamic performance in different flight conditions. This study explores the application of camber morphing, a biological concept involving wing deformation similar to those seen in bird-like flying organisms. The main goal of this study was to develop an adaptable mechanism, capable of changing the average camber line of the airfoil while keeping its structural integrity intact. The focus is put on a "Fishbone Active Camber" (Fish BAC), or [add name of the mechanism used, for instance, SMA or Rib-Linkage] based structure which replaces a hinge mechanism at the rear-spar position of the wing with a continuous flexible skin allowing for an even pressure distribution along the wingspan. The method involved a two-step approach. First, numerical simulations were carried out using an omega SST turbulence model to compare the aerodynamic parameters of the standard NACA 2412 airfoil with a morphing one. It is evident that the morphing wing has successfully reduced pressure drag significantly by removing the "hinge-gap" problem. More precisely, when the Angle of Attack (AOA) is 6 degrees, the morphing wing has shown a Lift-to-Drag ratio improvement of about 12 to 15 percent over the conventional flaps wing system. Also, flow visualization proved that the onset of turbulence occurred much later, thus broadening the aircraft's range of efficient flight.

Keywords— Morphing Wing, Adaptive Wing Structure, Smart Wing Design, Aircraft Wing Morphing, Variable Geometry Wing, Shape, Changing Aircraft Wing, Bio-inspired Wing Morphing

I. INTRODUCTION

1. About Aircraft Wing

The classic wing is a static or rigid wing component mounted on the airplane's fuselage structure. The basic function of the wing is to create a force called "lift," which makes the airplane take off in the sky regardless of whether there is propulsion or not due to its airfoil shape (the cross-sectional shape).

Fig-1. Conventional Aircraft Wing

A wing is an example of a fin. In contrast to changing wings that have moving surfaces for maneuvering purposes, non-changing wings use fixed surfaces that can alter their form through the use of movable flight control surfaces (flaps, ailerons, slats, and spoilers) . non-changing wings are the most common type of wings found in almost all modern commercial, private, and military airplanes.

Aircraft Wing Components

- Wing - "Generate Lift"
- Leading Edge Slats - "Increase Lift"
- Trailing Edge Flaps - "Increase Lift and Drag"
- Aileron - "Change Roll"
- Spoiler - "Air Brakes / Speed Brakes"
- Winglet - "Decrease Drag"

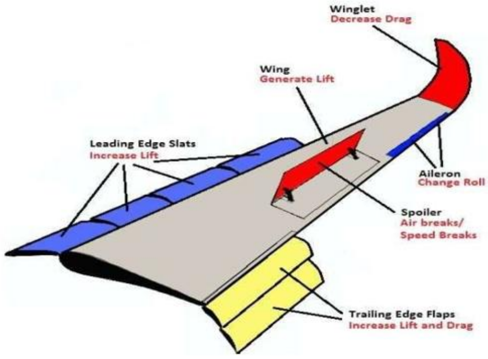


Fig-2 Aircraft Wing Components

Wing (Gray) — "Generate Lift"
This large gray structure is the main wing. It is the wing's aerodynamic shape, and is the fixed, rigid portion of the wing that does most of the aerodynamic work. What it does: As the wing moves through the air, the air moves at different speeds over and under the wing. Since the air moves faster over the top of the wing than underneath, a low pressure area is created above the wing. This pressure difference creates lift, which is the force that supports the aircraft against the pull of gravity.
Leading Edge Slats (Blue) — "Increase Lift" The blue panels along the entire leading edge (front edge) of the wing are leading edge slats — high-lift devices that extend forward and downward during take-off and landing. What they do: At low airspeeds (take-off and approach), the wing must operate at a high angle of attack to generate enough lift. Without intervention, the airflow would separate from the upper surface — causing a stall. Slats extend outward from the leading edge, opening a slot (a gap between the slat and the main wing). High-pressure air from beneath the wing is accelerated through this slot and blown over the upper surface, re-energizing the boundary layer and delaying flow separation. This allows the wing to reach a much higher angle of attack — effectively increasing the maximum lift coefficient (C_L max) by 40–60%.
Trailing Edge Flaps (Yellow) — "Increase Lift and Drag"

The yellow surface extending from the trailing edge (rear edge) at the inboard section is the trailing edge flap — the most powerful high-lift device on the wing. What they do: Flaps hinge downward (and in sophisticated designs, slide rearward as well), increasing the camber of the wing cross-section and in some types increasing the total wing area. Both effects dramatically raise C_L. Critically, flaps also significantly increase drag — which is intentional during landing, as extra drag allows the aircraft to descend on a steeper glidepath at low speed without accelerating.

Aileron (Red, inner panel) — "Change Roll"
The red panel at the outboard trailing edge is the aileron — the primary roll control surface.

What it does: Ailerons work differentially — the two wings always move in opposite directions. When the pilot commands a left roll, the left aileron deflects upward (reducing lift on the left wing) while the right aileron deflects downward (increasing lift on the right wing). The lift asymmetry generates a rolling moment, banking the aircraft.

Spoiler (Red, upper surface panel) — "Air Brakes / Speed Brakes"

The red panel on the upper surface of the wing (just forward of and above the aileron) is the spoiler — a multi-function panel that can be raised into the airflow.

What it does — three distinct roles: Speed brakes (symmetric): When the crew needs to slow down or descend rapidly, spoilers on both wings rise simultaneously. By disrupting the smooth airflow over the upper surface, they destroy lift and massively increase drag — slowing the aircraft without changing pitch attitude significantly.

Roll augmentation (asymmetric): Spoilers on one wing rise in coordination with the ailerons to enhance roll rate. On the descending wing (the wing being rolled toward), spoilers rise to kill lift and add drag — augmenting the aileron's rolling moment. This is especially important at high speed where large aileron deflections could overstress the wing.

Ground spoilers (touchdown): At the moment of touchdown, all spoilers deploy fully and simultaneously. This "dumps" the remaining lift so the full aircraft weight settles onto the wheels — maximizing brake effectiveness and preventing the aircraft from becoming airborne again in a gust.

Winglet (Red, vertical tip) — "Decrease Drag"
The curved red structure at the wingtip, turned nearly vertical, is the winglet -a drag-reduction device.

What it does: At the wingtip, high-pressure air from below the wing constantly escapes around the tip to the low-pressure upper surface, forming a large, spiraling tip vortex. This vortex represents wasted energy and creates a form of drag called induced drag (also called lift-induced drag). The winglet acts as a fence — it intercepts this escaping flow and converts some of the vortex energy into a small forward thrust component, while significantly weakening the vortex. The net effect is a 3–5% reduction in induced drag, directly translating to improved fuel efficiency.

History of Wings

Aircraft wings evolved from 19th-century gliders to modern high-speed airfoils, heavily influenced by Otto Lilienthal's cambered wing research in the 1890s and the Wright brothers' wind tunnel testing for lift. Key developments shifted from early biplanes to metal monoplanes, swept wings for jet speed, and specialized designs like delta and variable-sweep wings.

Key Eras and Developments

- The Wright Brothers Era (1903–1910): The very first powered aircraft — the Wright Flyer — used wing warping rather than rigid control surfaces. The Wright Brothers twisted the wing fabric by pulling cables, changing the lift distribution across each wing to control roll. This was, in essence, the earliest form of wing morphing. It was intuitive and effective, but structurally limited at higher speeds.

- Rigid Surfaces Take Over (1910s–1950s): As speeds increased, wing warping proved insufficient and structurally dangerous. Engineers switched to hinged, rigid control surfaces — ailerons, elevators, rudders — which were easier to manufacture and more reliable. This paradigm dominated aviation for decades and is essentially the same technology used in most aircraft today. Wing morphing was largely abandoned.
- Variable Geometry Wings (1950s–1970s): Cold War military demands revived interest in adaptive wings. Aircraft like the F-111, F-14 Tomcat, Tornado, and B-1 Lancer used variable-sweep wings — manually changing the sweep angle on the ground or in flight to optimize performance at both low-speed and supersonic conditions. This was
- morphing in a course, mechanical sense: a large discrete geometry changes via actuated pivot mechanisms.
- NASA's Active Flexible Wing (1980s–1990s): NASA pioneered research into truly flexible, adaptive wing structures. The Active Flexible Wing (AFW) project (1985–1993) tested computer-controlled wing twist to improve roll maneuverability, showing that structural flexibility could be an asset rather than a liability.
- Smart Materials Revolution (1990s–2000s): The advent of shape memory alloys (SMAs), piezoelectric actuators, and composite materials gave engineers new tools to induce small, precise, distributed shape changes without heavy hydraulic systems. DARPA's Smart Wing program (1995–2000) demonstrated conformal control surfaces with zero gap, dramatically reducing drag. NASA's Mission Adaptive Wing (MAW) project showed variable-camber airfoils in flight.
- Modern Era (2010s–Present): Today, morphing wing research is one of the most active areas in aerospace. Highlights include:
- NASA's MADCAT and LEAP programs - using flexible cellular lattice structures and distributed actuators.
- EU's Clean Sky 2 program - developing morphing wing tips and leading/trailing edges for commercial aircraft to reduce fuel burn.
- FlexSys Inc.'s adaptive compliant trailing edge - flight tested on a Gulfstream III, achieving seamless variable camber.
- MIT's "digital morphing wing" (2019) - a wing made of thousands of small, identical triangular composite pieces forming a flexible lattice that can be actuated with small motors.
- Shape memory alloy-driven morphing demonstrators in military UAVs.

Fig 3 – Timeline of wings

2. Morphing Wing

Morphing wings represent an advanced aircraft technology that allows a wing to actively change its geometry in flight. This concept is directly inspired by the natural world, specifically by the way birds change the shape of their wings while flying to achieve different performance goals. Morphing wings, also known as shape-shifting or adaptive wings, are aircraft wing designs that can change their geometric shape in real-time during flight.

A morphing wing is an advanced aerodynamic structure capable of undergoing continuous, reversible changes to its geometry during flight. Unlike traditional aircraft that rely on rigid wings with hinged control surfaces (like flaps or ailerons), morphing wings utilize compliant mechanisms and flexible skins to alter their shape seamlessly.

Fig-4 Morphing Aircraft

Key Aspects of Morphing Wing Technology

- Performance & Efficiency: By adapting to different flight conditions, these wings optimize structural efficiency and reduce noise.
- Mechanism & Materials: Technologies include flexible skins, Shape Memory Alloys (SMAs) that react to temperature changes, and Macro Fiber Composite (MFC) actuators.
- Applications: Primarily targeted at military drones and next-generation fighter jets to enhance maneuverability and stealth, with potential for sustainable commercial aviation.
- Design Goals: To achieve seamless shape changes—such as wing warping, span extension, or camber modification—without the structural weight of traditional joints.

