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Editorial

The Key Role of Research in Flight Dynamics, Control, and Simulation for Advancing Aeronautical Sciences

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1. Introduction

In the evolving field of research on civil and commercial aviation, the study of flight dynamics, control, and simulation is pivotal for technological progress. Indeed, these research areas are critical for enhancing the performance, safety, and efficiency of modern aircraft, and striving towards advanced and novel solutions. An in-depth understanding and characterization of flight dynamics are fundamental for comprehending and improving aircraft performance. As aviation moves towards more fuel-efficient and environmentally friendly designs [1,2], precisely predicting and controlling aircraft behavior under varying conditions has become increasingly important. This is not only essential for optimizing aircraft configurations, but also for ensuring stability and handling qualities that meet the stringent requirements of modern aviation. Innovative configurations, such as those proposed in refs. [3–5], require a thorough characterization from dynamic behavior, performance predictions, and safety perspectives. Flight mechanics tools and their advancements are therefore essential in this context. Control systems are intimately tied to flight dynamics. Sophisticated control algorithms allow for the precise management of increasingly complex and automated aircraft systems. The integration of advanced control strategies ensures that aircraft can operate safely and efficiently, even in challenging scenarios. Furthermore, the interaction between human pilots and automated systems is increasingly relevant, with research focused on optimizing this relationship to reduce pilot workload and improve overall reliability. Finally, simulation plays a pivotal role in bridging theory and practice. High-fidelity simulations allow researchers and engineers to test new concepts, validate models, and predict performance [6–10]. As the aviation industry faces pressure to reduce costs and increase safety, simulation provides a critical platform for rigorous testing without the risks and expenses associated with real tests. Furthermore, validated simulation platforms allow for reliable predictions even in the very early design stage, accelerating the development of new aeronautical technologies, such as novel propulsion integrations like hybrid electric [11–13] or hydrogen propulsion [14–16]. The advancement of simulation technologies is making it possible to explore new frontiers in aircraft design and operating performance, supporting the drive towards innovation.

This brief editorial is devoted to research advancements in this context, presented in the dedicated Special Issue "*Flight Dynamics, Control & Simulation*" of the *Aerospace* journal and available in open access format here: [17]. The motivation for this Special Issue was to collect the most up-to-date contributions on the application of flight dynamics models to the characterization of transport aircraft aeromechanic features. Great emphasis was placed on simulation models used to analyze the performance of aircraft with a high degree of innovation, whether in terms of architecture, systems, or propulsion. In addition, the development and validation of new methodologies for aeromechanical analysis and optimization, advanced simulation, novel flight control techniques, and flight dynamics analysis tools for multidisciplinary design workflows were highly relevant contributions that increased the knowledge in the field. In the following section, an overview of the papers published on this Special Issue is offered.

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2. Overview of the Published Articles

This Special Issue features 14 papers that discuss the study and applications of flight dynamics and simulation in a cross-cutting and multifaceted manner, featuring specific topics from different fields. The following is a summary outlining them and highlighting their main findings.

Ref. [18] uses specialized simulation tools to investigate the mission performance of regional aircraft equipped with hybrid electric propulsion systems. The study highlights how hybrid electric aircraft exhibit distinct operational characteristics compared to conventional thermal aircraft, particularly in terms of payload–range trade-offs. The research demonstrates that hybrid electric propulsion offers significant advantages, including reduced fuel consumption and extended operational range, especially for short regional missions (around 250 nautical miles). These findings underscore the potential of hybrid electric technology in reducing the environmental impact of regional aviation. Additionally, the study emphasizes the importance of optimizing power management strategies to further enhance performance.

Ref. [19] presents a method for accurately identifying lateral–directional aerodynamic parameters during early-stage aircraft design using wind tunnel virtual flight tests. The authors' model decouples the effects of free flight aerodynamics and support forces, and their method achieves high accuracy, with less than 10% difference from conventional wind tunnel measurements. The approach simplifies the identification process and enables the early validation of aerodynamic models, contributing to a shorter development cycle and reduced costs in aircraft design. The method is particularly beneficial for improving dynamic testing precision in wind tunnels.

Ref. [20] investigates the dynamics of a free-falling wing in airdrop launch technology for UAVs, focusing on the effects of the moment of inertia (MOI) and center of mass (COM) position. The study adapts the Andersen–Pesavento–Wang quasi-steady model to analyze the wing's motion, validated through CFD and experiments. The results show that changes in MOI and COM significantly impact the wing's behavior, leading to either tumbling or fluttering during free fall. This highlights the importance of carefully configuring the COM in UAV design to avoid destabilizing motions, which is crucial for the safety and performance of airdrop-launched UAVs.

Ref. [21] introduces a simulation model for analyzing aircraft take-off dynamics, suitable for the conceptual design phase of both traditional and innovative aircraft configurations. The model incorporates ground-effect aerodynamics, which significantly influence aircraft performance during take-off. The study compares a conventional tube-and-wing aircraft with a box-wing configuration, revealing key differences in their aerodynamic and dynamic behavior near the runway. The box-wing design shows advantages in lift, drag, and pitch dynamics due to its sensitivity to ground effects. The model's versatility and low computational cost make it a valuable tool for early-stage aircraft design.

Ref. [22] investigates the aerodynamic performance of a new aircraft concept with a box-wing configuration and rear-mounted engines, focusing on the benefits of boundary-layer ingestion (BLI). Wind tunnel tests using 1:28-scale models demonstrated that the BLI configuration improved propulsive efficiency by reducing jet velocity and power consumption by at least 7.41% compared to traditional designs. However, BLI also introduced flow distortion that could affect performance. These findings emphasize the potential of BLI to enhance aero-propulsive efficiency, though further research is needed to fully understand its impact on real aircraft performance, especially at full scale and in actual flight conditions.

