SHAPING SUSTAINABLE AVIATION WITH CFD-BASED DESIGN OPTIMIZATION

Joaquim R. R. A. Martins, M. A. Saja Abdul-Kaiyoom, Eytan J. Adler, Alasdair C. Gray, Hannah Hajdik, Eirikur Jonsson, Andrew H. R. Lamkin, Bernardo Pacini, and Anil Yildirim

Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI

Abstract

Air transportation's quest for sustainability requires groundbreaking advancements in aircraft design, particularly in the optimization of aircraft configurations, including aerodynamic shape, structural sizing, and propulsive performance. The latest developments in computational fluid dynamics (CFD)-based design optimization address the critical challenges and demonstrate innovative solutions to shape aircraft components for enhanced efficiency and reduced emissions. We explore the integration of CFD with structural mechanics to optimize wing aerodynamics, enhancing lift-to-drag ratios and reducing structural weight. The discussion extends to the aerodynamic optimization of propellers, turbofans, and thermal management systems, highlighting how CFD facilitates the design of propulsion systems that integrate optimally with the airframe. By employing multidisciplinary design optimization (MDO) approaches, we have advanced the design of these key aircraft components, considering complex interactions and design constraints. We use adjoint methods for efficient gradient computation, which is essential for handling the large number of shape and sizing variables required in aircraft design. We present case studies demonstrating the successful application of these methods in optimizing aircraft wings and full configurations, along with innovative designs of propellers and turbofans, demonstrating the role of CFD in driving the future of sustainable air transportation.

Keywords: Sustainable aviation, multidisciplinary design optimization, aerodynamics, aerostructural, aeropropulsive

1. Introduction

The interest in sustainable aviation has grown significantly in the last few years, with increased calls for achieving net-zero carbon emissions [1, 2]. Several new technologies and improvements to current technologies have been proposed. Realizing the potential of these technologies requires advanced design methodologies. Traditional aircraft design methods rely extensively on historical data and correlations from conventional technologies. This approach was effective for past designs but falls short when it comes to integrating novel technologies. Thus, we require physics-based models that accurately simulate the relevant physics for the technology being considered. Furthermore, it is crucial to consider the interactions with the other aircraft disciplines and components to capture the system-level effects.

An all-new aircraft design can be divided into two phases: (1) a design exploration phase where various options for technologies and configurations are considered and (2) a design refinement phase where the given technology or configuration is fine-tuned for optimal performance. Both of these phases require repeated evaluations of different design iterations. Manually conducting these iterations is time-consuming. Numerical optimization can automate the design cycle, significantly accelerating the design exploration and fine-tuning processes.

Multidisciplinary design optimization (MDO) is a powerful approach that addresses both the need to consider system interactions and design automation through numerical optimization [3, 4, Ch. 13]. Considering system interactions ensures that new technologies are integrated into the overall aircraft design. This is important because technologies that seem advantageous might be undesirable once the overall aircraft performance is considered. The design automation that MDO provides accelerates both the design exploration and design refinement phases, enabling designers to consider more options. Furthermore, MDO finds the optimal design trades for a given technology, enabling a fair comparison between different technologies.

Aerodynamics is one of the most critical disciplines in aircraft design, dictating the performance and efficiency of the entire system. To accurately evaluate lift and drag forces, computational fluid dynamics (CFD) is essential, especially at transonic speeds where the flow becomes compressible. CFD plays an even more significant role when designing aerodynamic shapes because only CFD can accurately capture the large effect that small changes in shape have on aerodynamic performance. However, CFD simulations are computationally expensive, and thus, manual design iterations with CFD are especially time-consuming. CFD-based optimization can alleviate this effort. Aerodynamic shape optimization with CFD has made great strides towards practical applications in the last decade, thanks to the integration with gradient-based optimization, efficient gradient computation with adjoint methods, and effective geometry and mesh manipulation [5]. Aerodynamics alone is not enough; hence, there is a need to consider other disciplines and their mutual interactions in MDO.

In this paper, we review our use of CFD in MDO in support of sustainable aircraft design. The review focuses on our own efforts and is not intended to be a broader review of the field, such as those of Afonso et al. [6] and Bravo-Mosquera et al. [7]. We start with an overview of the methodology focusing on MPhys, an open-source framework for MDO that integrates CFD with other aircraft design disciplines. Then, we describe several applications of this framework to sustainable aviation applications, including high aspect ratio wings, aeropropulsive integration, thermal management, and unconventional aircraft configurations. We also discuss emerging technologies and methods before ending with concluding remarks.

2. CFD-Based Methodology

In this section, we describe our approach to integrating CFD in MDO. We first describe the CFD-based aerodynamic shape optimization approach, then explain how it is coupled to other disciplines. The overall approach hinges on a coupled-adjoint approach for efficiently computing design sensitivities (derivatives) of the whole system. The combination of this efficient derivative computation and gradient-based optimization is the only way to enable design optimization involving expensive simulations and hundreds or thousands of design variables, as illustrated in Fig. 1 [4, Sec. 1.4.1].

At the core of the MDO approach is MACH-Aero, an open-source framework for CFD-based aerodynamic shape optimization. MACH-Aero integrates two RANS CFD solvers with adjoint derivative computation (ADflow [8, 9] or DAFoam [10, 11]), a geometry parametrization package (pyGeo [12]), a mesh movement algorithm (IDWarp [13]), and an optimization interface (pyOptSparse [14]). MACH-Aero has been used in the design of aircraft wings [15–21], wind turbines [22–24], and hydrofoils [25–30]. With another CFD solver and its adjoint (OpenFOAM [11]), MACH-Aero has been used to design cars [10], ship hulls [31], and cooling passages [32]. More recently, DAFoam has been extended for coupled design problems such as wing design considering propeller-wing interaction [33], propeller blade aerostructural optimization [34], and unsteady airfoil optimization considering propeller parameters [11].

As previously mentioned, aerodynamic considerations are not enough in aircraft design. One of the critical components in aircraft design is the wing. In wing design, the interplay between the structure and aerodynamics is particularly significant. Martins et al. [35] pioneered the coupled-adjoint approach for derivative computation for CFD coupled to finite-element structural models and applied it to aerostructural optimization [35, 36]. Kenway et al. [37] reimplemented the aerostructural adjoint by coupling ADflow and the open-source structural finite-element solver TACS [38] in the

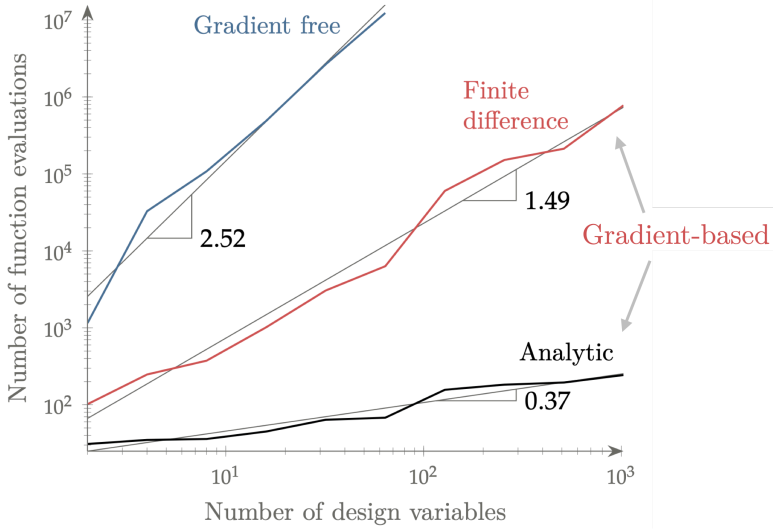

Figure 1 – Gradient-based optimization combined with implicit analytic derivative computation, such as the adjoint method, is a powerful combination enabling MDO with hundreds or thousands of design variables [4].

MACH framework. An extended design structure matrix (XDSM) [39] of MACH is shown in Fig. 2.

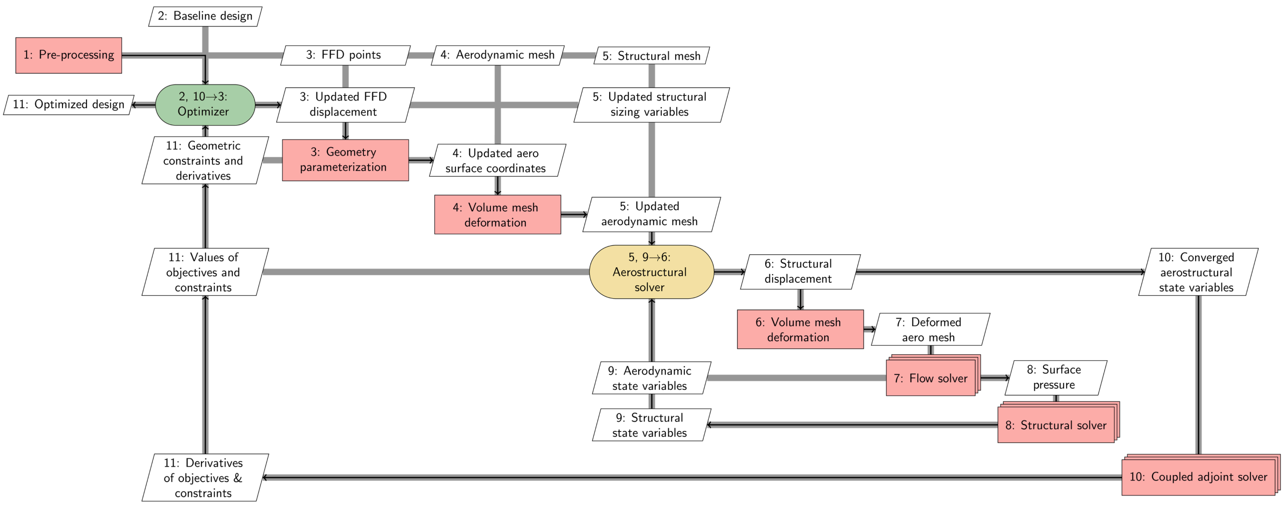

Figure 2 – Extended design structure matrix for the MACH framework. The diagonal rectangular boxes represent the different codes that are coupled, the wide gray lines represent data exchanges (above the diagonal they feed forward, and below the diagonal they feed backward), and the thin black lines with arrows show the process, which follows the number sequence in the diagram.

Based on the developed coupled-adjoint theory, Martins and Hwang [40] generalized derivative computation methods in the unified derivatives equation. Hwang and Martins [41] used this equation to develop the modular analysis and unified derivatives (MAUD) MDO architecture. The MAUD architecture was applied to perform the MDO of a satellite with tens of thousands of design variables considering orbit dynamics, thermal management, solar power, communication, and energy storage [42]. Gray et al. [43] implemented the MAUD architecture in OpenMDAO, a general-purpose, open-source framework for MDO.

Finally, the MPhys open-source multiphysics library was developed with OpenMDAO to handle simulation-based MDO [44]. MPhys is designed to be modular and extensible, standardizing and facilitating the development of coupled multiphysics models using OpenMDAO (see Fig. 3). By providing utilities for building high-fidelity simulation models and defining standard disciplinary interfaces, MPhys addresses the challenges of model coupling and analytic derivative computation.

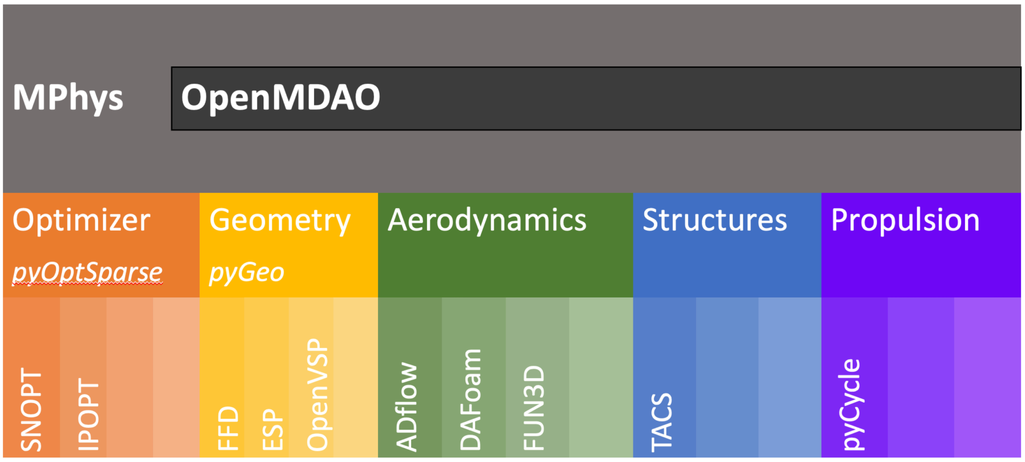

Figure 3 – The MPhys framework is built using OpenMDAO. It can couple all the disciplines relevant to aircraft design in a modular way while accommodating the demands of high-fidelity simulations such as CFD and FEM.

Like the MACH framework, MPhys can be used for aerostructural analysis and design optimization using ADflow and TACS. In the applications described in the next section, we used MACH for aerodynamics-only and aerostructural applications. MPhys was also used for these applications, as well as aeropropulsive and thermal management applications.

3. Sustainable Aviation Applications

The pursuit of sustainable aviation has driven significant advancements in various technological areas aimed at reducing aircraft's environmental impact. This section explores four key areas where we applied CFD-based MDO, contributing towards sustainable aircraft design. First, we discuss the aerostructural optimization of high-aspect-ratio wings, which offer enhanced aerodynamic efficiency and, thus, fuel burn reduction. Next, we address CFD-based aeropropulsive integration, focusing on the synergistic design of propulsion and airframe shape to optimize performance and reduce emissions. We then discuss thermal management applications, such as surface and ducted heat exchanger design optimization. Finally, we explore the design optimization of unconventional configurations.

