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SYSTEMATİC TRIZ AND CFD BASED FRAMEWORK FOR LİGHTWEİGHT ADDİTİVE MANUFACTURİNG OF FLAP BRACKETS

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ABSTRACT

This study introduces a systematic engineering framework for the development of high-lift aerospace mechanisms, integrating TRIZ (Theory of Inventive Problem Solving) with Computational Fluid Dynamics (CFD) and Design for Additive Manufacturing (DfAM). Unlike conventional iterative design, this approach begins with a functional decomposition to map energy and material flows, identifying the Fowler flap bracket as a critical load-transmission node. To resolve the inherent technical contradiction between structural integrity and weight, TRIZ principles specifically segmentation and porosity were applied to transition from monolithic to organic geometries. The research leverages CFD simulations to derive precise aerodynamic pressure distributions, ensuring that the initial design space reflects realistic operational envelopes beyond simplified analytical models. This physics-based data informs a SIMP-based topology optimization, which is strictly constrained by Laser Powder Bed Fusion (L-PBF) manufacturing limits, such as overhang angles and thermal gradients. The resulting design achieves a significant mass reduction while maintaining airworthiness standards. By bridging conceptual design finessed through TRIZ with high-fidelity CFD analysis and additive manufacturing constraints, this framework offers a repeatable and traceable methodology for producing the next generation of lightweight, high-performance aerospace components.

Keywords: Design for Additive Manufacturing, TRIZ, Structural Mechanics

1. INTRODUCTION

In the commercial aviation sector, improving fuel efficiency and minimizing carbon emissions have emerged as dominant drivers for modern engineering design [1]. Structural lightweighting represents the most direct and effective pathway to reduce operational costs while maximizing overall aircraft performance [2]. High-lift systems, which operate during takeoff and landing phases to enhance lift forces, play a critical role in this domain by dynamically altering the wing area and camber [3]. As a vital component of these assemblies, Fowler flap mechanisms function as primary load-transmission nodes, transferring high-magnitude aerodynamic forces from the flap surfaces to the main wing structure [4]. However, because these brackets must sustain immense multi-axial loads and guarantee structural integrity under stringent airworthiness standards, conventional design and manufacturing constraints often result in monolithic, bulky, and over-engineered components [5].

Traditional iterative design processes have reached localized optimization limits when applied to complex aerospace brackets. Frequently relying on conservative safety factors and empirical "trial-and-error" approaches, conventional methods tend to accept a compromised trade-off between mass and structural integrity rather than resolving the underlying contradiction [6]. The primary motivation of this study is to eliminate this structural compromise by establishing a systematic, innovation-driven engineering framework.

To achieve this, the paper introduces a holistic methodology integrating the TRIZ, CFD, and DfAM [7]. Diverging from typical design workflows that begin with direct geometric manipulation, the proposed framework initiates with a "Functional Decomposition" phase to map energy, material, and signal flows. This abstract analysis isolates the flap bracket's primary roles, defining the core technical contradiction between structural strength and moving mass. By implementing specific TRIZ inventive principles namely segmentation and porosity the design transcends monolithic constraints, shifting toward an organically optimized architecture where material is allocated solely along primary load paths [1].

While TRIZ establishes the conceptual foundation for this organic geometry, translating it into a viable aerospace component demands highly accurate operational boundary conditions. Traditional workflows often utilize simplified analytical models or experimental constants that fail to capture localized fluid behavior. To address this, the second pillar of this framework leverages high-fidelity CFD simulations using the Shear Stress Transport (SST) k-ω turbulence model over a representative Boeing 737 wing profile [8]. Deriving precise, physics-based aerodynamic pressure distributions ensures that the subsequent design space reflects realistic flight envelopes [9].

The high-resolution aerodynamic pressure fields are seamlessly mapped into a Solid Isotropic Material with Penalization (SIMP) topology optimization algorithm [10]. Going beyond purely theoretical mass reduction, the optimization process is strictly constrained by L-PBF manufacturing limits, accounting for overhang angles and thermal gradients [11]. Finally, the optimized geometry is subjected to a virtual thermo-mechanical print simulation to evaluate residual stresses and thermal distortions, ensuring conformity with aviation airworthiness requirements [12]. Ultimately, this paper provides a traceable, repeatable framework that bridges systematic conceptual design with advanced physics-based simulation and additive manufacturing constraints for next-generation aerospace components [7].

2. STUDIES

2.1 Conceptual Design

To systematically overcome conventional engineering trade-offs, the framework initiates with an abstract functional decomposition [6]. By mapping energy, material, and signal flows within a "black box" model, the Fowler flap bracket is isolated as the critical load-transmission node responsible for converting actuator forces into directed aerodynamic

equilibrium [4]. The energy and material pathways identified during this stage are explicitly mapped into a structured flow network, which is visualized in Figure 1.