3. Classification of Morphing Wings

Morphing wings can be classified across three primary dimensions:

Planform morphing,

- Span Morphing
- Sweep Morphing
- Chord Morphing

Out-of-plane morphing, and

- Twist Morphing (Spanwise Twist)
- Dihedral/Anhedral Change
- Winglet Deflection

Airfoil / Section Morphing

- Camber Morphing
- Thickness Morphing
- Profile Morphing

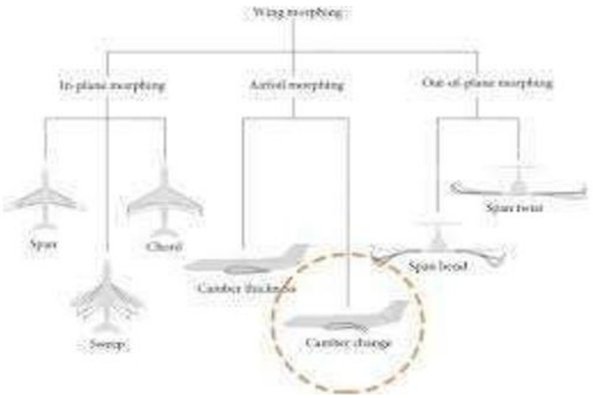


Fig-5 Classification of Morphing Wing

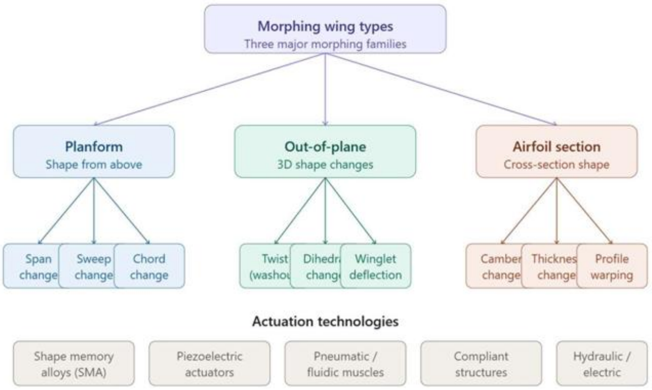


Fig-6 Classification of Morphing Wing with Actuation technologies

Planform Morphing

This changes the shape of the wing as seen from above - altering overall dimensions without necessarily changing the cross-section.

Span Morphing: The wingspan is physically extended or retracted. A longer span improves lift and fuel efficiency at cruise; a shorter span improves roll rate and reduces drag at high speed. NASA's Spanwise Adaptive Wing (SAW) project and several UAV designs have demonstrated this. Mechanisms include telescoping spar sections, inflatable ribs, or SMA-driven extendable tip segments.

Sweep Morphing: The wing is swept back or forward relative to the fuselage. Backward sweep reduces drag at supersonic speeds; forward or low sweep provides better lift at low speeds. The F-14 Tomcat is the classic example (16°–68° variable sweep). Modern research explores doing this continuously and smoothly with SMA actuators rather than bulky mechanical pivots.

Chord Morphing: The chord length (wing depth from leading to trailing edge) is changed, effectively enlarging or shrinking the wing area. This is the hardest to implement structurally because it requires the wing skin to stretch or retract, but inflatable skins and elastomeric composites are being explored.

Out-of-Plane Morphing

These are changes in the three-dimensional orientation of the wing — not its flat planform outline.

Twist Morphing (Spanwise Twist): Different sections of the wing rotate about the span axis by different amounts, changing the local angle of attack along the span. This is called geometric or aerodynamic washout. It is used to delay stall onset, optimize the lift distribution (approaching the ideal elliptical distribution), and replace ailerons. Birds constantly twist their wings in flight.

Dihedral/Anhedral Change: The upward or downward angle of the wing relative to horizontal is changed. Positive dihedral increases lateral stability; reduced dihedral improves roll agility. Variable dihedral could allow an aircraft to switch between stable cruise and agile combat maneuver modes.

Winglet Deflection: Adaptive winglets at the tip can adjust their cant angle and toe-in/out. Studies (including Airbus research) show that variable winglets could reduce induced drag by up to 5% more than fixed optimal winglets, because the optimal winglet angle varies with speed and load.

Airfoil Section Morphing

These changes alter the actual cross-sectional shape of the wing at any given spanwise location.

Camber Morphing: The curvature of the mean camber line (the center line of the airfoil) is changed. Increased camber generates more lift at low speed; reduced camber (flatter profile) is better at cruise. This is the most aerodynamically powerful form of morphing. A camber-morphing wing can replace both leading-edge slats and trailing-edge flaps with a single, smooth, seamless shape change — eliminating the drag penalty of gaps and steps. NASA's ACTE (Adaptive Compliant Trailing Edge) program demonstrated 12% drag reduction using this approach.

Thickness Morphing: The maximum thickness of the cross-section is varied. A thicker wing stores more fuel and generates lift more easily but has more drag; a thinner profile is more efficient at high speed. Thickness morphing is difficult but possible with pneumatic bladder structures inside flexible composite skins.

Profile Warping: The entire airfoil shape is continuously deformed — simultaneously changing leading edge radius, maximum thickness location, camber distribution, and trailing edge angle. This is the most ambitious form and requires sophisticated smart material actuation distributed throughout the wing structure. It most closely mimics biological wing function.

4. Advantages of Morphing Wing Technology

Aerodynamic Efficiency Across the Flight Envelope: A fixed wing is a compromise- optimized for one condition (usually cruise) but suboptimal everywhere else. A morphing wing can always maintain near-optimal geometry. Studies show potential fuel savings of 10–30% for commercial aircraft, primarily through camber optimization at cruise and reduced drag from eliminating conventional flap/slat mechanisms.

Elimination of Discontinuities and Gaps: Conventional flaps create gaps, steps, and flow separation zones that dramatically increase drag and noise. A morphing trailing edge is smooth and continuous. This also reduces aerodynamic noise — a key benefit for noise-sensitive operations near airports.

Adaptive Gust and Load Alleviation: Morphing wings can respond rapidly to atmospheric turbulence, reshaping in real time to redistribute structural loads, reduce fatigue, and improve passenger comfort. This could allow lighter wing structures (less material needed for gust load cases) — reducing structural weight.

Multi-Role Adaptability: For military aircraft, a morphing wing allows a single airframe to excel in multiple roles — high-altitude reconnaissance (extended span, high aspect ratio), air-to-air combat (swept, low-aspect ratio for agility), and low-level ground attack — without the mechanical complexity of variable-sweep pivots.

Improved Stall Characteristics: Spanwise twist morphing can progressively adapt the local angle of attack to keep outboard sections (near the tips) flying even as the root begins to stall, improving stall warning and post-stall behavior.

Reduced Control Surface Count: A single continuous morphing surface can perform the functions of ailerons, flaps, slats, spoilers, and even some elevator/rudder functions — reducing part count, maintenance burden, and radar cross-section (important for stealth aircraft).

Better Laminar Flow Maintenance: Precisely controlling leading-edge shape allows engineers to maintain laminar (smooth, low-drag) boundary layer flow over a larger fraction of the wing surface, reducing skin friction drag — potentially 15–25% of total drag on commercial aircraft.

Biomimetic and Bio-inspired Performance: Birds are far more aerodynamically efficient than aircraft at comparable scales. Morphing enables aircraft to approach bird-like adaptability, particularly relevant for small UAVs operating in turbulent, cluttered environments.

5. Disadvantages and Challenges of Morphing Wing Technology

- Structural Complexity and Weight Penalty: A morphing wing must simultaneously be stiff enough to carry aerodynamic loads (lift, bending moment, torsion) and flexible enough to change shape. These are fundamentally conflicting requirements. The additional mechanisms, smart materials, actuators, and sensors typically add weight that can partially or fully offset aerodynamic efficiency gains.

- Skin Design Challenge: The wing skin must be flexible enough to change shape without wrinkling or cracking, yet stiff enough to maintain aerodynamic contours under pressure. Conventional aluminum or carbon fiber skins cannot do this. Elastomeric skins, fiber-reinforced silicones, and
- shape-morphing composites are promising but not yet mature for commercial certification.
- Actuator Limitations: Existing smart material actuators — particularly SMAs — suffer from low frequency response, low energy efficiency, limited lifetime (fatigue under cyclic loading), and sensitivity to temperature. Piezoelectric actuators generate very small displacements. No single actuator technology currently offers the ideal combination of high force, large displacement, fast response, low weight, and long life.
- Control System Complexity: Morphing wings introduce many additional degrees of freedom. The flight control system must manage these continuously, integrating aerodynamic modelling, structural feedback, and mission objectives. This requires sophisticated real-time sensing (distributed strain sensors, pressure taps), computation, and control algorithms — including potentially AI/ML-based adaptive controllers.
- Aeroelastic Instability Risk: By making the wing more flexible, morphing designs increase the risk of flutter, divergence, and other aeroelastic instabilities. The coupling between structural deformation and aerodynamic forces becomes more complex. This requires careful aeroelastic tailoring and robust flutter suppression systems.
- Certification and Safety: Aerospace certification is extremely conservative. Novel structural concepts, smart materials, and complex control laws require extensive testing (thousands of hours) to prove reliability and fail-safety. A morphing skin that cracks, an SMA actuator that loses its trained shape, or a control failure that locks the wing in a non-optimal configuration could be catastrophic. Regulatory pathways for morphing aircraft remain immature.
- Manufacturing Difficulty: Fabricating wings with embedded actuators, sensors, and flexible structures is far more complex than conventional machining and autoclaving of composite parts. Novel manufacturing processes (additive manufacturing of lattice structures, integrated SMA-composite layup) are still maturing.
- Maintenance and Inspection: Detecting damage or degradation in flexible composite skins, embedded SMA wires, or distributed actuator networks is far more difficult than inspecting a conventional metal or CFRP wing. Structural Health Monitoring (SHM) systems must be embedded throughout, adding weight and complexity.
- Cost: Research, development, certification, manufacturing, and maintenance costs are significantly higher than for conventional wing technology. Economic viability for commercial aviation — where every kilogram and every dollar matter enormously — has not yet been fully demonstrated at scale.

6. Comparison between Morphing Wing and Convectional Wing

Table 1. Comparison between Morphing and Convectional Wing

Feature	Morphing Wing	Convectional(fixed) Wing
Shape Change	Adaptive and Continuous. The entire wing or major sections (planform, span, chord, twist) can change shape in real-time.	Fixed or Discrete. The main wing structure is rigid and fixed. Changes are limited to hinged components.
Control Surfaces	Control is achieved by seamlessly deforming the wing's surface (e.g., changing the curvature, or *camber*).	Control is achieved by hinged, separate movable surfaces like ailerons, flaps, and slats.

Aerodynamic Surface	Seamless and Gap-Free. This design eliminates gaps between the control surfaces and the main wing.	Discontinuous. Gaps and steps exist when control surfaces are deployed.
Aerodynamic Efficiency	Optimized for Multi-Point Performance. Can change shape to maximize the lift-to-drag ratio (L/D) in all flight phases (take off, cruise, landing).	Optimized for a Single Point (usually high-speed cruise). Performance is suboptimal in other phases.
Fuel Consumption	Lower. Greater efficiency leads to significant fuel savings.	Higher comparative fuel burn in non-optimized flight phases.
Noise	Lower Airframe Noise. Eliminating gaps and hinges reduces the aerodynamic noise generated during high-lift configurations.	Higher Airframe Noise (especially during landing) due to air flowing through the gaps of deployed flaps and slats.
Design/Structure	Higher Complexity. Requires advanced, flexible materials (composites, shape memory alloys) and intricate internal mechanisms to handle flight loads while being deformable.	Lower Complexity / Proven Structure. Uses rigid materials and well-understood mechanical linkages.
Drag	Reduced. The seamless surface minimizes the creation of vortices and turbulent flow caused by gaps.	Higher drag when control surfaces (like flaps) are deployed due to gaps and flow separation.

II. LITERATURE REVIEW

Morphing wing design has emerged as a transformative approach in Aerospace Engineering, aiming to improve aerodynamic efficiency, flight adaptability, and to reduce fuel consumption across various flight conditions. Unlike conventional fixed-wing designs that are optimized for specific operational regimes, morphing wings enable real-time shape adaptation, facilitating a dynamic response to changing flight conditions. This versatility has shown advantages in enhancing lift, reducing drag, and achieving better performance, particularly for applications in Unmanned Aerial Vehicles (UAVs) and next-generation commercial aircraft. Numerous studies have explored the core components of morphing wing technology, including the development of adaptive materials that maintain wings' structural integrity while enabling its flexibility, as well as innovative actuation systems that ensure efficient shape transformation. Additionally, recent work has advanced control methodologies to support these adaptations, allowing for

Tuba Majid and Bruce W. Jo [1] presented a detailed study on camber morphing mechanisms and classified them into structure-based, material-based, and hybrid systems. Their work showed that topology optimization and material anisotropy can remove traditional hinge gaps and improve aerodynamic smoothness, leading to better lift-to-drag performance and fuel efficiency. However, they also noted that balancing structural stiffness with actuation energy remains a significant challenge in practical implementation.