3.1 High Aspect Ratio Wings

One way to reduce aircraft drag and, hence, fuel burn is to increase the wing span, which reduces the induced drag. However, wing structural weight increases with span. Because fuel burn decreases with lower drag and weight, the wing span must be decided based on a design trade-off. By modeling the aerodynamics and the structures and simultaneously optimizing the structural sizing (which directly affects the structural weight) and the wing shape (which directly affects the drag), aerostructural optimization can find the optimal trade that minimizes the fuel burn. Furthermore, this directly optimizes the wing jig shape while accounting for the multiple wing shapes under different flight conditions.

In the last two decades, there has been a trend towards increasing the wingspan of commercial transport aircraft, driven by the need to improve aerodynamic efficiency and reduce fuel consumption. An increase in aspect ratio directly increases the span for the same wing area (and wing loading). For example, the outgoing Boeing 777 has an aspect ratio of around 9, reflecting its design optimization for long-haul efficiency at the time of its development. In contrast, the newer Boeing 787 features a higher aspect ratio of about 11, highlighting the advancements in materials and aerostructural design that allow for more slender wings without a proportional increase in weight.

One of the pressing current questions is how much more we can increase the wing aspect ratio in the pursuit of more sustainable aircraft. We have used aerostructural optimization to optimize wing planforms for different airframe technologies to reduce the fuel burn of next-generation sustainable aircraft. The typical aerostructural optimization in the studies described here involves minimizing fuel burn at several specified cruise conditions by varying structural element thicknesses and the wing's outer mold line. The shape includes planform variables such as span and spanwise chord distribution. This optimization process is subject to various constraints, including maintaining the required lift for each flight condition, ensuring structural integrity by adhering to failure constraints during several maneuver conditions and preserving sufficient wing fuel volume. By carefully balancing these factors, we design wings with optimal spans for a given aircraft size, mission, and airframe technology.

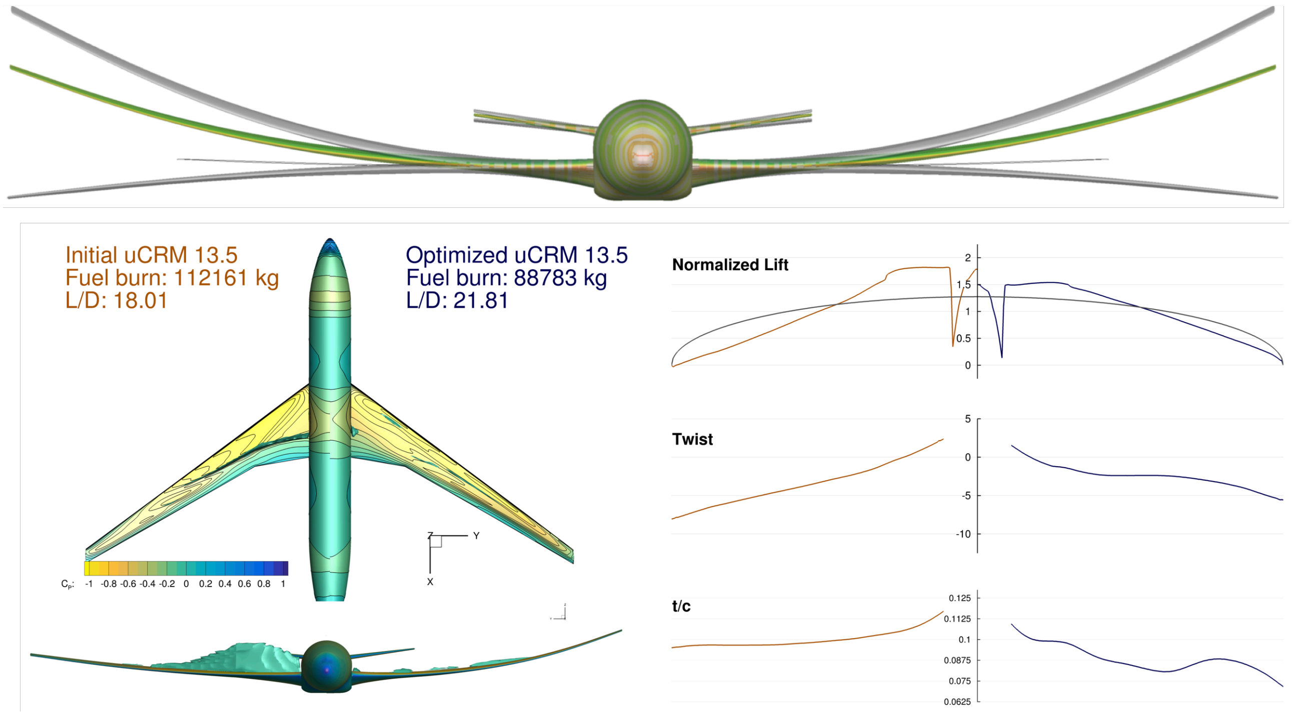

Figure 4 – The uCRM-13.5 is a high aspect ratio aerostructural benchmark based on NASA's Common Research Model [19].

Brooks et al. [19] developed the uCRM benchmark, an aerostructural version of the Common Research Model [45, 46], to demonstrate the effectiveness of aerostructural optimization and make the models available to the aircraft design community. The uCRM-9, with an aspect ratio of 9, serves as a baseline model representative of the Boeing 777 in terms of structural and aerodynamic characteristics. They also created a high-aspect-ratio version, the uCRM-13.5 (shown in Fig. 4) to explore new airframe technologies and challenge current design practices. This model, with an aspect ratio of 13.5, is designed using buffet-constrained multipoint aerostructural optimization. Gray and Martins [47] developed a simpler, wing-only benchmark model and a set of optimization problems that are currently the focus of an AIAA aeroelastic optimization working group[1]

Gray et al. [48] explored the optimization of high-aspect-ratio wings using advanced computational techniques to account for geometrically nonlinear behavior. As aircraft wings increase in aspect ratio to enhance aerodynamic efficiency, their structural flexibility introduces significant nonlinear aeroelastic effects that cannot be accurately modeled with linear methods. This study used RANS simulations coupled with geometrically nonlinear finite element analysis to optimize both the aerodynamic shape and structural sizing of a wing, as shown in Fig.6. The authors implemented these methods in the TACS finite element library, enabling a robust and efficient nonlinear solver and a constitutive model for stiffened shells. The research demonstrates the first simultaneous optimization of a wing's aerodynamic and structural properties using high-fidelity geometrically nonlinear models, showing that

[1] Up-to-date problem statements and model files can be found at `https://github.com/mdolab/AerostructuralOptBenchmark`

such effects significantly influence the trade-off between drag reduction and structural mass. This work provides critical insights into the design of next-generation transport aircraft, highlighting the necessity of incorporating geometrically nonlinear analysis to achieve accurate and practical high-aspect-ratio wing designs.

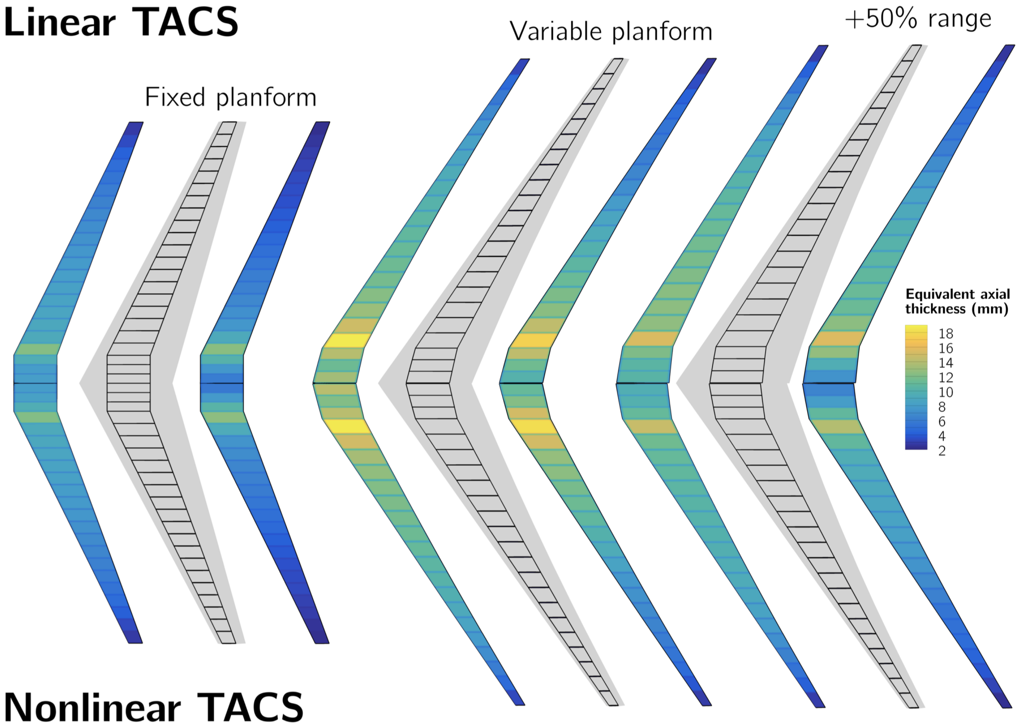

Figure 5 – Optimized wing designs for fixed planform, variable planform, and extended range scenarios. Although the planform of the wings optimized with linear and nonlinear structural models appear similar, their weight differs by up to 11%, suggesting that geometrically nonlinear effects change the trade-off between induced drag and wing weight [48].

3.1.1 Aerostructural Optimization of Tow-Steered Composite Wings

With the advent of automated fiber placement (AFP) machines, composite material fibers can be laid down in specified curved paths. This manufacturing technique enables *tow-steered composites*, which feature layers with spatially varying fiber orientations, allowing for more effective load distribution and *passive* aeroelastic tailoring. In this case, aeroelastic tailoring involves designing the wing structure and material properties to passively alleviate loads during flight, reducing stress without active control systems.

Brooks et al. [50] evaluated the potential benefits of tow-steered composites compared to conventional composites with fixed fiber orientations. The optimizations were performed on both a conventional aspect ratio wing (uCRM-9) and a high aspect ratio wing (uCRM-13.5).

The findings indicated significant improvements in performance metrics for tow-steered composite wings. For the uCRM-9, the tow-steered design resulted in a 2.4% reduction in fuel burn and a 24% reduction in wing weight compared to the optimized conventional composite design. The improvements were less pronounced for the uCRM-13.5, which had a 1.5% reduction in fuel burn and a 14% reduction in wing weight. The less pronounced improvement between tow-steered and conventional composites for the uCRM-13.5 was attributed to its increased flexibility, which results in stronger bend-twist coupling and, thus, inherent passive load alleviation. Another benefit of tow-steered composites they demonstrated was the local strength tailoring in high-stress regions, which contributed significantly to the reported weight reduction.

The tow-steered composite wing design study required specialized manufacturing constraints. To this end, Brooks and Martins [51] developed two primary constraints: tow-path curvature as well as gaps

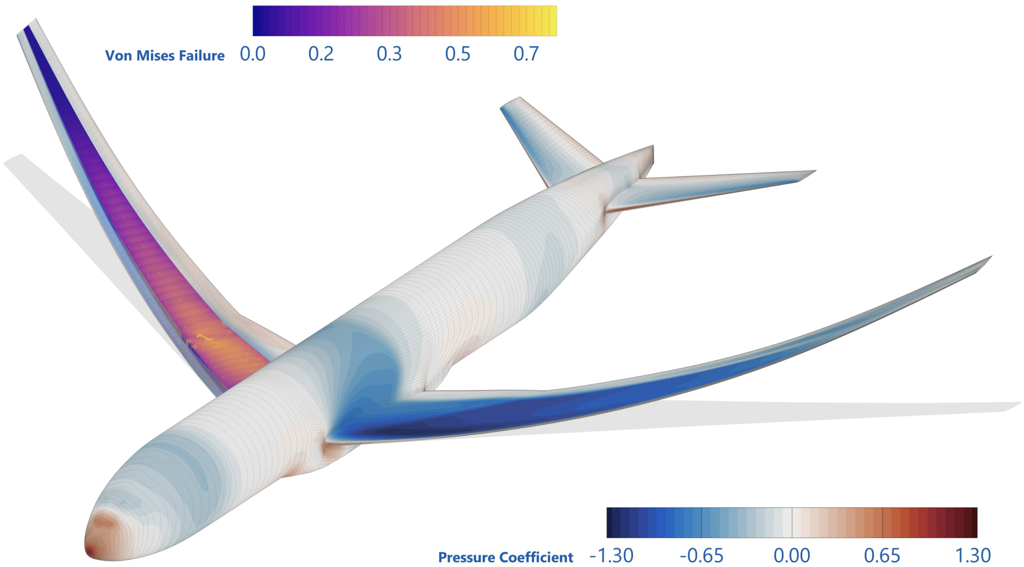

Figure 6 – The uCRM-13.5 simulated in a 3.5g pull-up maneuver at Mach 0.9. Our robust coupled aerostructural solver is key to converging these extreme cases when using potentially unstable nonlinear shell elements [49].

and overlaps. The tow path curvature constraint, defined by a minimum turning radius, ensures that the prepreg tow can be laid down without twisting or puckering. The gaps and overlaps constraint addresses the geometric limitations of laying down fixed-width tow in varying angles, which can lead to regions that are either void or overlapping. These constraints were mathematically formulated using vector field concepts, where tow paths are represented as streamlines of a 2D unit vector field. This approach allowed for the precise control of tow path curvature and the prediction of gap and overlap formation, ensuring manufacturability using current AFP machines.

Brooks et al. [21] also conducted a broader investigation consisting of a series of wing design optimization studies to explore the trade-offs between fuel burn and structural weight for different material technologies, including aluminum alloy, conventional carbon-fiber-reinforced composites, and tow-steered carbon-fiber-reinforced composites. By performing gradient-based optimization, they generated Pareto fronts that illustrate the competing objectives of minimizing fuel burn and structural weight, as shown in Fig. 7.

