MSc AE STR+ADO

Effect of structural/material ecodesign levers on wing design

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S2 Progress Report

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Abstract

This progress report provides an overview of our research on the impact of composite materials on the aeroelastic behavior of aircraft structures. The study explores how different materials influence modal parameters and dynamic stability, addressing a gap in existing literature that focuses primarily on mechanical properties and structural performance.

1 Introduction

In recent years, the aerospace industry has increasingly adopted composite materials due to their high strength-to-weight ratio, durability, and potential for fuel savings. While extensive research has been conducted on material selection, structural optimization, and life-cycle analysis, limited studies have focused on the aeroelastic effects of these materials. This research aims to fill that gap by analyzing how composites affect an aircraft's modal parameters and overall dynamic behavior, maintaining functionality and economic viability. The key approach involves geometrical optimization and material selection, with constraints such as yield stress, buckling, and aircraft range.

2 Goal of the Project

The main objective of this project is to analyze the aeroelastic behavior of composite materials in aircraft structures, focusing on how different composite configurations affect modal parameters such as natural frequencies, mode shapes, and damping ratios. Additionally, the project aims to work with the OpenAeroStruct (OAS) tool for optimization tasks (an example can be appreciated in Figure 1), coupled with the Aviary design tool. A key goal is to select materials that can efficiently replace conventional ones, thereby reducing the aircraft's carbon footprint. Furthermore, the project will compare the findings with traditional aerospace materials, such as aluminum and carbon-fiber-based composites, to evaluate their performance and potential for sustainable alternatives.

3 Project Issues

Despite the benefits of composite materials, several challenges must be addressed. One of the main challenges is the complex interaction between structural stiffness, aerodynamics, and mass distribution, which can affect the overall performance of the aircraft. Additionally, there is a lack of extensive experimental data on the aeroelastic effects of novel composites, making it difficult to fully understand their behavior in real-world applications. The need for high-fidelity finite element models to predict modal behavior accurately is another significant challenge, as these models are essential for ensuring the structural integrity of composite materials in flight. Finally, material selection must be carefully considered to ensure that it not only reduces the carbon footprint but also does not compromise the performance, scalability, or life-cycle efficiency of the aircraft.

4 Main Bibliography and State of the Art

4.1 Materials

The aerospace industry is increasingly reliant on composite materials such as Carbon Fiber Reinforced Polymers (CFRPs) due to their high strength-to-weight ratio. However, end-of-life disposal and recycling remain critical challenges. Recent research has focused on optimizing CFRP recycling methods, exploring alternative eco-friendly composites, and investigating their structural performance, particularly in aeroelastic applications.

CFRPs are widely used in aerospace for weight reduction, yet their recycling remains problematic due to the heterogeneous nature of the material. According to [1], existing recycling techniques include mechanical grinding (which results in low-quality recyclates), thermal pyrolysis (which degrades fiber properties), and chemical processes (which offer high-quality output but are costly). Despite industry initiatives such as the Aircraft Fleet Recycling Association (AFRA) and the Airbus PAMELA project, economic and regulatory barriers continue to hinder large-scale adoption of CFRP recycling.

Given the limitations of CFRP recycling, researchers have explored Natural Fiber Composites (NFCs) as a sustainable alternative. Studies have assessed materials such as ramie, hemp, flax, and sisal combined with epoxy and PLA matrices. Findings from [2] indicate that Ramie composites provide the highest weight reduction, with Epoxy/Ramie being 14% lighter than aluminum and PLA/Ramie achieving a 12% reduction. However, other NFCs, such as hemp and flax, have been found to increase wing mass. These materials also present challenges in aeroelastic performance due to lower stiffness, potentially increasing flutter risks in aircraft structures.

A comparative study ([3]) on composite performance for aerospace applications found that CFRP with an epoxy matrix remains the best-performing material, reducing weight by 4% for a 1000 nm mission. Phenol-CF composites performed similarly and present a more sustainable alternative, but natural fiber composites such as Phenol-NF and PLA-NF led to increased wingbox weight and higher fuel consumption. Additionally, buckling issues were observed in the use of Phenol-CF, indicating structural limitations in load-bearing applications.

Further research [4] on sandwich composites with lightweight cores investigated buckling and vibration responses in structures with sisal fabric/epoxy skins and syntactic foam cores. The study revealed that composites with treated cenospheres exhibited a 14.61% weight reduction and improved stiffness. Increasing filler loading was found to enhance buckling loads and natural frequencies, although frequencies decreased under axial compression.

