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# Bio-Inspired Deployable Morphing Wing Architecture for Space-Efficient Surveillance UAV Systems

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***Abstract*— Space-efficient unmanned aerial vehicle (UAV) systems are increasingly important for aerospace surveillance, autonomous deployment, and defense applications. This paper presents a bio-inspired deployable morphing wing architecture derived from the folding mechanism of the Ensign wasp, which exhibits both longitudinal and transverse wing folding. The proposed concept enables compact storage and rapid deployment of UAV systems while maintaining aerodynamic continuity in the deployed configuration. Two wing deployment mechanisms are investigated: an initially developed string-based mechanism employing servo-pulley coupling, and an improved umbrella-based mechanism designed to enhance structural robustness and deployment reliability. Geometric modeling and kinematic analysis of the folding topology were carried out using Autodesk Fusion 360. Preliminary aerodynamic evaluation across fully folded, partially deployed, and fully deployed configurations was conducted using ANSYS Fluent to investigate pressure distribution trends during deployment. Structural feasibility under aerodynamic loading was further examined through static structural analysis. In addition, state-space modeling concepts and Simulink-based control-system integration are introduced to assess deployment controllability and actuator coordination. Results indicate that the umbrella-based mechanism reduces coupling complexity while improving deployment stability and structural adaptability. The proposed architecture demonstrates strong potential for integration into compact surveillance UAV platforms, deployable aerospace robotics systems, and parent-child autonomous aerial networks.***

***Index Terms:*** *aerospace robotics, autonomous systems, biomimetic design, deployable UAV, morphing wings, surveillance systems.*

## I. INTRODUCTION

Biomimetic morphing systems have emerged as an important research area in aerospace engineering due to their potential to improve aerodynamic adaptability, deployment efficiency, and compact storage capabilities. Natural flying organisms, particularly insects and birds, demonstrate sophisticated wing-folding mechanisms capable of balancing structural flexibility with aerodynamic performance. These biological systems have inspired the development of deployable aerospace structures and intelligent morphing configurations for next-generation unmanned aerial vehicles (UAVs).



**Figure 1.** Supermarine Seafire

Space-efficient UAV deployment has become increasingly significant in surveillance and defense operations, especially for carrier-based and parent-platform deployment architectures. Conventional folding wing systems primarily employ single-axis folding methods, which limit achievable storage reduction. In contrast, certain insects such as the Ensign wasp demonstrate multi-axis wing folding involving both longitudinal and transverse creases, enabling substantial reduction in occupied volume while preserving large deployed wing spans.

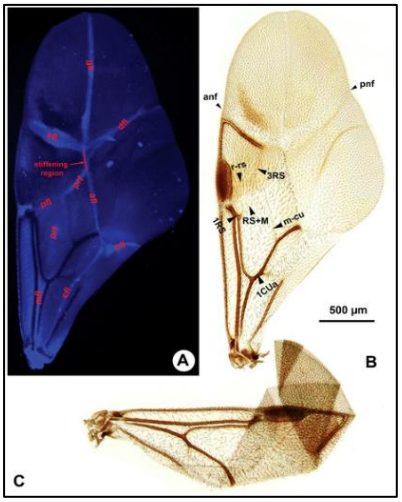



**Figure 2.** Fold-Lines on surface of Ensign Wasp wing

ISSN (Online) 2456 -1304

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Volume 13, Issue 06, June 2026

**Abbreviations:**

*afl- Anal-marginal fold line*
*pfl- Pre-stigmal fold line*
*sfl- Post-stigmal fold line*
*dfl- Discal fold line.*

The present work investigates a bio-inspired deployable wing mechanism based on the folding topology of the Ensign wasp. The proposed design simplifies the biological folding pattern into an engineering-compatible morphing wing architecture suitable for compact UAV deployment. Two deployment mechanisms are explored: a string-based mechanism intended to decode the coupled wing kinematics, and a structurally improved umbrella-based mechanism developed to address limitations related to component coupling, structural stability, and deployment control.