3.1.2 Adaptive Morphing for Higher Aspect Ratio Wings

Morphing technologies in aircraft design enable shape changes to improve aerodynamic efficiency and reduce fuel burn. This can involve various mechanisms, including control surfaces and high-lift systems, that adapt to different flight conditions. Aerodynamic and aerostructural design optimization plays a crucial role in exploring these technologies by quantifying their impacts, accounting for all relevant disciplines, and ensuring that new systems provide tangible performance benefits.

Lyu and Martins [52] studied the aerodynamic shape optimization of an adaptive morphing trailing edge wing. They found that incorporating an adaptive morphing trailing edge can reduce drag by up to 1% at on-design conditions and up to 5% at off-design conditions. This optimization resulted in a 1% cruise fuel burn reduction for a typical long-haul twin-aisle mission, demonstrating the potential of adaptive morphing technology to enhance aerodynamic efficiency and significantly reduce fuel consumption. However, this gain is not probably enough to compensate for the added cost, weight, and maintenance of the morphing mechanism.

The study by Burdette and Martins [53] investigated the potential of adaptive morphing trailing edges to enhance fuel efficiency in commercial transport aircraft using multipoint aerostructural optimization. This study used a detailed optimization model that incorporated both aerodynamic and struc-

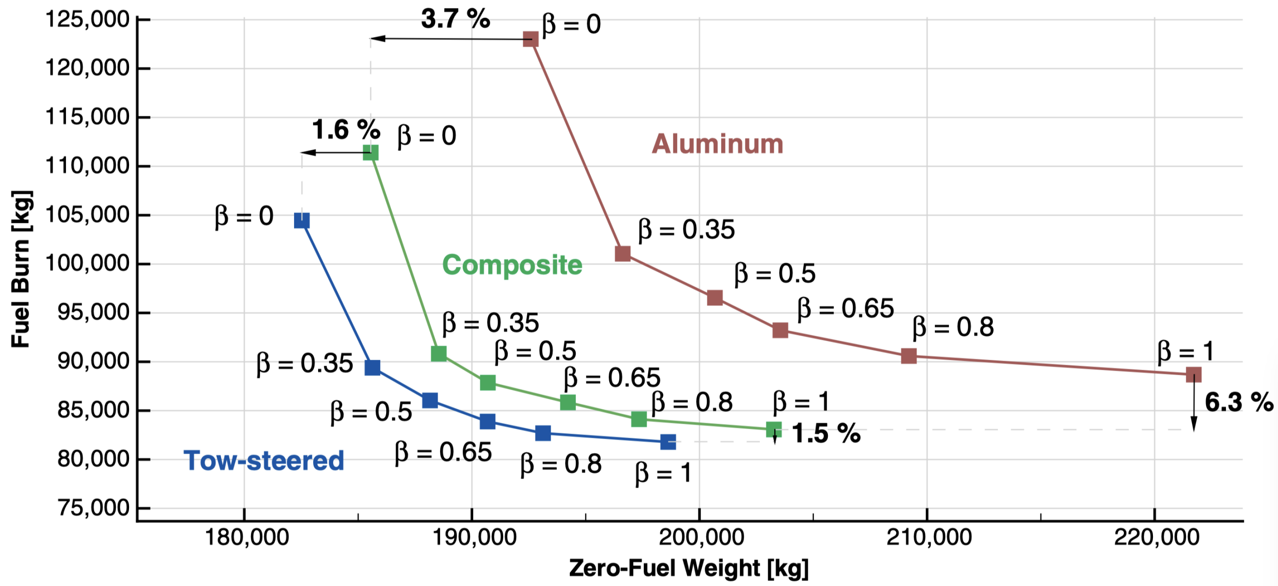

Figure 7 – Pareto front showing the trade-off between fuel burn and weight for aluminum, conventional composite, and tow-steered composite wing designs [21].

tural design variables, allowing for comprehensive multipoint optimizations across five to seven flight conditions. They optimized two baseline wing planforms (uCRM-9 and uCRM-13.5), finding that morphing was more effective for wings with higher aspect ratios. The research demonstrated that adding a morphing trailing edge device along the aft 40% of the wing could reduce cruise fuel burn by more than 5%, primarily through significant reductions in structural weight achieved via adaptive maneuver load alleviation. Additionally, the study found that a smaller morphing device along the aft 30% of the wing could achieve nearly the same fuel burn reduction. Burdette and Martins [54] expanded this previous research by giving morphing the freedom to adapt to different flight conditions throughout the aircraft mission. Through a series of aerodynamic and aerostructural optimizations, they showed that morphing trailing edges could yield a 1% reduction in fuel burn with aerodynamic optimization alone and up to 2.7% when considering structural deformations and weight reductions.

Morphing technologies have significant potential to enhance aerodynamic efficiency and reduce fuel burn in commercial aircraft, with adaptive trailing-edge camber technologies offering reductions of 3–10%. Although some morphing mechanisms may not currently “buy their way” into aircraft due to added weight, cost, and maintenance, continuous advancements in materials and design processes might make these technologies more viable over time [55]. Aerostructural optimization is crucial to realizing the full potential of morphing technologies. It considers all relevant disciplines and ensures that morphing can take advantage of aerodynamics, structures, and their coupling. More broadly, MDO should consider more disciplines, including the overall aircraft design system level.

3.1.3 Flutter and Post-flutter Constraints in Wing Design Optimization

Aerostructural optimization, including span as a design variable, can lead to flutter-critical high aspect ratio wings. Therefore, the aerostructural optimization formulation should include flutter constraints. Implementing flutter constraints is challenging due to the need to accurately capture the dynamic and potentially nonlinear aeroelastic instabilities that flexible wings experience under various flight conditions [56]. The sequence of contributions described here outlines the progress in the methodologies to address these challenges, from initial flutter constraints using simplified models to advanced higher-fidelity approaches considering geometrically nonlinear effects.

Jonsson et al. [57, 58] developed a flutter solver specifically designed for gradient-based optimization using the doublet lattice method. The flutter constraint formulation utilizes an efficient and robust non-iterative *p-k* method, an effective bounding curve, and an aggregation technique. This results in a single continuous constraint function in the optimization problem that ensures the aircraft is flutter-free over a range of flight conditions. Accurate and efficient derivatives of the constraint, including mode shape derivatives, with respect to structural sizing and geometric changes, were implemented using a combination of analytic and reverse-mode automatic differentiation. This efficient implementation allowed the flutter constraint to be included in a multipoint aerostructural optimization of the Airbus XRF1 aircraft configuration with 1200 design variables and 1200 constraints (shown in Fig. 8). Optimizing the aircraft without the flutter constraint produced an unsafe design while including the constraint produced a flutter-free design with less than a 1% increase in fuel-burn [58].

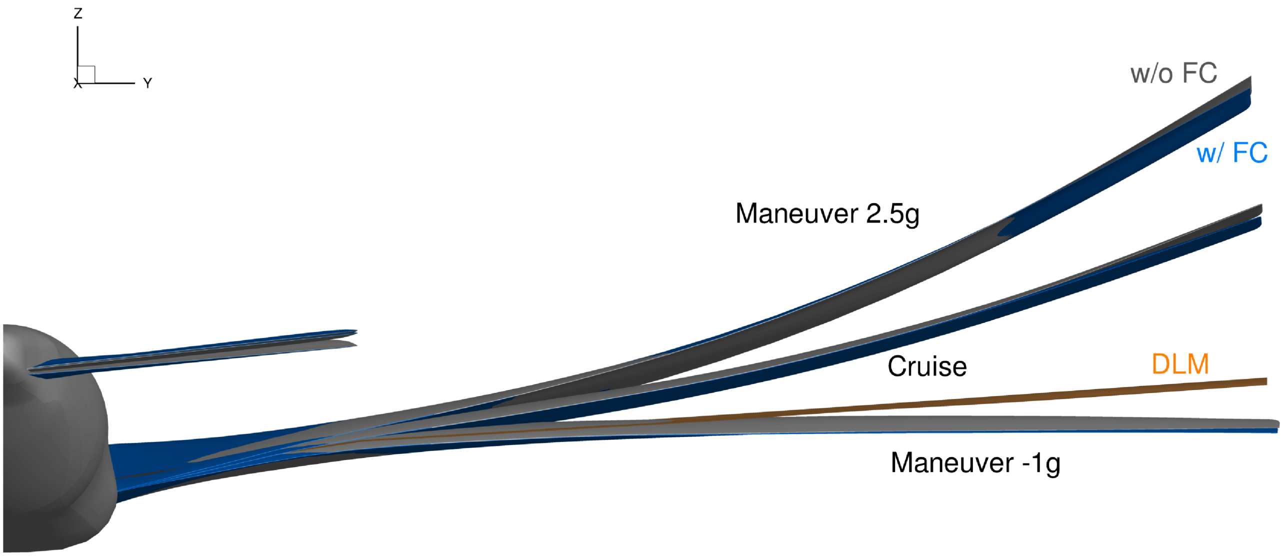

Figure 8 – Including a flutter constraint in the optimization of the XFR1 produced a slightly stiffer, flutter-free design with only a small fuel-burn penalty [58]

One of the approaches for determining flutter and post-flutter behavior is the time-spectral approach based on CFD. He et al. [59] developed a new coupled Newton–Krylov method for solving time-spectral problems. They used this solver and the time-spectral implementation in ADflow to solve the limit cycle oscillations (LCO) and flutter onset of an airfoil undergoing pitching and plunging motion. The proposed Newton–Krylov method was easier to implement and required less memory than previous methods. The results were verified against time-accurate CFD solutions and compared to other time-spectral results reported in the literature. The LCO velocities and frequencies predicted by the proposed method and the time-accurate solution were within 1% of each other. The method was shown to be more efficient than the time-accurate method in LCO response simulations. When extended to three dimensions and coupled to a full finite-element structural model, this method has the potential to be a viable way to predict LCO in the transonic regime and be integrated into aerostructural optimization as a flutter constraint.

Jonsson et al. [60] and Gray et al. [61] introduced a high-fidelity aerostructural optimization framework that integrates a geometrically nonlinear flutter constraint, which accounts for large in-flight wing deflections and their impact on the flutter boundary. The framework centers around a fully differentiated condensation process that translates a detailed built-up wing model to a low-order aeroelastic model. This allows for aerostructural optimizations where objectives and constraints such as cruise drag and maneuver stresses are computed using a detailed finite element model (FEM) coupled with RANS computational fluid dynamics (CFD) in MACH. The geometrically nonlinear flutter constraint is computed using the low-order model in UM/NAST [62]. The study demonstrated that this advanced modeling approach could accurately predict flutter onset and its impact on the optimized wing design. It showed significant differences in the optimal configurations depending on the in-flight deformation level. The conclusion emphasized the importance of incorporating geometrically nonlinear effects in flutter analysis to design the next generation of highly flexible wings with high aspect ratios.

3.2 Aeropropulsive Integration

Aeropropulsive integration in aircraft design optimization involves simultaneously considering aerodynamics and propulsion systems to achieve the most efficient overall aircraft performance. This integration is essential because it ensures that the interactions between the airframe and the propulsion system are accounted for in the analysis. When used in MDO, aeropropulsive integration takes advantage of mutually beneficial interactions. Traditional optimization approaches often treat aerodynamics and propulsion separately, leading to suboptimal designs. By considering them together, MDO can exploit synergies between the two systems, such as improved fuel efficiency and reduced emissions, making it a critical area of research for next-generation aircraft.

3.2.1 Ducted Fans and Turbofans

Gray et al. [63] developed a fully coupled aeropropulsive design optimization framework to study the impact of boundary layer ingestion (BLI) on aircraft efficiency. They used a high-fidelity RANS aerodynamic analysis (ADflow) combined with a thermodynamic cycle model of an electric fan propulsor (pyCycle [64]). The optimization aimed to minimize the shaft power required at cruise by varying the propulsor size, as well as propulsor nacelle and aft fuselage shapes, subject to inlet distortion constraints. Enforcing inlet distortion constraints increased the required propulsor shaft power by up to 1.2%, but smaller propulsors experienced lower performance degradation. This work demonstrated the importance of using fully coupled models to predict BLI performance accurately and demonstrated the effectiveness of aeropropulsive optimization in designing BLI configurations.

Yildirim et al. [65] used the developed aeropropulsive optimization framework to evaluate the benefits of BLI for NASA's STARC-ABL concept. They used a high-fidelity aeropropulsive optimization framework to study the impact of BLI on fuel efficiency and performance. By integrating a detailed aerodynamic model with a propulsion system model, they optimized the design of the aft-mounted BLI propulsor. The design variables consisted of shape variables for the propulsor nacelle, including the nacelle diameter, as well as the propulsor fan pressure ratio (FPR). The results indicated significant potential fuel savings, with optimized designs showing up to a 10% reduction in shaft power requirement. This study highlighted the effectiveness of BLI in improving aircraft efficiency and demonstrated the necessity of simultaneously considering both aerodynamic and propulsion aspects for accurate performance predictions and optimal design outcomes.

Lamkin et al. [66] improved upon previous aeropropulsive coupling methods by including a gas turbine thermodynamic cycle model using pyCycle. This led to the first gradient-based optimization of a high-bypass turbofan engine, including nacelle shape and thermodynamic cycle parameters. Their approach involved a hybrid coupling strategy implemented in the MPhys framework. The optimization successfully met both feasibility and optimality tolerances while satisfying performance, operability, and consistency constraints (see Fig. 9). The hybrid coupling scheme enables efficient solutions for complex engine flow paths across different levels of physical and geometric fidelity. Such an aeropropulsive optimization early in the design cycle enhances confidence in preliminary designs through higher fidelity analyses. These methods could be applied to new or existing propulsion architectures to reduce fuel burn, limit emissions, and improve overall performance.

