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Editorial: Recent developments in aerodynamics

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Editorial on the Research Topic
Recent developments in aerodynamics

This editorial paper examines the cutting-edge advancements in aerodynamics, a critical field within fluid mechanics, with wide-ranging applications in aviation, automotive engineering, wind energy, and beyond. As aerodynamics evolves, it influences the design of aircraft, turbines, vehicles, and energy systems, necessitating specialized tools and methods for in-depth research and application. Recent advancements in experimental techniques, computational methods, material science, and flow control technologies are driving significant changes in aerodynamic design and performance. Figure 1 presents a detailed chart illustrating the recent advancements in aerodynamic tools, methodologies, technologies, and applications.

Experimental aerodynamics, particularly through sub-scale and full-scale testing and flight experiments, will make significant strides with the development of advanced sensors, instruments, and measurement systems. For example, the future of time-resolved PIV is expected to be shaped by technological advancements in imaging, data processing, and integration with emerging techniques. Future developments could allow researchers to observe flows over multiple scales simultaneously, helping to link small-scale turbulent dynamics with large-scale flow structures and improve our understanding of turbulence at all scales. The combination of higher resolution, real-time analysis, multi-dimensional measurements, and the use of machine learning will make PIV an even more powerful tool for studying aerodynamics. Wind tunnel testing will remain a crucial method for assessing aircraft performance, particularly in different flight phases (Taleghani et al., 2020; Zhang et al., 2024; Arthur, 2024). Simultaneously, computational tools, such as CFD, will progress. More accurate simulations of airflow around complex geometries are now possible, with techniques like LES (Tonicello et al., 2022) and DNS (Chiarini and Quadrio, 2021) offering higher resolution but at the increased computational cost. Machine learning and artificial intelligence are also gaining importance in aerodynamics, enabling the optimization of designs, improving CFD accuracy, and developing new turbulence models (Sabater et al., 2022). CFD is anticipated to undergo a paradigm shift with the integration of artificial intelligence and machine learning, enabling faster, more accurate simulations of complex flows, including turbulent and hypersonic regimes.

