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HIGHLIGHTS

- UAV wing aerostructural synthesis
- Rigid wing lift error analysis
- 3D-printed structural defect evaluation
- Integrated Co-Design methodology proposal

Aerostructural Design and Manufacturing of UAV Wings: A Systematic Review

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ABSTRACT

This systematic review aims to synthesize the multi-disciplinary optimization problem of Unmanned Aerial Vehicle (UAV) wing design, specifically addressing the conflicting requirements between maximizing aerodynamic efficiency and minimizing structural weight in high-aspect-ratio (>15) wings intended for long-endurance missions. Design/methods/approach: A total of 39 studies from the last 15 years were critically analyzed through an integrated perspective encompassing Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), and advanced manufacturing technologies to identify systemic gaps in the design-to-production cycle. Findings/results: The investigation identifies the NACA 4412 airfoil as a primary reference geometry for low Reynolds number regimes due to its superior resistance to the Laminar Separation Bubble (LSB) phenomenon, which is shown to increase drag by up to 50%. Furthermore, the analysis reveals a critical modeling deficiency in current literature: the widespread "rigid wing" assumption neglects the aeroelastic negative twist (washout) effect in flexible structures, leading to a systematic lift overestimation error of approximately 7%. Regarding manufacturing, the study highlights that Z-axis anisotropy in topology-optimized structures produced via additive manufacturing leads to significant structural strength reductions of up to 50%. Conclusions: The review concludes that traditional sequential design paradigms are insufficient; successful UAV development is only achievable through an "Integrated Design (Co-Design)" approach where aerodynamic, structural, and manufacturing constraints are conducted concurrently to effectively bridge the quantifiable gap between digital simulation and physical workshop realities.

Keywords: Low Reynolds Number Aerodynamics, Additive Manufacturing, UAV Wing Design, Laminar Separation Bubble, Topology Optimization

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) play a strategic role in modern operations, and their mission-specific designs are governed by the fundamental engineering conflict between aerodynamic efficiency and structural integrity. Performance criteria such as range and endurance depend directly on the aerodynamic efficiency of the wing, yet the geometric choices that maximize this efficiency often impose severe structural penalties [1], [2], [3], [4].

The design of UAVs including HALE, MALE, and Tactical variants requires mission-specific configurations [1], [4]. Fundamental performance criteria such as range and endurance are directly dependent on the aerodynamic efficiency of the wing design [4]. However, wing design necessitates establishing a critical engineering balance between aerodynamic efficiency and structural integrity; for instance, a high aspect ratio, which is aerodynamically desirable, increases structural weight and root moments, thereby creating design challenges [2], [4]. In this context, the design process focuses on maximizing the lift-to-drag (L/D) ratio, which directly influences fuel consumption and range [3]. The effects of design decisions and geometric parameters on aerodynamic performance are subsequently validated using numerical analysis tools such as the Vortex Lattice Method, thus completing the theoretical design cycle [5].

Literature Review and Limitations of Current Studies

Existing studies on wing design in the literature are generally concentrated along three main axes. First, aerodynamics-focused studies have extensively investigated the performance of airfoils operating at low Reynolds numbers. For example, the characteristics of the NACA 4412 airfoil have been detailed through wind tunnel and XFLR5 analyses [6], and comprehensive datasets have been established for low-speed profiles [7]. Although pressure distributions have been modeled with high precision using Computational Fluid Dynamics (CFD) [8], these studies typically exclude the wing's structural integrity and manufacturing constraints [3].

The second axis, structural analysis studies, has concentrated on stress and deflection calculations for composite wing boxes [9]. Although significant success has been achieved in weight reduction through topology optimization [10], these studies often treat aerodynamic loads as static, thereby neglecting interdisciplinary interactions. The third axis, encompassing morphing wings and bio-inspired designs, promises performance enhancements [11], yet falls short in offering practical solutions for the manufacturing of these complex structures with existing composite production techniques [12], [13].

1.1 Problem Definition

Aerodynamic Ideals and Structural Realities :

Aircraft wing design is a multi-dimensional optimization problem where aerodynamic ideals clash with structural realities. While high aspect ratios [4], [5] and thin airfoils [6], [7] are targeted for aerodynamic performance, these choices introduce structural problems. A high aspect ratio increases root moments, necessitating heavier structural elements [4], while thin profiles offer insufficient volume for load-bearing components, thereby increasing buckling risk and manufacturing costs [13]. The isolated use of numerical tools is inadequate for solving this problem; CFD analyses ignore the internal structure [8], [5], while single-discipline structural optimizations cannot fully account for manufacturing [12] and anisotropic material properties [13], [14]. This situation leads to designs that are "perfect on paper" but impractical to implement.

1.2 Aim and Original Contribution of the Study

In contrast to the fragmented nature of the existing literature, this study treats UAV wing design as an integrated engineering cycle encompassing aerodynamic, structural, and manufacturing processes. The primary aim of this article is to present an end-to-end practical guide, starting from airfoil selection at the conceptual stage, proceeding through numerical analyses (CFD and FEM), and extending to physical manufacturing and testing processes. The proposed methodology begins with the selection of the NACA 4412 airfoil using wind tunnel and XFLR5 data [6], [4], [7]. The resulting aerodynamic loads are directly transferred to structural analysis models to verify the integrity of critical components such as the wing box [9], [8].

The most original aspect of this work is its fusion of digital optimization with workshop practice. Internal structures lightened through topology optimization [10] are converted into physical prototypes using additive manufacturing (3D printing) and bio-inspired lattice structures [15], [16]. In the final stage, the mechanical properties and integrity of these structures are validated through static load and vibration tests, thereby confirming the physical-world applicability of the virtual analyses [17], [18].

This review systematically deconstructs the design process, starting with the selection of geometric parameters and proceeding to detailed numerical analysis and manufacturing considerations.

A comprehensive synthesis of the 39 selected studies, highlighting their methodological approaches, primary research problems, and critical findings regarding the simulation-reality gap, is given in Table 1.