Abdul-Kaiyoom et al. [67] performed a comprehensive study on the aeropropulsive integration of an over-wing nacelle (OWN) configuration using the developed framework (see Fig. 10). They emphasized the potential benefits of the OWN design, such as enabling higher bypass ratios and increasing noise shielding, which contribute to more efficient and sustainable aircraft designs. They optimized the OWN for different fan pressure ratios (FPR). When the OWN design was optimized for various FPRs, the researchers discovered that the differences in wing shape were not significant. The fan diameter increases when the FPR decreases. As a result, the required shaft power decreases when FPR decreases. The results also show that optimizing the OWN configuration can yield significant improvements in performance compared to conventional under-wing nacelle (UWN) configurations. They optimized the OWN and UWN designs, where the OWN is optimized for a low FPR of 1.40 (OWN-1.4) and the UWN is optimized for a low FPR of 1.40 (UWN-1.4), and for a current typical

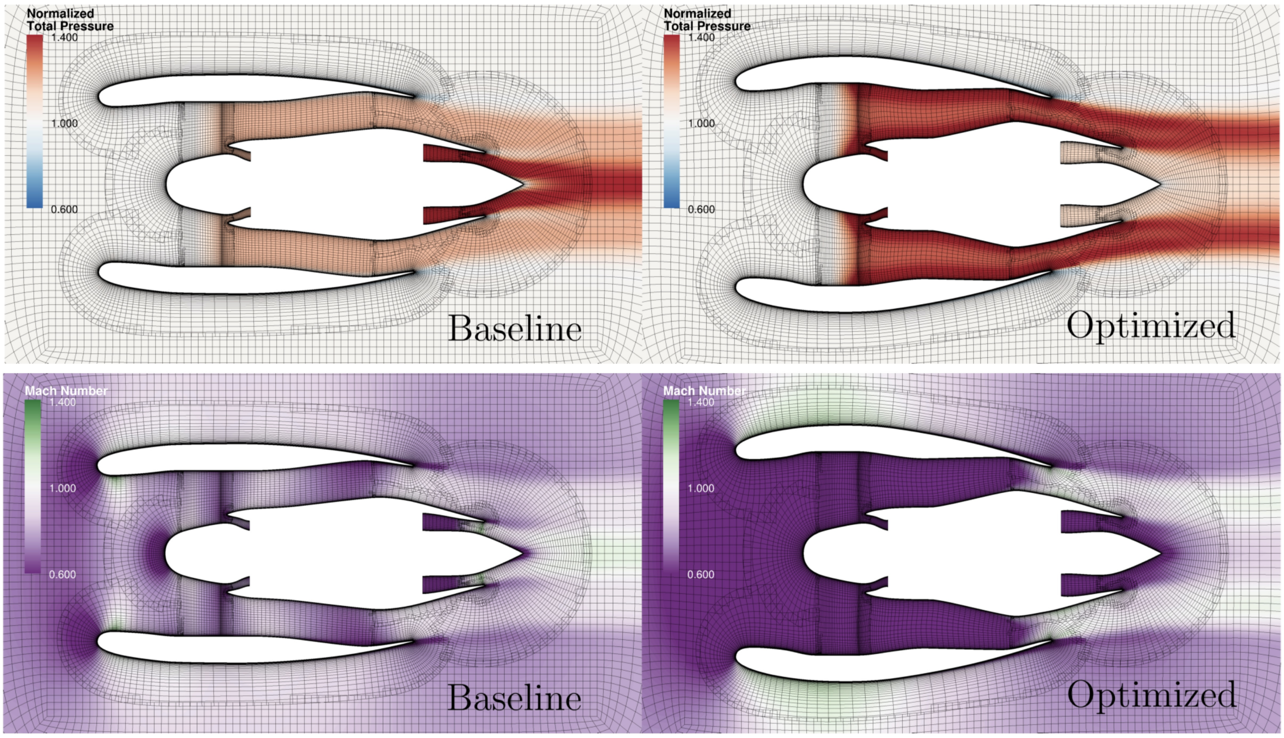

Figure 9 – Normalized pressure (top) and Mach (bottom) contours on the turbofan engine symmetry plane for the baseline and optimized designs [66].

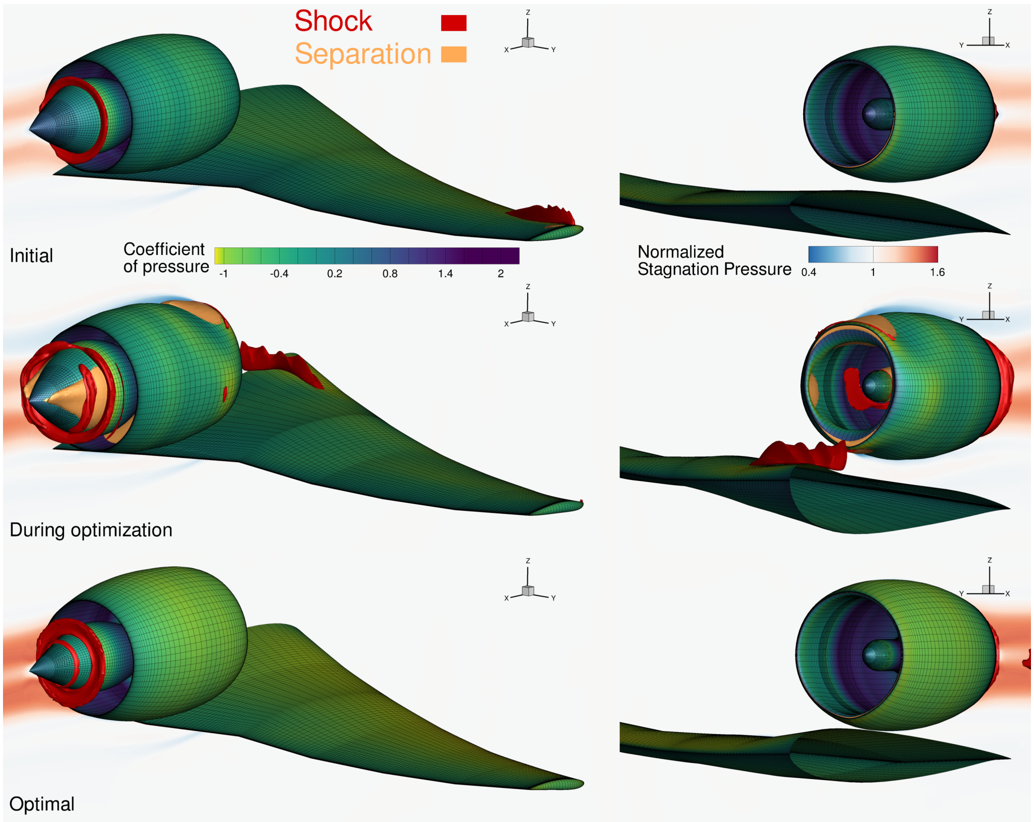

Figure 10 – C_p contours of the surfaces and the stagnation pressure contours for the nacelle vertical symmetry plane (x-z plane) for the OWN and UWN cases. (Generated from results of Abdul-Kaiyoom et al. [67]).

turbofan FPR of 1.50 (UWN-1.5). Thanks to the larger fan diameter and favorable aerodynamic interference effects between the wing and the propulsor, the OWN-1.4 achieved lower required shaft power than the UWN-1.5. For a similar propulsor size, the propulsor in the OWN has a lower drag than the propulsor in UWN because of the favorable flow interaction between the wing and propulsor in the OWN. They also did a parametric study for the location of the propulsor in the OWN design. They found that when the propulsor is close to the wing's root in the aft of the trailing edge position, the wing performs better. Nevertheless, total drag reduces when the propulsor is positioned farther from the wing's root at the aft of the trailing edge. Again, the study highlights the importance of considering the coupled effects of aerodynamics and propulsion in aircraft design and provides insights for future investigations into OWN configurations.

3.2.2 Propellers

Propeller-wing interaction plays a crucial role in the design and optimization of smaller transport aircraft, especially those using distributed propulsion systems and electric motors. Because the propeller's induced flow significantly affects the aerodynamic characteristics of the wing, considering these interactions in the optimization process is essential for achieving efficient designs.

Chauhan and Martins [68] investigated the aerodynamic shape optimization of a wing considering the interaction between the propeller and the wing using RANS simulations. The study implemented an actuator-disk model and coupled it to RANS to simulate the propeller's effects on the wing's aerodynamic performance. The optimization minimized cruise drag with respect to twist and airfoil shape design variables. The results demonstrate that while optimizing the wing with the propeller model provides detailed insights into the interaction effects, the overall benefits in drag reduction are minimal compared to optimizing the wing without considering the propeller slipstream. This indicates that for certain configurations, a sequential optimization approach may be nearly as effective.

Chauhan and Martins [69] extended their investigation to a configuration where the propeller is placed in front of the wingtip. This study used the same RANS simulation coupled to an actuator-disk model to capture the propeller-induced flow effects on the wing. They minimized total drag by varying wing twist and airfoil shapes, considering the propeller's slipstream during the optimization process. Similarly to the previous study, optimizing the wing while accounting for the propeller slipstream yields negligible additional benefits over optimizing it without the propeller model. The results show that it is more important to select the propeller location and rotation direction strategically. Changing the propeller rotation direction from outboard-up to inboard-up resulted in significant drag reduction.

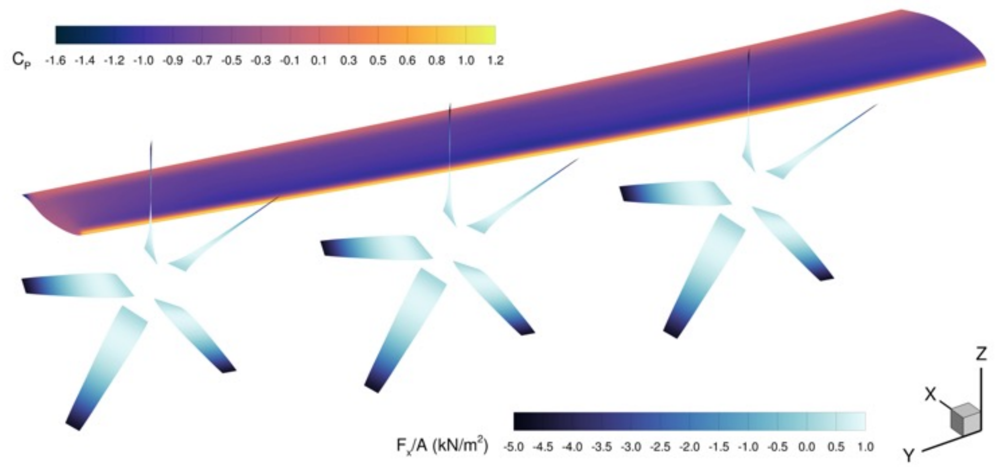

Figure 11 – Three-propeller case from the distributed propulsion investigation of Pacini et al. [70].

Pacini et al. [70] used a similar approach to that of Chauhan and Martins [69] to investigate distributed propulsion. However, instead of ADflow as described in Section 2., they used the OpenFOAM CFD solver with the DAFoam adjoint implementation [10, 11]. The paper explored configurations ranging from zero to five evenly spaced propellers along the wing. Figure 11 shows the three-propeller case. The results showed that the number of propellers impacts the wing's aerodynamic performance and that a single propeller mounted at the wing tip is the most effective way to reduce drag. However, similarly to Chauhan and Martins [68] and Chauhan and Martins [69], they found that the benefit of incorporating propeller-wing interaction into the optimization process is negligible compared to optimizing an isolated wing and subsequently adjusting it for the desired flight condition with a propeller.

Pacini et al. [71] performed aerostructural optimization of the NASA tiltwing concept [72] using the MPhys framework. The structural model was built and solved using TACS as in the aerostructural optimizations described in Sec. 3.1. The research achieves more realistic optimizations for vehicles with wing-mounted propellers by considering propeller deflection due to wing deformation and additional loads from the propeller. Due to a redistribution of lift across the wing, they achieved a reduction in wing drag compared to the baseline. The optimized lift distribution closely follows an elliptical one, although local lift variations due to propeller effects remain. These results highlight the potential for further enhancing performance with expanded design freedom.

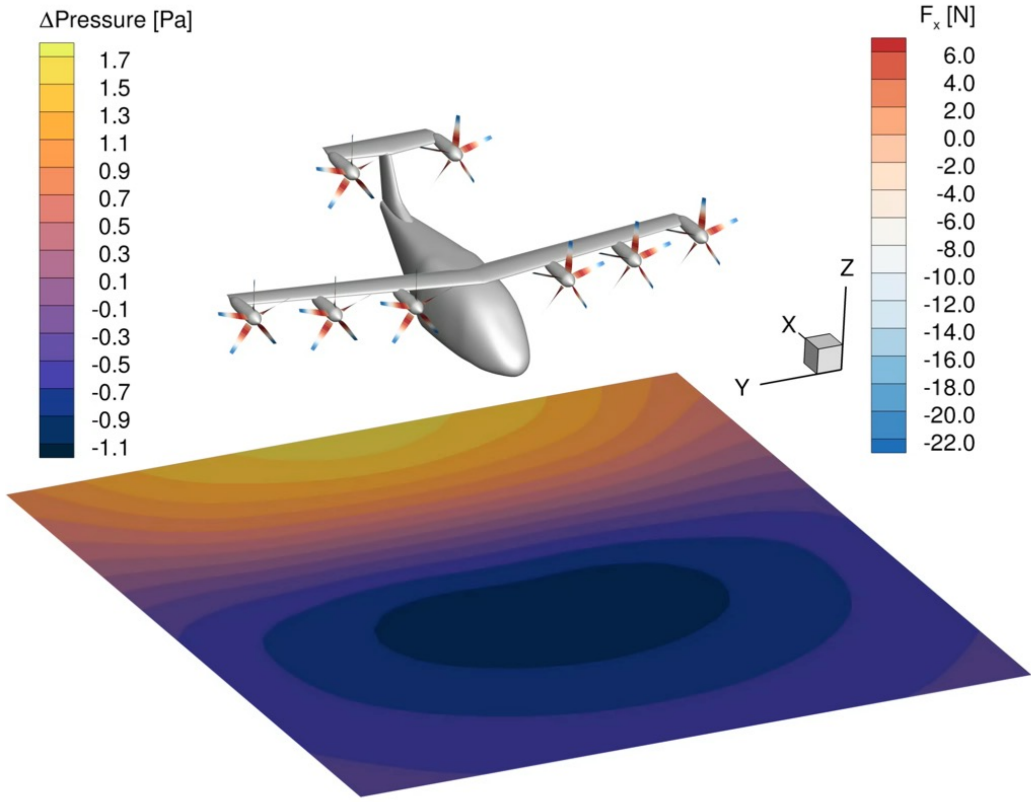

Figure 12 – Coupled aerodynamic and aeroacoustic models developed by Pacini et al. [73].