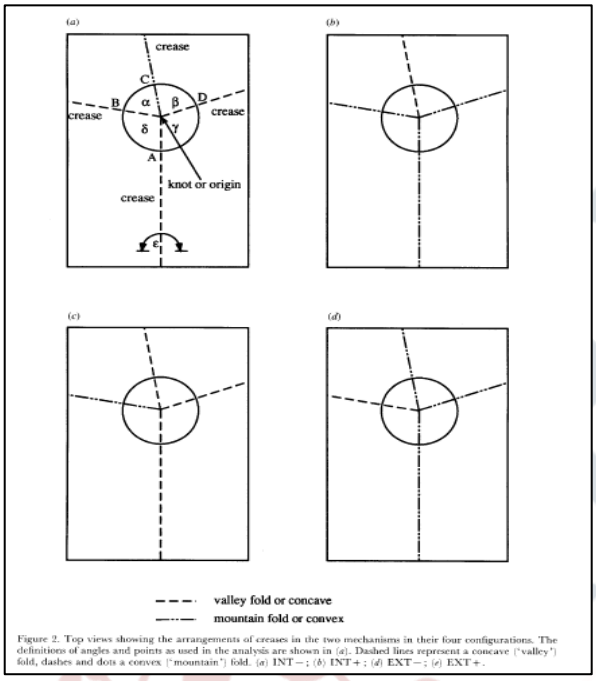



**Figure 3.** Arrangements of creases in the two mechanisms (a) INT- (b) INT+ (c) EXT- (d) EXT+

The work integrates geometric modeling, kinematic mechanism development, aerodynamic analysis, structural feasibility assessment, and preliminary control-oriented state-space modeling. Aerodynamic behavior is evaluated for multiple intermediate deployment configurations using ANSYS Fluent, while structural implications of aerodynamic loading are investigated through static structural analysis. State-space concepts and Simulink-based control frameworks are further introduced to assess deployment controllability for autonomous UAV applications.

The proposed morphing architecture aims to contribute toward deployable aerospace robotic systems capable of compact storage, rapid deployment, and adaptive operation in surveillance and defense environments.

## II. BIO-INSPIRED FOLDING ARCHITECTURE

### A. Ensign Wasp-Inspired Folding Topology

The proposed wing architecture is inspired by the folding mechanism of the Ensign wasp, whose forewings exhibit both longitudinal and transverse folding. Unlike conventional aircraft folding mechanisms, the biological structure achieves high packaging efficiency through intersecting fold lines distributed across the wing surface.

The original biological folding geometry was simplified into a reduced engineering model consisting of two primary folds: a longitudinal fold and a V-shaped transverse fold. This simplification preserves the essential deployability characteristics while enabling practical mechanical implementation for UAV applications.

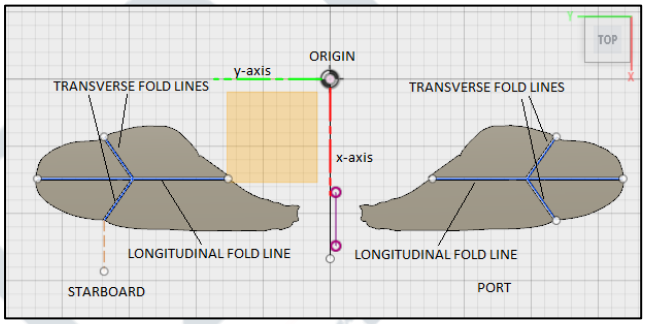



**Figure 4.** Fold lines on the wing

**Table I:** Geometry of Fold lines

| Aspect | Longitudinal Fold | Transverse fold (from L.E) | Transverse fold (to T.E) |
|---|---|---|---|
| Length | 142 mm | 38 mm | 38 mm |
| Starboard Coordinates | [74, 76, 0] to [74, 218, 0] | [105, 169, 0] to [74, 147, 0] | [74, 147, 0] to [43, 169, 0] |
| Port Coordinates | [74, -76, 0] to [74, -218, 0] | [105, -169, 0] to [74, -147, 0] | [74, -147, 0] to [43, -169, 0] |

The wing geometry was modeled using Autodesk Fusion 360. The deployed wing possesses a maximum spanwise length of 194.5 mm and a maximum width of 75 mm. Two aerodynamic cross-sectional concepts were investigated during the study: a curved plate profile for the string-based mechanism and a NACA0012 airfoil profile for the umbrella-based mechanism.

### B. Folding Kinematics

The morphing wing is divided into four articulated sections connected through hinge joints. Longitudinal folding occurs about a continuous central fold line, while transverse folding occurs along a V-shaped crease intersecting the longitudinal fold.

