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STRUCTURAL ANALYSIS AND OPTIMIZATION OF A FLAP MECHANISM OF AIRPLANES INTEGRATED WITH FEA SIMULATIONS

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Keywords

Airplane Flap Mechanism
Design Optimization
Structural Analysis
Finite Element Method

Abstract

In this study, the flap mechanism of an aircraft was optimized by integrating its aerodynamic and structural behavior under operational conditions. First, a flow simulation was performed to obtain the pressure distribution on the flap surface and to calculate the resulting lift and drag forces. These aerodynamic loads were subsequently used as boundary conditions in a detailed finite element analysis to identify critical stress regions, deformation patterns, and load paths within the mechanism. Based on the structural response, topology optimization was applied to one of the primary components to reduce its weight while preserving the required strength and operational performance. The optimization process resulted in a substantial mass reduction of approximately 28.23% without compromising mechanical integrity. Overall, the findings of this study contribute to the development of more efficient, lightweight, and structurally reliable aircraft mechanisms.

SONLU ELEMANLAR ANALİZİ SİMÜLASYONLARIYLA ENTEGRE EDİLMİŞ UÇAKLARIN KANAT MEKANİZMASININ YAPISAL ANALİZİ VE OPTİMİZASYONU

Anahtar Kelimeler

Uçak Kanat Mekanizması
Tasarım Optimizasyonu
Yapısal Analiz
Sonlu Elemanlar Yöntemi

Öz

Bu çalışmada, bir uçağın flap mekanizması, operasyonel koşullar altındaki aerodinamik ve yapısal davranışı birlikte değerlendirilerek optimize edilmiştir. İlk olarak, flap yüzeyindeki basınç dağılımını elde etmek ve buna karşılık gelen kaldırma ve sürükleme kuvvetlerini hesaplamak için bir akış simülasyonu gerçekleştirilmiştir. Elde edilen aerodinamik yükler, mekanizma içindeki kritik gerilme bölgelerini, deformasyon şekillerini ve yük yollarını belirlemek amacıyla ayrıntılı bir sonlu eleman analizinde sınır koşulu olarak kullanılmıştır. Yapısal tepkiye bağlı olarak, mekanizmanın ana bileşenlerinden birine ağırlık azaltımı sağlamak ve gerekli dayanım seviyesini korumak amacıyla topoloji optimizasyonu uygulanmıştır. Optimizasyon süreci, mekanik bütünlükten ödün vermeden yaklaşık %28,23 oranında önemli bir kütle azaltımı sağlamıştır. Genel olarak, bu çalışma, daha verimli, hafif ve yapısal olarak güvenilir uçak mekanizmalarının geliştirilmesine önemli katkılar sunmaktadır.

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Highlights

- Optimum design of a flap mechanism of an aircraft was investigated under aerodynamic operational conditions.
  Ttopology optimization was performed on one of the key structural components to minimize its weight while maintaining the required stiffness and strength.
- The optimization results demonstrated a significant potential for weight reduction %28.23 rate.

Graphical Abstract

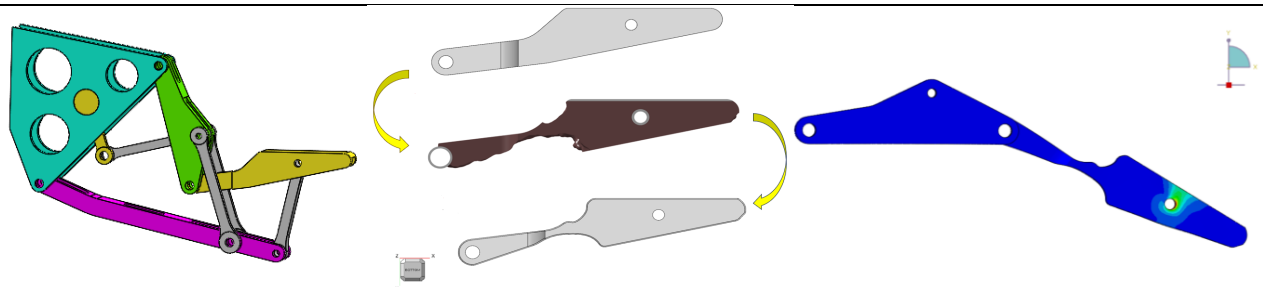


Figure. Optimum Design of Flap Mechanism

Purpose and Scope

In this study, the flap mechanism of an aircraft was analyzed to investigate its aerodynamic and structural behavior under operational conditions.

Design/methodology/approach

A flow simulation was conducted on the flap to evaluate the pressure distribution and determine the corresponding lift and drag forces acting on its surface. The obtained aerodynamic loads were then applied as boundary conditions in a detailed structural analysis of the flap mechanism to identify critical stress regions and load paths. Based on these results, topology optimization was performed on one of the key structural components to minimize its weight while maintaining the required strength.

Findings

As a result of the optimization, the part weight was reduced from 13.457 kg to 9.659 kg. Although the part volume decreased by approximately 30%, the maximum stress increased from 13.36 MPa to 19.53 MPa, corresponding to a 46% rise.

Research limitations/implications

The obtained stress level remains far below the material's yield strength of 434.37 MPa. Therefore, the optimized mechanism maintains sufficient structural integrity while achieving a lightweight design with roughly a 29% reduction in mass.