Pacini et al. [73] also coupled aerodynamic and aeroacoustic models for gradient-based optimization. They coupled a blade element momentum theory model for rotor performance modeling with a Ffowcs Williams and Hawkings model for tonal aeroacoustic analysis (see Fig.12). The coupling was implemented using the OpenMDAO framework, and the resulting framework computed coupled derivatives using the direct approach. Both the aerodynamic and aeroacoustic models were validated independently, and their derivatives were verified. They then applied the developed framework to the optimization of the NASA quadrotor concept vehicle. They later expanded the framework to include broadband noise prediction and optimized the NASA ideally twisted rotor used for aeroacoustic experiments using the adjoint method. The optimization minimized noise by varying blade-shape design variables, demonstrating the potential for significant noise footprint reduction in propeller-powered aircraft.

Further advancing this research, another study by Pacini et al. [74] focused on coupling aerodynamics, structures, and acoustics using a mixed-fidelity approach for the optimization of urban air mobility vehicles. For this study, they coupled the existing models and solvers for the aerodynamics, structures, and aeroacoustics. The application focused on optimizing the NASA tiltwing concept vehicle, demonstrating substantial reductions in wing drag and overall power consumption during cruise flight subject to aeroacoustic constraints. The study demonstrated the importance of design trades between power consumption and aeroacoustic constraints.

3.3 Thermal Management

Thermal management is a critical aspect of aircraft design, particularly for hybrid and electric propulsion systems [75]. Traditional turbine engines exhaust their waste heat directly into the freestream, but electric propulsion systems accumulate heat within their components, requiring efficient thermal management systems (TMS). These systems must keep component temperatures within operational limits while minimizing additional weight and drag penalties.

The OpenConcept framework is an aircraft design framework developed by Brelje et al. [76]. They use OpenMDAO to implement physics-based thermal analysis components, such as heat sinks, heat exchangers, and coolant loops, with analytic derivatives for efficient gradient-based optimization. OpenConcept was used to optimize a Beech King Air with a series hybrid electric propulsion system, minimizing fuel burn while enforcing thermal constraints. The results demonstrated that considering thermal constraints led to a more robust design, effectively managing component temperatures throughout the mission profile. This highlights the importance of including thermal management in early-stage aircraft design optimization. Adler et al. [77] built on the initial version of OpenConcept to investigate using vapor cycle and thermoacoustic refrigeration to cool the battery of a parallel hybrid single-aisle commercial transport aircraft. The research highlighted the need for heat exchangers with low-pressure losses to make thermoacoustic systems viable for aircraft applications, emphasizing the complex trade-offs involved in thermal management system design.

To address this need, Anibal and Martins [79] developed a conjugate heat transfer model in ADflow. Their first application was to the aerodynamic shape optimization of an electric aircraft motor surface heat exchanger. The optimization was successful in making optimal trades between heat transfer capacity and aerodynamic drag, resulting in the shapes shown in Fig. 13. Anibal and Martins [79] then used the same approach to optimize the shape of plate-fin heat exchangers. The optimization results revealed that drag-minimizing designs feature channels stretched in the height and width directions, reducing corners and improving drag-to-heat transfer ratios. In contrast, mass-minimizing designs are characterized by shorter, wavy channels that enhance mixing. These results underscore the potential of gradient-based methods to innovate heat exchanger designs for various applications, including aerospace, automotive, and industrial sectors.

Ducted heat exchangers are much more effective than surface heat exchangers because they can slow the airflow before passing through the heat exchanger, reduce the pressure drop, and then recover some of the thermal energy with the nozzle. Ducted heat exchangers have been used in aircraft since the 1930s, but there has recently been a renewed interest in electrified aircraft. Adler et al. [80] optimized a ducted heat exchanger for rejecting waste heat from a hydrogen fuel cell aircraft. They optimized the duct shape, heat exchanger size, heat exchanger channel geometry, and coolant flow rate to minimize the ducted heat exchanger's power requirements while rejecting a specified amount of heat. The duct was modeled by solving the RANS equations, which were coupled to an OpenConcept heat exchanger model using MPhys. The study demonstrated significant performance improvements, achieving the design shown in Fig. 14, which has five times less cruise drag than the baseline. This demonstrates the potential of advanced optimization methods in enhancing the efficiency of thermal management systems in modern aircraft.

3.4 Systems Packaging

Considering systems packaging in aerodynamic shape optimization is essential to achieving practical designs with the lowest possible drag. Aircraft designers are exploring new propulsion architectures and other technologies that require substantial internal space for components such as batteries,

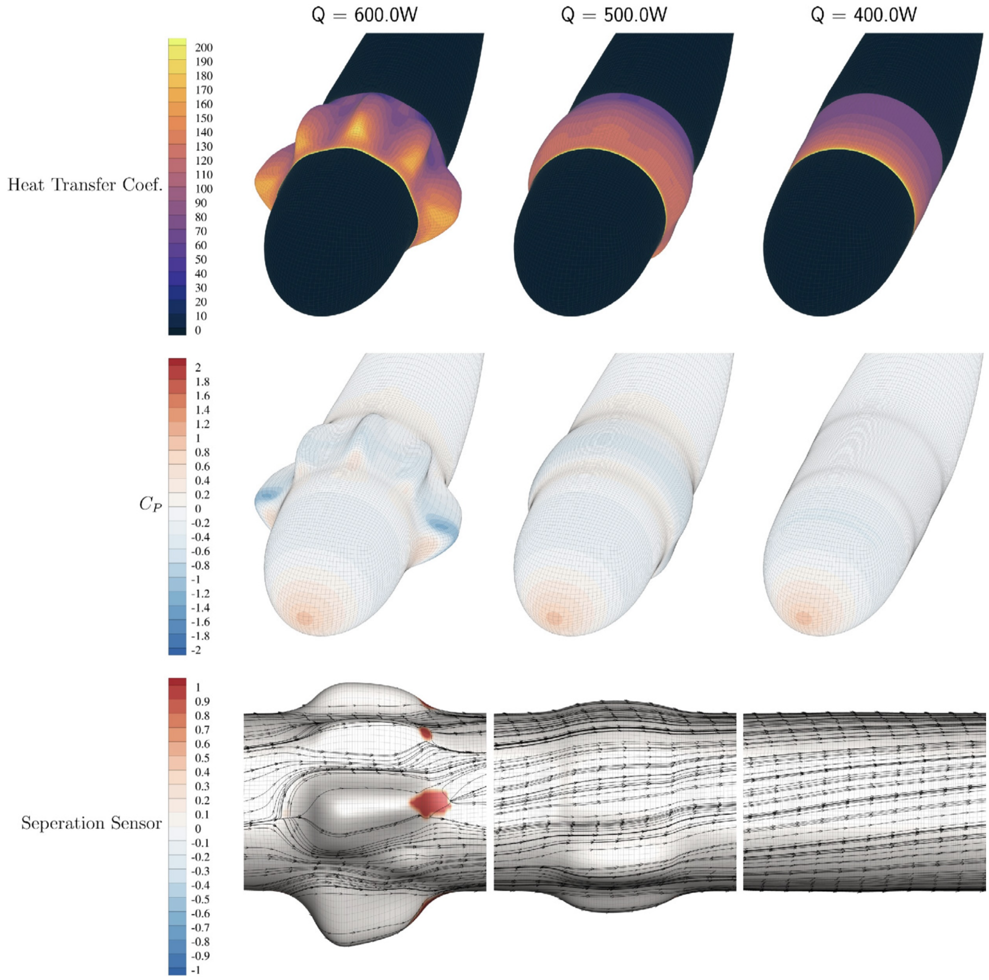

Figure 13 – As the heat transfer requirement increases, the aerodynamic shape optimization adds streamlined fins with minimum drag [78].

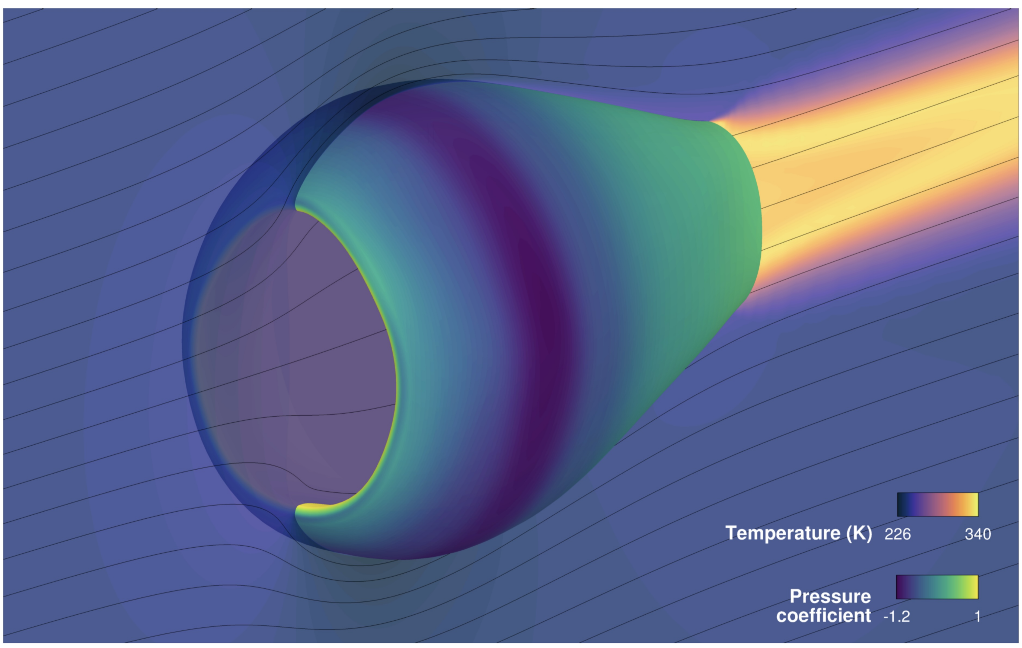

Figure 14 – Cruise flight condition pressure coefficient contours on the duct and temperature contours on the symmetry plane for the optimized duct heat exchanger. The optimizer rounds the corners of the baseline duct design and reduces the airspeed at the heat exchanger's face to nearly one-tenth of the freestream speed by manipulating the duct's shape [80].

fuel cells, and hydrogen tanks. Ignoring the spatial integration of these systems can lead to significant discrepancies between optimized theoretical designs and practical solutions. For instance, the placement and volume of fuel tanks, batteries, or other critical systems directly influence the aircraft's shape, which in turn affects aerodynamic performance and structural integrity. By integrating systems packaging constraints into the MDO process, designers can ensure that all necessary components fit within the aircraft while achieving optimal performance.

Traditional aerodynamic optimization tools have been limited by simple geometric constraints, which do not adequately handle the complex spatial requirements of aircraft systems. Brelje et al. [81] addressed the challenge of spatial integration in aerodynamic shape optimization by proposing a general geometric constraint formulation based on triangulated 3D geometry. The approach relies on metrics that are fast to compute and analytically differentiable, making them suitable for gradient-based optimization. The paper validates this approach through three RANS-based optimization problems, demonstrating its robustness and efficiency in handling the spatial integration of objects with arbitrary shapes. The approach enables aerodynamic shape optimization including systems packaging.

Hydrogen fuel is a promising alternative to conventional fuels, but its lower energy per unit volume and special tank requirements make it a challenging systems packaging problem. Brelje and Martins [82] applied their spatial integration approach to the aerostructural optimization of a wing containing liquid hydrogen tanks. The optimization successfully made trade-offs between weight, drag, and fuel storage capacity. The results indicate that optimal wing designs for hydrogen fuel storage thickened the wing root to accommodate the hydrogen tanks efficiently.

