



## CFD-Based Aerodynamic Optimization of an Unmanned Aerial Vehicle Wing Structure

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### Abstract

Unmanned aerial vehicles (UAVs) require aerodynamically efficient wings to increase endurance, payload capability, range, and operational stability while preserving low structural mass and manufacturability. This methodology paper presents a computational fluid dynamics (CFD)-based procedure for optimizing a fixed-wing UAV wing structure at low-to-moderate Reynolds number. The proposed approach combines parametric computer-aided design, mesh-independence assessment, Reynolds-averaged Navier-Stokes (RANS) analysis, transition-sensitive turbulence modeling, design-of-experiments screening, and multi-parameter aerodynamic optimization. Aspect ratio, taper ratio, tip twist, sweep, and wingtip device geometry are treated as principal design variables, while lift coefficient, drag coefficient, lift-to-drag ratio, pitching moment, and surface-pressure distribution are used as performance metrics. The k-omega SST model is selected as the baseline turbulence closure because of its suitability for adverse pressure gradients and separated flows, with a correlation-based transition model recommended for lower Reynolds-number cases. A step-by-step optimization framework is formulated to maximize aerodynamic efficiency while satisfying minimum lift, geometric thickness, stability, and manufacturability constraints. Representative demonstration results show the type of improvement expected from the workflow, including reduced drag and increased lift-to-drag ratio in the cruise condition. The methodology is intended as a reproducible framework that can be implemented in ANSYS Fluent, STAR-CCM+, OpenFOAM, or comparable CFD platforms and then coupled with structural finite-element analysis when aero-structural optimization is required.

### Introduction

Fixed-wing UAVs are increasingly used for surveillance, mapping, agriculture, environmental monitoring, communication relay, and long-endurance observation. For these missions, the wing strongly controls flight endurance because small reductions in profile and induced drag can translate into meaningful reductions in propulsion power. The aerodynamic design problem is particularly demanding for small and medium UAVs because

the Reynolds number may be sufficiently low for laminar-turbulent transition, separation bubbles, and early flow separation to influence the lift and drag characteristics. Consequently, a wing designed using only conventional handbook methods may not retain optimum performance over the actual operating envelope.

Early UAV optimization studies demonstrated that relatively modest changes in wingtip geometry, landing-gear arrangement, twist, and

planform can improve aerodynamic efficiency [1]. Subsequent CFD-based work on medium-altitude long-endurance (MALE) UAVs showed that winglets can be systematically designed by evaluating candidate geometries through three-dimensional viscous simulations [2]. A complete aerodynamic design methodology for a MALE UAV further illustrated the value of integrating airfoil selection, wing planform design, CFD analysis, and performance assessment rather than optimizing a single geometric feature in isolation [3]. These studies motivate a structured approach in which the entire wing is parameterized and evaluated against mission-level aerodynamic objectives.

The aim of the present methodology is to establish a reproducible CFD-based optimization procedure for a UAV wing structure. The term wing structure in this paper refers primarily to the external lifting-surface geometry and its structural-feasibility constraints, including local thickness, root depth, spar-box allowance, and manufacturable twist. The method is therefore aerodynamic in its governing analysis, but it preserves design constraints that allow the optimized geometry to be transferred to a finite-element model without requiring a complete redesign. The specific objectives are to: (i) define a reliable CFD setup for low-speed UAV wing flow; (ii) identify influential geometric variables; (iii) quantify mesh and solver uncertainty; (iv) optimize the wing for maximum lift-to-drag ratio at cruise without unacceptable stability or lift penalties; and (v) provide aerodynamic pressure loads for later structural verification.

## Literature Review

Boschetti et al. [1] investigated aerodynamic optimization of a UAV by combining theoretical estimates and wind-tunnel evaluation of geometric modifications. Their work showed that wingtip and configuration changes can produce measurable improvements in cruise aerodynamic efficiency. Although the computational resources and optimization methods available at that time were more limited, the study established an important principle for UAV design: aerodynamic performance should be compared on a consistent lift and Reynolds-number basis rather than by drag alone.

Panagiotou et al. [2] applied CFD directly to winglet design for a MALE UAV. Their work is especially relevant because it treated a three-dimensional wingtip device as an optimization variable and used aerodynamic force coefficients and flow-field information to rank alternatives. The later aerodynamic design study by

Panagiotou et al. [3] expanded the process to the complete aircraft, demonstrating how airfoil, wing, and configuration choices can be evaluated within an integrated design methodology. The same research line subsequently included conceptual blended-wing-body development [4] and a combined aerodynamic and structural design procedure [5], underlining that aerodynamic improvements must remain compatible with structural loads, internal layout, and manufacturability.