Dr. P. V. Selvan, G. P. Gokulnath, and M. Kowshalya [2] analyzed four morphing wing configurations using CATIA and ANSYS. Their results showed that aluminum is more suitable than steel for internal morphing mechanisms because

it produces lower stress and deformation while maintaining a lightweight structure. This finding is particularly important for aircraft wing design, where mass reduction and structural safety are both essential.

Ahmad et al. [3] investigated polymer-based skins for morphing wing applications and examined four vacuum-bagged composite configurations. Their work demonstrated that combinations of glass and carbon fibers with aluminum and date pit powders can provide lightweight alternatives to conventional spars while improving flexion resistance and structural efficiency. This study highlights the growing role of hybrid composites in next-generation adaptive wing structures.

Faisal Mahmood, Seyed M. Hashemi, and Hekmat Alighanbari [4] examined the free vibration behavior of a reconfigurable modular morphing wing using finite element

methods and beam theories. Their study revealed that topological architecture and spherical joint connections strongly influence natural frequencies and vibration modes. This shows that dynamic stability is a key issue in morphing-wing design, especially when geometric reconfiguration changes the structural response.

Aishwarya Dhara's [5] systematic review classified morphing technologies into in-plane, airfoil, and out-of-plane categories. The review explained that changes in wingspan, chord, sweep, and camber can improve maneuverability and fuel efficiency compared with rigid, hinged surfaces. This paper provides a broad overview of morphing-wing evolution and confirms the move toward bio-inspired adaptive aircraft designs.

Faisal Mahmood, Seyed M. Hashemi, and Hekmat Alighanbari [6] also conducted a structural dynamic characterization of a modular morphing wing using finite elements and Taguchi methodology. Their work identified the geometric parameters most strongly affecting aerodynamic efficiency, structural integrity, and weight reduction. The study demonstrates that morphing wings should be optimized through combined structural and aerodynamic considerations rather than geometry alone.

Subash Dhakal, Sudip Dhakal, and Santosh Prakash [7] studied wing rib configurations to improve aerodynamic performance using computational methods. Their results showed that rib geometry directly affects lift, drag, and lift-to-drag ratio, and optimized rib shapes can significantly improve aerodynamic efficiency. This is relevant to morphing wings because the internal rib structure plays an important role in both load transfer and shape control.

J. Sun, Q. Guan, Y. Liu, and J. Leng [8] reviewed morphing aircraft based on smart materials and structures. They highlighted shape memory alloys, shape memory polymers, and piezoelectric materials as lightweight alternatives to heavy hydraulic systems. Their review is important because it shows the shift toward intelligent, bio-inspired wing structures that can adapt to changing flight conditions with less mass and higher energy efficiency.

P. Jia, S. K. Lai, W. Zhang, and C. W. Lim [9] performed experimental and finite element modal analysis of a deployable-retractable wing. Their study showed that changes in wing length during deployment significantly alter the vibration modes and natural frequencies. This confirms that modal evaluation is necessary in any morphing or adaptive wing concept to prevent resonance and maintain stability.

S. Srividhya, K. Nehru, A. Salamon Rago, and Peratchi Selvan [10] carried out vibrational analysis of an aircraft wing model using ANSYS Workbench. Their modal study identified natural frequencies and mode shapes to ensure the wing does not enter resonance under dynamic conditions. This type of analysis is especially important for morphing wings because they may experience frequency shifts as the geometry changes.

K. S. S. Sravan, S. S. Sharan, and V. R. Sanal Kumar [11] evaluated four morphing wing configurations—telescopic, folding, sweeping, and camber change—using CFD simulation. Their study compared lift, drag, and stability, showing how morphing concepts can replace traditional control surfaces with seamless adaptive structures. This supports the aerodynamic motivation for morphing-wing development.

S. Ravi Kumar and B. Venkatesh [12] investigated the modal and harmonic response of an aircraft wing under dynamic loading. Their work showed that harmonic analysis is useful for identifying resonance-prone frequency regions and predicting vibration levels under excitation. This is directly relevant to morphing wings, where dynamic performance must be checked carefully to ensure structural safety.

R. Ajaj, M. Abdalla, and C. S. Tsavdaridis [13] reviewed the status and challenges of camber morphing mechanisms. They emphasized that weight penalties, power requirements, and the stiffness-flexibility trade-off are the main obstacles to practical implementation. Their review shows that although camber morphing can improve aerodynamic efficiency and fuel economy, the concept still requires better materials and structural solutions.

S. Deepraj, P. Kumar, and S. C. Rana [14] studied the design and vibration analysis of a morphing wing using ANSYS. Their results showed that morphing skins and internal mechanisms significantly influence the wing's modal behavior compared with conventional rigid wings. This confirms that vibration analysis is essential during the design stage of a morphing wing.

Andrea Cini, Alexander S. J. van Ommeren, and Roeland De Breuker [15] developed an aerostructural model for morphing laminar wing optimization in a wind tunnel. Their work demonstrated that aerodynamic and structural coupling can be used to control drag and maintain laminar flow through real-time shape adjustments. This research supports the idea that future morphing wings should be studied as integrated aero-structural systems.

Dr. T. S. Sagar Santhosh, M. S. Varun, and J. S. Abishek [16] compared aluminum alloy and CFRP for aircraft wing structures using finite element analysis. Their findings showed that CFRP reduces weight and deformation more effectively, while aluminum alloys still offer practical advantages in cost, reliability, and manufacturability. This comparison is useful when selecting materials for morphing wing structures, especially for balancing performance and fabrication ease.

S. Vigneshwaran, R. Sundara Kannan, and K. M. Sridhar [17] investigated an aluminum-carbon fiber composite for wing spar applications. Their results showed improved tensile strength, hardness, fatigue resistance, and reduced structural weight compared with aluminum alone. This supports the potential of hybrid composites for future morphing wing applications where both stiffness and deformability are require

III. METHODOLOGY

Methodology of morphing wing Fish bone aircraft design involves the following five major steps:
Selection of concept, CAD modeling, Material selection, Structural analysis & Performance evaluation

Fish BAC concept selection

The Fish BAC concept is selected because it uses a compliant spine and flexible trailing edge to create continuous camber change. It is suitable for morphing applications because it can improve lift-to-drag ratio while keeping the leading portion of the wing structurally stable.

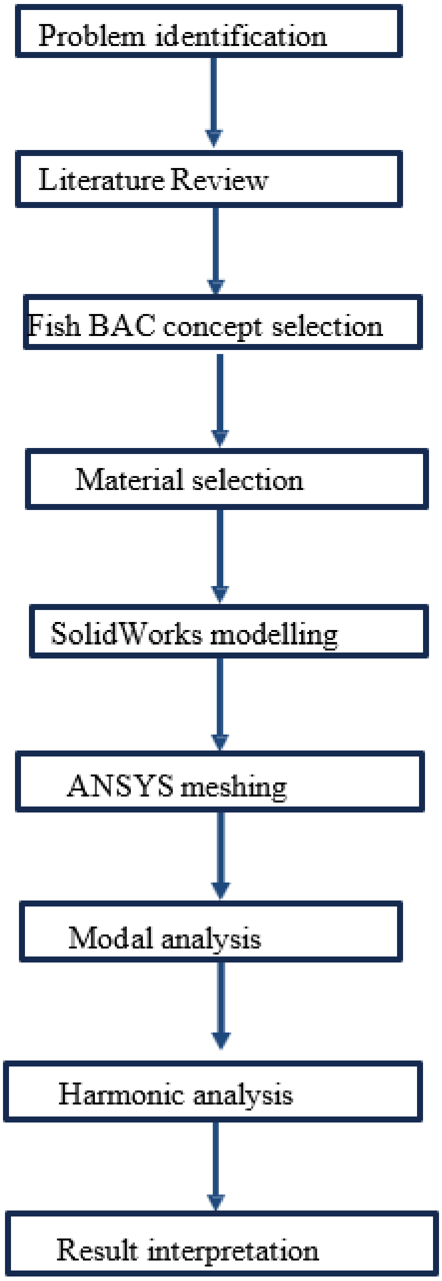
SolidWorks modeling

The wing geometry is created in SolidWorks by modeling the fishbone ribs, skin, spar, and support members. This step converts the conceptual Fish BAC design into a detailed 3D model that can later be analyzed in ANSYS.

Material selection

Aluminum alloy 6061 is selected as the structural material because it is lightweight, practical, and widely used in aerospace applications. It provides a good balance of strength, machinability, and cost for the complete wing assembly.

Flowchart of the project:



ANSYS meshing
The SolidWorks model is imported into ANSYS and meshed to divide the structure into smaller elements for finite element analysis. Proper meshing is important because it improves solution accuracy while keeping the computation efficient.

Modal analysis
Modal analysis is used to determine the natural frequencies and mode shapes of the morphing wing. This step identifies whether the structure may experience resonance under operating conditions and helps verify dynamic stability.

Harmonic analysis
Harmonic analysis is performed to study the wing response under sinusoidal or frequency-based loading. It helps determine how the wing behaves near resonance and whether the structure can safely withstand vibration during flight.

Procedure for the project:
Conceptual Design
- Defining Morphing Type
- Airfoil Selection

Structural Design and Material Selection
- Design Structure
- Material Selection

Analysis
- Modal Analysis using Ansys
- Harmonic Analysis using Ansys

Conceptual Design
- Defining Morphing Type

What is Camber Morphing?
Camber morphing is the continuous, seamless alteration of the curvature of the wing's mean camber line — the imaginary line equidistant between the upper and lower surfaces along the chord — without the use of discrete hinged flaps or slats. Instead of deploying a separate surface that creates a gap and a step, the entire airfoil profile deforms smoothly from one shape to another, the way a bird's wing flexes under muscle control. The mean camber line shift directly changes how much lift the airfoil generates at a given angle of attack and speed. A high-camber configuration produces more lift at low speed (take-off, landing); a low-camber or flat configuration minimizes drag at cruise. A camber-morphing wing does both — and everything in between — continuously and gaplessly.

Why Camber Morphing is Selected for this Design
Among all morphing strategies — span morphing, sweep morphing, thickness morphing, twist morphing — camber morphing is selected for this conceptual design for the following well-justified reasons:

Camber has the highest direct aerodynamic impact per unit of shape change of any wing parameter. A 2% increase in maximum camber increases C_L by approximately 0.2 at a given angle of attack — a significant margin achievable with small physical deflections (a few millimeters at the trailing edge). Camber morphing replaces both the trailing edge flap and the leading-edge slat with a single continuous shape change, eliminating the two largest sources of parasitic gap-and-step drag on a conventional wing.

It is mechanically the most feasible morphing type for near-term demonstrators the required trailing-edge deflection is only 10–20 mm for a typical chord, well within the capability of SMA wire actuators or compliant rib mechanisms. It is fully compatible with the NACA 2412 baseline airfoil, which was explicitly designed with a 2% camber that can be varied above and below for different flight phases.

Mechanism of Camber Morphing — How it Works in Practice

In this design, camber morphing is achieved by a compliant trailing-edge mechanism. The rear 30% of the chord (from the rear spar aft) is constructed as a flexible sub-structure — a series of thin composite ribs connected by a flexible skin — that can be deflected upward or downward by a Shape Memory Alloy (SMA) wire actuator running chordwise inside the structure. When the SMA wire is heated (by passing an electrical current), it contracts and pulls the trailing edge downward, increasing camber for high-lift. When cooled, it returns to the baseline shape. A secondary piezoelectric actuator provides fine trim authority for precise C_L control in cruise.