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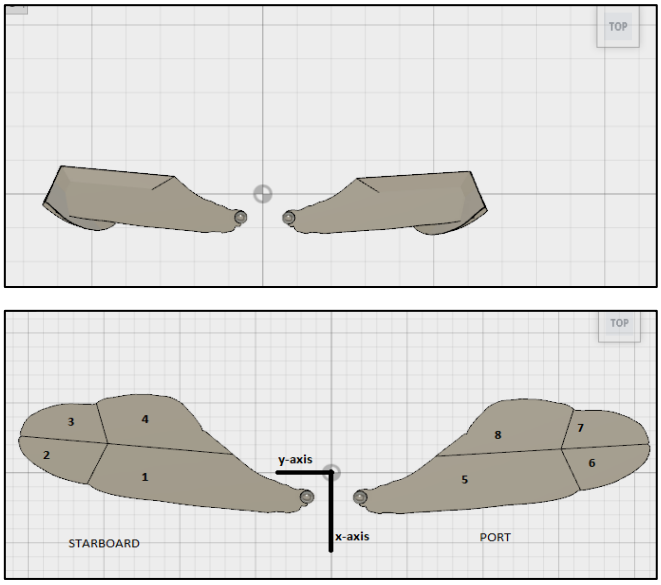



**Figure 5.** Top view of Folded and Unfolded configurations

The fully folded configuration enables substantial reduction in occupied storage volume, thereby increasing deployability within confined aerospace platforms. Such compact packaging is particularly beneficial for surveillance UAV systems intended for deployment from carrier aircraft or autonomous mothership platforms.

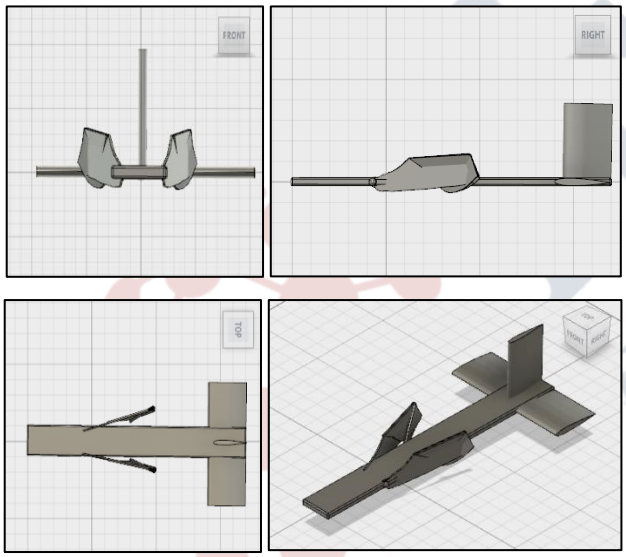



**Figure 6.** Configuration while at rest (Folded and Closed) a. Front View b. Side View c. Top View d. Perspective View

## III. MECHANISM DEVELOPMENT

### A. String-Based Mechanism

The initial mechanism utilized servos, pulleys, strings, gears, hinges, and elastic wing surfaces to achieve coupled deployment motion. In this configuration, the wing sections were connected using flexible elastic material that remained tensioned in the folded state and relaxed during deployment.

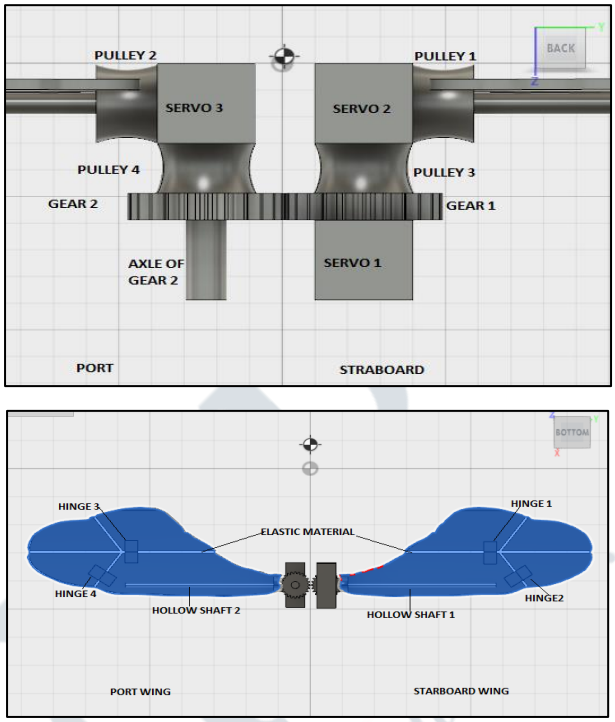



**Figure 7.** Components in the String-Based Mechanism (Front and Bottom views)

Servo-driven pulley systems controlled both opening and unfolding motions simultaneously through string coupling. Gears were incorporated to synchronize starboard and port wing rotations while minimizing the number of actuators required.