Table. 1. Summary Of Reviewed Studies On UAV Wing Design

Author(s) and Year	Methodology	Primary Research Problem	Key Findings and Critical Data	Methodological Limitations / Gaps
Selig et al. (1995/2022)	Experimental (Wind Tunnel)	Aerodynamics at Re < 500k	Laminar Separation Bubble (LSB) formation increases drag by 50%.	Aerodynamics only; structural constraints excluded.
Aktaş (2012)	Hybrid (CFD + FEA + Experimental)	Structural Behavior Validation	Accurate prediction along the wingspan, but deviation exists along the chord.	Assumption of idealized interface continuity (perfect bond).
Kennedy & Martins (2012)	Integrated (Aerostructural)	Composite Optimization	Weight minimization achieved via "discrete ply" technique.	Discrete layer thicknesses in production cause deviations.
Sadraey (2012)	Analytical / Systems Eng.	Conceptual Design	Aspect Ratio (AR) > 15 is required for HALE/MALE class platforms.	Structural weight penalties addressed with simplified models.
Şahin (2013)	Vortex Lattice Method (VLM)	Aerodynamic Analysis	Rapid iteration capability in conceptual design phases.	Lifting surface only; no internal structure or thickness effect.
Johnson (2022)	CFD (XFLR5 / ANSYS)	Profile Performance	NACA 4412 is the reference profile for LSB resistance.	Rigid wing assumption; aeroelastic interaction excluded.
Özcan (2004)	CFD	High-Precision Modeling	Pressure distribution mapped with high precision.	Structural integrity and manufacturing constraints are out of scope.
Adeleke et al. (2023)	FEA	Wing-Box Design	Structural integrity of lightened wing-box architectures validated.	Aerodynamic loads assumed static and simplified.
Korkut et al. (2023)	Topology Optimization	Weight Reduction	Ideal load paths and organic geometries via SIMP method.	Low manufacturability with traditional production methods.
Uzun et al. (2021)	Literature Review	Morphing Wings	High potential for performance increase in multi-regime flight.	Lack of practical solutions for production with current composite techniques.
Grodzki (2016)	Production Analysis	Composite Mfg. Technology	Production difficulties in complex geometries defined.	Limited integration with numerical optimization data.
Niu (1999)	Structural Reference	Rib/Spar Architecture	Standards for traditional aircraft structural architecture.	Does not include modern additive manufacturing constraints.
Jones (1999)	Material Mechanics	Composite Characterization	Anisotropic material models and Tsai-Wu failure criterion.	Micro-damage processes under dynamic loading are missing.
Bougherara (2023)	Experimental + FEA	Bio-inspired Lattice Structures	High energy absorption cellular structures obtained.	Z-axis anisotropy effect in additive manufacturing is critical.
Patel et al. (2020)	Experimental	3D Printed Lattice Structures	Lightweight in-fill solutions for UAV wings.	Material defects and production tolerances are outside simulation.
Sarı et al. (2022)	FEA	Vibration Analysis	Free vibration characteristics of tapered	Aerodynamic damping effects not included in the model.

			wings determined.	
Vinoth Kumar (2015)	FEA (Nastran)	Static & Dynamic Analysis	Critical stress points and natural frequencies determined.	Uniform loading assumption; actual pressure distribution missing.
Johansen & Sørensen (2006)	CFD	Winglet Performance	5-10% reduction in induced drag with blended winglets.	Root moment penalty caused by winglet mass excluded.
Genç et al. (2008)	CFD / Experimental	Flap Effect	Flap effectiveness validated on NACA 0012 profile.	Structural control surface flexibility not considered.
Kurtoğlu (2014)	Statistical Energy Analysis	Acoustic Loading	Acoustic stress distribution in fuselage panels.	Wing-body interaction simplified.
Başekin (2023)	CFD	NACA 6412 Analysis	Aerodynamic parameters at low Reynolds numbers.	y+ sensitivity in boundary layer transition models is uncertain.
Göv et al. (2019)	CFD	Adjustable Profile	Performance increase via in-flight profile change.	Mechanical complexity and weight penalty not included in analysis.
Budarapu (2016)	FEA	Auxetic Structures	Flexible solutions for morphing wing design.	Production cost and certification difficulties.
Alsahlani (2017)	FEA / Analytical	Solar-Powered UAV	Structural stability in high-flexibility wings.	Aeroelastic wash-out effect simplified.
Kaplanlıoğlu (2015)	FEA	Mesh Sensitivity	Mesh refinement creates an 8.68% difference in stress results.	Static loading; variable flight conditions missing.
Akar & Selver (2023)	CFD	High-Speed Flow Effect	Aerodynamic characteristics in different profiles.	Heat transfer and aero-thermal effects excluded.
Zhang et al. (2019)	CFD + DOE	Winglet Optimization	DOE-based optimal winglet geometry.	Structural fatigue and flutter risks not examined.
Jiapeng et al. (2013)	FEA	Parametric Modeling	Rapid FE model generation for wing structures.	Production tolerance deviations not included in parameters.
Soğukpınar (2017)	CFD	Optimum Angle of Attack	Determination of sharp suction peaks.	Rigid structure assumption; no structural deformation effect.
Kasmaiee (2024)	CFD (SST k-ω Transition)	Time-Dependent Flow	Success in capturing boundary layer and LSB with y+ < 1.	Fluid-Structure Interaction (FSI) missing in the model.
Al Rifaie (2017)	Experimental + FEA	Additive Mfg. Lattice	Z-axis weakness; 4-14% deviation in Specific Energy Absorption (SEA).	Isotropic material assumption leads to deviation from real results.
Kayacan (2024)	Topology Optimization	Adaptive Design	Additive manufacturing compatibility in aviation.	Risk of delamination between layers should be added to the model.
Rajappan (2013)	FEA	Composite Wing Analysis	Stress distribution of layered composite structures.	Resin accumulation and voids in production are ignored.
Akdoğan & Sülü (2023)	FEA	Rib Design	Stress concentration in ribs with elliptical holes.	Uniform loading assumption; aerodynamic moment arm

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				missing.
Kaminsky (2012)	CFD	Turbine/Wing Aerodynamics	Prediction of boundary layer separation points.	Low Reynolds number instabilities not fully modeled.
Günay & Özbay (2019)	FEA	Structural Analysis	FEA-based validation in UAV wing design.	Interpolation errors in the transfer of aerodynamic data.
Rabbey et al. (2014)	FEA	Deformation Analysis	Wing deflection characteristics under load.	Aeroelastic twist effect excluded.
Elsakka (2019)	CFD	Angle of Attack Analysis	Effect of AoA on lift/drag.	Inadequate turbulence model in the post-stall region.
Yaylı et al. (2017)	Optimization	Fixed-Wing UAV	Multidisciplinary design optimization processes.	Production constraints missing as optimization variables.

II. METHOD AND PROCEDURE

A systematic and transparent methodology is strategically important for a review article, ensuring the creation of a focused and relevant literature base. This section outlines the data collection and filtering criteria used to establish the foundation of this study.

This work presents a systematic review of the literature encompassing unmanned aerial vehicle wing design, aerodynamic analysis, structural optimization, and manufacturing methods. The research aimed to identify studies that address the aerodynamic (CFD), structural (FEA), and manufacturing processes of the design cycle in an integrated manner. At the outset of the systematic screening process, keyword queries yielded over 100 candidate articles relevant to the topic. However, following the application of the inclusion and exclusion criteria detailed below, publications falling outside the scope were eliminated, resulting in a final pool of 39 studies for evaluation.

The strategic keywords and focused research areas used to establish a relevant literature base for aerodynamics and structural optimization are given in Table 2.

Table. 2. Categorized Search Query Keywords and Strategic Focus Areas.

Focus Area	Strategic Keywords
Design & Optimization	UAV wing design, Topology Optimization, SIMP method (Solid Isotropic Material with Penalization), Lattice Structures.
Analysis & Aerodynamics	Low Reynolds Number Aerodynamics, Laminar Separation Bubble (LSB), Transition SST k-ω turbulence model, Aeroelasticity & Washout effect, Integrated FEA/CFD analysis.

The technical inclusion and exclusion criteria, such as timeframe and methodological depth used to ensure scientific currency, are given in Table 3.

Table. 3. Technical Inclusion and Exclusion Criteria For The Systematic Literature Selection.

Category	Inclusion Criteria	Exclusion Criteria
Timeframe	2010–2025 (Representing the last 15 years of	Pre-2010 (Outdated technological data or

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	technological evolution)	legacy methodologies)
Platform Type	Fixed-wing tactical UAV configurations	Rotary-wing, helicopters, or multicopter propeller designs
Geometric Scope	Specific wing geometry and internal components	Full-body, tail-unit, or landing gear designs
Methodological Depth	Transition SST k-ω models, y+ < 1 mesh resolution	Unreported boundary conditions or opaque mesh details
Structural Approach	Aeroelastic deformation and washout analysis	Rigid wing assumptions (ignoring structural elasticity)
Manufacturing Focus	Z-axis anisotropy and fabric drapability	Idealized models ignoring production limits or resin pooling

2.1 Data Collection

The literature search was conducted across three fundamental academic databases that host high-impact publications in the fields of engineering and aerospace sciences: **Web of Science, Scopus, and Google Scholar**.