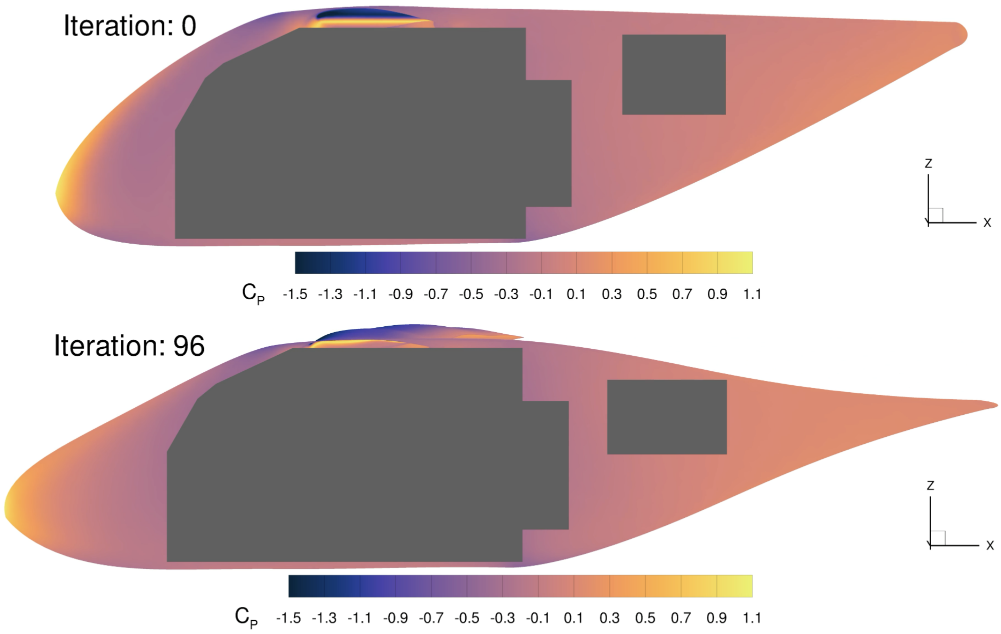

Figure 15 – Aerodynamic shape optimization of the NASA tiltwing vehicle considering packaging constraints, showing the baseline (top) and optimized (bottom) shapes. (Results based on Hajdik et al. [83])

Hajdik et al. [83] applied the same approach to optimize the aerodynamic shape of the NASA tiltwing concept vehicle [72] while packaging hybrid propulsion system components. As shown in Fig. 15, the optimization significantly changed the outer mold line of the fuselage, extending the nose section and reshaping the tail cone while moving the system components to more favorable positions. The result was a drastic reduction in drag. The findings highlight the significant design freedom and efficiency gains made possible by considering both the position of the internal systems and the aircraft's outer mold line in an MDO framework.

3.5 Unconventional Configurations

Since the dawn of the jet age, tube-and-wing aircraft configurations have dominated the air transportation industry. This configuration has been refined over many decades. One of these wing refinements was wing area reduction, thanks to better high-lift devices to satisfy field length requirements. Another significant refinement was a span increase, thanks to advancements in materials and structural design. The result was the previously mentioned increase in wing aspect ratio. However, there is a limitation to how much the wingspan can be increased to enhance efficiency. Overall, the potential improvements to conventional aircraft configurations are reaching a plateau.

To achieve significant advancements in sustainable aviation, unconventional aircraft configurations such as blended-wing body (BWB), truss-braced wing (TBW), and the D8 should be explored. These configurations promise to break the barriers of conventional designs by offering potential improvements in aerodynamics, structural efficiency, and, thus, fuel burn. In this section, we review applications of the developed methods to these unconventional configurations. The papers summarized below are only a small fraction of all the studies performed on unconventional configurations; Bravo-Mosquera et al. [7] provide a comprehensive review.

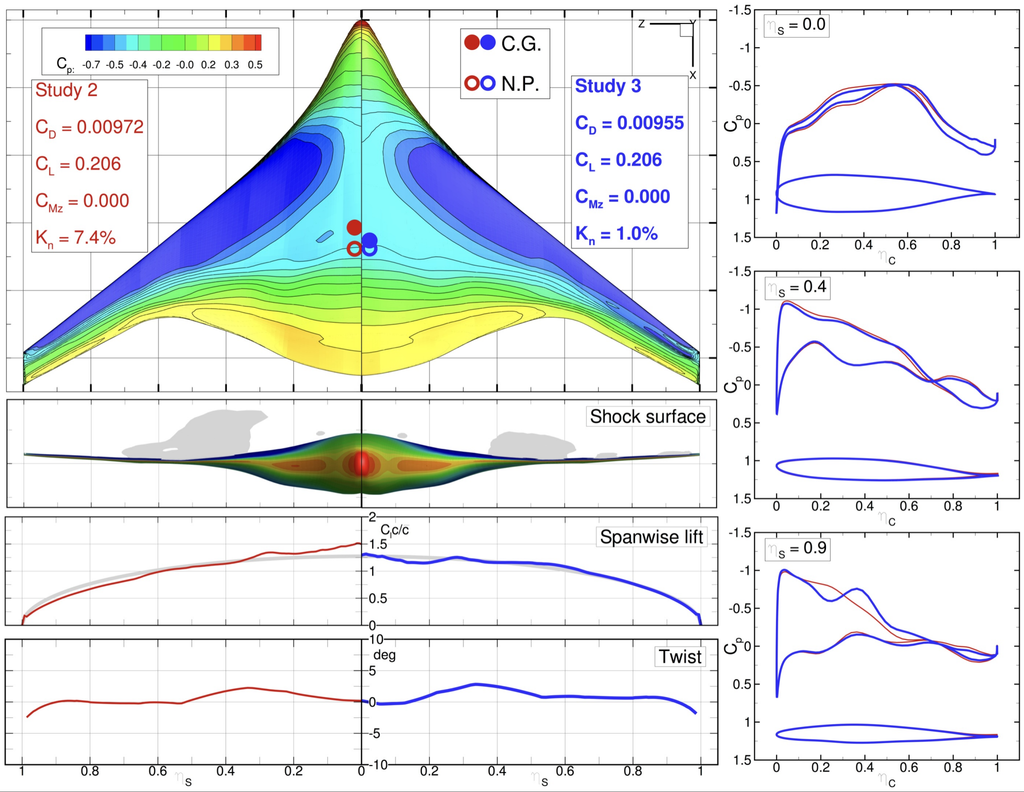

Figure 16 – Comparison of optimized BWB shapes with different center of gravity positions [84].

Lyu and Martins [84] investigated RANS-based aerodynamic shape optimization of a BWB aircraft considering trim and longitudinal static stability. In a sequence of increasingly complex optimization studies, they minimized drag with respect to different sets of design variables subject to various constraints. They started by just enforcing a lift constraint and varying spanwise twist distribution and then added airfoil shape design variables, In addition to the lift constraint, they performed optimization studies with trim moment and static margin constraints, as shown in Fig. 16. In one of the studies, they also varied sweep and chord distribution. This paper contributed to the understanding of the trade-offs between aerodynamic performance and constraints on trim and stability. It also demonstrated how RANS-based aerodynamic shape optimization can be used to explore and refine new aircraft configurations more quickly.

Mader et al. [85] performed the aerostructural optimization of the D8 aircraft, also known as the "double-bubble" configuration. This unconventional design features a wider fuselage that provides

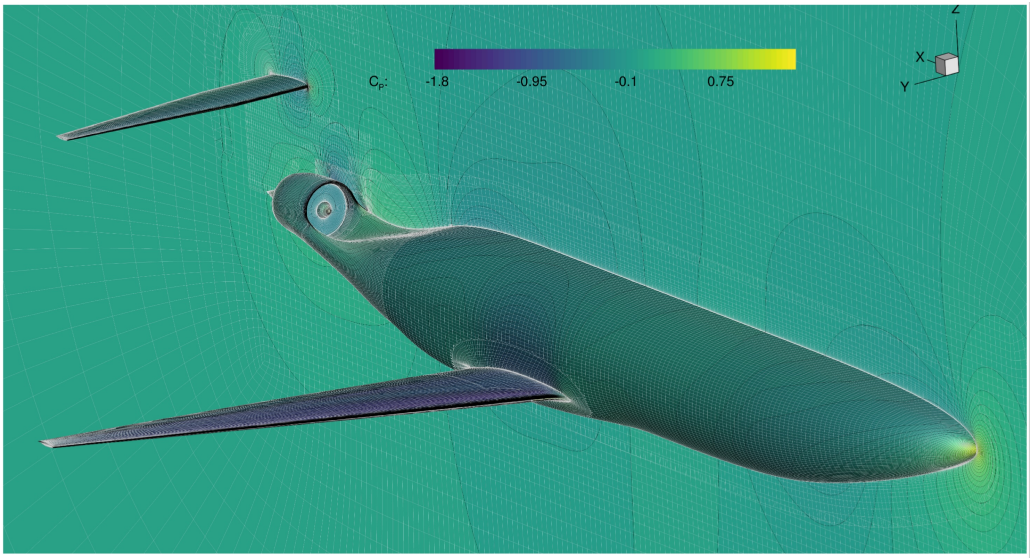

Figure 17 – Overset RANS mesh and flow solution for the D8 configuration [85].

additional lift and reduces the overall drag, as shown in Fig. 17. The authors minimized the average fuel burn considering multiple flight conditions by varying wing twist and chord distributions, span, sweep, and airfoil shapes, as well as detailed structural sizing. They performed optimizations for three different transonic Mach numbers, and the optimal sweep increased with Mach number as expected. The results were compared with a conceptual design tool (TASOPT). While the gross performance numbers compared favorably, the CFD-based aerostructural optimization was able to determine the optimal sweep and design transonic airfoil shapes more accurately. Overall, the results showed that the D8 configuration is promising and can benefit from such aerostructural optimization.

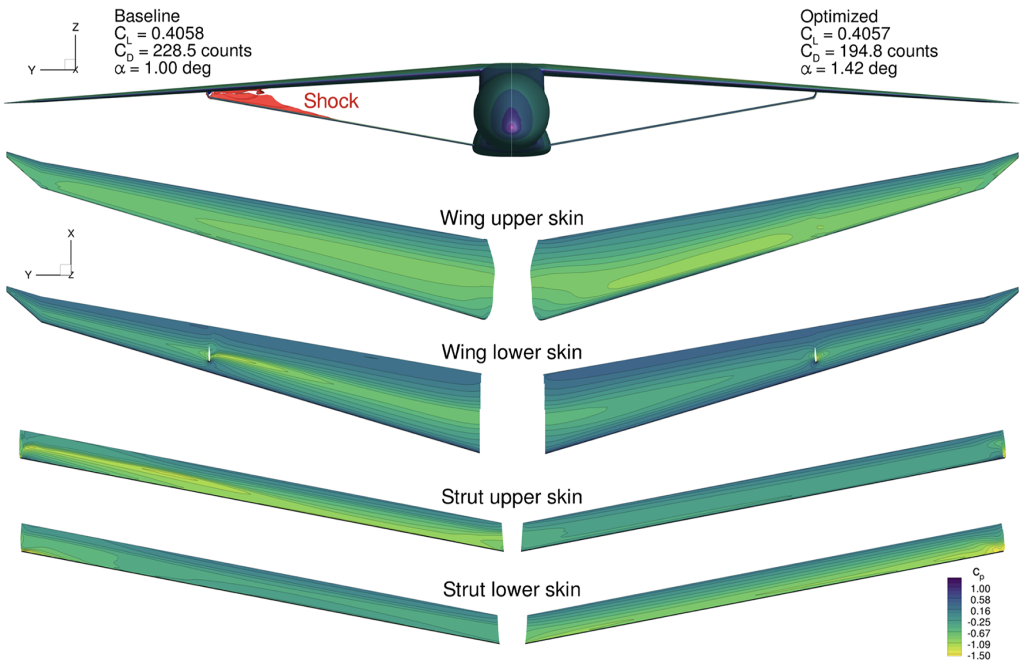

Figure 18 – Baseline and optimized shape for the TBW [86].

Secco and Martins [86] developed RANS-based aerodynamic shape optimization for a TBW configuration, which employs trusses to support high aspect ratio wings, allowing for greater wingspan with lower weight penalties than a cantilevered wing. This design aims to reduce induced drag, but keeping the additional drag due to the truss is challenging. The paper developed a methodology to optimize the shape of the wing and truss simultaneously, which drastically reduced the interference drag at and near the truss-wing junction, as shown in Fig. 18. This result demonstrated the need for CFD-based shape optimization to quantify the advantages of a new aircraft configuration accurately and to address potential challenges during the conceptual design phase. The designed optimization results indicated that the TBW configuration could achieve significant fuel savings and enhanced performance.

4. Conclusions

This paper reviewed the advancements made by the MDO Lab over the past decade in CFD-based MDO and its applications to sustainable aviation. CFD aerodynamic models and their coupling to other disciplines, such as structures and propulsion, are essential for accurately capturing the complex multidisciplinary physics involved in aircraft design. To enable the design optimization that captures these physics, we developed the coupled adjoint approach. This approach was later modularized with MPhys (which is based on OpenMDAO), enabling efficient optimization with respect to hundreds or thousands of design variables considering multiple disciplines.

In our applications, high aspect ratio wings proved to be an ideal use case for aerostructural optimization. This is because the optimal span depends on an accurate trade-off between aerodynamic drag and structural weight. Aerostructural optimization was particularly effective for exploring new technologies like tow-steered composites. We developed the uCRM-13.5 benchmark to explore these new technologies, providing the community with a valuable tool to test and validate new designs. Morphing technologies were also explored, demonstrating potential for improving aerodynamic efficiency and reducing fuel burn. Because high aspect ratio wings are more flexible, they are prone to flutter. To address this issue, we developed flutter constraints within our optimization framework to ensure structural integrity.

We pioneered aeropropulsive design optimization by coupling thermal cycle models to CFD, creating a more integrated approach to engine design. This method is particularly crucial for the rapid redesign cycles needed for turbofans using alternative fuels such as hydrogen. The method was also used to study the aeropropulsive integration of propellers and distributed propulsion.

As electrification becomes more prevalent in aviation, effective thermal management will be increasingly critical. We have prepared for this by coupling heat transfer to CFD in MPhys and designing both surface and ducted heat exchangers. Electrification also adds a systems packaging challenge, which we addressed by developing the capability to enforce packaging constraints for components of arbitrary shapes in aerodynamic and aerostructural optimization.

Due to the lack of historical data, MDO should play a crucial role in the design unconventional configurations, such as the BWB, TBW, and D8. MDO allows for a comprehensive analysis of trade-offs between aerodynamics, structures, propulsion, stability, and mission performance.

In conclusion, while investing in advanced airframe technologies is vital for sustainable aviation, investing in design methodologies is equally important. Advanced design approaches like MDO reduce design cycles and enable the exploration and refinement of new concepts, driving the future of sustainable aircraft design.

Acknowledgements

The cited references contain more detailed information on who contributed to each effort and the funding sources. The authors are thankful for the many current and former MDO Lab members who conducted some of the research summarized here: Josh Anibal, Benjamin Brelje, David Burdette, Timothy Brooks, Shamsheer Chauhan, Justin Gray, Ping He, Sicheng He, John Hwang, Graeme Kennedy, Gaetan Kenway, Zhoujie (Peter) Lyu, and Charles Mader.