A physical prototype of the mechanism was fabricated to validate the deployment concept and study the folding kinematics experimentally.

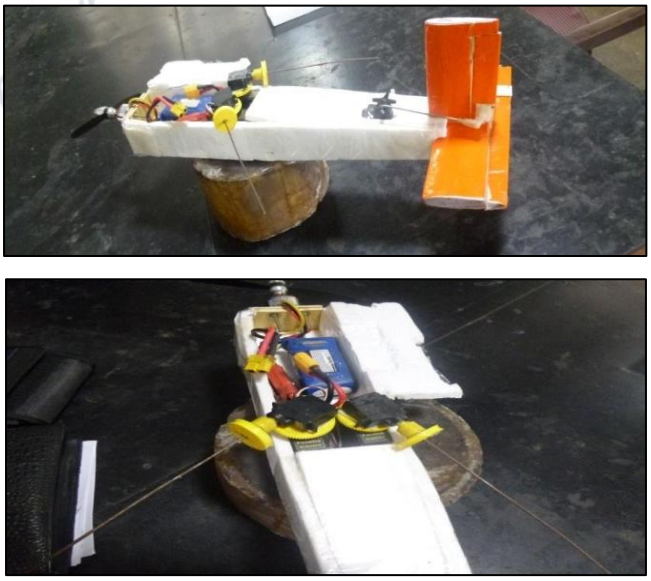


**Figure 8.** Images of Fabricated Model

#### *1) Limitations of the String-Based Mechanism*

Despite successful demonstration of the deployment

ISSN (Online) 2456 -1304

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Volume 13, Issue 06, June 2026

sequence, several limitations were identified:

- Excessive coupling between components reduced overall mechanical efficiency.
- Constant tension in the elastic material introduced creep-related deformation risks.
- Increased actuator and transmission complexity elevated system weight.
- Precise synchronization requirements reduced deployment reliability.

These limitations motivated the development of an alternative mechanism with improved structural robustness and simplified deployment dynamics.

### B. Umbrella-Based Mechanism

An improved umbrella-inspired deployment framework was subsequently developed to overcome the limitations of the string-based architecture. The mechanism consists of a structural framework integrated beneath the morphing wing canopy.

Linear servos actuate central shafts connected to strategically positioned struts that slide along predefined channels embedded within the wing structure. This arrangement enables controlled deployment while reducing dependence on highly coupled pulley-string systems.

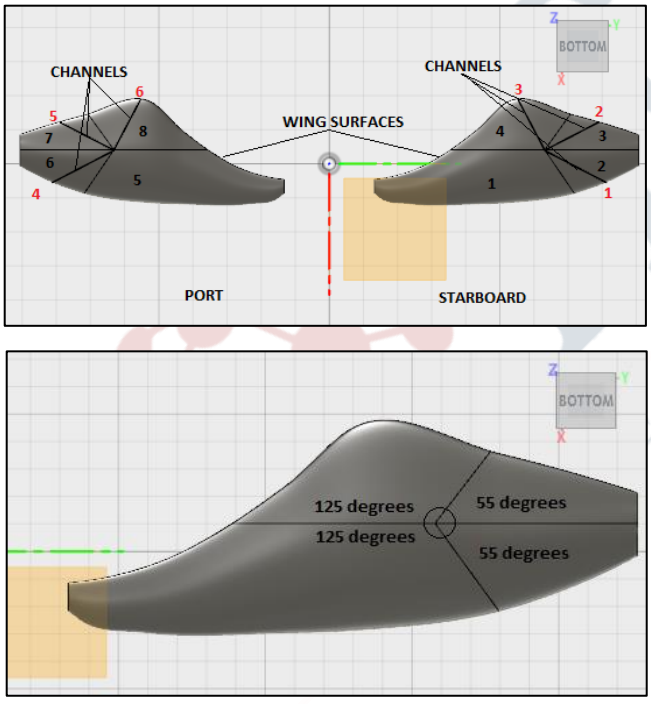



**Figure 9.** Components of the Airfoil-Wing and Bottom view of Starboard Wing

Unlike the previous design, the umbrella-based mechanism incorporates additional compliant skin material along fold regions to improve aerodynamic continuity during deployment. The mechanism also reduces long-term stress accumulation in the wing surface and improves structural adaptability.