During the search process, both Turkish and English keyword combinations were used to access relevant articles. The primary keywords used in the query strings were:

- *Aircraft wing design*
- *Unmanned aerial vehicle wing design*
- *Aircraft wing CFD analysis*
- *Aircraft wing FEA analysis*
- *"Wing CFD analysis*
- *"Wing FEA analysis*

Searches were customized using Boolean operators ("AND", "OR") in the title, abstract, and keyword fields to filter for studies with the highest relevance to the topic.

Inclusion and Exclusion Criteria

The resulting pool of publications was classified according to specific criteria to maintain the focus of the study and ensure scientific currency.

Inclusion Criteria

1. **Timeframe:** To maintain technological relevance, the scope of the review was limited to studies published within the last 15 years (2010–2025).
2. **Language:** Only articles with full-text access available in English and Turkish were included in the evaluation.
3. **Content:** Applied studies containing numerical analysis (CFD/FEA) or experimental validation were prioritized over those limited to theoretical discussions.

Exclusion Criteria

1. **Geometric Scope:** Studies examining the entire aircraft configuration (including fuselage, tail, and landing gear) as a whole were excluded; to allow for detailed analysis, only studies focusing on **"wing geometry"** were selected.
2. **Platform Type:** As the subject of the study is fixed-wing aircraft, aerodynamic studies concerning rotary-wing aircraft, helicopters, or multicopter propellers were excluded.
3. **Methodological Deficiency:** Studies that did not transparently report technical details such as boundary conditions, mesh structure, or the turbulence model used were eliminated.

This structured methodology provides a robust foundation for the first thematic area of the review: wing design parameters.

III. WING DESIGN PARAMETERS AND GEOMETRY

Wing design is a complex optimization problem governed by a persistent battle of trade-offs between conflicting engineering disciplines. For Tactical UAVs, this process involves managing the inevitable tension between maximizing aerodynamic performance and minimizing structural weight. This section deconstructs this conflict by examining the key geometric design parameters at three distinct levels: the micro-level of airfoil selection and boundary layer phenomena, the macro-level of planform geometry such as aspect ratio and taper, and the

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peripheral integration of winglets. Each parameter will be analyzed through the lens of its aerodynamic advantages versus the structural and manufacturing penalties it incurs. Airfoil Selection and Boundary Layer in the Low Reynolds Number Regime

The operational flight envelope of tactical UAVs is typically situated in the Re < 500,000 regime (often on the order of 10^5). In aerodynamic literature, this regime is referred to as the "transition region" and is a critical area where the inviscid flow assumptions of classical Potential Flow Theory lose their validity. The impact of viscous forces increases, which can lead to the formation of a complex phenomenon known as the Laminar Separation Bubble (LSB).

Experimental and numerical studies in the literature have detailed the detrimental effect of LSB on aerodynamic performance. The flow separates from the surface in a laminar state near the leading edge, transitions to turbulence in the free stream, and reattaches to the surface with increased energy, forming a "bubble." Wind tunnel tests conducted by Selig and Guglielmo (1995) showed that the presence of an LSB causes sudden drops in the lift coefficient and increases in the drag coefficient of up to 50% [7].

For this reason, profiles that are more resistant to flow separation and exhibit "soft stall" characteristics have become standard in the literature for this regime. The NACA 4412 airfoil, in particular, has become a "reference profile" in tactical UAV designs due to its moderate camber of 4%, stable stall behavior at low speeds, resistance to LSB formation, and high maximum lift coefficient [6]. However, the most significant shortcoming of this aerodynamics-focused approach in the literature is its general exclusion of structural integration from the analysis. Aerodynamicists recommend profiles that are as thin as possible to reduce drag. Yet, from a structural mechanics perspective, a wing's bending stiffness is proportional to the cube of its section thickness. The "aerodynamically perfect" thin profiles selected (e.g., NACA 4412 with a 12% thickness ratio) offer insufficient internal volume for the spar and rib structures to be placed inside the wing. This volume constraint forces the structural designer to use heavier materials or increase wall thicknesses to achieve the required bending stiffness, thus neutralizing the aerodynamic gain with a structural weight penalty.

A comparison of commonly used airfoils in low-Reynolds number applications, including their selection rationale and citation frequency, is given in Table 4.

Table. 4. Commonly Used Airfoils In Low-Reynolds Number UAV Applications and Selection Criteria.

Airfoil Designation	Selection Rationale & Characteristic Properties	Citation & Mention Frequency (Sources)
NACA 4412	• **Geometry:** 4% camber and 12% thickness ratio. • **Utility:** Designated "reference geometry" due to high structural volume for internal components and high C_{l,max}. • **Aerodynamics:** Exhibits significant resistance to the Laminar Separation Bubble (LSB) phenomenon in low Reynolds regimes and maintains stable stall characteristics.	Very High (Sources: [4, 6, 7, 23, 33])
NACA 0012	• **Geometry:** Symmetric baseline. • **Utility:** Serves as the primary control variable for evaluating flap (control surface) effectiveness. • **Aerodynamics:** Utilized to isolate thickness effects from camber-induced lift, providing a "null hypothesis" for pitch-moment sensitivity.	Medium (Sources: [20, 27, 30])
NACA 6412	• **Geometry:** High-camber profile. • **Utility:** Employed in high-speed and high-lift capacity analyses. • **Aerodynamics:** Primarily used as a benchmark to assess performance limits and the onset of compressibility effects relative to low-speed profiles.	Low (Source: [22])

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Macro-Geometric Configuration: Aspect Ratio, Taper, and Twist

Following airfoil selection, the determination of the wing's three-dimensional planform geometry governs the delicate balance between induced drag, structural weight, and flight stability.

3.1 Aspect Ratio (AR) and the Root Moment Dilemma

According to aerodynamic theory, increasing the Aspect Ratio (AR) reduces induced drag, which can constitute 40-50% of the total drag for low-speed UAVs. As foundational sources like Sadraey (2012) and Raymer (2012) recommend, AR values greater than 15 are suggested for long-range UAVs (HALE/MALE class) to increase range [4].

From a structural perspective, however, an increase in AR can create a catastrophic scenario. Increasing the wingspan extends the moment arm of the aerodynamic load center relative to the root. With a simplified beam model assumption, the root bending moment increases proportionally to the square of the wingspan. This increase necessitates much thicker spar flanges at the wing root, reinforced connection elements, and a heavier fuselage-wing attachment structure. It has been observed in multidisciplinary design optimization (MDO) studies that aerodynamic efficiency (L/D) is often prioritized over structural weight, and this structural "penalty" is overlooked, leading to aircraft that are much heavier than expected in the actual production phase [2].

3.2 Taper Ratio and Tip Stall Risk

The taper ratio, the ratio of the wing root chord to the tip chord, is used to approximate an ideal elliptical lift distribution and to centralize structural weight. However, Anderson (2017) and Selig (1995) draw attention to an aerodynamic trap of high taper ratios: Tip Stall. The shortening of the chord length at the wingtip reduces the local Reynolds number in that region, causing it to stall prematurely. Furthermore, in tapered wings, the local lift coefficient tends to increase towards the wingtip. When these two factors combine, the wingtip stalls while the wing root continues to generate lift. The aileron control surfaces, located at the wingtip, become ineffective in this separated flow, and the pilot loses control of the aircraft.