Practical implications

The findings of this study provide valuable guidance for engineers and designers seeking to reduce component weight without compromising structural safety. By demonstrating that a 29–30% reduction in part mass can be achieved while keeping the maximum stress significantly below the material's yield limit, the research confirms the feasibility of applying topology optimization techniques to real-world mechanical systems.

Social Implications

The lightweight design approach presented in this study has several potential societal and environmental benefits. Reducing the mass of mechanical components contributes directly to improved energy efficiency, lower fuel or power consumption, and decreased environmental impact, especially in transportation industry.

Originality

This paper provides a novel contribution by integrating detailed structural analysis with topology optimization to achieve significant lightweighting while maintaining safe stress levels within a mechanical mechanism.

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1. Introduction

With the accelerating pace of technological innovation, the aviation industry has witnessed profound and continuous transformation. Consequently, the deployment of aircraft for passenger transport, pilot training, commercial freight operations, disaster management, and various military missions has expanded substantially and become increasingly prevalent. The expansion of these operational domains has intensified competition among aerospace companies, making the efficient and cost-effective use of technology more critical than ever. One of the most effective strategies for enhancing aircraft performance is the reduction of unnecessary structural weight (Elham et al., 2016; Akçay and İlkılıç 2025).

Engineering-based modeling and simulation tools have become indispensable across modern industries. In particular, the aerospace and automotive sectors place growing emphasis on developing designs that not only ensure structural durability but also achieve lightweight construction and cost competitiveness (Altinel et al., 2023; Yildiz et al., 2022). In the aerospace field, maintaining an advantage in global markets requires the ability to balance strength, reliability, and production efficiency while minimizing overall system weight (Pıçak et al., 2025). The integration of advanced materials further enables the creation of components that are simultaneously lighter, stronger, and more economical. In addition, optimization methodologies have emerged as powerful tools for determining the most effective design configuration under specific constraints (Yildiz, 2021; Değirmencioğlu et al., 2023)

In the development of new engineering designs, achieving optimal attributes such as geometric dimensions, structural weight, operational lifespan, and strength limits provides a clear competitive advantage (Yildiz, 2019). Advances in modern manufacturing technologies, particularly additive and hybrid processes, now enable the fabrication of complex geometries that were previously unattainable using conventional methods. In parallel with these advances, topology optimization has become a fundamental methodology in structural design engineering (Peng, 2025). Contemporary design workflows increasingly incorporate topology optimization tools, which evaluate material-specific properties within a defined objective function to identify the most efficient material distribution that satisfies imposed constraints and targeted performance requirements (Zhu et al., 2016; Thang et al., 2024). This process produces a conceptual geometry representing the optimal load-bearing structure while significantly reducing component mass. On the other hand, optimized configuration is subsequently subjected to detailed engineering evaluation including structural refinement, finite element analysis, and manufacturability assessment to ensure its feasibility and structural reliability within the mechanical system (Zargham et al., 2024).

The increasing demand for high-efficiency, lightweight, and structurally reliable aircraft systems has accelerated research in aerodynamic modeling, structural assessment, and optimization-based design methodologies. In the development of new engineering designs, achieving optimal characteristics such as geometric accuracy, structural weight reduction, extended service life, and compliance with strength limits offers a significant competitive advantage (Yildiz et al., 2023; Aydogan et al., 2025). Advances in modern manufacturing technologies now allow for the realization of complex geometries that were previously infeasible using traditional methods. In parallel with these advancements, optimization methodologies have emerged as powerful tools for determining the most effective design configuration under specific constraints, without requiring any alteration to the intrinsic material properties (Kavala et al., 2022; Niş et al., 2024)

Among these methods, topology optimization has become a fundamental component of structural design engineering. Contemporary design workflows frequently incorporate topology-optimization tools that evaluate material-specific parameters within a defined objective function to identify the most efficient distribution of material while satisfying performance requirements and imposed constraints. As a result, these methods generate conceptual geometries that represent optimal load-bearing structures with significantly reduced mass. The resulting topology-optimized components subsequently undergo detailed engineering evaluations—including model refinement, finite element analysis (FEA), and manufacturability assessment—to verify their feasibility, structural soundness, and suitability for integration into mechanical systems.

The growing demand for high-efficiency, lightweight and structurally reliable aircraft systems has intensified research in aerodynamic modeling, structural analysis, and optimization-based design methodologies. Advances in computational fluid dynamics have made it possible to accurately predict pressure distributions, flow separations and aerodynamic loads acting on high-lift devices such as wing flaps and slats. These aerodynamic evaluations play a crucial role in the design of reliable flight control mechanisms by supplying the external loads necessary for assessing the structural behavior under realistic flight conditions. Complementing aerodynamic analysis, the finite element method has become the cornerstone of structural assessment in aerospace engineering, allowing researchers and engineers to evaluate stress concentrations, displacement patterns, fatigue-sensitive regions and internal load paths within complex assemblies. Indeed, many aerostructural optimization studies

show how coupling aerodynamic and structural analyses enables weight reductions while maintaining performance (Kenway and Martins, 2014; Kayacan et al., 2024). Topology optimization further supports this objective by optimizing the internal material distribution of components, directly contributing to lightweight, high-performance aerospace structures (Elelwi et al., 2021). Moreover, recent reviews outline that advances in topology optimization theory—especially accounting for multi-scale structures, additive manufacturing constraints, and FEM-driven sensitivity analyses—are crucial for next-generation structural design (Wu et al., 2021; Tang, 2024). Integrating FEM results into topology optimization loops has been shown to improve convergence and operational feasibility of designs under real-world boundary conditions and manufacturing constraints (Zhang et al., 2025).