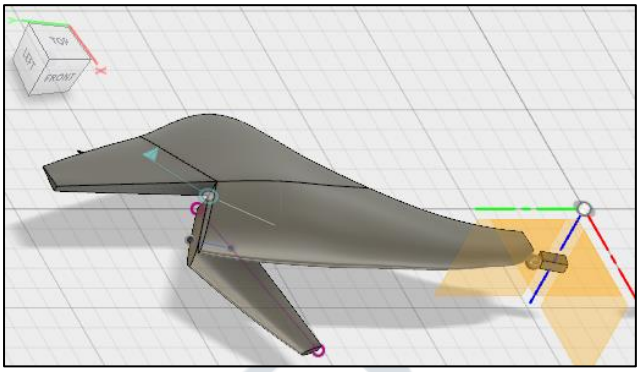


**Figure 10.** Maximum distance between edges on Upper surface

The wing canopy utilizes a NACA0012 airfoil profile to provide improved aerodynamic characteristics during flight. Channel paths and strut geometries were mathematically modeled to achieve controlled deployment trajectories across multiple wing sections.

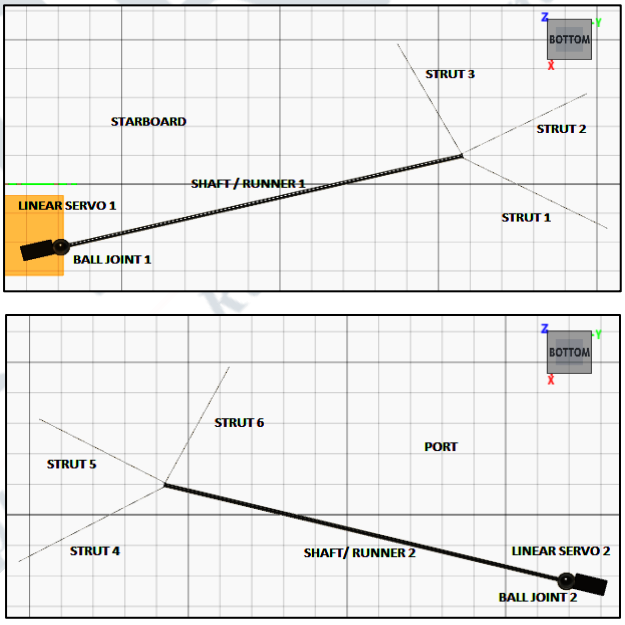



**Figure 11.** Components of the Structural Framework

The umbrella-based mechanism demonstrates improved deployment stability, reduced mechanical complexity, and enhanced suitability for autonomous UAV deployment systems.

## IV. AERODYNAMIC EVALUATION

### A. CFD Methodology

Aerodynamic analysis was conducted using ANSYS Fluent to evaluate pressure distribution behavior during wing deployment. Structured meshing and a pressure-based steady-state solver were employed for all simulations. The Spalart–Allmaras turbulence model was selected due to its suitability for aerospace wall-bounded flow applications.

ISSN (Online) 2456 -1304

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Volume 13, Issue 06, June 2026

*Energy Equation:* FLUENT solves the energy equation in the following form:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left( k_{\text{eff}} \nabla T - \sum_j h_j \vec{J}_j + (\bar{\bar{\tau}}_{\text{eff}} \cdot \vec{v}) \right) + S_h$$

where $k_{\text{eff}}$ is the effective

$\vec{J}_j$ is the diffusion flux of species $j$

$S_h$ includes the heat of chemical reaction, and any other volumetric heat sources

Five deployment configurations were analyzed:

1. Fully folded configuration
2. 25% deployed configuration
3. 50% deployed configuration
4. 75% deployed configuration
5. Fully deployed flight configuration