The Eco-Compass project ([5]) has focused on developing bio-based and recycled composite materials for secondary structures and aircraft interiors. The approach includes hybridizing recycled carbon fibers with bio-fibers in non-woven fabrics. These materials present promising environmental benefits while maintaining adequate mechanical performance.

Recent research ([6]) into Ultra-Light Carbon-Based Composites (ULCCs) suggests they could offer superior stiffness and lower density compared to conventional T300/Epoxy and T1000/Epoxy composites. Finite Element Analysis (FEA) has validated ULCC's mechanical superiority, highlighting potential benefits such as reduced aircraft weight, lower fuel consumption, and improved structural efficiency.

4.2 MDO

The paper [7] presents a compelling hybrid approach that integrates machine learning and evolutionary algorithms to optimize material selection and structural design for eco-friendly structures. By leveraging variational autoencoders (VAE) and mixed-variable solvers, the method enhances efficiency while balancing sustainability and performance. A key strength is its ability to incorporate environmental factors (CO2 emissions and energy consumption), alongside mechanical properties..

The aeroelastic design process for Multidisciplinary Design Optimization (MDO), as presented in [8], integrates loads analysis, structural optimization, and aeroelastic stability in an iterative loop. It starts with conceptual loads, mass models, and preliminary sizing, followed by parametric simulation setup (ModGen). Loads analysis (MSC Nastran) evaluates external forces, which feed into structural optimization to refine mass and stiffness. The process iterates until convergence, ensuring an optimal balance between weight, strength, and aeroelastic performance. Finally, post-analyses (e.g., flutter analysis) validate the design's stability and robustness.

The paper [9] tries to optimize High-aspect-ratio airframes, which offer significant aerodynamic benefits by reducing induced drag and improving efficiency. These advantages are further enhanced by incorporating composite materials, which contribute to weight reduction. However, the increased structural flexibility of such designs introduces challenges, including geometric nonlinearities and aeroelastic couplings. In the design and optimization process, low-fidelity models provide quick evaluations but lack accuracy, while high-fidelity models are precise but computationally expensive.

The work presented in [10] introduces AEco, a tool designed to integrate environmental considerations into the early phases of aircraft MDO. AEco applies streamlined Life Cycle Assessment (LCA) combined with Uncertainty Analysis via Monte Carlo Simulation to assess environmental impacts of different aircraft configurations. Unlike traditional MDO approaches that focus first on structural and aerodynamic performance, AEco considers CO2 emissions and resource depletion in the decision-making process. Additionally, sensitivity analysis using the Contribution to Variance (CTV) method highlights key design parameters influencing environmental impact.

The findings discussed in ([11]) present an aircraft design optimization framework focused on minimizing environmental impacts, specifically CO_2 emissions (fuel burn) and landing-takeoff (LTO) NO_x emissions. The study employs Multidisciplinary Design Optimization (MDO) to simultaneously optimize airframe, engine, and mission parameters.

For single-objective optimization, an Augmented Lagrangian Particle Swarm Optimizer (ALPSO) is used, effectively handling constraints without requiring gradient information. For multi-objective optimization, a Genetic Algorithm (GA) is applied to explore trade-offs between conflicting objectives, such as fuel efficiency vs. direct operating cost (DOC). The results show that aircraft optimized for fuel burn feature high-aspect-ratio wings and high-bypass-ratio engines, while minimum NO_x designs utilize low-thrust, low-pressure-ratio engines, significantly reducing emissions but increasing fuel burn. The framework also investigates large aircraft for short-range (LASR) routes, demonstrating potential reductions in fuel consumption per passenger-mile. Overall, the study highlights non-gradient-based optimizers as effective tools for handling the complex, multi-disciplinary nature of aircraft environmental design.

The OAD optimization process in ([12]) extends traditional single-mission design by integrating multi-disciplinary analysis (MDA) within an eXtended Design Structure Matrix (XDSM) framework. Optimizing wing area (Swing) and reference thrust (Tref) for fuel economy across multiple mission ranges, it employs linear scalarization weighting from real flight data. Six performance constraints guide the design, while a hybrid mission analysis model—combining high-fidelity simulation (HFS) for dynamic phases and the Bréguet range equation (BRE) for cruise—ensures both accuracy and efficiency.

4.3 OpenAeroStruct

When modifying the structural characteristics of the wing, it is essential to consider aerodynamic-structural coupling, as these changes directly influence the aircraft's aerodynamic behavior. As part of this project, OpenAeroStruct was selected as the primary computational tool for aerodynamic and structural optimization. Over the past few weeks, we have studied its documentation, analyzed example cases, and conducted trial runs to familiarize ourselves with its capabilities. Additionally, we engaged in discussions with PhD candidate Ousmane Sy to gain deeper insights into the software's application.