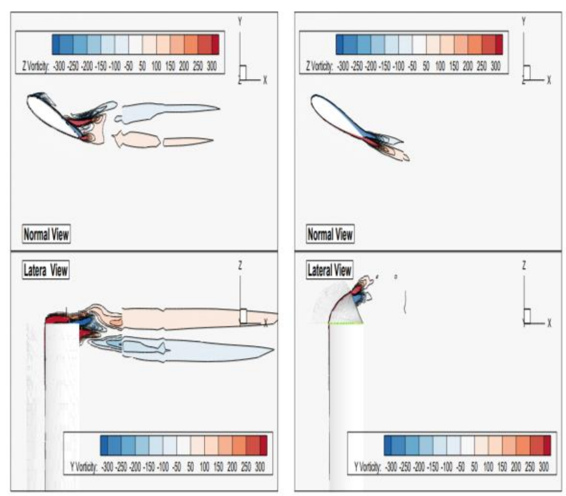
3.3 Aerodynamic and Geometric Twist (Washout)

The most common and effective method in the literature for resolving the "Tip Stall" problem is the application of Twist/Washout. In geometric washout, the angle of attack of the wingtip is physically reduced relative to the root (typically -2° to -4°). This forces the stall to initiate at the wing root rather than the tip. When the root stalls, the aircraft gently pitches down (natural stall recovery), but the wingtips and ailerons remain in clean flow, allowing the pilot to maintain control. However, a literature review shows that many academic CFD studies model the wing as "untwisted" for analytical convenience, thus excluding this critical stability parameter from the analysis.

Winglet Integration and Structural Effects

Another geometric parameter highlighted in the literature to reduce induced drag is the use of Winglets. Winglets weaken the "wingtip vortices" formed by the passage of high-pressure air from under the wing to the low-pressure region above, effectively increasing the wing's aspect ratio without physically extending the span.

A scientific comparison of wingtip vorticity magnitude contours, demonstrating the physical effect of vortex dissipation through winglet integration, is given in Figure 1.



(a) The reference blade (b) The blade with the designed winglet

Figure. 1. Comparison of wingtip vorticity magnitude contours showing vortex dissipation.

In detailed CFD studies by Johansen & Sørensen (2006) and Cengiz & Genç (2020), the performance of different winglet types was compared. The results indicate that the "Blended Winglet" type, which has a smooth transition with the wing, reduces induced drag by 5-10% while keeping parasitic drag to a minimum [19], [20].

However, winglet integration is often treated in the literature solely as an "aerodynamic add-on," with its structural cost disregarded. A winglet increases the aerodynamic loading at the wingtip. This extra load, being at the very end of the moment arm, causes a significant increase in the wing root bending moment. Furthermore, as a mass added to the end of the wing, the winglet changes the wing's natural frequency and aeroelastic flutter characteristics. Researchers advocating for an integrated co-design approach point out that winglet designs optimized solely through CFD without integration with structural analysis (FEA) could lead to unexpected fatigue damage at the wing root and even aeroelastic instability at the wingtip under actual flight conditions.

This transition from geometric design parameters leads directly to the numerical methods used to analyze them.

3.4 aerodynamic analysıs approaches (cfd)

After defining the geometry, the next step is to analyze its aerodynamic performance. This section delves into the nuances of Computational Fluid Dynamics (CFD), evaluating the critical choices in turbulence modeling and the profound errors that can arise from common but flawed assumptions like the "rigid wing" model.

Turbulence Modeling and Accuracy

3.5 Selection and Application of Turbulence Models in Low Reynolds Number Flows

The selection of an appropriate turbulence model is critically important for accurately simulating the complex flow physics of systems operating at low Reynolds numbers, such as Unmanned Aerial Vehicles (UAVs). A review of findings in the literature indicates that the SST (Shear Stress Transport) model is widely preferred for simulations in this flow regime. This model's popularity is attributed to its robust performance in predicting flow separation under adverse pressure gradients and its ability to capture flow with high accuracy both within the boundary layer and in separation zones. For this reason, the model is frequently chosen for predicting the aerodynamic characteristics of UAV rotors [21], [18].

3.6 The Importance of Modeling Laminar-to-Turbulent Transition

One of the fundamental challenges of aerodynamics at low Reynolds numbers is the presence of laminar-to-turbulent transition phenomena, which standard, fully turbulent models are not adequately equipped to handle. Assuming the flow is fully turbulent leads to the failure to capture critical flow features such as laminar separation bubbles, which significantly affect airfoil performance at low Reynolds numbers [14]. These modeling deficiencies significantly reduce the predictive performance of CFD simulations, especially in the post-stall operating range, which is critical for the maneuverability and safety of UAVs [9].

Therefore, the use of transition-sensitive models, such as **transition SST k-ω**, has become a necessity to improve simulation accuracy in applications like vertical-axis wind turbines [4]. These models can predict the onset and progression of the transition from laminar to turbulent flow, capturing the formation and effects of laminar separation bubbles where standard approaches fail, thus providing more realistic aerodynamic performance predictions.

3.7 The Effect of Mesh Resolution and Wall Modeling

To obtain reliable and accurate CFD results with advanced turbulence models, the resolution of the mesh structure, particularly within the boundary layer, plays a fundamental role. Among the technical requirements for the boundary layer mesh, the most critical is the dimensionless wall distance (y+) value. In the literature, it is consistently reported that a y+ < 1 value is targeted in wall-resolved simulations using the SST model to accurately capture the physics of the viscous sublayer; this enables the direct resolution of wall shear stress and viscous effects, eliminating the need for wall functions [21], [22].

The boundary layer mesh topology and the specific y+ < 1 scheme required for accurate viscous sublayer resolution in transition modeling are given in Figure 2.

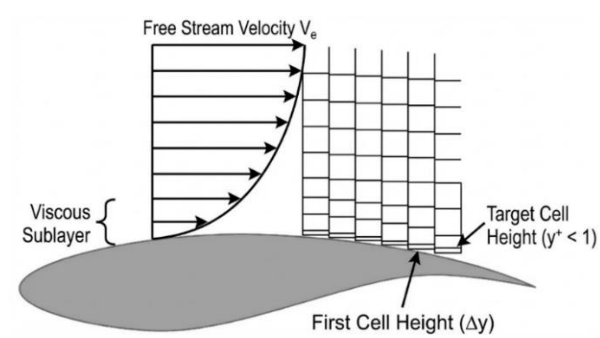


Figure. 2. Boundary layer mesh topology and viscous sublayer resolution (y+) scheme for wall-resolved turbulence models.

The reliability of the numerical solution is intrinsically linked to the discretization quality. As illustrated in the

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representative finite element model in **Figure 3**, appropriate element density and structured mesh generation are prerequisites for capturing continuous field variables. While coarse meshing strategies reduce computational cost, they often lead to "checkerboard" stress patterns or diffused pressure gradients. In contrast, the high-fidelity nodal solution shown in **Figure 3(b)** demonstrates how a refined mesh resolution enables the accurate capture of local gradients and stress concentrations, which are essential for validating the structural integrity under aerodynamic loads.