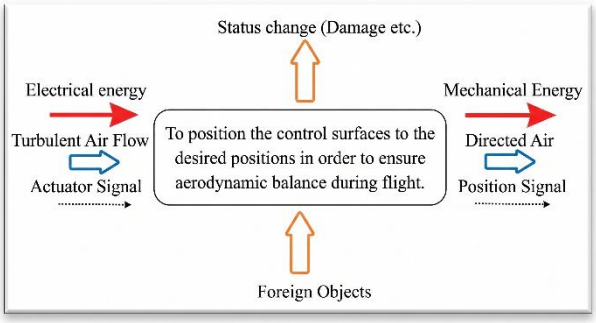


Figure 1. Black box diagram of the flap system.

This functional abstraction translates the physical bottleneck into a formal TRIZ (Theory of Inventive Problem Solving) technical contradiction [13]:

- Improving Parameter: Structural Integrity / Strength (TRIZ Parameter 14)
- Worsening Parameter: Weight of Moving Object (TRIZ Parameter 1)

Rather than accepting a compromised design, specific inventive principles were extracted from the TRIZ matrix to resolve the contradiction [13]:

- Principle 1 (Segmentation): Utilized to decouple load-bearing paths from overall geometric volume. This conceptual shift transitions the component from a monolithic block to a highly segmented architecture, justifying subsequent algorithmic material removal [1].
- Principle 40 (Composite/Advanced Materials): Applied by selecting Ti-6Al-4V titanium alloy for the dynamic bracket, ensuring high specific stiffness and excellent compatibility with Laser Powder Bed Fusion (L-PBF) processing constraints [11].

3. ANALYSIS RESULTS

3.1 CFD Analysis

To bypass the limitations of idealized mathematical load models, high-fidelity Computational Fluid Dynamics (CFD) simulations were executed within Ansys Fluent to map authentic operational aerodynamic loads [9]. The numerical analysis utilized a representative multi-element wing-flap assembly operating under critical high-lift

deployment envelopes [8]. The specific aerothermal and kinematic boundary conditions governing the flight simulation domain are structured and presented in Table 1.

Table 1. Aerodynamic simulation parameters and boundary conditions for CFD analysis.

Parameter	**Value**
Coefficient of Lift (CL)	0,2611
Coefficient of Drag (CD)	0,0201
Static Pressure	1,21 × 10^3 Pa
Dynamic Pressure	2,37 × 10^3 Pa
Total Pressure	1,52 × 10^3 Pa
Reynolds Number	5,42 × 10^5
Radial Velocity	55,6 m/s
Turbulent Kinetic Energy (TKE)	24,2 m^2/s^2

The Shear Stress Transport (SST) k−ω turbulence model was applied due to its exceptional accuracy in resolving strong adverse pressure gradients and localized flow separations typical of multi-element airfoil setups. The extracted aerodynamic behavior and fluid-structure interactions are comprehensively visualized in Figure 2.

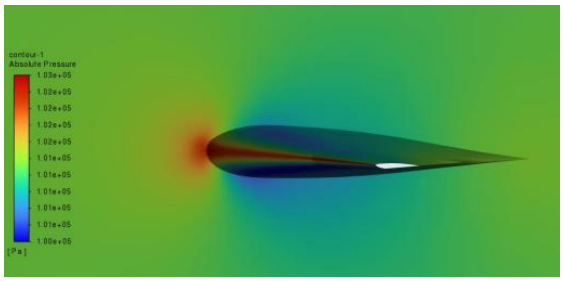


Figure 2. Result contours CFD Analysis.

Figure 2 illustrates the pressure distribution around the multi-element wing-flap configuration. A pronounced high-pressure region is observed near the leading edge of the airfoil, whereas a low-pressure zone develops along the upper surface. This pressure differential generates the aerodynamic lift force acting on the wing. Furthermore, the smooth pressure gradients observed around the flap element indicate stable flow attachment with limited separation under the investigated operating conditions. The obtained pressure field was subsequently transferred to the structural analysis stage as the aerodynamic loading condition for stress and deformation assessment.

3.2 DfAM Constrained Topology Optimization

Driven by the TRIZ conceptual framework and the exact CFD-derived pressure loads, a Solid Isotropic Material with Penalization (SIMP) topology optimization was executed

[Sun et al., 2024]. The objective was to maximize stiffness while aggressively minimizing mass for a Ti-6Al-4V titanium structure [11].

To ensure the resulting organic geometry was physically producible, DfAM constraints were directly embedded into the optimization loop [7]. Specifically, an overhang angle limit ($\leq 45°$) was enforced to eliminate the need for excessive sacrificial support structures [11]. The algorithm successfully removed non-load-bearing regions, yielding a highly segmented, load-path-optimized architecture without critical stress concentrations [1].

By embedding these manufacturing thresholds directly into the SIMP material distribution loop, the structure undergoes a mathematical mass reduction without sacrificing localized stiffness [2]. The stark geometric transformation, contrasting the primitive monolithic CAD boundaries with the final optimized biomimetic architecture, is displayed in Figure 3.