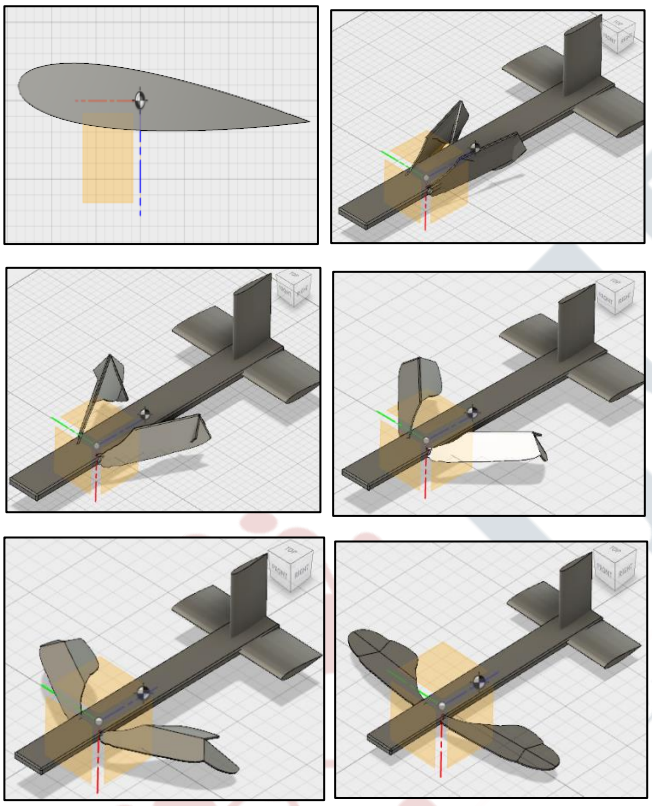


**Figure 12.** Geometries of the six cases: a. Verification Case b. Case 1 c. Case 2 d. Case 3 e. Case 4 f. Case 5

A verification study using a rectangular NACA0012 wing at an angle of attack of 3.93° was additionally performed to compare numerical pressure coefficient distributions with published experimental data.

### B. Aerodynamic Behavior During Deployment

Simulation results revealed significant variation in pressure distribution across deployment stages. High pressure concentrations were observed near fold intersections and wing-fuselage joints due to abrupt geometric discontinuities and bluff-body effects.

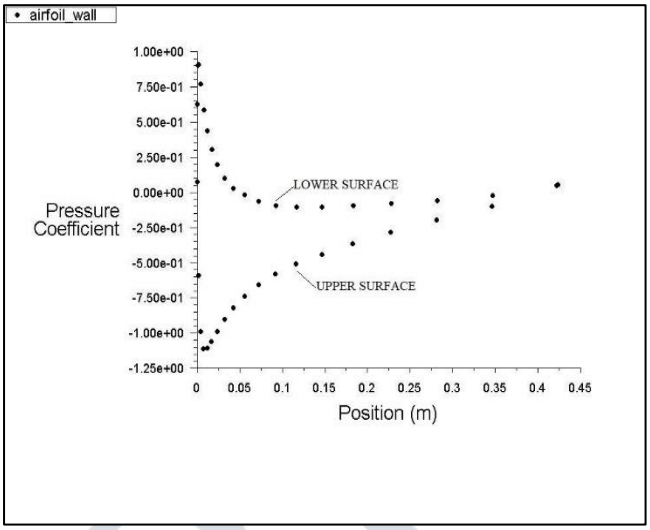



**Figure 13.** Cp Plot using ANSYS Fluent

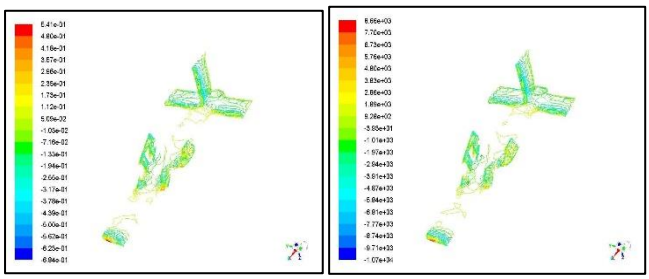
As deployment progressed, wing sections aligned into smoother aerodynamic surfaces, reducing localized pressure accumulation along fold regions. The fully deployed configuration demonstrated the most aerodynamically continuous pressure distribution among all cases.

The analysis further indicated that incorporation of compliant skin material along fold lines could significantly reduce pressure discontinuities and drag penalties during deployment transitions.