Eytan Adler is supported by the Department of Defense through the National Defense Science and Engineering Graduate (NDSEG) Fellowship Program and by the University of Michigan Rackham Predoctoral Fellowship Program. He is also supported in part by the Michigan Institute for Computational Discovery and Engineering (MICDE) Graduate Fellowship program. Alasdair Gray was sponsored by the NASA Revolutionary Computational Aerosciences (RCA) subproject of the Transformational Tools and Technologies (TTT) project, grant number 80NSSC23M0216, with Technical Officer Kevin Jacobson. Hannah Hajdik and Andrew Lamkin were supported by the U. S. Air Force Research Laboratory (AFRL) under the Michigan–AFRL Collaborative Center in Aerospace Vehicle Design (CCAVD) with Richard Snyder and Nathan Wukie as the task technical monitors. Eirikur Jonsson was supported by NSF under award 2223670. Anil Yildirim was supported by the NASA Advanced Air Transport Technology (AATT) and Transformational Tools and Technologies (TTT) projects. Bernardo Pacini was supported by the Hyundai Motor Company, the NASA Transformational Tools and Technologies (TTT) project, and Orb Aerospace. M. A. Saja Abdul-Kaiyoom was supported by NASA under grant number 80NSSC18M0151.

Computational resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center. This work also used the stampede2 cluster at the Texas Advanced Computing Center through allocation TG-DDM140001 from the Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS) program, which is supported by National Science Foundation grants #2138259, #2138286, #2138307, #2137603, and #2138296.

5. Contact Author Email Address

The first author can be contacted at jrram@umich.edu.

6. Copyright Statement

References

[1] International Civil Aviation Organization Industry High Level Group, "Aviation Benefits Report 2019," https://www.icao.int/sustainability/Documents/AVIATION-BENEFITS-2019-web.pdf, 2019. Accessed November 17, 2022.

[2] Anonymous, "Environmental Protection —Volume II—Aircraft Engine Emissions, Annex 16," Tech. rep., ICAO, July 2023.

[3] Martins, J. R. R. A., and Lambe, A. B., "Multidisciplinary Design Optimization: A Survey of Architectures," *AIAA Journal*, Vol. 51, No. 9, 2013, pp. 2049–2075. doi:10.2514/1.J051895.

[4] Martins, J. R. R. A., and Ning, A., *Engineering Design Optimization*, Cambridge University Press, Cambridge, UK, 2022. doi:10.1017/9781108980647, URL https://mdobook.github.io.

[5] Martins, J. R. R. A., "Aerodynamic Design Optimization: Challenges and Perspectives," *Computers & Fluids*, Vol. 239, 2022, p. 105391. doi:10.1016/j.compfluid.2022.105391.

[6] Afonso, F., Sohst, M., Diogo, C. M., Rodrigues, S. S., Ferreira, A., Ribeiro, I., Marques, R., Rego, F. F., Sohouli, A., Portugal-Pereira, J., Policarpo, H., Soares, B., Ferreira, B., Fernandes, E. C., Lau, F., and Suleman, A., "Strategies towards a more sustainable aviation: A systematic review," *Progress in Aerospace Sciences*, Vol. 137, 2023, p. 100878. doi:10.1016/j.paerosci.2022.100878.

[7] Bravo-Mosquera, P. D., Catalano, F. M., and Zingg, D. W., "Unconventional aircraft for civil aviation: A review of concepts and design methodologies," *Progress in Aerospace Sciences*, Vol. 131, 2022, p. 100813. doi:10.1016/j.paerosci.2022.100813.

[8] Mader, C. A., Kenway, G. K. W., Yildirim, A., and Martins, J. R. R. A., "ADflow: An open-source computational fluid dynamics solver for aerodynamic and multidisciplinary optimization," *Journal of Aerospace Information Systems*, Vol. 17, No. 9, 2020, pp. 508–527. doi:10.2514/1.I010796.

[9] Kenway, G. K. W., Mader, C. A., He, P., and Martins, J. R. R. A., "Effective Adjoint Approaches for Computational Fluid Dynamics," *Progress in Aerospace Sciences*, Vol. 110, 2019, p. 100542. doi:10.1016/j.paerosci.2019.05.002.

[10] He, P., Mader, C. A., Martins, J. R. R. A., and Maki, K. J., "An Aerodynamic Design Optimization Framework Using a Discrete Adjoint Approach with OpenFOAM," *Computers & Fluids*, Vol. 168, 2018, pp. 285–303. doi:10.1016/j.compfluid.2018.04.012.

[11] He, P., Mader, C. A., Martins, J. R. R. A., and Maki, K. J., "DAFoam: An Open-Source Adjoint Framework for Multidisciplinary Design Optimization with OpenFOAM," *AIAA Journal*, Vol. 58, No. 3, 2020. doi:10.2514/1.J058853.

[12] Hajdik, H. M., Yildirim, A., Wu, N., Brelje, B. J., Seraj, S., Mangano, M., Anibal, J. L., Jonsson, E., Adler, E. J., Mader, C. A., Kenway, G. K. W., and Martins, J. R. R. A., "pyGeo: A geometry package for multidisciplinary design optimization," *Journal of Open Source Software*, Vol. 8, No. 87, 2023, p. 5319. doi:10.21105/joss.05319.

[13] Secco, N., Kenway, G. K. W., He, P., Mader, C. A., and Martins, J. R. R. A., "Efficient Mesh Generation and Deformation for Aerodynamic Shape Optimization," *AIAA Journal*, Vol. 59, No. 4, 2021, pp. 1151–1168. doi:10.2514/1.J059491.

[14] Wu, N., Kenway, G., Mader, C. A., Jasa, J., and Martins, J. R. R. A., "pyOptSparse: A Python framework for large-scale constrained nonlinear optimization of sparse systems," *Journal of Open Source Software*, Vol. 5, No. 54, 2020, p. 2564. doi:10.21105/joss.02564.

[15] Chen, S., Lyu, Z., Kenway, G. K. W., and Martins, J. R. R. A., "Aerodynamic Shape Optimization of the Common Research Model Wing-Body-Tail Configuration," *Journal of Aircraft*, Vol. 53, No. 1, 2016, pp. 276–293. doi:10.2514/1.C033328.

[16] Kenway, G. K. W., and Martins, J. R. R. A., "Multipoint Aerodynamic Shape Optimization Investigations of the Common Research Model Wing," *AIAA Journal*, Vol. 54, No. 1, 2016, pp. 113–128. doi:10.2514/1.J054154.

[17] Lyu, Z., Kenway, G. K. W., and Martins, J. R. R. A., "Aerodynamic Shape Optimization Investigations of the Common Research Model Wing Benchmark," *AIAA Journal*, Vol. 53, No. 4, 2015, pp. 968–985. doi:10.2514/1.J053318.

[18] Kenway, G. K. W., and Martins, J. R. R. A., "Multipoint High-Fidelity Aerostructural Optimization of a Transport Aircraft Configuration," *Journal of Aircraft*, Vol. 51, No. 1, 2014, pp. 144–160. doi:10.2514/1.C032150.

[19] Brooks, T. R., Kenway, G. K. W., and Martins, J. R. R. A., "Benchmark Aerostructural Models for the Study of Transonic Aircraft Wings," *AIAA Journal*, Vol. 56, No. 7, 2018, pp. 2840–2855. doi:10.2514/1.J056603.

[20] Bons, N. P., and Martins, J. R. R. A., "Aerostructural Design Exploration of a Wing in Transonic Flow," *Aerospace*, Vol. 7, No. 8, 2020, p. 118. doi:10.3390/aerospace7080118.

[21] Brooks, T. R., Martins, J. R. R. A., and Kennedy, G. J., "Aerostructural Trade-offs for Tow-steered Composite Wings," *Journal of Aircraft*, Vol. 57, No. 5, 2020, pp. 787–799. doi:10.2514/1.C035699.

[22] Madsen, M. H. A., Zahle, F., Sørensen, N. N., and Martins, J. R. R. A., "Multipoint high-fidelity CFD-based aerodynamic shape optimization of a 10 MW wind turbine," *Wind Energy Sciences*, Vol. 4, 2019, pp. 163–192. doi:10.5194/wes-4-163-2019.

[23] Caprace, D.-G., Cardoza, A., Ning, A., Mangano, M., He, S., and Martins, J. R. R. A., "Incorporating High-Fidelity Aerostructural Analyses in Wind Turbine Rotor Optimization," *AIAA SciTech Forum*, 2022. doi:10.2514/6.2022-1290.

[24] Mangano, M., He, S., Liao, Y., Caprace, D.-G., and Martins, J. R. R. A., "Towards Passive Aeroelastic Tailoring of Large Wind Turbines Using High-Fidelity Multidisciplinary Design Optimization," *AIAA SciTech Forum*, 2022. doi:10.2514/6.2022-1289.

[25] Garg, N., Kenway, G. K. W., Lyu, Z., Martins, J. R. R. A., and Young, Y. L., "High-fidelity Hydrodynamic Shape Optimization of a 3-D Hydrofoil," *Journal of Ship Research*, Vol. 59, No. 4, 2015, pp. 209–226. doi:10.5957/JOSR.59.4.150046.

[26] Liao, Y., Yildirim, A., Martins, J. R. R. A., and Young, Y. L., "RANS-based Optimization of a T-shaped Hydrofoil Considering Junction Design," *Ocean Engineering*, Vol. 262, 2022, p. 112051. doi:10.1016/j.oceaneng.2022.112051.

[27] Garg, N., Kenway, G. K. W., Martins, J. R. R. A., and Young, Y. L., "High-fidelity Multipoint Hydrostructural Optimization of a 3-D Hydrofoil," *Journal of Fluids and Structures*, Vol. 71, 2017, pp. 15–39. doi:10.1016/j.jfluidstructs.2017.02.001.

[28] Garg, N., Pearce, B. W., Brandner, P. A., Phillips, A. W., Martins, J. R. R. A., and Young, Y. L., "Experimental Investigation of a Hydrofoil Designed via Hydrostructural Optimization," *Journal of Fluids and Structures*, Vol. 84, 2019, pp. 243–262. doi:10.1016/j.jfluidstructs.2018.10.010.

[29] Liao, Y., Martins, J. R. R. A., and Young, Y. L., "3-D High-Fidelity Hydrostructural Optimization of Cavitation-Free Composite Lifting Surfaces," *Composite Structures*, Vol. 268, 2021, p. 113937. doi:10.1016/j.compstruct.2021.113937.

[30] Liao, Y., Martins, J. R. R. A., and Young, Y. L., "Hydrostructural Optimization of Single-layer and Multi-layer Composite Lifting Surfaces," *Composite Structures*, Vol. 307, 2023, p. 116650. doi:10.1016/j.compstruct.2022.116650.

[31] He, P., Filip, G., Martins, J. R. R. A., and Maki, K. J., "Design Optimization for Self-Propulsion of a Bulk Carrier Hull Using a Discrete Adjoint Method," *Computers & Fluids*, Vol. 192, 2019, p. 104259. doi:10.1016/j.compfluid.2019.104259.

[32] He, P., Martins, J. R. R. A., Mader, C. A., and Maki, K., "Aerothermal Optimization of a Ribbed U-Bend Cooling Channel Using the Adjoint Method," *International Journal of Heat and Mass Transfer*, Vol. 140, 2019, pp. 152–172. doi:10.1016/j.ijheatmasstransfer.2019.05.075.

[33] Koyuncuoglu, H. U., and He, P., "Simultaneous wing shape and actuator parameter optimization using the adjoint method," *Aerospace Science and Technology*, Vol. 130, 2022, p. 107876.

[34] Zoppelt, S. A., Koyuncuoglu, H. U., and P, H., "High-fidelity Aerostructural Optimization Benchmark for Aircraft Propellers in Hover," *AIAA SciTech Forum*, Orlando, FL, 2024. doi:10.2514/6.2024-2773.

[35] Martins, J. R. R. A., Alonso, J. J., and Reuther, J. J., "A Coupled-Adjoint Sensitivity Analysis Method for High-Fidelity Aero-Structural Design," *Optimization and Engineering*, Vol. 6, No. 1, 2005, pp. 33–62. doi:10.1023/B:OPTE.0000048536.47956.62.

[36] Martins, J. R. R. A., Alonso, J. J., and Reuther, J. J., "High-Fidelity Aerostructural Design Optimization of a Supersonic Business Jet," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 523–530. doi:10.2514/1.11478.

[37] Kenway, G. K. W., Kennedy, G. J., and Martins, J. R. R. A., "Scalable Parallel Approach for High-Fidelity Steady-State Aeroelastic Analysis and Adjoint Derivative Computations," *AIAA Journal*, Vol. 52, No. 5, 2014, pp. 935–951. doi:10.2514/1.J052255.

[38] Kennedy, G. J., and Martins, J. R. R. A., “A Parallel Finite-Element Framework for Large-Scale Gradient-Based Design Optimization of High-Performance Structures,” *Finite Elements in Analysis and Design*, Vol. 87, 2014, pp. 56–73. doi:10.1016/j.finel.2014.04.011.

[39] Lambe, A. B., and Martins, J. R. R. A., “Extensions to the Design Structure Matrix for the Description of Multidisciplinary Design, Analysis, and Optimization Processes,” *Structural and Multidisciplinary Optimization*, Vol. 46, No. 2, 2012, pp. 273–284. doi:10.1007/s00158-012-0763-y.

[40] Martins, J. R. R. A., and Hwang, J. T., “Review and Unification of Methods for Computing Derivatives of Multidisciplinary Computational Models,” *AIAA Journal*, Vol. 51, No. 11, 2013, pp. 2582–2599. doi:10.2514/1.J052184.

