Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA30030

A Review of Current Status and Future Trends in Aerodynamic Optimization of Civil Airliners

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Abstract. In recent years, civil aviation has increasingly focused on improving aerodynamic performance to reduce fuel consumption and emissions. This emphasis is driven by rising fuel costs and stricter environmental regulations, thereby prompting the industry to explore innovative drag reduction strategies. This study reviews passive and active flow-control systems applied to large commercial aircraft, aiming to provide an in-depth assessment of their effectiveness and development potential. Based on a survey of relevant literature, these studies can be categorized into five areas: airfoil design, micro-vortex generators, pulsed blowing and suction, plasma actuators, and multidisciplinary design optimization (MDO) frameworks. Then, each approach is analyzed with respect to drag reduction, the complexity of implementation, and the extent of experimental validation. The results show that passive devices offer advantages in simplicity and reliability, whereas active control and AI-based MDO systems demonstrate high adaptability and optimization potential. Building on this, it also discusses future trends, like morphing wing designs and integration with green aviation, serving as a reference for future aircraft aerodynamic optimization.

Keywords: Aerodynamic Optimization, Passive and Active Flow Control, Multidisciplinary Design Optimization (MDO), Morphing Structures, Sustainable Aircraft Design

1. Introduction

In both civil aviation and its associated research, aerodynamics is critical, since the sector generates around 2.5% of human-induced CO_2 emissions. In recent years, rising fuel prices and increasingly stringent environmental regulations have encouraged ongoing efforts to explore innovative methods for drag reduction. By enhancing aerodynamic performance, fuel use, emissions, and operational costs can be lowered, supporting sustainable aviation. While extensive research has been conducted on passive and active flow-control technologies, comprehensive evaluations for large commercial aircraft remain relatively limited, and their integration within multidisciplinary design optimization (MDO) frameworks has not been fully explored. This situation makes it challenging to thoroughly understand the advantages, limitations, and potential synergies of different aerodynamic strategies. Thus, this study reviews the literature on both conventional aerodynamic optimization methods and novel active control techniques, organizing the research into five key areas: airfoil design, micro-vortex generators, pulsed blowing and suction, plasma actuators, and MDO frameworks. Then, each approach is evaluated with respect to its drag reduction performance, effectiveness across various

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DOI: 10.54254/2755-2721/2026.KA30030

flight conditions, and implementation feasibility. By integrating these findings, this paper aims to provide an overview of the current state of aerodynamic optimization for large commercial aircraft, summarize the strengths and weaknesses of each method, and highlight potential research directions and applications for sustainable aircraft design, offering guidance for future development.

2. Aerodynamic optimization technologies

There are two primary types of aerodynamic optimization technologies, passive and active, both designed to minimize drag, postpone flow separation, and enhance overall aerodynamic efficiency. Passive methods enhance performance by adjusting the aircraft's structure or shape without using additional energy, while active methods actively modify the flow field through external actuation. Their respective advantages and limitations are considered, as well as the potential for synergistic application of the two approaches.

2.1. Passive aerodynamic optimization techniques

Passive aerodynamic optimization improves airflow characteristics via fixed structural or geometric modifications without requiring external energy. These methods are straightforward, reliable, and cost-effective, and are widely used in commercial aircraft design, where maintainability and energy efficiency are paramount.

In particular, the shape of the airfoil plays a critical role in determining lift-to-drag ratio, shock wave formation, and boundary layer behavior. Optimization of airfoils for varying flight conditions typically involves techniques such as adjoint solvers, evolutionary algorithms, or machine learning. For example, supercritical airfoils are widely adopted in modern jet airliners, delaying shock wave formation in transonic flows and thereby improving cruise efficiency. Recent studies on biomimetic airfoils, inspired by natural flow-control mechanisms, can minimize drag by promoting the stability of laminar flow regions [1]. Besides, winglets are among the most successful passive improvements in commercial aviation. By modifying the wingtip shape, they weaken wingtip vortices and reduce induced drag, thus directly boosting fuel efficiency. Moreover, computational fluid dynamics (CFD) analyses show that optimized passive winglets can significantly reduce induced drag, especially for narrow-body aircraft [2]. Moreover, surface textures and microstructures represent effective passive optimization strategies. For example, riblets and micro-patterned surfaces, inspired by shark skin, have been empirically shown to mitigate turbulent skin friction and lower overall drag, while micro vortex generators (MVGs) enhance boundary layer energy, delaying flow separation and improving cruise stability [3]. These devices operate without active control systems, can be readily integrated into existing aircraft designs, and require minimal structural modifications.