The leading-edge section (forward 15% of chord) uses a flexible elastomeric composite skin supported by a compliant rib, allowing the nose droop to change slightly in coordination with the trailing edge — preventing flow separation at the leading edge under high-camber conditions.

Airfoil Selection: The Logic of Choice

When you choose an airfoil like the NACA 2412, you aren't just picking a shape; you are picking a set of mathematical constants.

- NACA 2412 Analysis: This airfoil has a 4% maximum camber located at 40% of the chord from the leading edge, with a 12% maximum thickness.
- It is a "high-lift" airfoil. Since morphing is about lift optimization, starting with an airfoil that already has a natural camber allows you to see how "extra" morphing-induced camber affects performance compared to the original design.
- Decoding the NACA 2412 Designation
- The NACA 4-digit series is one of the most extensively studied families of airfoils in aeronautical history, developed by the National Advisory Committee for Aeronautics (the predecessor to NASA) in the 1930s. The four digits encode the airfoil's geometry directly and precisely:
- "2" — Maximum camber is 2% of the chord length. This means the highest point of the mean camber line sits 0.02c above the chord line.
- "4" — The maximum camber is located at 40% of the chord from the leading edge. This is a moderately forward position, producing a gentle, favorable pressure gradient over most of the upper surface.
- "12" — Maximum thickness is 12% of the chord length. This is a medium-thickness profile — thin enough for reasonably low drag, thick enough for structural depth, good lift, and a soft stall.

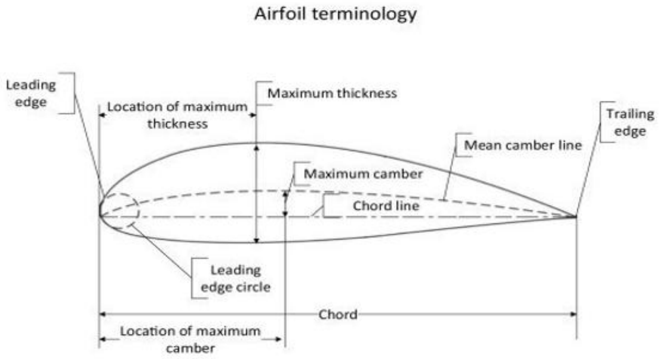


Fig-3.1 Airfoil Terminology

Leading edge: The leading edge is the frontmost point of the airfoil that first meets the airflow. In your thesis, it can be described as the starting point of aerodynamic interaction and an important reference for shaping the wing profile.

Trailing edge: The trailing edge is the rear end of the airfoil where the upper and lower surfaces meet. It strongly influences lift generation, flow separation, and the effectiveness of morphing or control-surface deflection.

Chord line: The chord line is the straight line joining the leading edge and trailing edge. It is used as the main geometric reference for defining airfoil angle, camber, and wing design parameters.

Chord: The chord is the straight-line distance from the leading edge to the trailing edge. It is a key dimension in wing design because it affects lift, structural depth, and the overall aerodynamic behaviour.

Mean camber line: The mean camber line is the line halfway between the upper and lower surfaces of the airfoil. It represents the basic curvature of the airfoil and is important for understanding lift characteristics and wing efficiency.

Maximum camber: Maximum camber is the greatest distance between the mean camber line and the chord line. It determines how much curvature the airfoil has and directly affects lift generation and pitching behaviour.

Location of maximum camber: This is the position along the chord where the maximum camber occurs. It is important because the camber position influences pressure distribution, lift, and stall behaviour.

Maximum thickness: Maximum thickness is the largest distance between the upper and lower surfaces of the airfoil. It is a major structural parameter because it affects stiffness, internal volume, and the wing's ability to carry load.

Location of maximum thickness: This is the point along the chord where the airfoil reaches its maximum thickness. It matters for both aerodynamic performance and structural design because it influences load transfer and spar placement.
Leading edge circle: The leading-edge circle is the rounded nose region of the airfoil. It reduces flow separation at the front and helps the wing perform smoothly at different angles of attack.

Modelling

Structural Design and Material Selection

Structural Design in SolidWorks

To assemble a morphing wing in SolidWorks, you cannot use "standard" rigid joints. You must design for Elastic Deformation.

Step A: The Internal Skeleton (Compliant Mechanism)
Instead of a solid rib, design a Fishbone Active Camber (Fish BAC) structure.

- The Backbone: A central longitudinal beam.
- The Riblets: Thin, vertical "fingers" branching from the backbone.
- Material Assignment: In SolidWorks, assign a flexible material (like Nylon or Polypropylene) to these parts so they can sustain strain without fracturing.

Component – 1: Servo Arm

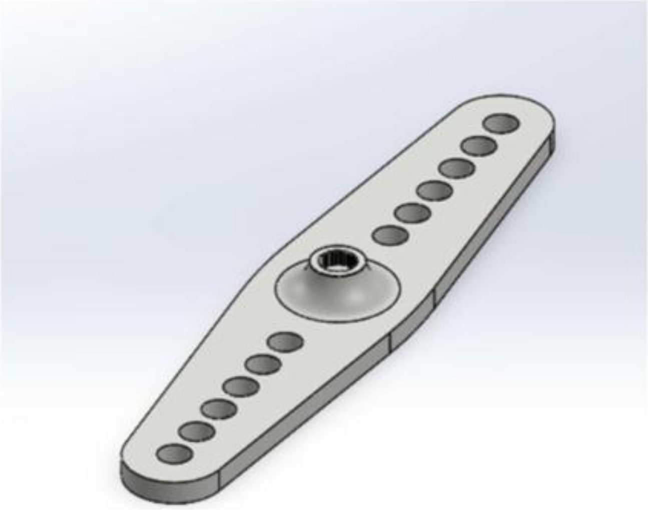


Fig-3.2 Model of Servo Arm

Sketching the Profile (The Skeleton)
- Plane Selection: Start on the Top Plane.
- Geometry: Draw two circles at a set distance (the length of the arm) and connect them with tangent lines to create the "pill" shape.
- Hole Pattern: Use the Linear Sketch Pattern tool to create the series of small mounting holes. These holes are essential for the linkage that will pull your morphing ribs.
- Central Spline/Gear: Draw a circle at the center for the servo spline attachment.

Base Extrusion
- Feature: Use Extruded Boss/Base.
- Depth: Set a thickness (e.g., 2–3 mm) depending on the material you chose (ABS or Aluminum). Ensure the "Selected Contours" includes the main body but leaves the holes empty.

Creating the Hub (The "Raised" Center)
- Reference Geometry: Sketch another circle on the top face of the extruded body.
- Extrude: Give it a secondary extrusion to create the hub where the servo gear inserts.
- Fillet: Apply a small Fillet (radius) to the base of the hub to reduce stress concentrations—this is important for your vibrational analysis, as sharp corners are where cracks start.

Adding Technical Detail
- Spline Teeth: To be highly detailed, you would use an Extruded Cut with a circular pattern to create the small teeth inside the center hole. This is the "female" part of the gear that locks onto the servo motor.

- Material Assignment: Right-click "Material" in the Feature Tree. If this is for a drone, select 6061 Aluminum or a High-Density Polyethylene. This allows SolidWorks to calculate the exact Mass (m) needed for your vibration equations.

Transition to the Morphing Assembly

- Motion Study: You will later bring this into an Assembly and use a Hinge Mate at the center.
- Linkage: You will attach a "push-rod" to one of the outer holes, which connects to the trailing edge of your morphing wing. As this arm rotates, it pulls the wing skin to change the camber.

Component -2: Fins

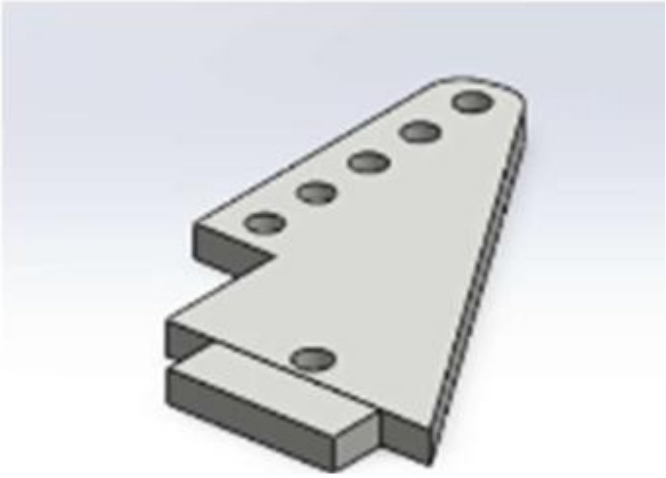


Fig 3.3 Model of Fins

The Main Sketch (Base Profile)

- Select Plane: Open a new sketch on the Front Plane or Top Plane.
- Draw the Outline: Use the Line Tool to draw the trapezoidal profile.
  - o Start with the long-angled edge.
  - o Add the vertical back edge and the notched horizontal base.
- Geometric Constraints: Ensure the bottom lines are horizontal and the back edge is vertical.
- Dimensioning: Use Smart Dimension to set the overall height and the width of the base.

Extruding the Body

- Go to the Features tab and select Extruded Boss/Base.
- Thickness: Set the "Depth" to match the thickness of your material (e.g., 2 mm or 3 mm).
- End Condition: Use "Mid Plane" if you want the origin to stay centered in the part, which is helpful for future vibrational analysis.

Creating the Leading Holes (The Tapered Pattern)

- New Sketch: Select the top flat face of the part.
- Single Hole: Draw one circle at the top tip.
- Construction Line: Draw a Centre line along the angled edge to act as a guide.
- Patterning: * Use Linear Sketch Pattern.
  - o Select the first circle as the "Entity to Pattern."
  - o Set the direction along your center line.
  - o Adjust the spacing and number of instances (looks like 5 holes in your image).
- Cut: Exit the sketch and select Extruded Cut -> Through All.

Creating the Secondary Mounting Hole

- Sketch on the same face.
- Draw a single circle at the wider base of the part (near the notch).
- Align it vertically or horizontally using Add Relation relative to the origin or edges.
- Perform another Extruded Cut.

Refining the Design (Fillets)

- To prevent the "Stress Concentrations" we discussed in the Vibration Analysis section, use the Fillet tool.
- Apply small fillets (e.g., 0.5 mm) to the sharp corners of the notch and the outer edges. This makes the part much stronger in real-world flight conditions.

Defining Physics (Material Assignment)

- Right-click Material in the Feature Tree.
- Choose a lightweight material like PLA (Plastic) for 3D printing or 6061 Aluminum Alloy.
- Check the Mass Properties tool under the "Evaluate" tab. This weight is what you will plug into your 15 Hz vibration formulas earlier.

Component -3: FISHBONE STRUCTURE / RIB

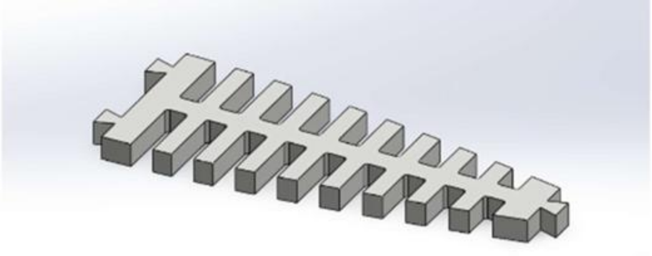


Fig – 3.4 Model of Rib / Fishbone structure

Primary Sketch (The "Spine")

- Plane: Top Plane
- Tool: Centre Rectangle (or Corner Rectangle)

▪ Dimensions: Length: 100mm (Adjust based on your specific needs)

o Width: 10mm

▪ Feature: Extrude-Base → Depth: 5mm

The First "Tooth" (Seed Feature)

▪ Plane: Select the top face of the extruded spine.