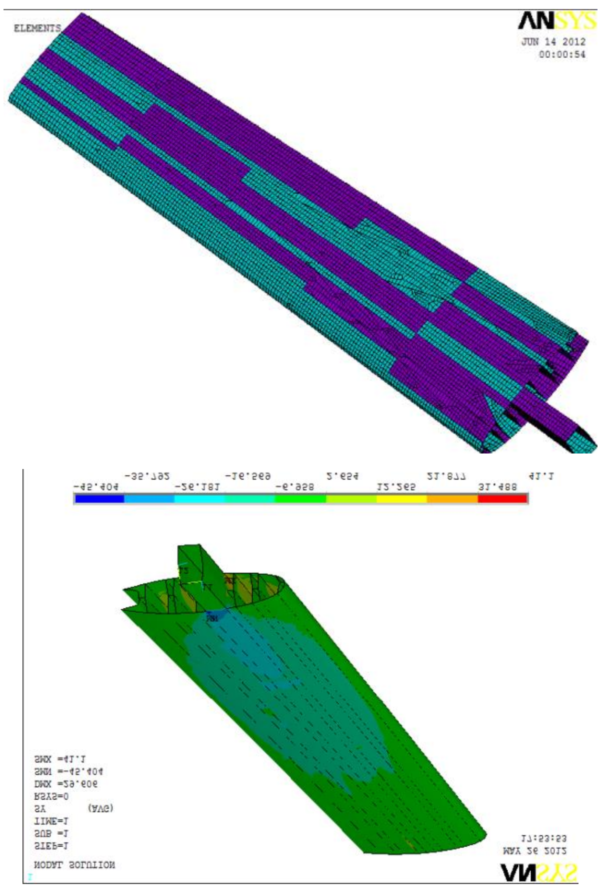

Figure. 3. Visualization of numerical discretization quality: **(a)** High-density finite element mesh structure applied to the wing geometry; **(b)** Resulting nodal solution contour showing smooth field distribution, indicative of adequate mesh resolution (Adapted from [1]).

In this context, conducting mesh or grid independence studies to ensure that the numerical results are independent of the mesh resolution is a standard and mandatory verification step that establishes the reliability of the solution. For instance, in a study by Kasmaiee et al. (2024) [21], multiple grid densities were systematically tested to verify the independence of the solution, demonstrating that the results were not affected by grid resolution.

The Rigid Wing Assumption Fallacy

While the rigid body assumption is a cornerstone of preliminary aerodynamic analysis, it loses significant validity when applied to the slender, high-aspect-ratio wings characteristic of modern Unmanned Aerial Vehicles (UAVs). In such flexible systems, aeroelastic deformation is not a secondary effect but a primary factor determining actual flight performance and structural loading.

3.8 The Prevalence of the "Rigid Model" in Literature and its Rationale

The widespread adoption of the rigid wing assumption in UAV wing design literature is fundamentally driven by the need to manage computational cost and model complexity, especially during the conceptual and preliminary design phases. The primary priority in these stages is the ability to rapidly evaluate different design alternatives. Therefore, less costly methodologies are preferred over computationally intensive analyses that fully couple fluid-structure interaction (FSI) [13]. Simplified aerodynamic analysis tools like the Vortex Lattice Method (VLM) or coarse-meshed Finite Element Models (FEM) are frequently used to accelerate the design cycle and enable optimization studies in the early stages [23], [13], [24].

3.9 Evidence of Numerical Deviation and the Rigid Model's Lift Prediction Error

High-aspect-ratio UAV wings possess an inherent flexibility due to their design [25]. This flexibility leads to a critical aeroelastic behavior known as "bending-torsion coupling" under aerodynamic loads. The aerodynamic lift force acting along the wingspan causes the flexible wing to bend upwards, which in turn creates a nose-down torsional moment around the wing's elastic axis. This moment results in a negative twist or "wash-out" effect, which is particularly pronounced towards the wingtips [25], [2].The primary consequence of this deformation is a reduction in the local "effective angle of attack" along the outer portions of the wing.

As a direct consequence of this physical mechanism, rigid models systematically overestimate the lift coefficient compared to flexible (aeroelastic) models. A rigid model calculates aerodynamic forces based on the wing's undeformed, or "jig," shape. In contrast, an aeroelastic model accounts for the "wash-out" effect that occurs under load, which reduces the effective angle of attack at the wingtips. This reduction in effective angle of attack leads to the generation of less sectional lift on the outer parts of the wing, causing the total wing lift coefficient to be lower than that predicted by the rigid assumption.

Although existing sources do not provide a specific percentage value for the deviation between rigid and flexible models, a quantitative context for the magnitude of error arising from modeling simplifications can be provided. It has been reported that even the choice between two different simplified aerodynamic models, such as VLM and Prandtl's Lifting Line Theory (PLL), can lead to inconsistencies of up to 7% in the lift coefficient for low-aspect-ratio wings [6]. This suggests that abandoning a more fundamental assumption like rigidity could lead to even larger and more critical errors. This systematic estimation error underscores the importance of advanced aeroelastic modeling to achieve more realistic flight performance predictions. The challenges of aerodynamic analysis thus lead to the corresponding need for robust structural analysis.

IV. STRUCTURAL STRENGTH AND OPTIMIZATION (FEA)

An accurate aerodynamic analysis is only useful if the resulting loads can be applied correctly to a structural model. This section critically examines the methods for defining load boundary conditions in Finite Element Analysis (FEA) and explores the shift from traditional structural design to advanced topology optimization.

The Problem of Loading Boundary Conditions

4.1 The Common Misconception: "Uniform Load" and Simplified Analytical Models

In a significant portion of structural analysis studies in the literature, aerodynamic loads on the wing are modeled using simplified methods. These approaches include distributing loads proportional to the chord length at each section [26], using loads derived from the Vortex Lattice Method (VLM) [1] , or concentrating the total lift force at specific nodes on the wing surface [29]. These simplified approaches are widely preferred in the literature for practical reasons. As noted by Gudmundsson (2014) [4], Computational Fluid Dynamics (CFD) analyses are computationally expensive and time-consuming. Furthermore, as implied in the work of Kennedy and Martins (2012) [2], the complex software infrastructure and interdisciplinary data flow required for fully integrated aero-structural analyses make such high-fidelity analyses even more challenging.

4.2 The Correct Approach: Realistic CFD-Based Pressure Distribution

The method considered the "gold standard" for defining aerodynamic loads in structural analysis is the direct application of pressure distributions obtained from Computational Fluid Dynamics (CFD) analyses to the finite element model. This approach captures the realistic distribution of aerodynamic forces on the wing surface, revealing local effects that are overlooked by simplified models.

CFD analyses provide a detailed map of the pressure coefficient distribution along the upper and lower surfaces of the airfoil. Pressure distribution graphs presented in studies by Soğukpınar (2017) [30] and Kasmaiee et al. (2024) [31] clearly demonstrate the power of this approach (see Figure 4). These graphs distinctly show the sharp suction peaks occurring very close to the leading edge and the continuously varying pressure gradients along the chord. This sudden and intense negative pressure at the leading edge creates a highly localized load on the structure—a critical phenomenon that simplified approaches, which distribute the load more homogeneously along the chord, inherently fail to capture.

The aerodynamic load graph comparing a realistic CFD-based pressure distribution with the simplified uniform load assumption is given in Figure 4.