2.2. Active flow control techniques and methods

By applying external energy, active flow control (AFC) actively regulates the airflow in real time. Unlike passive approaches, this approach can be actively adjusted or toggled, enabling enhanced adaptability to different flight stages and aerodynamic challenges. It holds significant potential for enhancing high-lift performance, managing stall, and providing real-time drag control.

In pulsed blowing and suction, a common AFC method, air is cyclically introduced or removed in key boundary layer regions to preserve shear layer stability and delay flow separation [4]. By adjusting the frequency and amplitude of the pulses, these systems can substantially reduce pressure drag and increase lift, particularly at high angles of attack. Although experiments have exhibited its

DOI: 10.54254/2755-2721/2026.KA30030

aerodynamic benefits, high energy consumption and integration difficulties with existing systems have limited its widespread application, leading to hybrid design approaches that combine passive shaping with localized actuation. Moreover, plasma actuators are active devices that produce near-surface body forces via dielectric barrier discharge (DBD), imparting momentum to the boundary layer to suppress flow separation [5]. Their lightweight, fast response, and ease of integration make them well-suited for high-lift devices and stall control. Recent studies indicate that DBD plasma actuators can improve the aerodynamic performance of two-dimensional airfoils, though attaining adequate control effectiveness at high Reynolds numbers remains a technical challenge. Besides, other typical active methods include synthetic jets, flexible surfaces, and adaptive shape control systems. Specifically, synthetic jets create local disturbances without adding mass, allowing precise flow control, whereas adaptive surfaces alter shape in flight to handle changing aerodynamic loads. With feedback control, these systems show strong potential, though challenges remain in durability, energy supply, and control algorithms [6]. By enabling real-time flow control, active systems raise complexity, energy demand, and maintenance requirements, while ongoing efforts focus on actuator efficiency and sensor-algorithm integration.

2.3. Comparison and applications of the techniques

In terms of function, active and passive aerodynamic optimization technologies complement each other. Passive devices are well-suited for cruise conditions and retrofitting existing fleets, as they reduce drag and boost efficiency while keeping operational complexity low and maintenance simple. In contrast, active systems require more energy and involve system integration but can manage critical flow regions on demand, such as during takeoff, landing, or abrupt flight condition changes.

Based on comparisons, active technologies perform well in managing local flow phenomena, whereas passive approaches are usually more dependable and cost-efficient. Consequently, hybrid systems that integrate both methods are gaining increased interest. For instance, airfoil designs can be integrated with pulsed blowing systems or plasma actuators to enhance stall margin and cruise efficiency [5,7]. These hybrid methods fit current trends in adaptive aircraft design and morphing structures, integrating technologies to adjust dynamically to flight condition changes. Due to their maturity and clear cost-effectiveness, passive technologies currently dominate modern civil aircraft design. However, advances in sensor technology, control algorithms, and lightweight actuators are rapidly driving the development of active and hybrid systems. This trend indicates that future aircraft aerodynamic systems will be more efficient and adaptable, delivering optimal performance across a wider range of flight conditions.