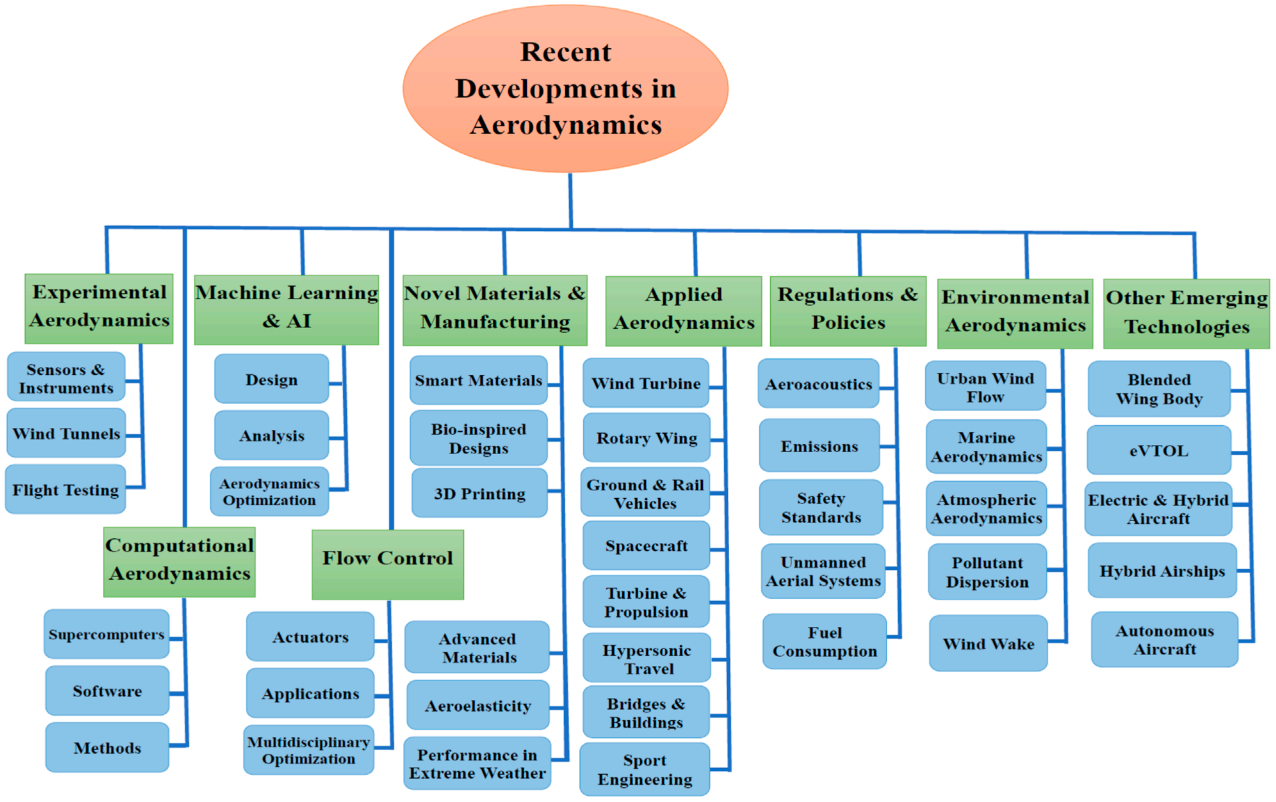

FIGURE 1
Chart of the key research domains in recent developments in aerodynamics.

Flow control technologies, which optimize aerodynamic performance by manipulating natural airflow around structures, have evolved considerably. Advances in actuators, including modulated pulse jets (Abdolahipour et al., 2022a; Abdolahipour et al., 2022b), plasma actuators (Taleghani et al., 2018), model-free closed-loop systems (Ren et al., 2024), and hybrid methods (Azadi et al., 2024), aim to enhance control, reduce energy consumption, and improve robustness. These technologies will become particularly useful in applications where efficient aerodynamic performance is critical under varying conditions. These innovations are expected to enhance both the performance and sustainability of next-generation aircraft. Material science will continue to play a pivotal role in improving aerodynamic performance. Lightweight composites, shape-memory alloys, and advanced materials like polymeric gyroid structures (Overbeck et al., 2024) are being developed to reduce weight, enhance structural integrity, and lower drag. Finally, smart materials with adaptive surface properties will enable real-time optimization of drag and lift, ushering in a new era of dynamic, responsive aerodynamic systems. These advancements, underpinned by computational, material, and environmental innovations, will redefine the role of aerodynamics in addressing global challenges and driving technological progress. Additionally, the rise of 3D printing technology has revolutionized the production of complex aerodynamic components, enabling the creation of intricate shapes previously difficult to manufacture. This capability will open new avenues for optimizing designs in aerospace and automotive applications.

Nature has long been a source of inspiration for aerodynamic design. Bio-inspired aerodynamics (De Manabendra et al., 2024), which studies natural flight patterns and fluid dynamics in animals, is expected to become an even more prominent field in engineering solutions. For example, the study of owl wings (Harbi Monfared et al., 2022) has led to the development of quieter flight mechanisms, which are particularly beneficial for urban air mobility applications. By mimicking the aerodynamic features of birds and fish, engineers are developing more efficient designs for both aircraft and wind energy systems. Biomimetic approaches inspired by natural systems, such as bird flight and marine locomotion, are expected to revolutionize aerodynamic design, enhancing energy efficiency and adaptability. Applied aerodynamics bridges theoretical fluid dynamics with practical engineering challenges. Researchers are increasingly focusing their efforts on the design of vehicles (including aircraft, spacecraft, drones, and cars) to withstand extreme weather conditions such as turbulence, crosswinds, and heavy rain. For aircraft, this involves developing systems to predict and manage weather-related disturbances. In automotive design, the focus is on optimizing aerodynamics for all-weather conditions, improving both safety and efficiency. Hypersonic vehicles, which face extreme aerodynamic and thermal stresses, will benefit from new materials and models designed to maintain stability at high speeds.