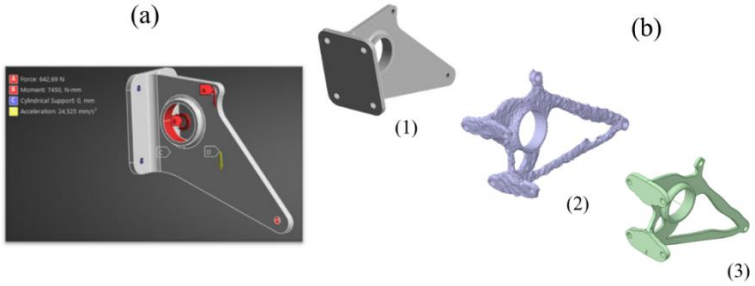


Figure 3. Constraints and steps of Topology Optimization of bracket structure.

Figure 3 illustrates the complete DfAM-driven topology optimization workflow. The initial CAD geometry shown in Figure 3a served as the design domain for the SIMP optimization process. The raw optimization output in Figure 3b reveals the primary load transfer paths identified by the algorithm, highlighting regions where material contributes most effectively to structural stiffness. Based on this topology map, a manufacturable and smooth CAD model was reconstructed, as shown in Figure 3(b3). Compared with the original design, the final geometry exhibits substantial material reduction while preserving the essential load-carrying framework required for mechanical performance.

3.3 Thermo-Mechanical Simulation of the L-PBF Process

A theoretical mass reduction is invalid if the component fails during manufacturing [7]. Therefore, the optimized Ti-6Al-4V geometry was subjected to a virtual thermo-mechanical printing simulation using Altair Inspire Print3D to validate its Laser Powder Bed Fusion (L-PBF) manufacturability [1]. The layer-by-layer simulation analyzed extreme thermal gradients and residual stresses inherent to the laser melting process [12]. The results confirmed a maximum thermal displacement (warpage) of only 23.1 µm, which is well within the stringent dimensional tolerances of aerospace manufacturing [14].

The simulated layer-by-layer residual stress accumulation, localized distortion contours peaking at 23.1 µm, and the corresponding recoater clearances are comprehensively visualized in Figure 4.

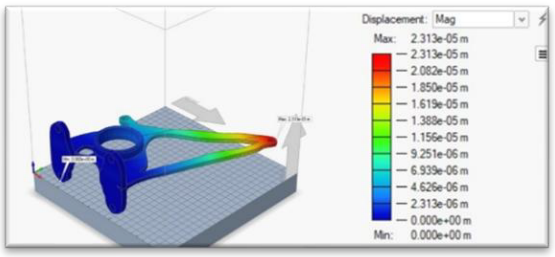


Figure 4. Thermomechanical analysis of bracket structure in Altair Insipe Print3D.

As shown in the displacement contours of Figure 4, the highest warpage values are localized near the upper regions of the structure, while the critical load-bearing hinge interfaces remain minimally affected by thermal distortion. Furthermore, the recoater interference analysis indicates that the localized thermal expansion remains below the allowable clearance limit throughout the build process. Consequently, no recoater collision is predicted during fabrication. These results confirm that the optimized bracket satisfies both the structural lightweighting objectives and the manufacturability requirements associated with the L-PBF process.

The validated geometry was subsequently considered suitable for physical production and further structural performance assessment. Therefore, the optimized design proceeded to the final performance evaluation stage.

4. CONCLUSION

This study presented and validated a comprehensive, physics-driven engineering framework that successfully resolves the fundamental technical contradiction between structural integrity and moving mass in aerospace high-lift mechanisms. By departing from traditional iterative design methodologies, the integration of functional decomposition and TRIZ principles established a conceptual foundation that breaks conventional monolithic trade-offs, guiding the design toward an optimized organic architecture.

To ensure the structural integrity of this new architecture, the dependency on simplified, conservative analytical load estimations was entirely eliminated. Instead, the framework utilized high-fidelity CFD simulations to extract localized aerodynamic pressure fields. Mapping these highly accurate, physics-based boundary conditions into a SIMP topology optimization algorithm strictly governed by DfAM constraints, such as limiting overhang angles to 45° resulted in a highly efficient, biomimetic Ti-6Al-4V flap bracket. The

algorithm successfully identified the optimal load-transmission paths, aggressively removing non-functional mass without introducing critical stress concentrations.

Crucially, the theoretical mass reduction was proven viable through rigorous virtual L-PBF manufacturing simulations. The layer-by-layer thermo-mechanical analysis confirmed that the optimized geometry is inherently printable, exhibiting a maximum thermal distortion of just 23.1 µm and ensuring completely collision-free recoater operations. Ultimately, this holistic methodology bridges the gap between conceptual innovation and manufacturing reality. It offers the aerospace industry a robust, scalable, and repeatable blueprint for developing flight-ready, next-generation lightweight components that directly contribute to advanced fuel efficiency and stringent airworthiness demands.

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