Inputs and Boundary Conditions:

**Table II:** Fluent Conditions for Turbulent Models

| **Input** | **Value** |
|---|---|
| Solver | Pressure-Based |
| State | Steady |
| Viscous Model | Transition k-kl-omega |
| Material | Air |
| Density | 1.225 kg/m$^3$ |
| Viscosity | 1.7894e-05 |
| Reynolds Number | 3 x 10$^5$ |
| Inlet Velocity | 4.3822 m/s |
| Chord Length | 1 m |
| Pressure-Velocity Coupling | Coupled |



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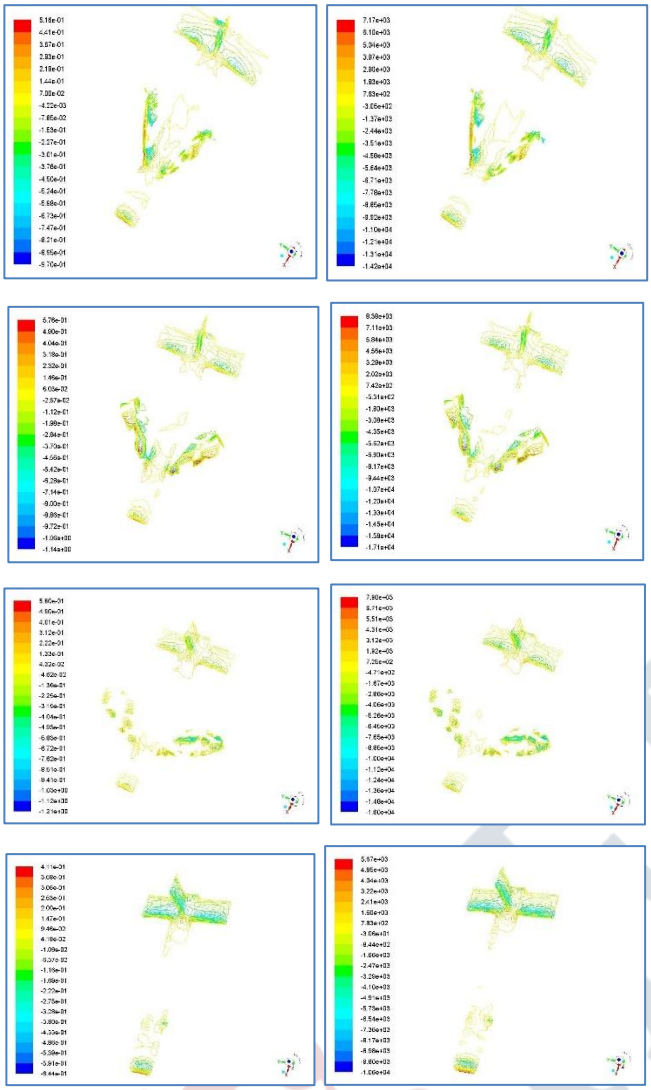


**Figure 14.** Static Pressure and Cp of the five cases

The present CFD study primarily provides qualitative insight into deployment-state aerodynamics. Higher-fidelity simulations using refined meshes are recommended for future quantitative force estimation and optimization.

## V. STRUCTURAL AND CONTROL-ORIENTED ANALYSIS

### A. Structural Feasibility Assessment

Preliminary structural analysis was conducted using aerodynamic loads extracted from CFD simulations. Static structural analysis was performed to evaluate deformation trends, elastic strain distribution, shear strain behavior, and equivalent stress concentration regions.

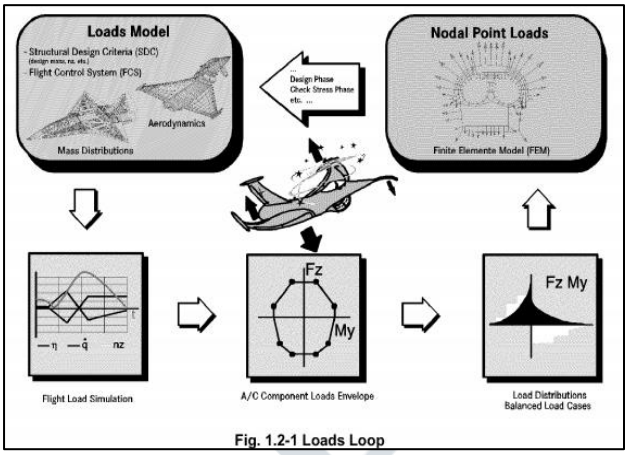



**Figure 15.** Loads Loop

The forces and Centre of Pressure stated below have been taken from the ANSYS Fluent Results.