3. Performance comparison and comprehensive evaluation

3.1. MDO fundamentals and frameworks

By integrating aerodynamics, structures, propulsion, and control systems, Multidisciplinary Design Optimization (MDO) enables the design of aircraft configurations that approach global optimality. Unlike traditional sequential design, MDO simultaneously accounts for the coupling effects among disciplines, making design space exploration more efficient and balanced, while supporting overall performance optimization of complex aircraft systems. In high-fidelity aero-structural optimization, computational fluid dynamics (CFD) and finite element analysis (FEA) are often combined, with gradient-based solvers employed to guide the optimization process [8]. For architecture selection, MDO commonly adopts Multidisciplinary Feasible (MDF), Individual Discipline Feasible (IDF), or

DOI: 10.54254/2755-2721/2026.KA30030

hybrid frameworks [9]. In MDF, all disciplinary constraints are integrated under a central optimizer, making it suitable for tightly coupled systems but computationally costly. In IDF, disciplines solve independently, with coordinating variables updating the global solution, improving efficiency for high-dimensional systems. Hybrid architectures leverage the benefits of both approaches, achieving higher computational efficiency while preserving accuracy. By using coupled derivatives, gradients are solved faster, and design changes can simultaneously boost aerodynamics and structural loads. In terms of applications, Bons et al. applied an MDO framework to transonic wing optimization and found that coupled aero-structural optimization could reduce wing drag coefficient by about 4%, while improving structural stress distribution [10]. This highlights the importance of disciplinary coupling in achieving improved overall performance in practical aircraft design.

3.2. Performance assessment and multicriteria evaluation

Traditional aerodynamic metrics, like lift-to-drag ratio, drag coefficient, flow attachment, and stall margin, are no longer sufficient for comprehensively evaluating modern aircraft performance, and modern aircraft must address fuel efficiency, noise, emissions, and lifecycle environmental impact. Thus, performance assessment requires a multicriteria, multidisciplinary framework that considers discipline-specific results and trade-offs between objectives [10,11]. In this context, multi-criteria decision-making (MCDM) methods are widely used in aircraft design. By quantifying and ranking the performance of design alternatives across different criteria, MCDM can highlight the strengths and weaknesses of each design and support balanced decision-making among conflicting objectives. For example, Pareto frontier analysis can determine optimal compromises, while weighted scoring integrates fuel consumption, emissions, noise, and flight performance into a single metric.

To tackle complex design spaces and high computational costs, surrogate models and Bayesian optimization are introduced in the performance assessment process. These approaches enable rapid prediction of the effects of design variable changes on performance metrics, allowing designers to efficiently screen and rank numerous design alternatives while reducing the number of high-fidelity simulations. They also support multi-objective trade-off analysis by quantifying the advantages and disadvantages of different designs in terms of fuel consumption, noise, and emissions, and provide real-time or near-real-time decision support to accelerate design iterations [12]. By applying multi-criteria evaluation and quantitative decision-making, modern aircraft design balances performance, environmental impact, and operational efficiency, supporting optimization and design.

3.3. Adaptive and integrated aerodynamic optimization techniques

To optimize performance across different flight phases or mission conditions, adaptive aerodynamic technologies adjust wing shape, control surfaces, and flow control strategies dynamically. In this context, MDO frameworks integrate these technologies, coordinating aerodynamics, structures, and propulsion in one optimization loop. In adaptive optimization, Kenway and Martins applied aero-structural MDO to transport aircraft configurations. They showed that changing wing geometry and structure boosts lift efficiency across cruise conditions while also keeping structural loads uniform. This method effectively mitigates performance variations arising from changes in angle of attack and flight speed [8]. Further, Bons et al. found that simultaneous wing and structural optimization decreases local drag, boosts aerodynamic efficiency, and enhances static stability in transonic wings [10]. Moreover, active aerodynamic control techniques are also critical in integrated optimization. Mosca et al. incorporated boundary-layer suction into the MDO loop, controlling flow separation points on key wing sections to reduce drag by around 2 to 3% and improve wing load distribution.

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This illustrates the capability for close integration of active control with aero-structural optimization [13]. In the integration of aerodynamics and propulsion, Luo et al. applied MDO to capture the coupling between wing and propulsor layout, achieving simultaneous improvements in lift, drag, and propulsion efficiency. This enables practical design solutions for new distributed or embedded propulsion architectures [11]. In industry, Priem et al. combined Bayesian optimization with MDO at Bombardier, efficiently exploring high-dimensional design spaces under limited computational resources and integrating passive, active, and hybrid aerodynamic technologies with structural and propulsion systems [12].