In line with these advancements, the present study investigates the opening and closing mechanism of an aircraft wing flap through an integrated framework consisting of aerodynamic analysis, finite element evaluation, and topology optimization. In this paper, an integrated CFD–FEA–topology optimization framework aimed at achieving significant weight reduction in an aircraft flap mechanism under realistic aerodynamic loading while maintaining structural integrity. First, a detailed flow simulation was performed to determine the pressure distribution and to calculate lift and drag forces on the flap surface. These aerodynamic loads were then used as boundary conditions in a comprehensive finite element analysis of the flap mechanism, allowing the identification of critical stress regions, deformation behavior, and load paths. Based on the FEM results, topology optimization was applied to a key structural component to minimize mass while ensuring compliance with the operational strength requirements. The optimization process demonstrated that approximately 28–30% of the component's material volume could be safely removed. The mass of the component was reduced from 13.457 kg to 9.659 kg, while the maximum stress increased from 13.36 MPa to 19.53 MPa—a 46% rise that still remains far below the material's yield strength of 434.37 MPa. These findings verify that the optimized structure maintains adequate mechanical integrity. The obtained results reveal that considerable mass reduction—nearly 29%—can be achieved without compromising stress limits or structural safety, contributing to the development of lighter, more efficient, and more cost-effective aerospace systems.

2. Airplane Flap Mechanism Based on Four-Bar Linkage

In the airplane flap mechanism, a four-linkage mechanism consisting of 6 elements is generally used and those controls the outer flaps of this aircraft. The flaps in the deployed position for an example aircraft render are illustrated in Figure 1 displays the flap mechanism of a universal passenger airplanes.

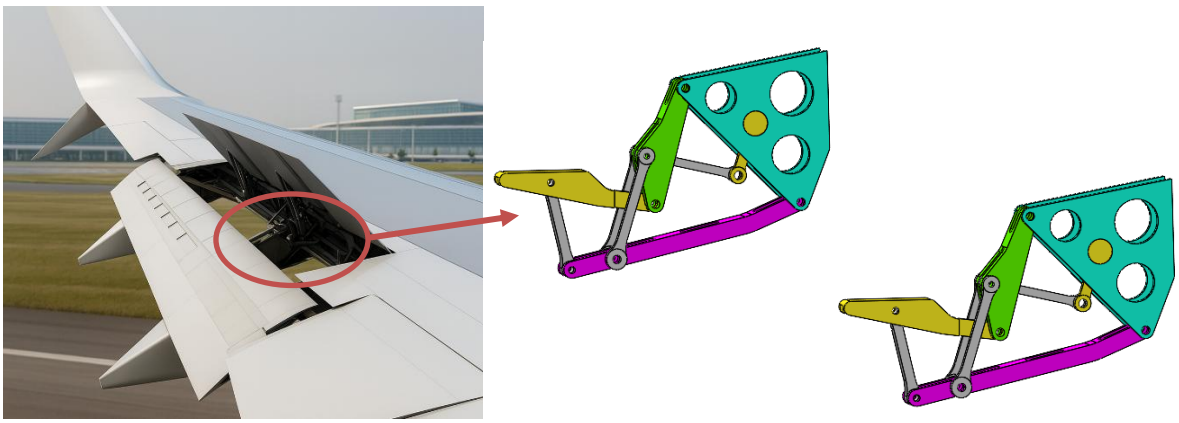


Figure 1. An example of design of flap mechanism with two four-bar linkage of an airplanes

Figure 2 illustrates the complete sequence of the wing flap mechanism as governed by the flap actuation system. The process begins with Position 1, where the flap remains fully retracted and forms a continuous aerodynamic surface with the trailing edge of the wing, thereby minimizing both drag and lift augmentation. In this configuration, the mechanism is in its neutral state. As the actuation mechanism initiates movement, the system transitions into Position 2, representing an intermediate stage in which the flap is partially extended. This phase is crucial because aerodynamic forces start to increase noticeably; lift enhancement becomes more pronounced while drag also begins to rise due to the change in camber and surface exposure. The structural components of the mechanism experience evolving load paths during this transition, reflecting the redistribution of aerodynamic forces. Finally, in Position 3, the flap reaches its fully deployed configuration, maximizing its deflection angle and surface exposure. This fully extended state provides the highest level of lift augmentation needed during low-speed phases such as landing and takeoff, when the aircraft requires enhanced aerodynamic support and increased control authority. Overall, the figure demonstrates the dynamic behavior of the flap system, highlighting the

interplay between aerodynamic performance requirements and the structural response of the deployment mechanism.