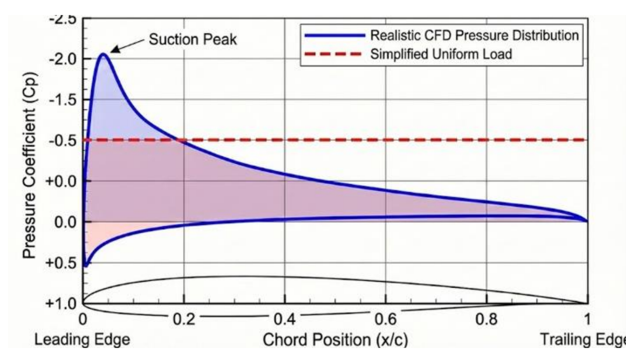

Figure. 4. Aerodynamic load graph.

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The technical challenges of this high-fidelity approach include high computational costs, mesh incompatibility between the fluid volume mesh (CFD) and the finite element mesh (FEA), and the difficulty of accurately transferring (mapping) pressure data between the two grids.

4.3 Consequences of Simplified vs. Realistic Loading Assumptions

The most dangerous consequence of simplified loading models is the risk of significantly underestimating stresses in critical regions. Spreading the load across the surface may cause the Von Mises stresses in areas of high stress concentration, such as the leading edge or wing root, to appear deceptively within safe limits. This can lead to serious miscalculations in fatigue life predictions and damage tolerance analyses.

While no study in the literature directly quantifies the error caused by load simplification, there are significant clues about the impact of modeling fidelity on results. For example, a study by Kaplanlıoğlu (2013) [26] found that simply refining the finite element mesh from a coarse to a detailed model created differences of up to 8.68% in stress values in a stress concentration region. If a modeling detail like mesh structure has this level of impact, it is a reasonable inference that simplifying a much more fundamental assumption like loading could cause similar or greater errors.

In conclusion, while simplified loading methods can be a practical and acceptable tool for rapid iterations during the conceptual and preliminary design phases, high-fidelity CFD-based load maps are a necessity for detailed design and validation to ensure structural integrity and flight safety.

Topology Optimization

4.4 Transition from Traditional Architecture to Algorithmic Design

Traditional UAV wing designs are largely based on the well-established **"Rib/Spar"** structural architecture shown in Figure 5 [13**]**, where a skeleton of spars carries bending and shear loads, and ribs define the airfoil shape. While this design philosophy offers reliable performance, it is being challenged by algorithmic design approaches.

The standard anatomy of a wing skeleton, illustrating the traditional rib and spar structural architecture, is given in Figure 5.

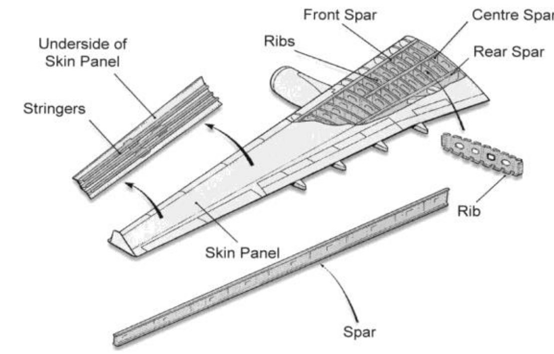

Figure 5. Wing skeleton anatomy.

At the heart of this algorithmic design revolution is density-based **Topology Optimization (TO)**, aimed at minimizing total mass under specific structural constraints. In particular, the **SIMP (Solid Isotropic Material with Penalization)** method has become a standard tool. This method reveals ideal load paths by distributing material most efficiently within the design space.

4.5 The Composite Material and Anisotropy Problem

When TO is applied to anisotropic materials like carbon fiber reinforced polymers, the algorithm must determine not only *where* the material should be located but also the **fiber orientation** at each point [2]. Advanced strategies have been developed to integrate this complexity. The optimization algorithm iteratively proposes a material distribution, which is then translated into a discrete stacking sequence. The mechanical response of the composite layup is characterized using Classical Laminate Theory (CLT) to establish baseline stiffness; however, to ensure flight safety against the aeroelastic effects observed in flexible wings, this framework integrates three-dimensional interlaminar stress evaluations and Progressive Failure Analysis (PFA). By moving beyond the non-mode-specific constraints of the Tsai-Wu criterion, the analysis explicitly accounts for the load redistribution occurring after micro-damage onset, effectively mitigating delamination risks. This methodology incorporates the 3D anisotropic foundations of Jones [14] and addresses the volume-constrained structural requirements identified by Niu [13], providing a high-fidelity assessment of ultimate strength that accounts for the Z-axis anisotropy and manufacturing-induced vulnerabilities inherent in modern airframes. Advanced approaches such as the **"discrete ply parameterization technique"** presented by

Kennedy and Martins (2012) treat not only the material distribution but also the fiber angles of the plies in each region as optimization variables, thereby maximizing structural efficiency [2].

4.6 Manufacturability of Optimization Results

Topology optimization algorithms tend to produce "organic" and topologically complex geometries that show significant similarities to the bio-inspired lattice structures studied in the literature [15]. A fundamental mismatch arises from how variables are treated: in composite optimization problems, ply thicknesses are often assumed to be **continuous** variables for mathematical convenience. However, in actual production, composite plies have **discrete** thicknesses. The necessity of rounding the optimized continuous thickness value to the nearest physical ply count leads to deviations from the theoretically obtained optimal solution. This moves the discussion from the digital world of optimization to the physical challenges of manufacturing.

V. MANUFACTURING TECHNOLOGIES AND TESTING

The ultimate goal of design and analysis is a manufacturable physical product. This section investigates the "technology mismatch" between digitally optimized designs and the practical constraints of both traditional and modern manufacturing techniques, and underscores the importance of physical testing to bridge the gap between simulation and reality.

Unmanufacturable Optima and Traditional Manufacturing Constraints

Topology optimization algorithms tend to produce "organic" and complex geometries by distributing material along stress paths [10]. While these structures are theoretically superior in their strength-to-weight ratio, traditional composite manufacturing methods like vacuum bagging and hand lay-up are often inadequate for these geometries.

Studies in the literature [1], [12] explain the primary reasons for this incompatibility through the following technical challenges:

Anisotropic Material Control and Fabric Drapability: The anisotropic nature of composite materials makes it difficult to drape them over complex, double-curvature surfaces. Defects such as wrinkles, bridging, and fiber waviness disrupt the precise fiber orientation predicted by the optimization, making the part's mechanical performance unpredictable.

Resin Pooling: In designs with complex internal cavities, resin tends to accumulate in certain areas due to gravity during curing. These resin-rich regions, lacking fiber reinforcement, cause the structure to behave brittly and can become sites for crack initiation.

Inspectability Issues: The non-destructive testing (NDT) of closed-cell internal structures produced by topology optimization is nearly impossible. An internal delamination or void, if undetected, creates a critical "black box" safety risk.

Additive Manufacturing and the Anisotropy of Lattice Structures

The most powerful solution proposed in the literature for producing complex geometries is Additive Manufacturing technology. In particular, for wing in-fill structures, Gyroid or Voronoi type "Lattice" structures produced by 3D printing are beginning to replace traditional honeycomb cores.

However, FDM (Fused Deposition Modeling) technology has its own critical structural weakness:

Z-Axis Anisotropy.

Experimental studies by Al Rifaie (2017) [32] have shown that the ultimate tensile strength in the "Upright" manufacturing orientation can be less than 50% of that in the "On-Flat" orientation. Parts exhibiting brittle behavior under load fail due to interlayer delamination. Many FEA studies in the literature incorrectly assume that 3D-printed parts are "isotropic" (having equal properties in all directions). This assumption leads to an overestimation of the part's resistance to loads applied perpendicular to the manufacturing direction (the Z-axis), resulting in design errors [33].