▪ Tool: Rectangle

▪ Placement: Draw one rectangle extending out from the side of the spine at one end.

▪ Dimensions:

▪ Length (protrusion): 15mm

▪ Width: 5mm

▪ Feature: Extrude-Base → Depth: 5mm (Ensure "Merge Result" is checked).

Linear Pattern (The Ribs)

▪ Tool: Linear Pattern

▪ Direction 1: Select the long edge of the spine.

▪ Spacing: 10mm

▪ Instances: 9 (Adjust to fit the length of your spine).

▪ Features to Pattern: Select the "Tooth" extrude you just made.

▪ Mirroring (Optional): Use the Mirror tool, selecting the Right Plane to flip the teeth to the opposite side of the spine.

End Connectors (Dovetails/Tabs)

▪ Plane: Top face of the spine at the ends.

▪ Tool: Polygon (set to 3 sides for triangles) or Line tool to draw the flared shape.

▪ Constraint: Ensure the base of the tab is coincident with the end face of the spine.

▪ Feature: Extrude-Base → Depth: 5mm.

Part 4 – Leading Edge

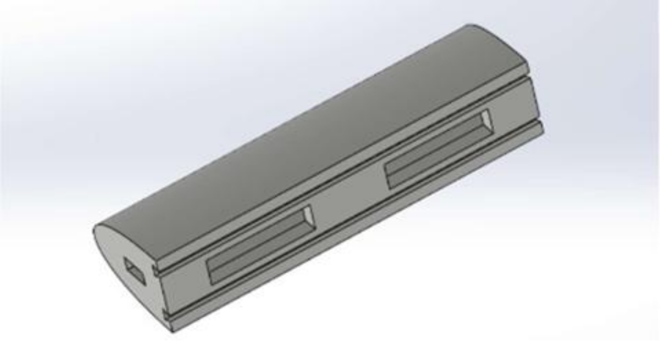


Fig 3.5 Model of Leading Edge

Base Airfoil/Cylindrical Profile

▪ Select the Right Plane. Sketch the teardrop or airfoil profile using an arc for the leading edge and tangent lines meeting at the trailing edge.

▪ Extruded Boss/Base → Select Mid Plane → Set desired length (e.g., 100mm).

Main Longitudinal Cut (Face Recess)

▪ Select the flat vertical face of the model. Sketch a rectangle centered on the face.

▪ Extruded Cut → Set depth (e.g., 2mm).

Edge Grooves (Rails)

▪ Select the same flat face. Sketch two small rectangles at the top and bottom edges of the flat surface.

▪ Extruded Cut → Select Through All.

Pocket Recesses

▪ On the recessed face created in Step 2, sketch two identical rectangles.

▪ Extruded Cut → Set deeper depth (e.g., 5mm). Use Linear Pattern if multiple identical pockets are needed.

Center Through-Hole (Internal Slot)

▪ Select the end face (cross-section). Sketch a centered rectangle.

▪ Extruded Cut → Select Through All.

Finishing

- Apply Fillet to the internal edges of the pockets for a machined look.
- Apply Chamfer to the outer edges of the flat face if required.

Component – 5: Traling Edge

Fig – 3.6 Model of Trailing Edge

Base Wedge Profile

▪ Select the Right Plane. Sketch a right-angled triangle (the side profile of the wedge).

▪ Extruded Boss/Base → Select Mid Plane → Set length (e.g., 200mm).

Longitudinal Side Groove

▪ Select the vertical rectangular end face. Sketch a small rectangle or "U" shape on the vertical edge.

▪ Extruded Cut → Select Through All.

Top Face Recess

- Select the slanted top face. Sketch a large rectangle covering the interior area, leaving a thin border (wall).
- Extruded Cut → Set a shallow depth (e.g., 2mm) → Use Offset from Surface if you want the bottom of the cut to follow the slant.

Corner Support/Bracket Details

- Select the inner floor of the recess created in Step 3 at both ends. Sketch the profile of the small raised brackets/connectors.
- Extruded Boss/Base → Set height (e.g., 5mm) → Ensure Merge Result is checked.

Intricate Internal Cutouts

- Select the top faces of the brackets created in Step 4. Sketch the specific "S" or zigzag patterns.
- Extruded Cut → Set depth or select Up to Surface (the bottom of the tray).

Shell (Optional Alternative)

- If the part is uniform thickness, use the Shell tool on the slanted face instead of an Extruded Cut for Step 3.

The Assembly Strategy

- Create a master sketch with "Blocks" representing the wing segments.
- Use Flex or Deform features to simulate the bending.
- Mates: Use "Limit Mates" for actuators (motors/pistons) to define the maximum and minimum morphing range.

1. Initialize Assembly

- Open a new Assembly file.
- Insert Component: Select the Airfoil/Main Body part first.
- Fixing: Right-click the Airfoil part in the design tree and select Fix (it should automatically fix to the Origin).

2. Assemble the Ribs (Comb Structures)

- Insert Component: Bring in the first Rib part.
- Mate 1 (Coincident): Select the flat back face of the Rib's "dovetail" connector and the corresponding recessed face on the Airfoil.
- Mate 2 (Distance/Coincident): Align the top face of the Rib with the top edge of the Airfoil slot to set the vertical position.
- Mate 3 (Center): Use a Width Mate or Coincident Mate on the side faces to center the Rib within the Airfoil's rectangular slot.
- Patterning: Use Linear Component Pattern. Select the long edge of the Airfoil as the direction, and pattern the Rib 3 times at the required spacing.

3. Assemble the Lower Wedge Support

- Insert Component: Bring in the Wedge/Tray part.
- Mate 1 (Coincident): Select the bottom "dovetail" or end-tab of the center Rib and the corresponding slot in the Wedge.
- Mate 2 (Parallel): Ensure the bottom face of the Wedge is parallel to the bottom plane of the Airfoil to keep the assembly squared.
- Mate 3 (Coincident): Align the side faces of the center Rib and the center slot of the wedge.

4. Assemble the End Brackets (Triangular Parts)

- Insert Component: Bring in the small Triangular Brackets.
- Mate 1 (Concentric/Coincident): Align the small holes/pins of the brackets with the matching features on the ends of the Wedge.
- Mate 2 (Coincident): Flush the side face of the bracket with the outer end face of the Wedge.
- Mirroring: Use Mirror Component using the Right Plane of the assembly to place the identical bracket on the opposite side.

5. Final Hardware/Servo Horn

- Insert Component: Bring in the Servo Horn/Linkage (the small horizontal part on the side of the airfoil).
- Mate 1 (Concentric): Align the center hole of the horn with the axis/hole on the side of the Airfoil.
- Mate 2 (Coincident): Flush the back face of the horn against the side face of the Airfoil.

6. Verification

- Use Interference Detection (Evaluate tab) to ensure the Ribs fit perfectly into the Airfoil and Wedge slots without overlapping geometry.

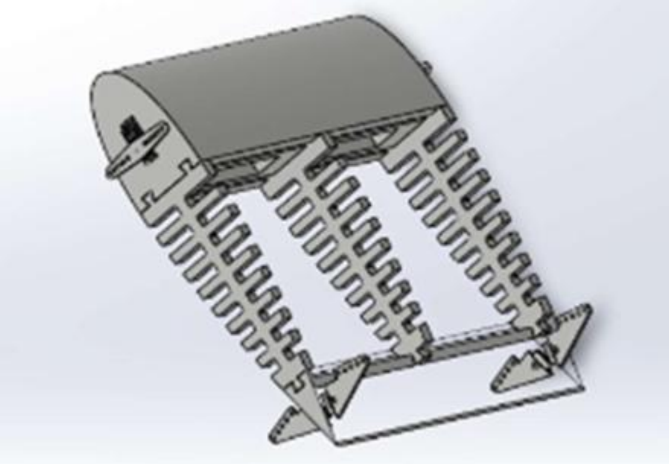


Fig – 3.7 Assembly of Morphing Wing

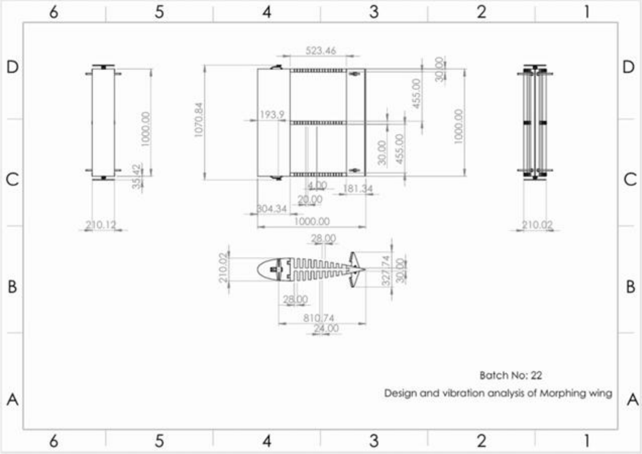


Fig 3.8 Model Drawing of Morphing wing

3.4 Material Selection

Table.3.1 Component wise Materials

Component	Materials Used	Properties
Spine/Rod	Carbon fiber composites; Polylactic Acid (PLA) for prototypes	High tensile strength – 313.1 MPa; lightweight
Stringers/Bones	PLA (3D printed); Carbon fiber reinforced composites	Tensile strength of 38–47.8 MPa, density of 1.08–1.12 g/cc, heat deflection temperature of 80 °C
Skin/Panels	Thermoplastic Polyurethane (TPU) – soft/high-strain variant; Eco flex silicone, natural rubber, latex	Tensile strength of 12 to 60 MPa, low Poisson's ratio of 0.2, wrinkle-free, Elongation at break of 300% to 700%, high flexibility

For this project the material is aluminum alloy 6061 is used for all the components of wing because the structure needs to be light enough to move but still strong enough to carry aerodynamic and mechanical loads. It is especially useful for internal components, ribs, support members, and connectors where ease of fabrication and predictable behavior are important. Its use also makes the model closer to realistic aerospace design practice.

Table 3.2 Different material alloys and composites

Material	Category	Advantages	Limitations
Aluminum 6061-T6	Alloy	Lightweight, easy to machine, good corrosion resistance	Lower strength than 7075
Aluminum 7075-T6	Alloy	High strength-to-weight ratio	Lower corrosion resistance, less weldable
Titanium Ti-6Al-4V	Alloy	Very high strength, Excellent fatigue and temperature resistance.	Expensive, heavier than aluminum
Carbon Fiber/PEEK	Composite	Tough, damage tolerant, good for repeated morphing	Costly, processing difficulty
Aramid Fiber/Epoxy (Kevlar/epoxy)	Composite	Excellent impact resistance, good	Lower compressive stiffness

		toughness	
Glass Fiber/Epoxy (GFRP)	Composite	Low cost, good corrosion resistance, easier to manufacture	Lower stiffness than CFRP

Aluminum 6061 - “Aluminum alloy 6061 was selected for the Fishbone morphing wing because it offers a favorable strength-to-weight ratio, good corrosion resistance, and excellent machinability. These properties make it suitable for an aircraft morphing structure, where the main wing must remain load-bearing while the trailing region undergoes controlled deformation.”

3. Analysis

Simulation & Optimization

- Meshing: Create a high-density mesh around the trailing edge to capture the "Seamless" flow.
- Fluid-Structure Interaction (FSI): Simulate how the air pressure deforms the flexible material to ensure it doesn't "buckle" under high speeds.
- Comparison: Compare the (Lift-to-Drag) of the morphed shape against the conventional hinged-flap shape.