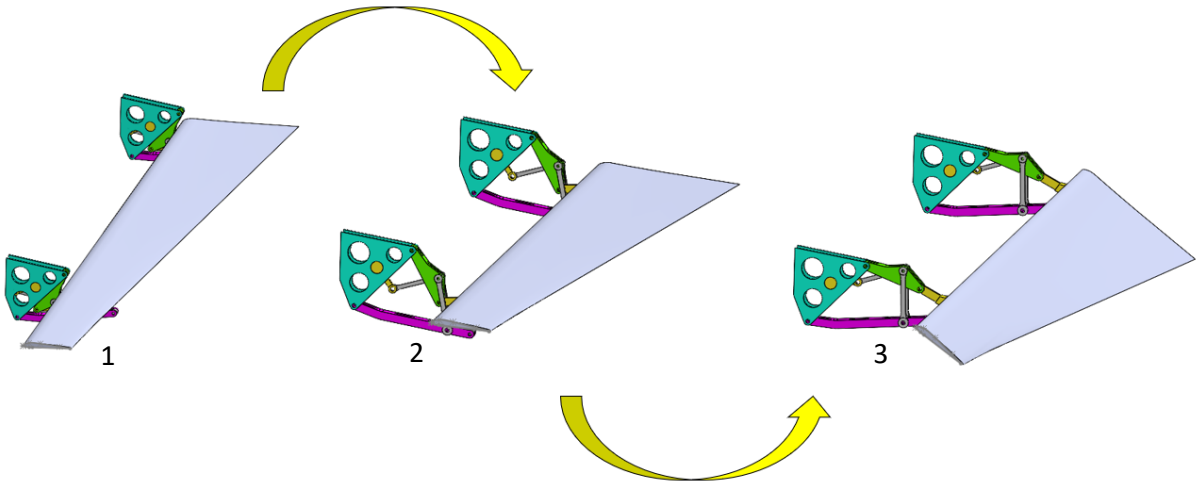


Figure 2. Flap mechanism movement

Figure 3 shows an estimated dimensions of flap mechanism of passenger aircraft. The wing profile used in the flap mechanism is the NACA23012 profile. An airflow analysis was conducted on the flap designed according to these dimensions. The pressure acting on it was calculated, and lift and drag forces were determined accordingly. The forces acting on the elements of the flap mechanism were then calculated.

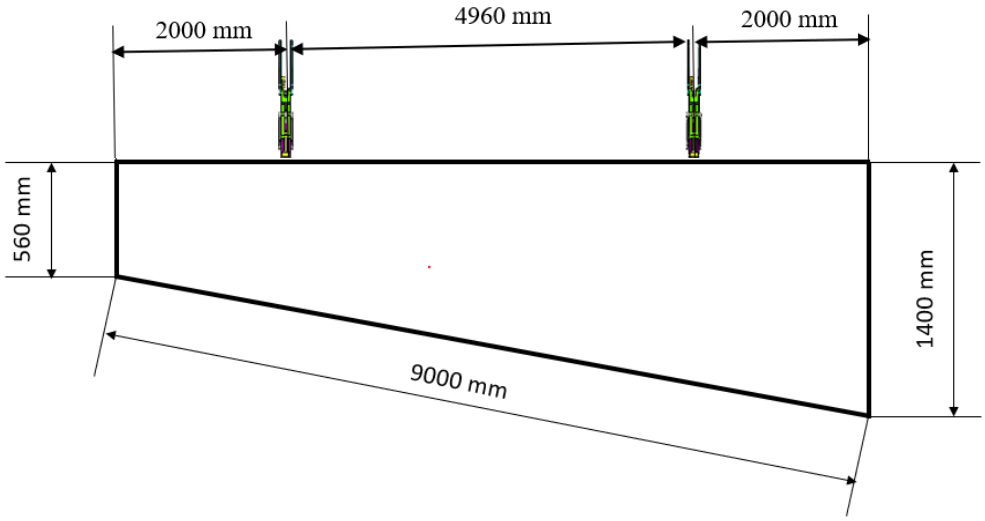


Figure 3. Estimated flap dimensions

3. Determining Forces Acting on the Flap Mechanism

The flap mechanism is simplified as shown in Figure 4. To determine the forces acting on the flap mechanism, flow analysis was conducted on the flap mechanism using CFD analysis as the flap in the fully open position (position 3). The values obtained from this analysis were used to calculate the forces acting on the mechanism components. The angle at which the maximum load is applied to the flaps occurs when the flaps are fully open at a 38° angle. Therefore, the flap angle is taken as 38° and as shown in Figure 4, the flaps have a 38° angle when fully open. This angle was achieved by making modifications to the dimensions of the mechanism components.