To apply OpenAeroStruct in a practical scenario, we were tasked with adapting an existing optimization example based on the Bombardier Q400 to the Airbus A321-200 and A320-200. This required searching the necessary aircraft parameters, making estimations where data was unavailable, and using the Vortex Lattice Method (VLM) mesh code for accurate wing mesh generation. The wing configuration was inspired in the CERAS model, from [13]. These modifications enabled us to conduct a complete aerodynamic and structural optimization.

Material	A320		A321		Units
	Fuel Burn	Wingbox Mass	Fuel Burn	Wingbox Mass	
Al	11,233.45	4,316.62	11,984.69	5,299.17	kg
CFRP	10,358.77	1,649.44	11,345.22	1,683.10	kg
Ti	10,932.21	3,604.41	11,933.59	4,383.65	kg
Steel	13,873.20	11,571.71	15,531.61	16,218.50	kg

Table 1: Results of the Optimization for A320 and A321

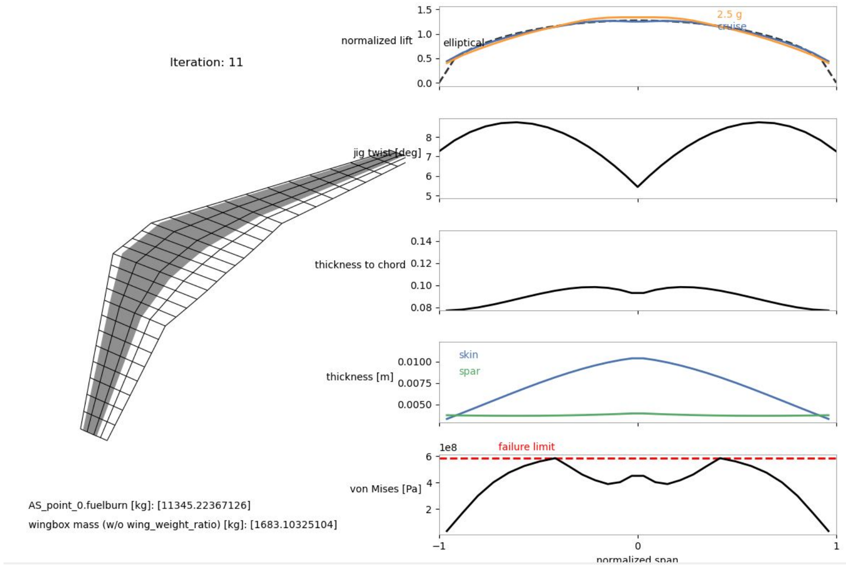

Figure 1: Example optimization with OpenAerostruct

Our initial optimization focused on minimizing fuel burn while estimating the wingbox mass, with Aluminum 7075 selected as the material. Moving forward, we refined the model and extended the analysis to alternative materials, including Titanium, Steel, and CFRP, to assess their impact on aircraft performance and structural efficiency.

5 Milestones of the Project

The Gannt diagram describing the task schedule is as follows:

Figure 2: Gantt diagram describing the task schedule

6 Research Tasks

So far, this research has focused on two main tasks: conducting an in-depth literature review on composite materials, aeroelasticity, and multi-objective optimization, and gaining proficiency in OpenAeroStruct (OAS) for aeroelastic analysis. This initial phase allowed for a conceptual understanding of the challenges associated with wing weight reduction and sustainable material selection. Additionally, initial simulations using OAS on existing aircraft have been performed to better understand the optimization framework, including variable definition, constraints, and result interpretation.

Moving forward, the next phase will focus on incorporating multi-objective optimization, balancing trade-offs between cost, range, and CO2 footprint. This will involve analyzing fuel burn and wingbox weight minimization across different materials, introducing material selection as an optimization variable, and developing a CO2 emissions estimation model. Parallel to this, we will be interested in integrating OAS with the Aviary aircraft design tool to simulate different composite configurations and evaluate their impact on performance.

Further discussions with our supervisor have also led to new research ideas. One of them is investigating the role of Sustainable Aviation Fuel (SAF) within the optimization framework, as a decarbonization strategy. Another one is exploring the use of Variational Autoencoders (VAE) to enable continuous gradient-based optimization in structural analysis, potentially improving the efficiency of the design space exploration. The final stage of the project will focus on analyzing and interpreting simulation results to assess how different material choices influence aircraft performance and environmental impact.

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