Transferring Geometry form Solid works to Ansys

1. Preparation (SolidWorks)
   - Cleanup: Remove small fillets and text.
   - Check: Run Interference Detection to ensure parts don't overlap.
   - Export: Save As → STEP AP214 or Parasolid.
2. Import (ANSYS Workbench)
   - System: Drag Modal into the schematic.
   - Geometry: Right-click Geometry > Import.
   - Topology: Open in Space Claim and use the Share tool (Workbench tab) to lock rib-to-wing connections.
3. Setup (ANSYS Mechanical)
   - Materials: Re-assign specific properties to each part.
   - Mesh: Apply local sizing to the flexible ribs.
   - Supports: Apply Fixed Support to the wing root.
   - Solve: Define the number of modes (e.g., 6) and click Solve

Analysis in Ansys

Vibrational Analysis (specifically Modal Analysis) is critical because morphing wings are inherently flexible. You must prove that your wing won't vibrate itself to pieces (flutter) during flight.

The process is divided into two main stages: Modal Analysis (to find natural frequencies) and Aeroelastic Coupling (to see how wind affects those vibrations).

Pre-Processing in FEA (ANSYS)

1. Material Properties: Defining Nonlinearity

In a camber morphing wing, you aren't using just one material. You have a Hybrid System.

- The Skeleton (Ribs): Usually made of a "Linear Elastic" material like Carbon fiber. You must input the Young’s Modulus, which defines how much force is needed to bend the bone.
- The Flexible Skin: This is the tricky part. If you use an elastomer (like rubber or silicone), standard linear equations don't work. You may need to use a Hyperplastic Material Model (like Mooney-Rivlin or Ogden).
- The Variable of Interest: For vibration, the Density is just as important as stiffness. The natural frequency is mathematically related to:
- If your material is too heavy (high density), your wing will vibrate at dangerously low frequencies.

2. Boundary Conditions: The "Cantilever" Setup

In SolidWorks Simulation or ANSYS, your "fixtures" simulate how the wing is physically bolted to the airplane.

- Fixed Support (Root): You must select the "Root Face" of the wing (the cross-section that touches the fuselage) and apply a Fixed Support. This locks all 6 Degrees of Freedom (DO F):
  - No movement in X, Y, Z (Translations).
  - No rotation in X, Y, Z (Rotations).
- The "Fishbone" Connection: If your ribs are separate from the skin, you must define Interactions/Contacts. Use a "Bonded" contact to simulate that the skin is glued or chemically fused to the ribs. If you forget this, the software will think the skin is floating, and the vibration results will be "garbage."

3. Meshing: The Art of Discretization

Meshing breaks your wing into thousands of tiny elements (Tetrahedrons). For a morphing wing, a "Standard Mesh" is not enough.

- Tetrahedral vs. Hexahedral: While Tetrahedrons are easier for complex shapes, Hexahedral (brick) meshes are more accurate for thin skins.
- Mesh Refinement (Sizing Controls): You cannot have the same size "bricks" everywhere.
    - Global Mesh: Use a medium size for the main wing body.
    - Local Refinement: Apply a "Mesh Control" to the thin "fishbone" joints and the trailing edge. These are "High-Gradient" areas were stress changes rapidly. If the mesh is too coarse here, the software will underestimate the vibration stress.
- Convergence Study: In your thesis, you must mention this. You run the study with a coarse mesh, then a medium mesh, then a fine mesh. When the natural frequency (e.g., that 15 Hz) stops changing, your mesh has "converged

GEOMETRY & MATERIAL ASSIGNMENT

- Import: Load the SolidWorks Assembly into Space Claim or Design Modeler.
- Material Allocation:
    - Airfoil & Wedge: High-Modulus Polymer or Aluminum.
    - Morphing Ribs: Flexible Polyurethane or Nylon (for compliant mechanism behavior).
- Shared Topology: Set to Share to ensure nodes are connected at the dovetail interfaces.

MESHING STRATEGY (FINITE ELEMENT MODELING)

- Global Sizing: 2.0 mm (Standard).
- Local Refinement (Sizing): Rib Teeth/Fingers: 0.5 mm to 1.0 mm (Capture high-stress gradients).
    - Airfoil Trailing Edge: 0.8 mm.
- Element Types: * Solid Body: Tetrahedral (C3D10) for complex curvature.
    - Thin Sections: Hexahedral (C3D8R) where geometry allows for better accuracy.
- Inflation Layers: 3-5 layers on the outer airfoil surface for aerodynamic pressure mapping.

Connections & Contacts

- Type: Linear.
- Rib-to-Airfoil Slots: Bonded (Standard) or No Separation (to allow slight sliding if modelled as a hinge).
- Rib-to-Wedge Slots: Bonded.
- Joints: Revolute Joint on the Servo Horn pivot axis (Ground-to-Body).

BOUNDARY CONDITIONS (STATIC STRUCTURAL)

- Fixed Support: Apply to the Inboard Face (root) of the Airfoil body.
- Displacement/Rotation: Apply a Rotation (e.g., 15°) to the Servo Horn axis to simulate actuation.
- External Loads (CFD Mapping): Import Pressure Profile from CFD (6° AOA).
    - Map to Top and Bottom Surfaces of the Airfoil and compliant Ribs.

Analysis Settings

Analysis Type: Modal Analysis (To find its Natural Frequency)
Import Geometry - Materials Apply - Meshing - Analysis Setting - Frequency range - Boundary Conditions - Solve - Solution Information - Total Deformation
Running the Modal Analysis

1. The Mathematical Foundation (The "Deep" Logic)

When you click "Run," the software solves the General Eigenvalue Problem:

$$K\{\ddot{u}\}+M\{U\}=0$$

- M (Mass Matrix): How much material is there and where is it located?
- K (Stiffness Matrix): How resistant is the material to bending?
- u (Displacement): How the wing moves.

Because this is a "Free Vibration" analysis, the software ignores external wind and focuses only on the internal physics of the wing. It extracts Eigenvalues (which the software converts into Frequency in Hz) and Eigenvectors (which the software converts into the Mode Shape).

2. Solution Outputs (Result data)

- Total Deformation: To visualize the wing morphing contour.
- Modal Analysis: Extract the first 3 Natural Frequencies to check for Resonance Risk during actuation.

Analysis Type: Harmonic Analysis (To find its Natural Frequency)
Import Geometry - Materials Apply - Meshing - Analysis Setting - Frequency range - Boundary Conditions - Solve - Solution Information
- Total Deformation, Equivalent stress, Frequency Response

- Large Deflection: Set to ON (Crucial for morphing/compliant structures).
- Non-linear Controls: Full Newton-Raphson.
- Sub-steps: Initial Sub-steps: 10
    - No. of Iteration Sub-steps: 100

Solution Outputs (Result Data)

- Total Deformation: To visualize the wing morphing contour.
- Equivalent (von-Mises) Stress: To identify potential failure points in the compliant "spine."
- Reaction Force: At the Servo Horn to determine required torque.

- Modal Analysis (Optional): Extract the first 6 Natural Frequencies to check for Resonance Risk during actuation.

MESH QUALITY METRICS

- Aspect Ratio: < 5:1.
- Orthogonal Quality: > 0.15.
- Skewness: < 0.85. Running the Modal Analysis

1. The Mathematical Foundation (The "Deep" Logic)

When you click "Run," the software solves the General Eigenvalue Problem:

$K\{\ddot{u}\}+M\{U\}= 0$

- M (Mass Matrix): How much material is there and where is it located?
- K (Stiffness Matrix): How resistant is the material to bending?
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Because this is a "Free Vibration" analysis, the software ignores external wind and focuses only on the internal physics of the wing. It extracts Eigenvalues (which the software converts into Frequency in Hz) and Eigenvectors (which the software converts into the Mode Shape).

2. Frequency Extraction: The First 5–10 Modes

- Why 5 to 10 nodes? Most of the energy in a vibration is contained in the first few modes. High-order modes (Mode 50+) happen at such high frequencies that they rarely occur in real-world flight.
- The solver uses algorithms (like the Lanczos or Subspace method) to find the lowest frequencies first.

3. Detailed Breakdown of Mode Shapes Mode 1: Out-of-plane Bending

The wing behaves like a cantilever beam. The root stays fixed while the tip moves vertically (up and down).

- Significance: This is usually the lowest frequency and the most dangerous. It mimics the "flapping" of a bird's wing. If this frequency is too low, the wing might hit resonance due to atmospheric turbulence.

Mode 2: Torsion (The "Twist")

The wing rotates around its elastic axis (from leading edge to trailing edge).

- Significance: This is critical for Camber Morphing. Since your wing is designed to be flexible at the trailing edge, it might be weak in torsion. If the wing twists too easily, it can cause "Control Reversal," where moving the morphing surface makes the plane turn in the opposite direction than intended.

Mode 3: In-Plane / Chordwise Bending

The wing moves forward and backward (from nose to tail).

- Significance: This is generally much stiffer than vertical bending because the "depth" of the wing is much larger than its thickness. However, in high-speed drones, this mode can lead to structural fatigue where the wing meets the fuselage.

4 Interpretation: Mass Participation Factors

A deep methodology must mention Mass Participation.

- The software calculates how much of the wing's total mass is actually moving in each mode.
- The Goal: You want to ensure that the cumulative mass participation for your first few modes reaches at least 80%. This proves that your modal analysis has captured the "dominant" behaviors of the structure and isn't just looking at tiny, localized vibrations in the skin.

Result Analysis

Modal Analysis

Importing Geometry from SolidWorks to Ansys Workbench

The following figure shows the importing of the SolidWorks model into Ansys Workbench to perform Analysis.

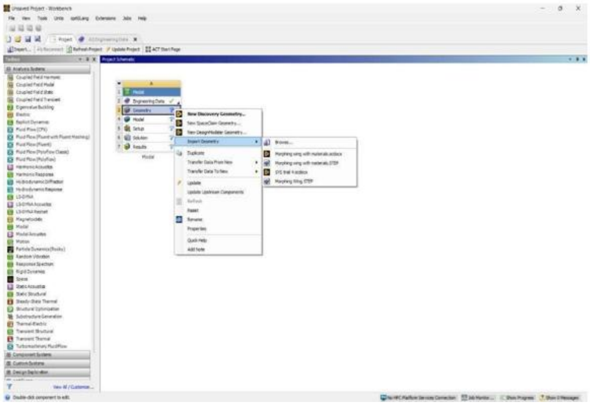
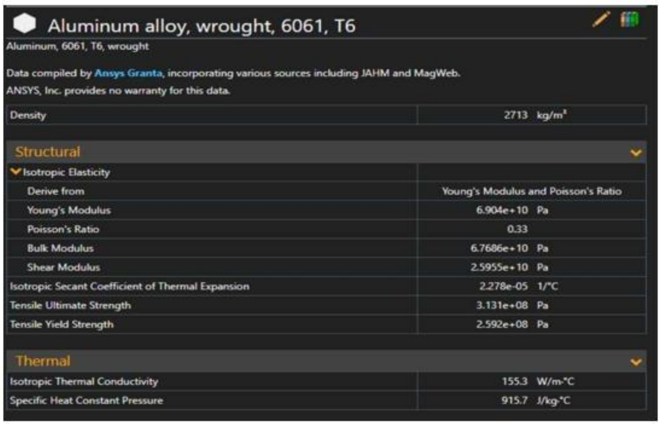


Fig- 3.9 Importing the Geometry from SolidWorks to Ansys Workbench

Material Applied

In this project, we applied the Aluminum alloy of 6061 with the following required values.



Aluminum alloy, wrought, 6061, T6

Aluminum, 6061, T6, wrought

Data compiled by Ansys Granta, incorporating various sources including JAHM and MagWeb.
ANSYS, Inc. provides no warranty for this data.

Density	2713 kg/m³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	6.904e+10 Pa
Poisson's Ratio	0.33
Bulk Modulus	6.7686e+10 Pa
Shear Modulus	2.5955e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	2.278e-05 1/°C
Tensile Ultimate Strength	3.131e+08 Pa
Tensile Yield Strength	2.592e+08 Pa
Thermal	
Isotropic Thermal Conductivity	155.3 W/m-°C
Specific Heat Constant Pressure	915.7 J/kg-°C

Fig – 3.10 Details of material applied

3 Meshing

The meshing involves the linear mesh across the wing assembly. This has square elements for the flat and plain surfaces and Tetrahedral elements for curved surface i.e. Leading Edge.