4. Emerging trends and future prospects

4.1. Integrated aero-propulsive optimization

Under evolving industry demands, aerodynamic design is changing significantly. Traditional single-objective optimization focused on lift-to-drag ratio is gradually being replaced by multi-objective, system-level optimization. These methods balance aerodynamic efficiency with cost-effectiveness, operational performance, and environmental impact. Besides, the aviation industry faces increasing pressure from tighter noise and emission regulations, higher fuel costs, and stronger decarbonization goals, thus driving a shift in aerodynamic design philosophy. In this context, the deep integration of aerodynamics with structures and propulsion systems has become critical. By leveraging advanced MDO frameworks, aerodynamic-propulsion optimization achieves simultaneous adjustment of wing planform layout, fuselage positioning, and propulsion system integration, which reduces drag and boosts propulsive efficiency [9,11]. For emerging distributed propulsion and hybrid-electric aircraft, this integrated approach is especially important, as aerodynamics and propulsion demonstrate strong, nonlinear interactions. However, emerging aircraft configurations like blended-wing-body, tailless, and truss-braced wings present considerable aerodynamic challenges. Despite their potential to boost performance, these configurations necessitate new flow control and optimization strategies to tackle intricate boundary layer growth, flow separation at the wing-fuselage junction, and lowered static stability. Enabled by high-fidelity simulations, MDO frameworks are vital tools for tackling complex multidimensional design spaces

4.2. Intelligent adaptive development

Driven by several new technologies, aerodynamic optimization is undergoing significant changes. Intelligent algorithms, like machine learning, evolutionary computation, and Bayesian optimization, are increasingly used to build fast and high-accuracy surrogate models, accelerating design-space exploration [12]. These methods enable complex configurations to be optimized in real time or near real time, reducing reliance on traditional brute-force CFD or FEA evaluations. Besides, morphing structures represent another promising direction. For example, wings that can change shape or adapt can adjust their configuration during flight to optimize performance across different phases (takeoff, cruise, landing). Moreover, new materials, such as shape-memory alloys and piezoelectrics, along with lightweight structures, are speeding up the development of morphing technologies. Importantly, recent studies indicate that integrating morphing surfaces into MDO frameworks can enhance lift, drag, noise, and control effectiveness simultaneously. High-fidelity digital simulation environments and digital twins enable close integration of simulation, optimization, and validation, significantly reducing the time needed to assess new aerodynamic concepts. In particular, digital twins support continuous interaction between design and operational data, allowing adaptive optimization across

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the aircraft lifecycle. Meanwhile, the integration of green aviation is becoming an important focus of future aerodynamic research. Thus, optimization must align with electric and hybrid propulsion, sustainable aviation fuels (SAF), and NOx/contrail reduction. As a result, designs will be judged on both flight performance and full lifecycle environmental impact [11].

5. Conclusion

This paper reviews the current status, methods, and future directions of aerodynamic optimization for civil aircraft, exploring passive and active flow-control technologies and their application within MDO frameworks. Specifically, passive technologies, such as optimized airfoils, winglets, surface texturing, and micro-vortex generators, consistently reduce drag due to their simplicity, reliability, and cost-effectiveness. In contrast, active methods, including plasma actuators, synthetic jets, and pulsed blowing and suction, are more flexible and allow real-time control, but they require more energy and increase system complexity. Studies show that hybrid strategies combining passive and active elements can therefore enhance overall performance. Meanwhile, MDO frameworks play a key role in integrating aerodynamic, structural, propulsion, and operational objectives, and high-fidelity simulations, derivative-based computations, and multi-objective decision-making methods make MDO a powerful tool for addressing complex design problems and improving performance across various flight conditions. Looking ahead, aerodynamic optimization is moving toward multi-objective, integrated, and adaptive design. In this context, new propulsion systems, blended wing bodies, tailless aircraft, advanced digital design environments, and technologies such as intelligent algorithms, morphing structures, and digital twins are expected to enable efficient, flexible, and environmentally friendly aircraft designs. As a result, aerodynamic optimization is evolving from individual component enhancements to comprehensive multidisciplinary approaches, designed to ensure high performance and environmental sustainability in future civil aviation.

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