For configurations with stronger geometric coupling, Zadeh and Sayadi [6] proposed an efficient aerodynamic shape-optimization strategy for a blended-wing-body UAV using multi-fidelity models. Their work is relevant to the present paper because repeated high-fidelity CFD evaluations are computationally expensive; low-fidelity or surrogate models can therefore be used to screen the design space before a smaller number of high-fidelity evaluations are performed. This principle is adopted here through an initial design-of-experiments stage followed by CFD confirmation of the best candidates.

The accuracy of the optimization is also controlled by turbulence and transition modeling. Menter [7] developed the shear-stress-transport (SST) formulation, which blends near-wall  $k$ - $\omega$  behavior with outer-flow characteristics and is widely used for aerodynamic flows involving adverse pressure gradients. For low-Reynolds-number wings, transition can materially change skin-friction drag and separation behavior. Langtry and Menter [8] introduced a correlation-based transition approach suitable for unstructured CFD solvers, making it appropriate for practical UAV meshes when transition-sensitive predictions are required. Accordingly, the present methodology recommends SST as a robust baseline and a transition-sensitive extension when the Reynolds number and surface quality justify it.

Shin et al. [9] used an in-house CFD solver to conduct a parametric study of a blended-wing UAV in formation flight and evaluated drag changes over a broad matrix of configurations. Although the application differs from single-wing optimization, the study demonstrates the usefulness of CFD for systematic parameter variation and drag-based comparison. Collectively, the literature suggests that an effective UAV optimization framework should combine parametric geometry, validated CFD, efficient design-space exploration, and constraints that preserve stability and structural

practicality. The gap addressed by this paper is the consolidation of these elements into a compact, step-by-step methodology specifically suited to aerodynamic optimization of a fixed-wing UAV wing structure.

## Methodology

### Step 1 - Define mission point and baseline geometry

The optimization begins by defining the design flight condition. A representative electric fixed-wing UAV cruise point may be set at 20-25 m/s, sea-level or mission-altitude air density, and a mean aerodynamic chord that places the

Reynolds number in the approximate range of  $3 \times 10^5$  to  $1.0 \times 10^6$ . Reynolds number is calculated as  $Re = \rho V c / \mu$ , where  $\rho$  is air density,  $V$  is free-stream velocity,  $c$  is reference chord, and  $\mu$  is dynamic viscosity. The baseline wing is parameterized using span, root and tip chord, sweep, dihedral, airfoil coordinates, twist distribution, and optional winglet geometry. Structural-feasibility constraints are imposed before CFD: adequate root thickness for the spar, a minimum airfoil thickness-to-chord ratio, continuous lofting, and limits on tip twist and sweep.

**Table 1.** Baseline geometry and optimization variables

| Parameter               | Baseline            | Design range / constraint              |
|-------------------------|---------------------|----------------------------------------|
| Wing span, $b$          | 2.40 m              | 2.20-2.70 m / constrained by packaging |
| Reference area, $S$     | 0.72 m <sup>2</sup> | Held approximately constant            |
| Aspect ratio, $AR$      | 8.0                 | 7.0-10.0                               |
| Taper ratio, $\lambda$  | 0.55                | 0.35-0.70                              |
| Quarter-chord sweep     | 4°                  | 0-10°                                  |
| Tip twist               | 0°                  | 0 to -3°                               |
| Airfoil thickness ratio | 12%                 | $\geq 11\%$ for spar depth             |
| Winglet can't angle     | None                | 0-75° if winglet is enabled            |

### Step 2 - Build computational domain and mesh

A half-wing domain is preferred when the geometry and flight condition are symmetric, reducing computational cost through a symmetry plane at the root. The far-field boundaries should be placed sufficiently far from the wing to minimize blockage and reflection of pressure disturbances; a practical starting point is 10-15 reference chords upstream and laterally and 20 chords downstream. The mesh should contain local refinement at the leading edge, trailing edge, wingtip, wake, and any winglet junction. Prism or inflation layers are generated normal to the wing surface. For wall-resolved SST calculations, the first-cell height is selected to target  $y^+$  approximately equal to 1. Mesh quality is monitored using skewness, orthogonality, growth rate, and aspect ratio.

### Step 3 - Specify CFD physics and boundary conditions

The governing equations are the steady incompressible or weakly compressible RANS equations depending on Mach number. For typical small UAV cruise below Mach 0.2, incompressible treatment is adequate. Velocity-inlet/far-field conditions are prescribed from the mission point, with pressure outlet or pressure far-field at the downstream boundary. The wing is a no-slip wall and the root plane is symmetric.