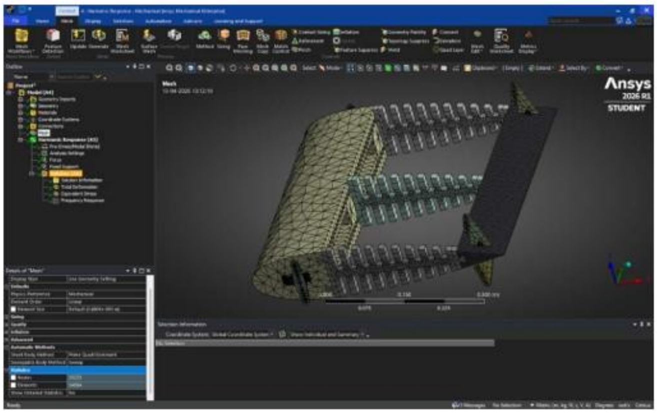


Fig- 3.11 Meshing of morphing wing

4 Boundary Conditions

The Boundary conditions that we are applied on the wing is one end is fixed because one end of the wing is connected to the fuselage of aircraft which is called as body.

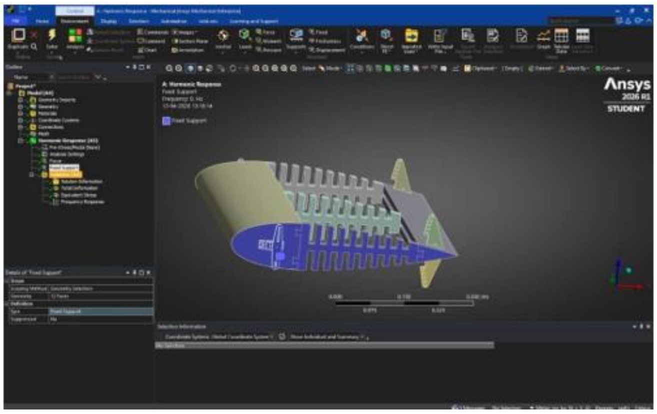


Fig – 3.12 Boundary conditions applied on the wing

5 Solve

Solution Information – Total Deformation

The solution is obtained of Total Deformation of wing through Ansys Software to achieve the Natural Frequency.

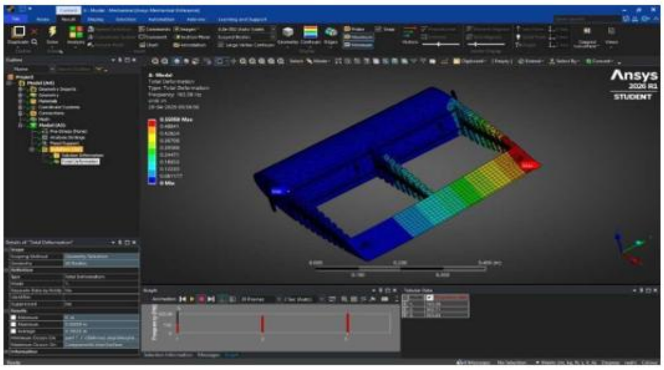


Fig – 3.13 Total Deformation of wing with Natural Frequency

The Natural frequency of 3 modes as occurred within in a frequency range of 0-420 Hz. This gives us the wing vibrating condition and resonance of wing where it can be occurred.

Natural Frequency Table:

Table 3.3 Natural Frequency with modes

Sl.NO	Mode No	Natural Frequency Hz
1	1	165.58
2	2	303.71
3	3	353.04

3.6 Harmonic Analysis using Ansys

Connecting Modal analysis to Harmonic Analysis in Ansys Workbench:

The following figure shows the connecting of Modal Analysis to Harmonic Analysis in Ansys Workbench to perform Analysis.

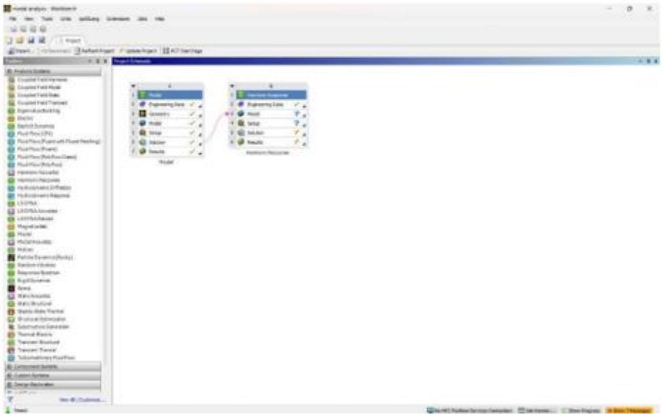


Fig – 3.14 Harmonic Analysis Profile in Ansys Workbench

Analysis Setting
Frequency range: 0-420 Hz are applied as the frequency range for the wing.

i. Boundary Conditions

- Force applied

The 2 forces are applied on the wing of total force of 2000N.

1. The force applied at the middle rib is Fy = -500N. It is indicated as red color in the following picture.

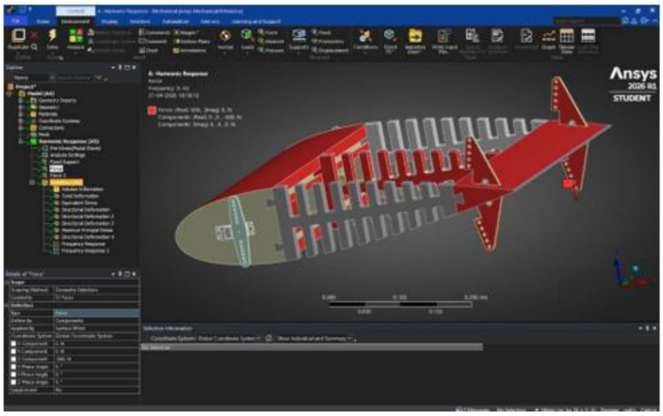


Fig – 3.15 Fy = -0.5KN Force applied as boundary condition at middle rib

2. The force applied at the end rib is Fy = -1500N. It is indicated as red color in the following picture.

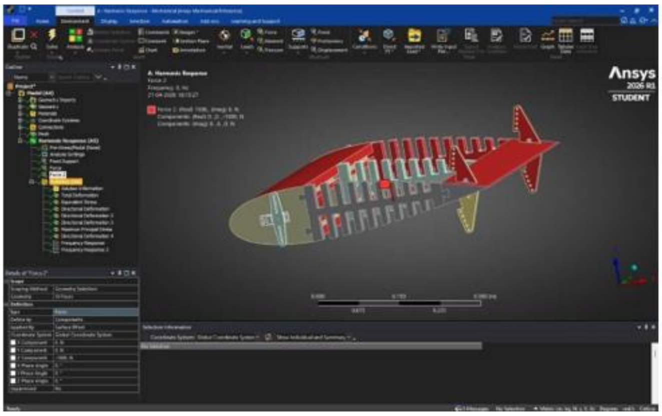


Fig – 3.16 Fy = -1.5KN Force applied as boundary condition at end rib

Solve
Solution Information - Finding the Total Deformation, Equivalent (Von Mises) Stress and Frequency Response for the wing under Harmonic response.
Total Deformation –
The total deformation the wing is found as the 0.00034559m or 0.34559mm at the trailing edge of the wing.

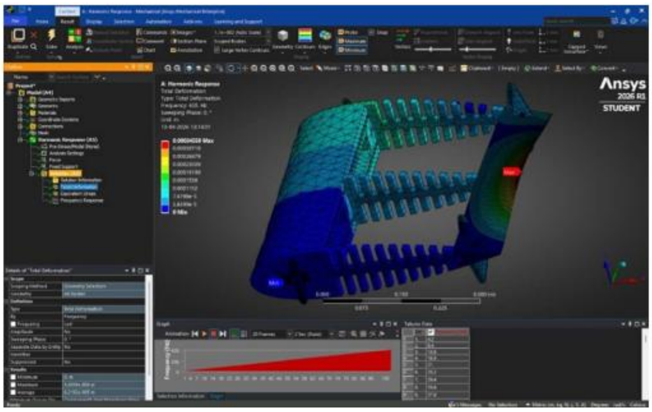


Fig – 3.17 Total Deformation of the wing under Harmonic Response

Equivalent stress –
The Minimum and Maximum stress is obtained for the wing is
Minimum stress: 0 Pa or 0 MPa
Maximum stress: 2.4327e7 Pa or 24.327 MPa

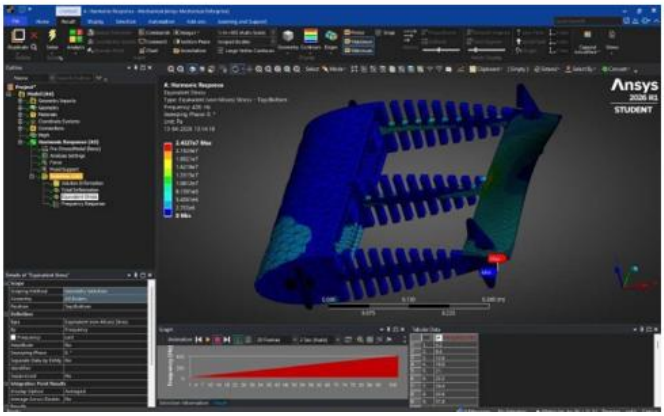


Fig – 3.18 Equivalent stress obtained under Harmonic Response

Frequency Response
The frequency response graph is obtained under the Harmonic response with the frequency range of 0-420 Hz in 100 solution intervals and found that 125 Hz is peak resonance period.

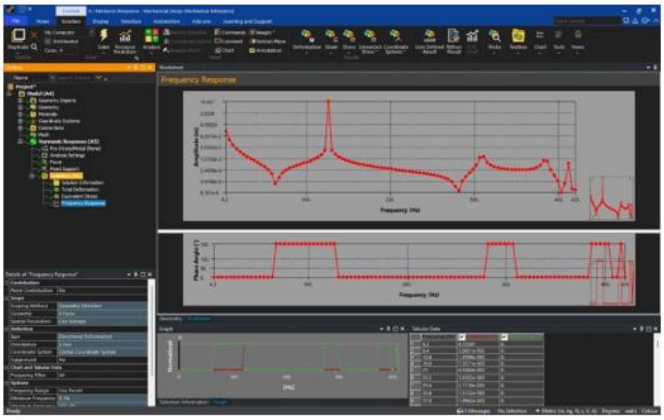


Fig – 3.19 Frequency Response Graph under Harmonic Analysis

Solution Interval Frequency Table
The below is the 100-iteration table for the Frequency and Amplitude