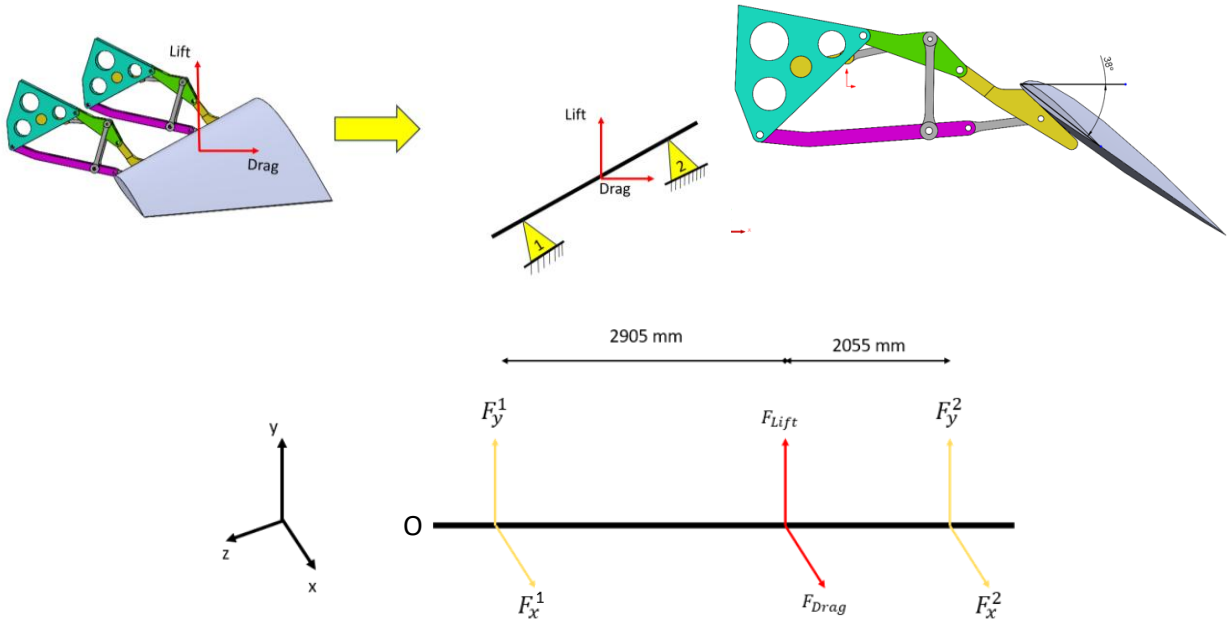


Figure 4 Representation of forces in simplified form as the flaps are fully open (38 degrees)

The related drag (F_{Drag}) and lift (F_{Lift}) force in the simulations are related Figure 4 and the Equations (1) and (2) provide these force from equilibrium relations as follows:

$$F_x^1 + F_x^2 = F_{Drag} \quad (1)$$

$$F_y^1 + F_y^2 = F_{Lift} \quad (2)$$

The terms F_x^1 and F_y^1 denote the x- and y-direction components of the aerodynamic force acting at the first load transfer point of the flap mechanism, while F_x^2 and F_y^2 represent the corresponding force components transmitted to the second linkage point. If we take moments about point O the drag and lift force in x and y direction can be found as given in Table 1 under the moment when the flaps are open at a 38° angle, the aircraft speed is assumed to be 140 knots with the air density of 1.225 kg/m^3. The obtained velocity profile and pressure distribution contours were plotted as a result of the analysis in Figures 5 and 6 respectively.

Table 1. The force of acting on flap mechanism

x-y direction	Force
F_x^1	15553.27 N
F_y^1	15390.60 N
F_x^2	21986.49 N
F_y^2	21756.54 N

The CFD simulations are performed with the created flow volume and "Tetrahedrons" elements using the "Patch Independent" algorithm were selected for the flow volume mesh, and face meshing was applied for the wing surface void. The node number and element number are selected as 189465 and 1063294. The model used for flow analysis in the Ansys Fluent environment was selected as "Viscous Model – SST – Production Limiter". The material was selected as structural steel with a Young's modulus of 210 GPa, a Poisson's ratio of 0.3, and a density of 7850 kg/m^3.