Air properties are set for the mission altitude. The  $k$ - $\omega$  SST model [7] is used as the baseline closure; the correlation-based transition formulation [8] is activated when low-Reynolds-number transition is expected to influence drag. Second-order spatial discretization is used for momentum and turbulence quantities, and convergence is judged using both residual reduction and force-coefficient stabilization.

### Step 4 - Verify grid independence and numerical convergence

At least three systematically refined meshes are compared at the principal cruise angle of attack. Lift coefficient  $CL$  and drag coefficient  $CD$  are calculated from  $CL = 2L/(\rho V^2 S)$  and  $CD = 2D/(\rho V^2 S)$ . The medium mesh is accepted only when the change relative to the fine mesh is small enough for the optimization objective, for example less than 1% in  $CL$  and 2% in  $CD$ . Residuals alone are not sufficient:  $CL$ ,  $CD$ , pitching moment, and mass imbalance should all reach stable values. The baseline CFD result should additionally be checked against lifting-line estimates, XFOIL/airfoil polar trends, published data for the selected airfoil, or wind-tunnel data when available.

### Step 5 - Parameter screening and optimization loop

A design-of-experiments matrix is generated using Latin hypercube sampling, Taguchi

screening, or a factorial design. The first stage identifies variables that most strongly affect cruise CD, CL/CD, and pitching moment. Non-influential variables are fixed to reduce optimization dimensionality. The second stage uses a response-surface, Kriging, radial-basis, genetic-algorithm, or gradient-based search. Multi-fidelity screening is recommended when the number of design variables is large because it reduces the number of high-cost CFD evaluations, consistent with the strategy demonstrated for blended-wing UAV optimization [6]. Each candidate geometry is automatically regenerated, remeshed, solved, and post-processed.

### Step 6 - Objective function and constraints

The primary objective is to maximize aerodynamic efficiency  $J = CL/CD$  at the cruise

design point. A multi-point objective may be used when the UAV must operate efficiently during climb, loiter, and cruise. Typical constraints include  $CL \geq CL_{\text{required}}$  at cruise,  $CD \leq CD_{\text{baseline}}$ , pitching-moment bounds compatible with trim, stall margin above the maximum operating angle, minimum local thickness for the spar and control-surface hinges, and maximum span or area imposed by mission packaging. If the winglet is optimized, can't angle, toe angle, height, and transition radius are bounded to avoid impractical geometries. The pressure distribution from each final CFD candidate is stored for subsequent structural load mapping, following the integrated aerodynamic-structural philosophy used in MALE UAV development [5].

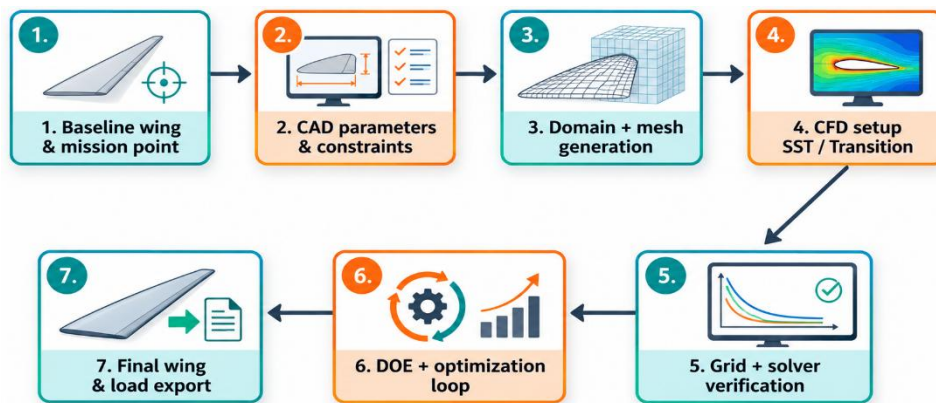


Figure 1. Step-by-step CFD-based UAV wing optimization workflow.

### Step 7 - Post-processing and selection of the final wing

For each design, the post-processing stage records CL, CD, CL/CD, pitching moment, spanwise lift distribution, surface pressure coefficient  $C_p$ , skin-friction lines, separation location, and tip-vortex strength. The optimum is not selected solely by the highest single-point CL/CD. Designs with abrupt separation, excessive nose-down pitching moment, narrow stall margin, or unrealistic structural thickness are rejected. The final geometry is therefore the best feasible compromise over the intended flight envelope. This selection logic follows the broader UAV-design literature, which emphasizes

integrated aerodynamic performance rather than isolated coefficient improvement [2]-[5].