Table 3.4 Frequency and amplitude of solution Intervals

Sl. No	Frequency [Hz]	Amplitude [m]	Sl. No	Frequency [Hz]	Amplitude [m]
1	4.2	0.12	51	214.2	0.00
2	8.4	0.03	52	218.4	0.00
3	12.6	0.01	53	222.6	0.00
4	16.8	0.01	54	226.8	0.00
5	21	0.00	55	231	0.00
6	25.2	0.00	56	235.2	0.00
7	29.4	0.00	57	239.4	0.00
8	33.6	0.00	58	243.6	0.00
9	37.8	0.00	59	247.8	0.00
10	42	0.00	60	252	0.00
11	46.2	0.00	61	256.2	0.00
12	50.4	0.00	62	260.4	0.00
13	54.6	0.00	63	264.6	0.00
14	58.8	0.00	64	268.8	0.00
15	63	0.00	65	273	0.00
16	67.2	0.00	66	277.2	0.00
17	71.4	0.00	67	281.4	0.00
18	75.6	0.00	68	285.6	0.00
19	79.8	0.00	69	289.8	0.00
20	84	0.00	70	294	0.00
21	88.2	0.00	71	298.2	0.00
22	92.4	0.00	72	302.4	0.00
23	96.6	0.00	73	306.6	0.00
24	100.8	0.00	74	310.8	0.00
25	105	0.00	75	315	0.00
26	109.2	0.00	76	319.2	0.00
27	113.4	0.00	77	323.4	0.00
28	117.6	0.00	78	327.6	0.00
29	121.8	0.01	79	331.8	0.00
30	126	15.96	80	336	0.00
31	130.2	0.01	81	340.2	0.00
32	134.4	0.00	82	344.4	0.00
33	138.6	0.00	83	348.6	0.00
34	142.8	0.00	84	352.8	0.00
35	147	0.00	85	357	0.00
36	151.2	0.00	86	361.2	0.00
37	155.4	0.00	87	365.4	0.00
38	159.6	0.00	88	369.6	0.00
39	163.8	0.00	89	373.8	0.00
40	168	0.00	90	378	0.00
41	172.2	0.00	91	382.2	0.00
42	176.4	0.00	92	386.4	0.00
43	180.6	0.00	93	390.6	0.00
44	184.8	0.00	94	394.8	0.00
45	189	0.00	95	399	0.00
46	193.2	0.00	96	403.2	0.00
47	197.4	0.00	97	407.4	0.00
48	201.6	0.00	98	411.6	0.00
49	205.8	0.00	99	415.8	0.00
50	210	0.00	100	420	0.00

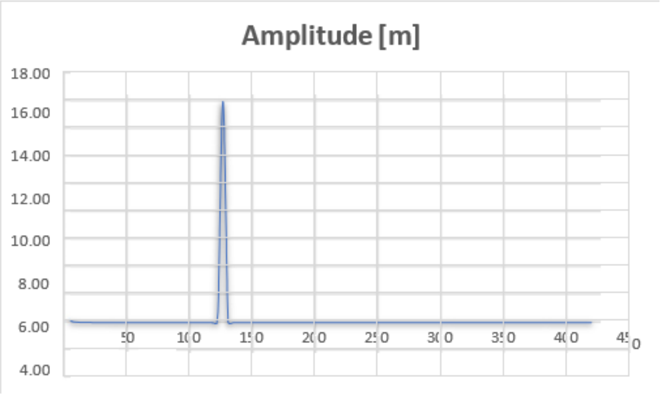


Fig – 3.20 Frequency v/s Amplitude Graph

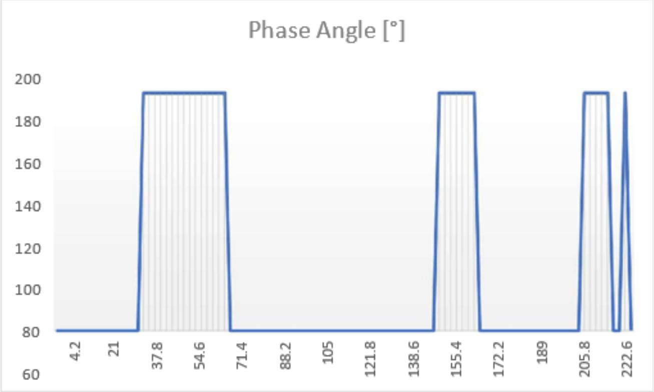


Fig- 3.21 Frequency v/s Phase Angle Graph

IV. RESULTS & DISCUSSION

The project demonstrates high stiffness for load-bearing through its elevated natural frequencies of 165.58 Hz, 303.71 Hz, and 353.04 Hz, which indicate good resistance to structural deformation under loading. At the same time, the deformation is localized in the compliant morphing region, confirming that the load-bearing spine remains sufficiently stiff while allowing controlled camber change. Below is the comparison of results with journal reference.

Table 4.1 Comparison on results

Our result	Journal value	Discussion
Maximum stress: 2.4327×10^7Pa; harmonic peak stress from your ANSYS result.	“Investigation on Four Distinct Wing Configuration Using Morphing Technology” tells us that the maximum stress 4.3488×10^6 Pa; deformation 0.0086798 m for aluminium	Your stress is higher, which usually means stronger local stress concentration at the morphing section or a more severe load case.
Total deformation: 3.4559×10^{-4}m in harmonic response; 0.55059m in modal shape display.	“Investigation on Four Distinct Wing Configuration Using Morphing Technology” tells us that Aluminum wing has the 0.0086798m max deformation.	The harmonic deformation is much smaller, suggesting a stiffer response; the modal deformation is not directly comparable to static deformation.
First natural frequency: 165.58Hz.	“Vibrational Analysis of an Aircraft Wing Model Using ANSYS Workbench” gives that first bending mode 23.231 Hz.	Your wing is dynamically stiffer and less sensitive to very low-frequency excitation.

Second natural frequency: 303.71Hz.	“Vibrational Analysis of an Aircraft Wing Model Using ANSYS Workbench” gives that second bending mode: 12.11Hz; first torsional mode: 186.76Hz.	Your second mode lies above the reference’s low bending band and indicates better frequency separation.
Third natural frequency: 353.04Hz.	“Vibrational Analysis of an Aircraft Wing Model Using ANSYS Workbench” gives that sixth bending mode: 1175.8Hz; torsional modes begin at 186.76Hz.	Your result is still within a realistic wing-vibration range and remains well separated from the first mode.
Flexible trailing region shows the highest deformation.	“Multi objective Optimization for the Aero-Structural Design of Adaptive Compliant Wing Devices” morphing structures must be stiff enough to carry load and flexible enough to achieve shape change	This matches morphing-wing behavior, where deformation should localize in the compliant region.
Resonance peak appears in the harmonic response plot.	Harmonic response peaks near resonant frequencies, especially around 8.1325Hz and 12.834Hz from “Modal and Harmonic Analysis of Aircraft Wing”.	Both results confirm the importance of avoiding resonant operating conditions.
Material used: Aluminum 6061.	Aluminum performed better than steel in the morphing-wing comparison from “Investigation-on-four-distinct-wing-configuration-usingmorphing- technology”	Your material choice is consistent with the literature because aluminum offers a good strength-to-weight balance.

Our wing shows a higher stiffness-like dynamic response than the comparison wing in the modal paper, because your first natural frequency is much larger than the reported 23.231 Hz first bending mode in the journal wing. This usually means the structure is either shorter, more constrained, or internally reinforced more strongly, which fits a Fishbone layout with a rigid front region and a rib-supported rear section. The deformation pattern in our model is also meaningful because the maximum deformation appears in the morphing region rather than the rigid portion. That is exactly what a Fishbone morphing wing should do: preserve the load-carrying ability of the main structure while allowing controlled flexibility in the trailing section. In the reference wing study, aluminum showed a maximum deformation of 0.0086798 m, while your harmonic case shows a much smaller deformation amplitude of 3.4559 × 10–4 m, which suggests your model is less compliant under the tested harmonic condition.

The harmonic response plot in your project shows a clear resonance peak, which matches the behavior reported in the wing-box study where the response rises sharply near resonant frequencies. This is important because it confirms that your structure behaves like a real aeroelastic system and not a purely static shape model. In thesis language, you can state that the frequency-response curve demonstrates the presence of resonance-sensitive regions, and that operating frequencies should be kept away from these zones to avoid excessive vibration and fatigue.

The stress level in your harmonic result is higher than the stress reported in the morphing wing paper, but the comparison is not perfectly direct because the reference paper reports a different geometry, different load case, and a different analysis context. Even so, the general trend remains acceptable: stress is highest near the transition or support region, which is exactly where local load transfer is strongest in morphing-wing structures. That concentration is expected and should be discussed as a critical design region rather than a failure sign, provided the stress stays below the allowable limit for aluminum 6061.Overall, your results are consistent with the literature trend that morphing wings must balance flexibility for shape change with stiffness for structural safety. The modal frequencies indicate a dynamically stable structure, the deformation localizes where morphing is intended, and the harmonic response confirms the need for resonance-aware design. This supports the conclusion that your Fi

V. CONCLUSIONS

Conclusion for Design

- The morphing wing design was successfully developed from the aluminium alloy material 6061 which possesses good mechanical properties along with relatively less density.
- A reduction in weight of the plane can be expected in comparison to the conventional rigid wing, thus improving efficiency and decreasing the force caused by inertia.
- The wing geometrical parameters have been optimally chosen such that there will be no compromise to its structural stability while under load conditions.
- The selected Aluminium 6061 material shows very high-density strength ration and has resistance to corrosion, along with the ability to fabricate multiple loading.
- The morphing approach applied here involves the change in the shape of the wings without altering their geometrical form.
- The morphing design may look compact and suitable for developing a prototype although it includes deformation in the wing structure.
- Conclusions from the Analysis
- The analysis of finite elements shows that the wing is capable of withstanding loads and deformations.
- The von Mises stress does not exceed the yield point of Aluminum 6061
- There was a lot of deformation at the wing tip or at the morphing wing region as expected in wings, but at the non-moving portion, there was very minimal deformation.
- The safety factor obtained from the analysis was greater than 1, hence the structure is deemed safe under the loadings used in this research programme.
- The modal analysis shows that the natural frequencies of the structure are far apart from the usual excitation frequencies, hence minimizing the risk of resonance leading to structural failure.
- Stress concentrations observed occurred mostly at points where there were changes in geometries or morphing interfaces and can be improved through reinforcements or smooth transitions.
- The deformation pattern showed that the morphing section acted as expected without compromising the stability of the whole wing structure.
- In general, the analysis provides a basis for concluding that the proposed structure is structurally sound and hence dependable for further development and testing.

The synthesis between design and analysis indicates that morphing wings are feasible and effective to use as an aerospace structural member. This is because the design satisfies all main criteria such as lightweight construction, capability to morph, and structural integrity, and analysis indicates that the structure is able to withstand the loads applied on it.

Future Scope of Work

The future scope of the morphing wing work can be expanded in several important directions. Based on current morphing-wing research, the next steps should focus on improving aerodynamic efficiency, reducing structural weight, and integrating smarter actuation and control systems.

Material optimization

A major future improvement is the use of advanced lightweight materials such as composites, smart materials, and hybrid structures instead of only conventional metals. Research on morphing wings shows that flexible skins, smart actuators, and tuned stiffness architectures can significantly improve shape-changing performance while maintaining strength.

Actuation development

The wing can be upgraded by introducing more efficient actuation methods such as shape memory alloys, macro-fiber composites, pneumatic actuation, or cable-driven mechanisms. These approaches are widely discussed in recent morphing-wing studies because they allow smoother deformation and better control of camber, sweep, and trailing-edge motion.

Aeroelastic and flight testing

A good next step is to validate the design with aeroelastic analysis and wind tunnel testing. Experimental studies show that morphing wings can improve lift-to-drag ratio, delay stall, and enhance maneuverability, but these gains must be confirmed under realistic aerodynamic loading.

Structural and fatigue analysis

The current work can be extended to fatigue life prediction, stress concentration study, and repeated morphing-cycle durability analysis. Since morphing wings undergo continuous deformation, long-term reliability is a key challenge in practical aircraft use.

Control system integration

Future work should also include closed-loop control using sensors and feedback algorithms to ensure accurate wing shape adaptation during flight. Recent literature highlights that adaptive morphing structures will need intelligent control systems to be practical in next-generation aircraft.

Application expansion

The morphing wing concept can be extended beyond the current model to UAVs, high-efficiency small aircraft, defense platforms, and even space-related vehicles. Current research shows promising use in UAVs, urban air mobility, and next-generation aircraft where adaptability and fuel efficiency are essential.

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