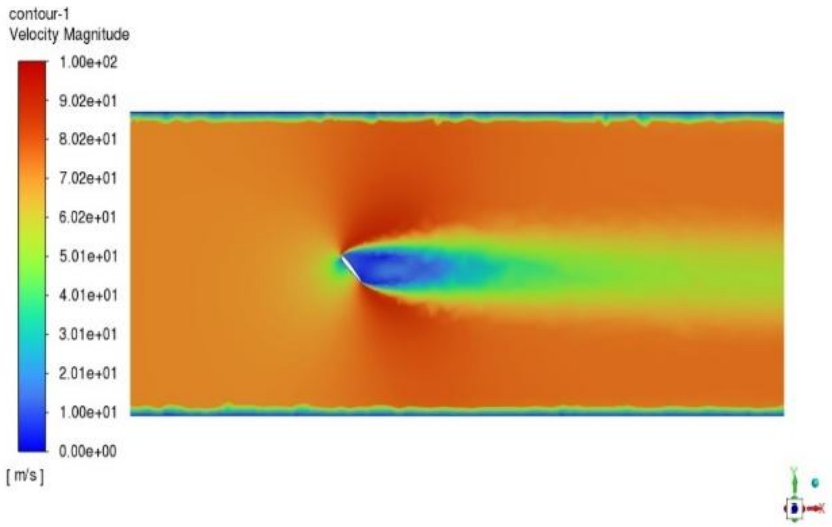


Figure 5. Velocity profile contour

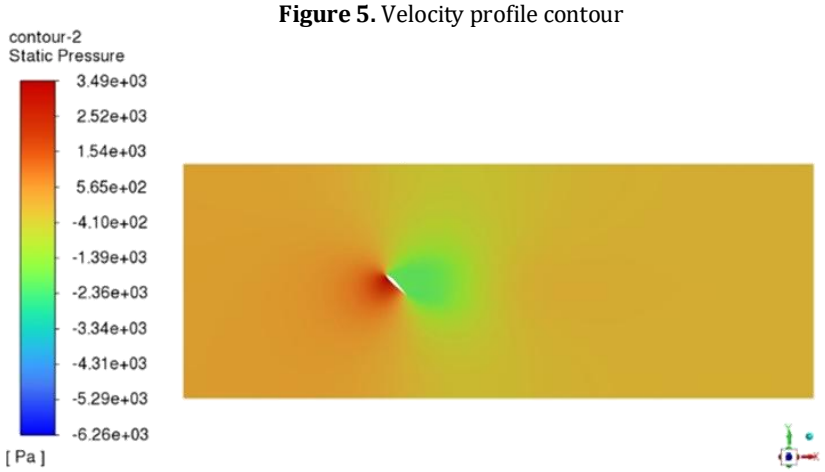


Figure 6. Pressure profile contour

As expected, the drag force has turned out to be higher than the lift force. This situation proves that when the flaps are open at a 38-degree angle, the speed of the aircraft decreases, indicating that the aircraft is in the landing phase. According to the simulations lifting force and drag force are calculated as 37147.14 N and 37539.76 N as respectively.

4. Optimum Design of Flap Carrier Mechanism

The optimum design of flap carrier mechanisms plays a critical role in enhancing the aerodynamic efficiency, structural reliability, and overall performance of modern aircraft, particularly during low-speed operations such as takeoff, approach, and landing. In the first stage of the analysis, a comprehensive flow simulation was conducted to determine the pressure distribution acting on the flap surface and to compute the corresponding lift and drag forces generated under operational conditions. The aerodynamic loads obtained from the CFD analysis were then incorporated into a detailed finite element model and applied as boundary conditions in order to identify critical stress concentrations, deformation characteristics, and principal load paths throughout the flap mechanism. Following the structural assessment, topology optimization was performed on one of the principal structural components to achieve a reduction in mass while ensuring that the required strength, stiffness, and overall operational performance of the mechanism were maintained. As indicated above, the second flap carrier bears more load; thus, in the topology analysis, this flap carrier has been examined. These members are shown in Figure 7.

Also the finite element size are shown in Figure 8 where hexahedral mesh elements were used in the structural analysis. Hexahedral mesh elements were employed in the structural analyses. The mesh discretization consisted of 119,300 elements for the upper control arm and 168,307 elements for the flap carrier.

In the simulation complete computational framework includes CFD analysis, force extraction, finite element analysis, topology optimization, redesign, and final validation.

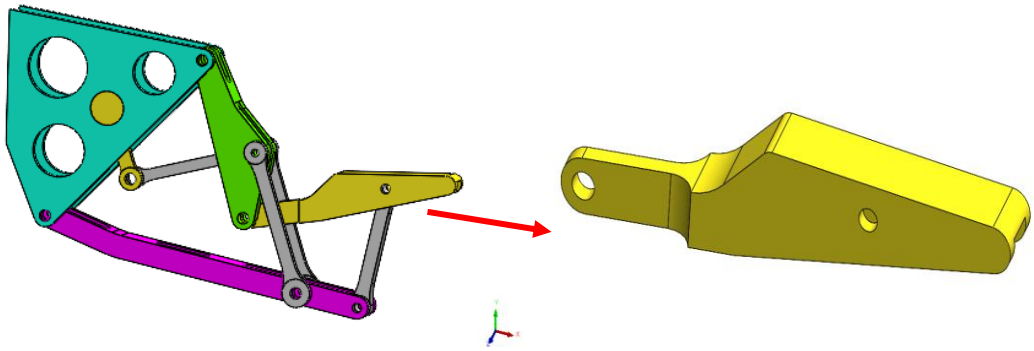
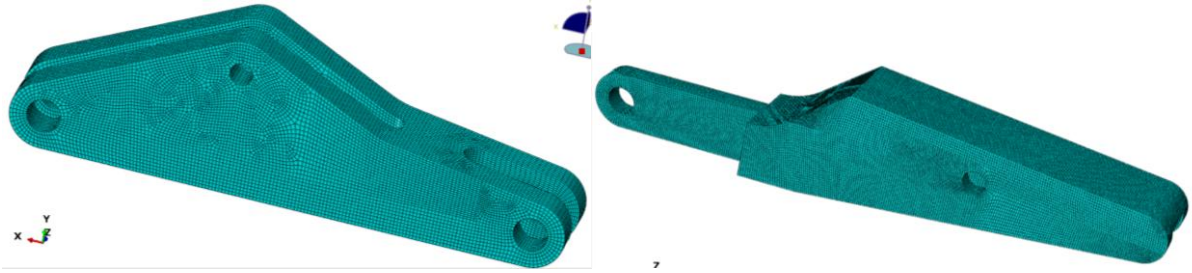


Figure 7. The flap carrier using in the flap mechanism of airplane



(a) (b)

Figure 8. Mesh structure of the upper control arm (a) and flap carrier (b) mesh structurer

The aim in this section is to find the stress values that the flap carrier is subjected to due to the forces applied by the wing. For this purpose, a structural analysis of our part along with the upper control arm was conducted.