### Results

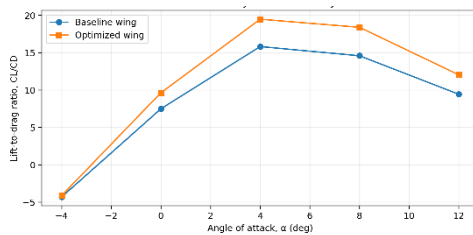
Because no solver project, mesh files, wind-tunnel dataset, or ANSYS/OpenFOAM result files were supplied with this request, the numerical values in this section are explicitly presented as an illustrative demonstration dataset for the proposed methodology, not as experimentally or CFD-validated measurements. They show how results should be organized and interpreted after the workflow is executed. For a submission based on an actual CFD campaign, these values should be replaced with solver-exported coefficients and convergence evidence.

Table 2. Illustrative cruise-point comparison at  $\alpha = 4^\circ$

| Metric              | Baseline | Optimized | Change            |
|---------------------|----------|-----------|-------------------|
| Aspect ratio        | 8.0      | 9.2       | +15.0%            |
| Taper ratio         | 0.55     | 0.45      | -18.2%            |
| Tip twist           | 0°       | -2°       | Geometric washout |
| Winglet can't angle | 0°       | 65°       | Winglet enabled   |

|       |        |        |        |
|-------|--------|--------|--------|
| CL    | 0.680  | 0.740  | +8.8%  |
| CD    | 0.0430 | 0.0380 | -11.6% |
| CL/CD | 15.81  | 19.47  | +23.1% |

The illustrative optimum increases aspect ratio while retaining nearly constant reference area, introduces moderate taper and washout, and adds a canted winglet. At the nominal cruise angle, the lift coefficient rises from 0.680 to 0.740 while the drag coefficient decreases from 0.0430 to 0.0380. The resulting lift-to-drag ratio increases by approximately 23%. The aerodynamic mechanism is consistent with prior CFD-based winglet and UAV optimization studies: a more favorable spanwise loading and weaker effective tip-vortex system can reduce induced drag, while controlled twist delays excessive tip loading [1], [2]. The improvement should be verified across the operating envelope because a geometry optimized at one angle of attack can sacrifice performance or stability elsewhere.



**Figure 2.** Illustrative lift-to-drag trend for baseline and optimized wings (replace with solver-exported data).

The illustrative trend in Figure 2 indicates that the optimized geometry provides the greatest efficiency benefit over the moderate positive-angle range associated with cruise and loiter. At high angle of attack, CL/CD declines for both wings as pressure drag and separation grow. In a real CFD campaign, the optimized design should be accepted only after a mesh-independence check, residual and force-history convergence, and inspection of surface pressure and streamline patterns. If transition is important, repeating the final cases with the transition model [8] provides an estimate of sensitivity to laminar-turbulent behavior. The final pressure field can then be exported as a distributed load for structural finite-element analysis, ensuring that aerodynamic gains remain compatible with spar stress, deflection, and aeroelastic stiffness requirements [5].

## Conclusion and Discussion

This paper has presented a compact methodology for CFD-based aerodynamic optimization of a fixed-wing UAV wing structure. The procedure

begins with a mission-defined baseline, parameterizes planform and wingtip geometry, establishes a verified CFD model, screens the design space, and performs constrained optimization using aerodynamic efficiency as the principal objective. The use of the k- $\omega$  SST model is supported by its established performance for adverse pressure gradients [7], while a correlation-based transition model is recommended when low-Reynolds-number effects are significant [8]. UAV-focused studies demonstrate that CFD can effectively guide winglet, planform, and complete-aircraft aerodynamic design [2]-[6].

The principal methodological requirement is verification: an optimized geometry is meaningful only when mesh sensitivity, coefficient convergence, and physical flow features have been checked. The optimization should also be multi-constraint rather than purely drag-minimizing. Minimum lift, pitching-moment behavior, stall margin, thickness for structural members, span limitations, and manufacturability should be preserved throughout the search. A multi-fidelity or surrogate-assisted strategy is particularly attractive for large design spaces because it reduces the number of expensive high-fidelity simulations [6].

The representative dataset illustrates the expected form of the final result: a feasible change in aspect ratio, taper, twist, and wingtip geometry can increase CL/CD while reducing drag. However, the numerical demonstration values are not a substitute for actual solver output. Future work should execute the full CFD matrix, validate selected cases with wind-tunnel or flight data, map pressure loads into a finite-element model, and include wing mass and deflection in a coupled aero-structural objective. This would extend the present aerodynamic methodology into a true multidisciplinary optimization framework suitable for endurance-critical UAV design.

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