Hypersonic aerodynamics will see significant breakthroughs in thermal management and flow control, facilitating safer, more stable designs for high-speed vehicles. Recent innovations in wind energy, such as optimized blade aerodynamics and turbine layout, have made wind power generation more efficient and sustainable (Torabi, 2022). Renewable energy systems, particularly wind turbines, will benefit from refined blade aerodynamics to maximize energy capture while minimizing environmental impacts. These advancements will reduce the number of turbines needed, minimizing the environmental footprint of wind farms while increasing power output. Aerodynamics will also play a pivotal role in the optimization of fuel efficiency and stability for both ground vehicles and rail systems. Effective aerodynamic design is essential for minimizing air resistance, improving handling, and maximizing energy efficiency in vehicles such as trucks, buses, and electric cars.

Regulations and policies significantly influence aerodynamic design. Safety standards established by agencies like the FAA and EASA will drive innovations in structural integrity and aerodynamic efficiency. As concerns regarding climate change intensify, policies designed to reduce emissions and fuel consumption, such as the ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), are likely to encourage the development of aircraft with enhanced aerodynamic efficiency (Taleghani et al., 2024). Regulations targeting noise pollution at urban airports will also lead to quieter aircraft designs, fostering advancements in technology and methodology. Additionally, policies supporting sustainable aviation technologies, including electric and hybrid propulsion systems, will encourage the development of novel aerodynamic solutions tailored to these emerging systems. In aviation, sustainable technologies will lead to ultra-efficient airframes optimized for electric and hydrogen propulsion, complemented by noise-reduction techniques critical for urban air mobility. Aerodynamics is also essential for understanding environmental phenomena such as air pollution, weather patterns, and climate change. By studying airflow and atmospheric dynamics, researchers can better predict and mitigate the impact of human activities on the environment (Christia et al., 2022). For example, urban airflow studies can inform city planning and improve pollution control strategies. The interdisciplinary field of environmental aerodynamics combines fluid dynamics, meteorology, and environmental science to address real-world challenges and enhance sustainability.

Innovative designs such as the blended wing-body concept (Gray and Zingg, 2024), which integrates the wings and fuselage into a single structure, will continue to improve aerodynamic efficiency by reducing drag and minimizing turbulence at the junction of wings and fuselage. This design is expected to allow for better lift-to-drag ratios, leading to reduced fuel consumption and increased efficiency. The exploration of electric and hybrid propulsion systems will drive further aerodynamic advancements. As electric aircraft become more viable, optimizing their aerodynamic performance will be essential for maximizing range and efficiency. Researchers will focus on designs that take into account the unique characteristics of electric motors and batteries, allowing for more efficient electric aircraft. Looking forward, several key areas are poised to shape the future of aerodynamics. One such area is the development of autonomous aircraft, which require innovative aerodynamic designs to ensure stability and control in real-time (Deniz et al., 2024). Advanced control surfaces and wing configurations are being studied to adapt to changing flight conditions autonomously. Another promising direction is the integration of renewable energy sources, such as solar-powered aircraft, which would require specialized aerodynamic designs to maximize energy efficiency and reduce reliance on fossil fuels. The growth of urban air mobility solutions, such as eVTOL aircraft (Simmons and Busan, 2024), presents unique aerodynamic challenges. The design of these vehicles must prioritize efficiency in urban environments, where concerns regarding noise and safety are particularly salient. Aerodynamic innovations will play a key role in ensuring the success of these emerging transportation solutions.

In conclusion, the field of aerodynamics continues to advance, driven by innovations in experimental methods, computational techniques, materials, and regulatory frameworks. As new challenges emerge in the design of autonomous, electric, and sustainable aircraft, aerodynamic research will remain central to addressing these issues and shaping the future of transportation and energy systems. The future evolution of aerodynamics is poised to be shaped by interdisciplinary innovation and sustainability imperatives, driving advancements across aviation, automotive, renewable energy, and space exploration. This Research Topic encompasses the latest developments in flow control, simulation methods, applied aerodynamics, and propulsion design, reflecting the multi-disciplinary nature of modern aerodynamic research.

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