[41] Hwang, J. T., and Martins, J. R. R. A., “A computational architecture for coupling heterogeneous numerical models and computing coupled derivatives,” *ACM Transactions on Mathematical Software*, Vol. 44, No. 4, 2018, p. Article 37. doi:10.1145/3182393.

[42] Hwang, J. T., Lee, D. Y., Cutler, J. W., and Martins, J. R. R. A., “Large-Scale Multidisciplinary Optimization of a Small Satellite’s Design and Operation,” *Journal of Spacecraft and Rockets*, Vol. 51, No. 5, 2014, pp. 1648–1663. doi:10.2514/1.A32751.

[43] Gray, J. S., Hwang, J. T., Martins, J. R. R. A., Moore, K. T., and Naylor, B. A., “OpenMDAO: An open-source framework for multidisciplinary design, analysis, and optimization,” *Structural and Multidisciplinary Optimization*, Vol. 59, No. 4, 2019, pp. 1075–1104. doi:10.1007/s00158-019-02211-z.

[44] Yildirim, A., Jacobson, K. E., Anibal, J. L., Stanford, B. K., Gray, J. S., Mader, C. A., Martins, J. R. R. A., and Kennedy, G. J., “MPhys: A Modular Multiphysics Library for Coupled Simulation and Adjoint Derivative Computation,” *Structural and Multidisciplinary Optimization*, 2024. (In press).

[45] Vassberg, J. C., DeHaan, M. A., Rivers, S. M., and Wahls, R. A., “Development of a Common Research Model for Applied CFD Validation Studies,” *26th AIAA Applied Aerodynamics Conference, Guidance, Navigation, and Control and Co-located Conferences*, 2008. doi:10.2514/6.2008-6919.

[46] Vassberg, J. C., DeHaan, M. A., Rivers, M. S., and Wahls, R. A., “Retrospective on the Common Research Model for Computational Fluid Dynamics Validation Studies,” *Journal of Aircraft*, Vol. 55, No. 4, 2018, pp. 1325–1337. doi:10.2514/1.C034906.

[47] Gray, A. C., and Martins, J. R. R. A., “A Proposed Benchmark Model for Practical Aerostructural Optimization of Aircraft Wings,” *AIAA SciTech Forum*, Orlando, FL, 2024. doi:10.2514/6.2024-2775.

[48] Gray, A. C., Kennedy, G. J., and Martins, J. R. R. A., “Geometrically Nonlinear High-fidelity Aerostructural Optimization Including Geometric Design Variables,” *AIAA Aviation Forum*, San Diego, CA, 2023. doi:10.2514/6.2023-3316.

[49] Gray, A. C., and Martins, J. R. R. A., “Geometrically Nonlinear High-fidelity Aerostructural Optimization for Highly Flexible Wings,” *Proceedings of the AIAA SciTech Forum*, 2021. doi:10.2514/6.2021-0283.

[50] Brooks, T. R., Martins, J. R. R. A., and Kennedy, G. J., “High-fidelity Aerostructural Optimization of Tow-steered Composite Wings,” *Journal of Fluids and Structures*, Vol. 88, 2019, pp. 122–147. doi:10.1016/j.jfluidstructs.2019.04.005.

[51] Brooks, T. R., and Martins, J. R. R. A., “On Manufacturing Constraints for Tow-steered Composite Design Optimization,” *Composite Structures*, Vol. 204, 2018, pp. 548–559. doi:10.1016/j.compstruct.2018.07.100.

[52] Lyu, Z., and Martins, J. R. R. A., “Aerodynamic Shape Optimization of an Adaptive Morphing Trailing Edge Wing,” *Journal of Aircraft*, Vol. 52, No. 6, 2015, pp. 1951–1970. doi:10.2514/1.C033116.

[53] Burdette, D. A., and Martins, J. R. R. A., “Design of a Transonic Wing with an Adaptive Morphing Trailing Edge via Aerostructural Optimization,” *Aerospace Science and Technology*, Vol. 81, 2018, pp. 192–203. doi:10.1016/j.ast.2018.08.004.

[54] Burdette, D. A., and Martins, J. R. R. A., “Impact of Morphing Trailing Edge on Mission Performance for the Common Research Model,” *Journal of Aircraft*, Vol. 56, No. 1, 2019, pp. 369–384. doi:10.2514/1.C034967.

[55] Martins, J. R. R. A., *Encyclopedia of Aerospace Engineering*, Wiley, 2016, Vol. Green Aviation, Chap. Fuel burn reduction through wing morphing, pp. 75–79. doi:10.1002/9780470686652.eae1007.

[56] Jonsson, E., Riso, C., Lupp, C. A., Cesnik, C. E. S., Martins, J. R. R. A., and Epureanu, B. I., “Flutter and Post-Flutter Constraints in Aircraft Design Optimization,” *Progress in Aerospace Sciences*, Vol. 109, 2019, p. 100537. doi:10.1016/j.paerosci.2019.04.001.

[57] Jonsson, E., Mader, C. A., Kennedy, G. J., and Martins, J. R. R. A., “Computational Modeling of Flutter Constraint for High-Fidelity Aerostructural Optimization,” *2019 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, American Institute of Aeronautics and Astronautics, San Diego, CA, 2019. doi:10.2514/6.2019-2354.

[58] Jonsson, E., “High-fidelity Aerostructural Optimization of Flexible Wings with Flutter Constraints,” Ph.D. thesis, University of Michigan, 2020.

[59] He, S., Jonsson, E., Mader, C. A., and Martins, J. R. R. A., “Coupled Newton–Krylov Time-Spectral Solver for Flutter and Limit Cycle Oscillation Prediction,” *AIAA Journal*, Vol. 59, No. 6, 2021, pp. 2214–2232. doi:10.2514/1.J059224.

[60] Jonsson, E., Riso, C., Monteiro, B. B., Gray, A. C., Martins, J. R. R. A., and Cesnik, C. E. S., “High-Fidelity Gradient-Based Wing Structural Optimization Including Geometrically Nonlinear Flutter Constraint,” *AIAA Journal*, Vol. 61, No. 7, 2023, pp. 3045–3061. doi:10.2514/1.J061575.

[61] Gray, A. C., Riso, C., Jonsson, E., Martins, J. R. R. A., and Cesnik, C. E. S., “High-fidelity Aerostructural Optimization with a Geometrically Nonlinear Flutter Constraint,” *AIAA Journal*, Vol. 61, No. 6, 2023, pp. 2430–2443. doi:10.2514/1.J062127.

[62] Su, W., and Cesnik, C. E. S., “Nonlinear Aeroelasticity of a Very Flexible Blended-Wing-Body Aircraft,” *Journal of Aircraft*, Vol. 47, No. 5, 2010, pp. 1539–1553. doi:10.2514/1.47317.

[63] Gray, J. S., Mader, C. A., Kenway, G. K. W., and Martins, J. R. R. A., “Coupled Aeropropulsive Design Optimization of a Three-Dimensional BLI Propulsor Considering Inlet Distortion,” *Journal of Aircraft*, Vol. 57, No. 6, 2020, pp. 1014–1025. doi:10.2514/1.C035845.

[64] Hendricks, E. S., and Gray, J. S., “pyCycle: A Tool for Efficient Optimization of Gas Turbine Engine Cycles,” *Aerospace*, Vol. 6, No. 87, 2019. doi:10.3390/aerospace6080087.

[65] Yildirim, A., Gray, J. S., Mader, C. A., and Martins, J. R. R. A., “Boundary Layer Ingestion Benefit for the STARC-ABL Concept,” *Journal of Aircraft*, Vol. 59, No. 4, 2022, pp. 896–911. doi:10.2514/1.C036103.

[66] Lamkin, A. H. R., Yildirim, A., Martins, J. R. R. A., and Wukie, N. A., “Advancements in Coupled Aeropropulsive Design Optimization for High-Bypass Turbofan Engines,” *AIAA Aviation Forum*, San Diego, CA, 2023. doi:10.2514/6.2023-3591.

[67] Abdul-Kaiyoom, M. A. S., Yildirim, A., , and Martins, J. R. R. A., “Coupled Aeropropulsive Design Optimization of an Over-Wing Nacelle Configuration,” *AIAA SciTech Forum*, 2023. doi:10.2514/6.2023-0327.

[68] Chauhan, S. S., and Martins, J. R. R. A., “RANS-Based Aerodynamic Shape Optimization of a Wing Considering Propeller-Wing Interaction,” *Journal of Aircraft*, Vol. 58, No. 3, 2021, pp. 497–513. doi:10.2514/1.C035991.

[69] Chauhan, S. S., and Martins, J. R. R. A., “RANS-Based Aerodynamic Shape Optimization of a Wing with a Propeller in Front of the Wingtip,” *Aerospace*, Vol. 11, No. 512, 2024. doi:10.3390/aerospace11070512.

[70] Pacini, B., Prajapati, M., Duraisamy, K., Martins, J. R. R. A., and He, P., “Understanding Distributed Propulsion on the NASA Tiltwing Concept Vehicle with Aerodynamic Shape Optimization,” *AIAA Scitech Forum 2023*, 2023. doi:10.2514/6.2023-0143.

[71] Pacini, B., Prajapati, M., Duraisamy, K., Martins, J. R. R. A., and He, P., “Towards Aerostructural Optimization for Urban Air Mobility Vehicle Design,” *AIAA Scitech Forum 2023*, 2023. doi:10.2514/6.2023-0326.

[72] Whiteside, S. K. S., Pollard, B. P., Antcliff, K. R., Zawodny, N. S., Fei, X., Silva, C., and Medina, G. L., “Design of a Tiltwing Concept Vehicle for Urban Air Mobility,” Tech. Rep. May, NASA Langley Research Center, Hampton, Virginia, 2021.

[73] Pacini, B., Yildirim, A., Davoudi, B., Martins, J. R. R. A., and Duraisamy, K., “Towards Efficient Aerodynamic and Aeroacoustic Optimization for Urban Air Mobility Vehicle Design,” *AIAA Aviation Forum 2021*, 2021. doi:10.2514/6.2021-3026.

[74] Pacini, B., Prajapati, M., Duraisamy, K., Martins, J. R. R. A., and He, P., “Towards Mixed-Fidelity Aero-Structural-Acoustic Optimization for Urban Air Mobility Vehicle Design,” *AIAA Aviation Forum*, 2023. doi:10.2514/6.2023-3905.

[75] Brelje, B., and Martins, J. R. R. A., “Electric, Hybrid, and Turboelectric Fixed-Wing Aircraft: A Review of Concepts, Models, and Design Approaches,” *Progress in Aerospace Sciences*, Vol. 104, 2019, pp. 1–19. doi:10.1016/j.paerosci.2018.06.004.

[76] Brelje, B. J., Jasa, J. P., Martins, J. R. R. A., and Gray, J. S., “Development of a Conceptual-Level Thermal Management System Design Capability in OpenConcept,” *NATO Research Symposium on Hybrid/Electric Aero-Propulsion Systems for Military Applications (AVT-RSY-323)*, Trondheim, NO, 2019. doi:10.14339/STO-MP-AVT-323.

[77] Adler, E. J., Brelje, B. J., and Martins, J. R. R. A., “Thermal Management System Optimization for a Parallel Hybrid Aircraft Considering Mission Fuel Burn,” *Aerospace*, Vol. 9, No. 5, 2022. doi:10.3390/aerospace9050243.

[78] Anibal, J., Mader, C. A., and Martins, J. R. R. A., “Aerodynamic shape optimization of an electric aircraft motor surface heat exchanger with conjugate heat transfer constraint,” *International Journal of Heat and Mass Transfer*, Vol. 189, 2022, p. 122689. doi:10.1016/j.ijheatmasstransfer.2022.122689.

[79] Anibal, J. L., and Martins, J. R. R. A., “Adjoint-based shape optimization of a plate-fin heat exchanger using CFD,” *Applied Thermal Engineering*, 2024. doi:10.1016/j.applthermaleng.2024.123570.

[80] Adler, E. J., Lamkin, A. H. R., and Martins, J. R. R. A., “Ducted Heat Exchanger Thermal and Aerodynamic Shape Optimization,” *34th Congress of the International Council of the Aeronautical Sciences*, Florence, Italy, 2022.

[81] Brelje, B. J., Anibal, J., Yildirim, A., Mader, C. A., and Martins, J. R. R. A., "Flexible Formulation of Spatial Integration Constraints in Aerodynamic Shape Optimization," *AIAA Journal*, Vol. 58, No. 6, 2020, pp. 2571–2580. doi:10.2514/1.J058366.

[82] Brelje, B. J., and Martins, J. R. R. A., "Aerostructural Wing Optimization for a Hydrogen Fuel Cell Aircraft," *Proceedings of the AIAA SciTech Forum*, 2021. doi:10.2514/6.2021-1132.

[83] Hajdik, H. M., Pacini, B., Yildirim, A., Brelje, B. J., and Martins, J. R. R. A., "Combined systems packaging and aerodynamic shape optimization of a full aircraft configuration," *AIAA Aviation Forum*, San Diego, CA, 2023. doi:10.2514/6.2023-3589.

[84] Lyu, Z., and Martins, J. R. R. A., "Aerodynamic Design Optimization Studies of a Blended-Wing-Body Aircraft," *Journal of Aircraft*, Vol. 51, No. 5, 2014, pp. 1604–1617. doi:10.2514/1.C032491.

[85] Mader, C. A., Kenway, G. K., Martins, J. R. R. A., and Uranga, A., "Aerostructural Optimization of the D8 Wing with Varying Cruise Mach Numbers," *18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA, Denver, CO, 2017. doi:10.2514/6.2017-4436.

[86] Secco, N. R., and Martins, J. R. R. A., "RANS-based Aerodynamic Shape Optimization of a Strut-braced Wing with Overset Meshes," *Journal of Aircraft*, Vol. 56, No. 1, 2019, pp. 217–227. doi:10.2514/1.C034934.