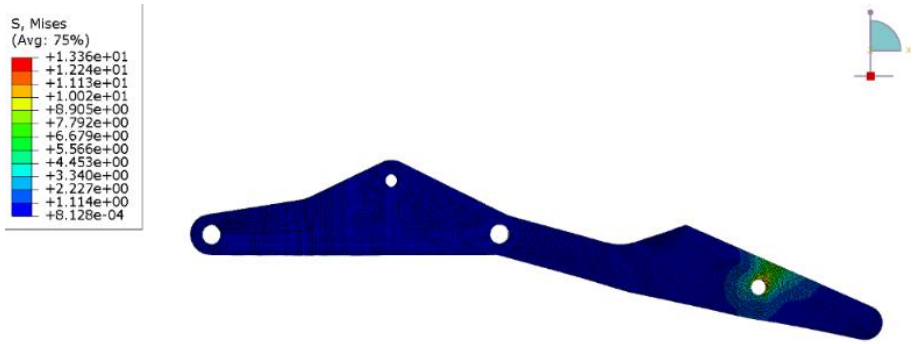


Figure 9. Stress results obtained from structural analysis

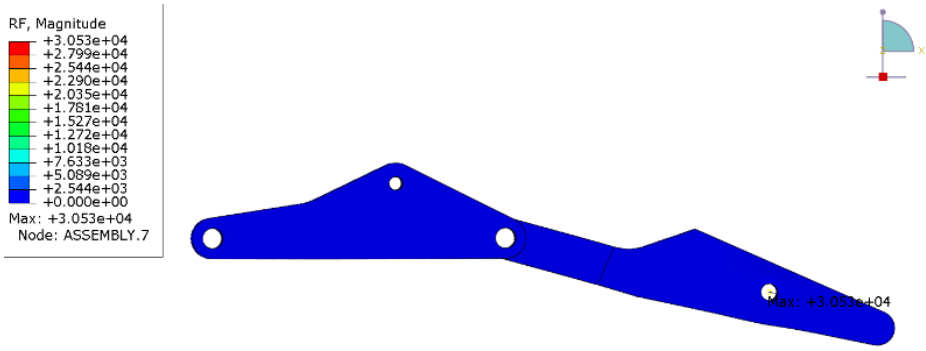


Figure 10. Reaction force results obtained from structural analysis

The value of the maximum stress according to the analysis results is 13.36 MPa as shown in Figure 9. The value of the maximum reaction force according to the analysis results is 30530 N given as in Figure 10. After these constrains, for maximum lightweight, topology analysis was performed on the flap carrier and the obtained result is given in the Figure 11. In the study, topology optimization was applied to the flap carrier component using a

density-based method (SIMP approach). The design domain was defined as the initial solid geometry of the flap carrier, excluding functional regions such as bolt holes, joint interfaces, and load application surfaces, which were preserved as non-design regions.

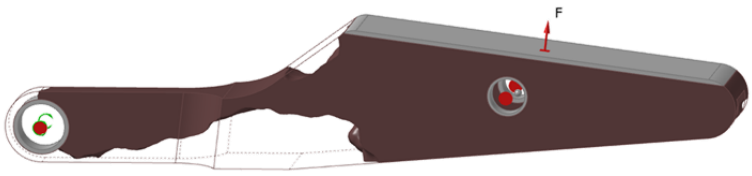


Figure 11. Appearance of the part as a result of topology optimization

The new geometry resulting from topology optimization was redesigned and this design is given in Figure 12. The revision process was designed taking into account the production method and part strength.

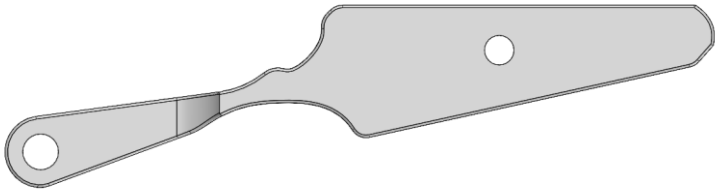


Figure 12. Revised flap carrier mechanism part

In Figure 13, the initial state of the part, its state as a result of topology and its revised state are shown in order to better understand the geometric change of the part after topology.

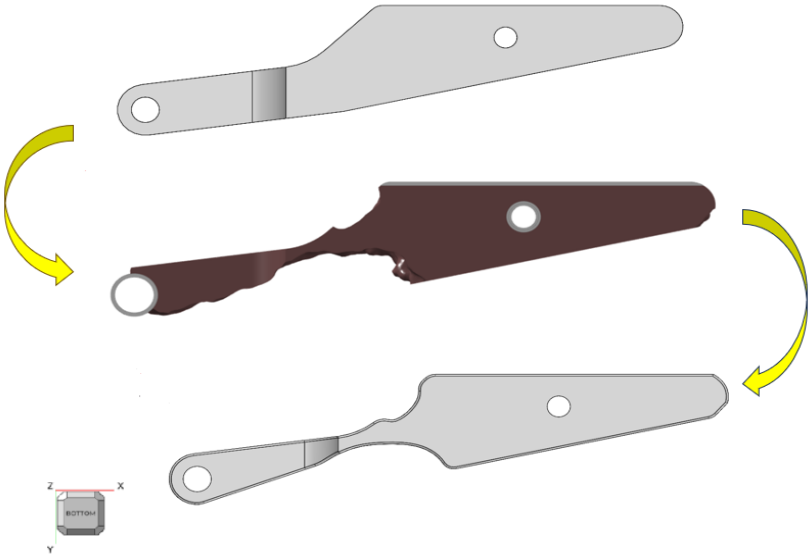


Figure 13. Initial and last version of the flap mechanism carrier part as a result of optimization