The Gap Between Simulation and Reality

The reliability of numerical analyses (CFD/FEA) is only confirmed when validated by physical tests. A comprehensive comparison conducted by Aktaş [1] on a tactical UAV wing reveals the causes of the deviation between simulation and reality with concrete data:

Deviation Along the Wing Chord: It was reported that the FEA model successfully predicted the overall bending behavior of the wing (along the wingspan) but did not yield results close to the test data in measurements taken along the wing chord.

Idealization of Structural Joints: The primary reason for this deviation is the idealized modeling of the adhesive line joining the two main parts of the wing. The simulation's "perfect bond" assumption fails to represent the complex stress transfer mechanism of the adhesive and manufacturing-induced voids, leading to inaccurate calculations of local deformations [1].

Energy Absorption Difference: Al Rifaie (2017) [32], in compression tests on polymer lattice structures, found deviations ranging from 4% to 14% between FEA results and experimental Specific Energy Absorption (SEA) values.

This data proves that micro-defects from the manufacturing process (voids, resin pooling) and material uncertainties cause a cumulative error that simulation cannot predict. Consequently, while simulation is an excellent guide, it can be misleading when the "imperfect reality" of manufacturing is not taken into account, which leads to a broader discussion of the systemic issues identified.

To bridge this gap, the implementation of the 'Whiffletree' apparatus is a mandatory requirement for full-scale structural validation. Unlike conventional sandbag loading, which applies homogeneous pressure, this system converts a single actuator's stroke into a multi-point distribution that accurately approximates the continuous aerodynamic pressure curve and suction peaks identified in CFD. As established by Niu [13], the Whiffletree setup is the authoritative standard for static testing of complex airframe geometries, ensuring that the 'imperfect reality' of the manufactured structure can be validated against the precise aeroelastic demands of the flight envelope.

VI. DISCUSSION AND CONCLUSION

6.1 Discussion

A critical synthesis of the reviewed literature reveals that while individual disciplines—aerodynamics, structures, and manufacturing—have achieved high levels of maturity, the lack of integration between them creates quantifiable performance deficits. The analysis of the 39 selected studies identifies two primary systemic failures: the divergence between aerodynamic optimization and structural feasibility, and the "reality gap" between digital simulation and physical manufacturing.

The Divergence of Disciplinary Optima The literature demonstrates a clear contradiction between aerodynamic and structural optimization goals. Aerodynamic studies consistently identify the NACA 4412 and similar thin, cambered profiles as reference geometries for the low Reynolds number regime (Re < 5 x 10^5) due to their resistance to the Laminar Separation Bubble (LSB) phenomenon [6], [7]. However, a cross-examination with structural studies reveals that these "aerodynamically ideal" profiles impose severe penalties. As noted by Niu [13] and Sadraey [4], the bending stiffness of the wing is proportional to the cube of its thickness (I ~ t^3). Consequently, the selection of a 12% thickness ratio to maximize the Lift-to-Drag (L/D) ratio forces the structural designer to increase spar mass significantly to compensate for the reduced internal volume, effectively neutralizing the aerodynamic efficiency gains with a structural weight penalty.

Quantifying the Simulation-Reality Gap A significant trend observed in the review is the reliance on simplified modeling assumptions that lead to systematic calculation errors.

1. **The Rigid Wing Error:** While the majority of reviewed aerodynamic studies rely on the "rigid wing" assumption, comparative studies indicate that this ignores the aeroelastic "washout" effect. Evidence suggests that ignoring the bending-torsion coupling and using simplified models (like VLM) instead of fully flexible models can lead to coefficient inconsistencies of up to 7% [6]. This systematic overestimation of lift is critical for the flight safety of long-endurance UAVs.

2. **The Loading Error:** Similarly, structural analyses often employ "uniform load" assumptions. However, CFD-based pressure mapping reveals sharp suction peaks at the leading edge. Kaplanlıoğlu's [26] investigation into mesh and load sensitivity demonstrates that modeling choices can alter stress concentration results by 8.68%. When combined with the uniform load assumption, the underestimation of local stresses in the wing root and leading edge creates a risk that exceeds standard safety margins.

The Manufacturing Paradox in Topology Optimization The most distinct contradiction emerges in the application of Topology Optimization (TO). While TO algorithms [10], [33] successfully generate organic, minimum-weight architectures, they fail to account for the anisotropy of Additive Manufacturing (AM). The synthesis of experimental data from Al Rifaie [32] and Bougherara [15] highlights a critical "blind spot" in standard FEA:

Z-Axis Anisotropy: Digital models often assume isotropic material properties, yet physical testing reveals that the ultimate tensile strength of 3D-printed parts in the Z-axis (upright orientation) can be 50% lower than in the flat orientation due to interlayer delamination risks.

Energy Absorption Deviation: This material discrepancy leads to a divergence between predicted and actual impact performance, with observed deviations in Specific Energy Absorption (SEA) ranging from 4% to 14% [32].

These findings indicate that current "siloed" design methodologies do not merely produce sub-optimal designs; they generate "false positives"—designs that appear feasible in simulation but possess critical structural weaknesses (e.g., Z-axis brittleness) or aerodynamic deficiencies (e.g., aeroelastic lift loss) when manufactured.

Multidisciplinary Design Optimization (MDO)

***1.* Strategic Context of the Co-Design Framework**

The development of modern Unmanned Aerial Vehicles (UAVs) necessitates a transition from fragmented disciplinary silos toward a highly integrated "Co-Design" workflow. Traditional methodologies often treat aerodynamic optimization and structural design as sequential, isolated processes, which frequently results in a significant "reality gap." This gap emerges when designs that appear "perfect on paper" fail to meet performance or structural requirements during physical implementation. By adopting a four-phase Co-Design framework outlined in Figure 6, the systemic failure of the sequential approach is mitigated, ensuring that high-fidelity aerodynamic performance and structural integrity are optimized concurrently. This integration is essential for producing manufacturable, high-aspect-ratio wing designs that maintain stable performance across the entire flight envelope. The integrity of this comprehensive workflow is fundamentally rooted in the initial accuracy of the flow physics modeling.

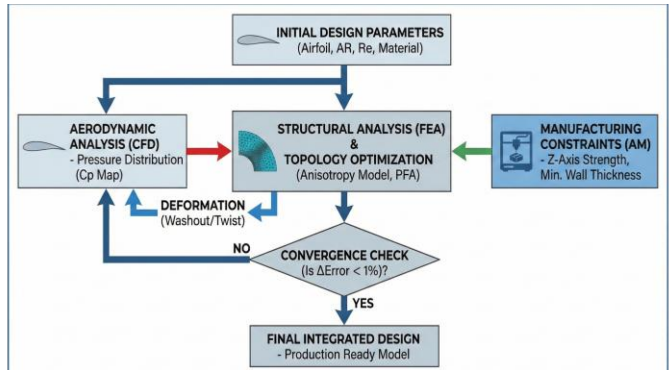

Figure. 6. Integrated Co-Design Workflow for UAV Wings

Phase 1: High-Fidelity Aerodynamic Modeling in the Transition Regime

Aerodynamic modeling for tactical UAVs typically occurs at low Reynolds numbers, specifically in the regime of Re $< 5\ 10^5$. In this transition region, the assumption of fully turbulent flow is insufficient, as standard turbulence models fail to account for the physical phenomenon known as the Laminar Separation Bubble (LSB). The LSB occurs when laminar flow separates from the wing surface near the leading edge, transitions to turbulence in the free stream, and subsequently reattaches as a turbulent boundary layer. Standard models, which assume fully turbulent conditions, are incapable of predicting the onset or progression of these bubbles, leading to a failure in capturing resultant drag increases of up to 50% and significant lift drops.