In the Steady State of Flight:

Lift = -21.36 N; Weight = 21.36 N

Drag = -36.73 N; Thrust = 36.73 N

Co-ordinates of Centre of Pressure: [-0.3798 m, 0 m, -0.0445 m]

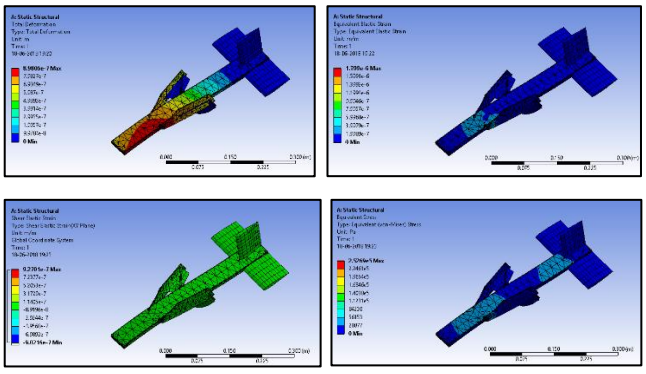
The simulations indicated that critical loading regions occur primarily near:

- wing-root connections,
- fold intersections,
- actuator attachment points.

After meshing the model, the following conditions have been applied.

**Table III:** Static Structural Analysis

| **Fixed End** | **At one end of the model** |
|---|---|
| Remote force | At [-0.3798 m, 0 m, -0.0445 m]<br>Forces:<br>X = -36.73 N<br>Z = -21.36 N |
| Remote force | At [-0.3798 m, 0m, -0.0445 m]<br>Forces :<br>X = 36.73 N<br>Z = 21.36 N |



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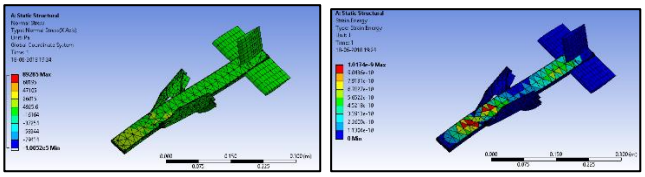


**Figure 16.** Total Deformation, Equivalent Elastic Strain, Shear Elastic Strain, Equivalent Stress, Normal Stress, Strain Energy

These regions are strongly influenced by deployment geometry and load transfer during morphing operations.

The umbrella-based structural framework demonstrated improved load distribution characteristics compared to the earlier string-based concept by reducing excessive stress concentration within flexible wing regions.

### B. State-Space and Control-System Integration

To evaluate deployment controllability and actuator coordination, a preliminary state-space modeling framework was investigated using MATLAB-Simulink collaborative simulation concepts.

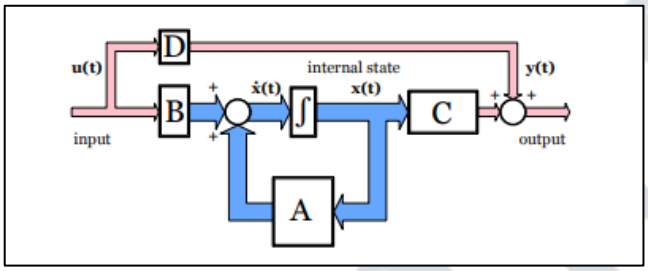



**Figure 17.** Block Diagram Representation of State-Space Equations

The deployment system can be represented using standard state-space equations:

$$\dot{x}(t) = A.x(t) + B.u(t)$$

$$y(t) = C.x(t) + D.u(t)$$

where the state variables represent deployment kinematics and actuator states, while the inputs correspond to servo actuation commands.

The study introduces controllability and observability considerations for future autonomous deployment control systems. Simulink-based integration provides a pathway toward coordinated multi-actuator deployment and closed-loop morphing control for aerospace robotic applications.

## VI. CONCLUSION

This paper presented a bio-inspired deployable morphing wing architecture derived from the folding mechanism of the Ensign wasp for compact surveillance UAV systems. Two deployment mechanisms were investigated: a string-based mechanism for understanding coupled deployment kinematics and an improved umbrella-based mechanism designed to enhance structural robustness and deployment reliability.

Geometric modeling and kinematic development demonstrated the feasibility of combining longitudinal and transverse folding to achieve significant storage reduction while maintaining deployable aerodynamic surfaces. CFD-based aerodynamic analysis across multiple deployment states revealed the influence of fold geometry on pressure accumulation and aerodynamic continuity. Preliminary structural assessment further identified critical load-transfer regions associated with morphing operations.

The integration of state-space concepts and Simulink-based control-system frameworks establishes a foundation for future autonomous deployment control and coordinated actuator management in deployable aerospace robotic systems.

Future work includes high-fidelity aerodynamic optimization, material selection for compliant morphing surfaces, remotely operated deployment control, advanced structural analysis, and integration into coordinated multi-UAV deployment architectures.

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