The new weight of our part after topology optimization is 9.659 kg. Static structural analysis was performed on the new geometry obtained with the program to see whether it was resistant to the applied forces. The analysis result appears in Figure 14. According to the analysis results, the maximum stress is 19.53 MPa. Since this value remains within the maximum material's yield strength of 434.37 MPa. In the optimized flap carrier, material removal was mainly concentrated in low-stress regions while preserving the primary load paths and stiffness-critical areas. As a result, the global stiffness of the structure is expected to remain largely unaffected, suggesting that the natural frequencies of the optimized component would likely shift toward higher values.

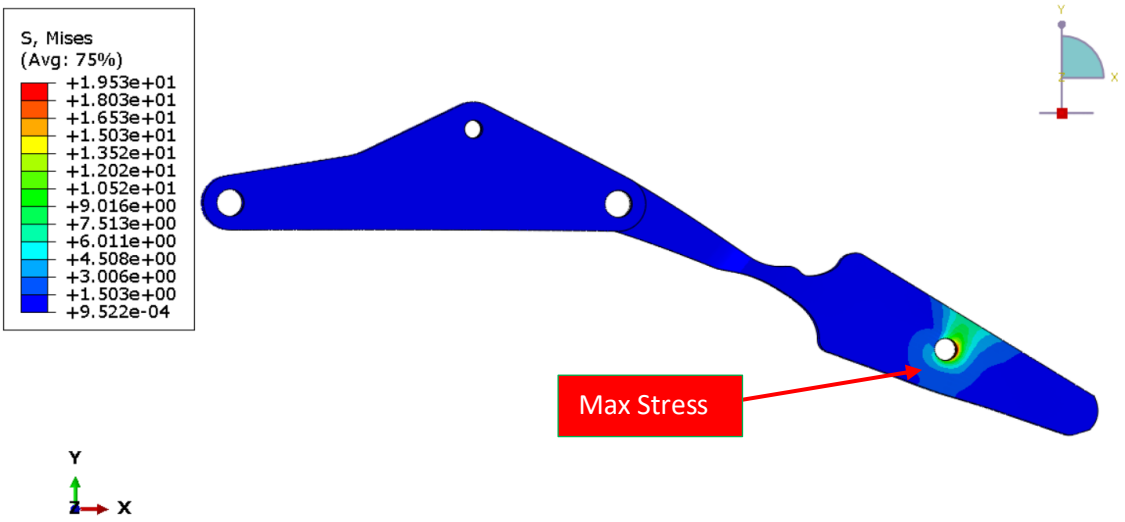


Figure 14. Structural analysis of the part after topology

5. Result and Discussion

In this study, the aerodynamic and structural behavior of an aircraft flap mechanism was integrated into an optimization framework, enabling a more efficient and lightweight structural design. By first determining the pressure distribution and corresponding aerodynamic forces through flow simulation, and subsequently applying these loads in a detailed finite element analysis, the critical stress regions and load paths within the mechanism were accurately identified. Based on this structural response, topology optimization was applied to one of the key components to minimize material usage while ensuring sufficient strength. The optimization results demonstrated a significant weight reduction, with the component mass decreasing from 13.457 kg to 9.659 kg—corresponding to a 28.23% improvement. Although the maximum stress increased from 13.36 MPa to 19.53 MPa (a 46% rise) due to the 30% reduction in component volume, the final stress level remained far below the material's yield strength of 434.37 MPa. The increase in maximum von Mises stress observed after topology optimization is a direct consequence of material removal from low-stress regions, which leads to a redistribution of internal load paths toward stiffness-critical areas. This behavior is consistent with classical structural optimization theory and has been widely reported in similar aerospace applications. Despite the 28.23% reduction in mass, the stress level remains significantly below the material yield limit, confirming that the optimized design maintains sufficient structural safety. Similar mass–stress trade-offs have been reported in previous studies on aircraft structural components, indicating that the obtained results align well with physical expectations and existing literature. This confirms that the optimized structure maintains adequate mechanical integrity despite the substantial weight savings. Overall, the findings highlight the effectiveness of combining aerodynamic load prediction, finite element analysis, and topology optimization for the design and enhancement of aircraft mechanisms. The proposed approach provides a robust pathway toward the development of lighter, structurally sound, and more efficient aerospace components, contributing positively to performance and fuel efficiency in aviation applications. In addition, future studies may incorporate manufacturing constraints directly into the topology optimization process and explore alternative materials or hybrid manufacturing approaches to further enhance structural efficiency and practical applicability.

Conflict of Interest

No conflict of interest was declared by the authors.

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