Consequently, the application of transition-sensitive models, such as the **Transition SST k-ω**, is necessitated. This model provides the required fidelity to capture the viscous sublayer and the laminar-to-turbulent transition, which is critical for predicting stable stall characteristics and high-lift performance. Reference geometries such as the NACA 4412 are frequently utilized in this regime due to a 4% camber and specific resistance to LSB formation. However, a conflict arises between aerodynamic ideals and structural requirements; while thin profiles reduce drag, bending stiffness is proportional to the cube of the section thickness ($EI \propto t^3$), meaning that aerodynamic gains are often neutralized by structural weight penalties in thin sections. These high-fidelity results serve as the prerequisite for accurate translation into structural requirements.

Phase 2: Aero-Structural Data Mapping and Pressure Distribution

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A critical deficiency in traditional structural analysis is the "Uniform Load" fallacy, where aerodynamic forces are modeled as simplified, chord-proportional, or homogeneous loads. Such assumptions fail to capture the localized physics of the wing, particularly the intense leading-edge suction peaks. To prevent the underestimation of local stresses, the direct mapping of pressure coefficient (C_p) data from Computational Fluid Dynamics (CFD) surfaces to Finite Element Analysis (FEA) nodes is established as the gold standard.

High-fidelity data mapping reveals the sharp gradients and varying pressure distributions along the chord that simplified analytical models ignore. Without this direct transfer of CFD data, Von Mises stresses in concentration regions—such as the leading edge or wing root—may appear deceptively safe, leading to catastrophic failures in fatigue life or damage tolerance. The static fidelity provided by C_p mapping represents a localized optimization that remains incomplete without the inclusion of dynamic aeroelastic feedback loops.

Phase 3: Aeroelastic Iteration and the Washout Phenomenon

The reliance on a "Rigid Wing" assumption in numerical simulations introduces a systematic overestimation of lift force. High-aspect-ratio UAV wings exhibit inherent flexibility, leading to a critical "bending-torsion coupling." Under aerodynamic loading, the upward bending of the wing creates a nose-down torsional moment around the elastic axis, a phenomenon known as "washout" (negative twist).

This washout effect is most pronounced at the wingtips and results in a reduction of the "effective angle of attack." Rigid models, which calculate forces based on the undeformed "jig" shape, fail to account for this reduction, leading to a systematic overestimation of lift. While discrepancies between simpler aerodynamic models like the Vortex Lattice Method (VLM) and Prandtl's Lifting Line Theory (PLL) are observed at approximately 7%, the error introduced by the rigid wing assumption is inferred to be even more significant and critical for flight safety. An iterative aeroelastic loop is required to reconcile these deformations, ensuring the final wing design is optimized for actual flight conditions. This optimized aeroelastic shape is subsequently reconciled with the physical constraints of the production process.

Phase 4: Manufacturing-Aware Constraints in Topology Optimization

The final phase involves the integration of manufacturing realities into the Solid Isotropic Material with Penalization (SIMP) topology optimization process. While density-based optimization reveals ideal, "organic" load paths, these digital optima often fail to account for physical production limits, creating a "black box" safety risk. Specifically, complex internal structures produced via topology optimization present significant challenges for non-destructive testing (NDT) and inspectability. A primary concern in additive manufacturing is "Z-axis anisotropy," where the ultimate tensile strength in the upright orientation can drop below 50% due to interlayer delamination.

To bridge the gap between digital optimization and physical prototypes, the incorporation of **Classical Laminate Theory (CLT)** and the **Tsai-Wu failure criteria** as active constraints within the optimization algorithm is required. This ensures that fiber orientation and material distribution account for the discrete nature of composite plies and the directional weaknesses of 3D-printed structures. By embedding these manufacturing-aware constraints, the workflow prevents the creation of unmanufacturable optima and ensures structural integrity under real-world loading.

2. Comparative Analysis: Traditional vs. Co-Design Approaches

The synthesis of these four phases facilitates a shift from a fragmented, sequential design paradigm toward an integrated "Co-Design" approach. This transition ensures that aerodynamic efficiency, structural safety, and manufacturing constraints are balanced simultaneously, as summarized in the following comparison:

A comparative analysis between the traditional sequential silo approach and the proposed integrated Co-Design framework is given in Table 5.

Table. 5. Comparative analysis of the traditional sequential design paradigm versus the proposed integrated Co-Design framework.

Feature	Traditional Silo Approach	Proposed Co-Design Approach
Disciplinary Interaction	Sequential and isolated	Concurrent and integrated
Aerodynamic Assumption	Fully Turbulent models	Transition-Sensitive (SST k-ω)
Structural Loading	Uniform or simplified chord-proportional	Direct CFD-Mapped distribution
Wing Fidelity	Rigid Wing assumption	Aeroelastic Washout Correction
Manufacturing Integration	Post-design consideration	Anisotropy-Aware (CLT/Tsai-Wu) constraints

6.2 Conclusion

The critical discussions conducted have clearly revealed the limitations of the current paradigm in the field of tactical UAV wing design. These analyses, by highlighting fundamental problems such as interdisciplinary disconnects and the idealized nature of simulations, enable us to draw clear, actionable, and strategic conclusions for future work.

Paradigm Shift: The Necessity of Integrated Design

The analyses performed definitively prove that UAV wing design is a problem too complex to be solved within the confines of a single discipline. The silo effect has been shown to cause suboptimal or impractical designs, as optimization in one discipline creates unaddressed constraints for another [35], [33]. The following paradigm shifts are therefore not preferences but necessities for future progress:

The Imperative of Integrated Design: The isolated execution of aerodynamic and structural analyses must be abandoned in favor of integrated approaches that target the holistic performance of the system. It has been observed that these disciplines, when pursued separately, disregard each other's critical requirements—for instance, aerodynamics ignoring structural volume and structural analysis ignoring realistic aerodynamic load distributions [35], [33].

The Need for a Concurrent (Co-Design) Approach: To overcome the inefficiencies of sequential design flow, future success depends on adopting "Concurrent (Co-Design)" approaches where aerodynamic and structural analyses are conducted simultaneously. This allows for the identification and management of interdisciplinary trade-offs from the earliest design stages, leading to more robust and optimized solutions [38], [39].

The Need for Digital Twins and Manufacturing-Aware Simulation: To bridge the gap between simulation and reality, there is an urgent need for "Digital Twin" approaches that simulate manufacturing defects—such as anisotropy, delamination, and residual stresses from additive manufacturing—at the design stage. This will ensure that optimized designs are not only theoretically superior but also physically robust and producible [25], [36], [13].

STATEMENT OF CONTRIBUTION RATE

Authors' contribution rates to the study are equal

CONFLICTS OF INTEREST

They reported that there was no conflict of interest between the authors and their respective institutions.

RESEARCH AND PUBLICATION ETHICS

In the studies carried out within the scope of this article, the rules of research and publication ethics were followed.

USE OF ARTIFICIAL INTELLIGENCE (AI):

We declare that no Artificial Intelligence (AI) tools were used in any stage of the preparation, data collection, analysis, or writing of this study. The article is entirely the original work of the authors and is not an AI product.

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