Ref. [23] investigates the jump-takeoff method for autogyros through simulation experiments with a high-confidence autogyro model. Using a simplified blade element theory, the study optimizes jump-takeoff performance by adjusting collective angle, prerotation speed, rotor diameter, and blade tip weighting. Key findings include the significant impacts of rotor diameter on jump-takeoff height and blade tip weighting on rotation speed decay. The research provides theoretical standards and practical guidelines for optimizing autogyro jump-takeoff, offering valuable insights for future experimental work and rotor design in autogyro engineering.

Ref. [24] presents a novel flight control design for variable-sweep morphing aircraft, combining dynamic inversion with L1 adaptive control. The approach integrates nonlinear dynamic inversion (NDI) and incremental NDI for control decoupling, along with LQR and L1 adaptive control to enhance robustness and accuracy. Simulation results demonstrate that this method significantly improves command tracking performance compared to conventional controllers, with notably lower tracking errors and better robustness against uncertainties. The proposed control scheme is promising for optimizing the performance of morphing aircraft under varying flight conditions, showing superior results in both attitude and path control scenarios.

Ref. [25] introduces a novel nonlinear rigid–elastic coupled model to analyze Category II rotor-body–slung-load coupled oscillation (RBSLCO) in helicopters with a 2.5–8 Hz frequency range. The model integrates rotor dynamics, fuselage elasticity, and cable stretching. Key findings include the following: The strongest RBSLCO occurs with maximum slung load, which increases rotor–fuselage coupling and reduces stability margins by up to 15%. Lightweight loads can also cause a distinct RBSLCO mode involving fuselage bending and cable stretching. Finally, improper cable stiffness may lead to a "vertical bouncing" phenomenon characterized by high-frequency anti-phase and low-frequency in-phase oscillations.

Ref. [26] uses Kane's equation for analyzing airdrop dynamics, specifically addressing status continuity during the out-of-cabin process and parachute line behavior in extra-vehicular scenarios. By applying Kane's equation, the study simplifies complex dynamics without extensive derivations. Key contributions include the analysis of payload dynamics and safety using Kane's equation, and the application of a neural network for predicting payload status with notable efficiency. Additionally, the spring network method was utilized to model parachute line behavior. The findings highlight Kane's equation's potential in enhancing precision airdrop missions with minimal reliance on experimental data.

Ref. [27] presents a cooperative control strategy for multi-quadrotor suspension systems, leveraging consistency theory and nonlinear control techniques. A detailed eight-degree-of-freedom model incorporates load dynamics and swing effects. The study introduces a formation control algorithm based on virtual piloting and designs both integral backstepping and backstepping sliding mode controllers. These controllers manage quadrotor position, attitude, and load swing, ensuring precise trajectory tracking and reduced load oscillation. Stability is established via Lyapunov functions. Simulation results demonstrate that the proposed method significantly improves control accuracy and load swing suppression compared to traditional backstepping methods.

Ref. [28] introduces a virtual flight testing (VFT) platform for large-scale, high-speed wind tunnels to address nonlinear coupling issues in aerodynamics, flight mechanics, and control during high maneuvers. The VFT integrates a three-degree-of-freedom model, aerodynamic and motion measurement devices, and a virtual control system, enabling realistic simulation of maneuvers and verification of flight control laws. The platform effectively identifies pitch and roll coupling at high angles of attack and validates control strategies for decoupling these motions. Following comparisons with real flight data, the results confirm the VFT's reliability and its potential to reduce flight test risks and costs.

Ref. [29] introduces a novel architecture for a fully autonomous autorotative flare, integrating rapid trajectory generation with model-based control. The approach uses optical Tau theory to compute longitudinal and vertical flare trajectories, which are tracked using a nonlinear dynamic inversion (NDI) control law. This NDI approach avoids complex gain scheduling by relying on linearized models for steady-state autorotation, and demonstrates effective trajectory tracking in UH-60 aircraft simulations. The proposed method accurately mimics piloted maneuvers and predicts successful landing conditions, offering a versatile solution for autonomous flare control across different rotorcraft configurations.

Ref. [30] presents a novel anti-input saturation control method for hypersonic flight, integrating Radial Basis Function Neural Networks (RBFNNs) with adaptive control theory. The approach includes an RBFNN adaptive controller and a specialized anti-saturation auxiliary system. Simulation results demonstrate a significant reduction in error fluctuations by over 50% and a 20% improvement in convergence speed under severe input saturation constraints. These advancements enhance control accuracy and system robustness, marking substantial progress in hypersonic vehicle control. The method's effectiveness in real-world scenarios suggests the improved performance and adaptability of hypersonic flight control systems.

Ref. [31] investigates control laws for Urban Air Taxis (UATs) facing urban airflow disturbances, using a linearized flight dynamics model based on Bell Nexus 4EX aircraft features. It compares the effectiveness of Proportional–Integral–Derivative (PID) and Active Disturbance Rejection Control (ADRC) systems. The study finds that while PID control reduces passenger accelerations to acceptable levels, ADRC further improves performance by reducing lateral accelerations to below discomfort levels. ADRC also outperforms PID in handling urban turbulence. This research advances urban air mobility by demonstrating the superior efficacy of ADRC in mitigating passenger discomfort in dynamic urban environments.

3. Concluding Remarks

Transport aviation research is constantly facing complex and ambitious new challenges. Novel aircraft concepts, types of propulsion, techniques for aircraft control, and overall disruptive innovations are increasingly being studied, investigated, and developed. The study of flight dynamics has always been of particular relevance in investigating the behavior of innovative transport aircraft, assessing their stability and controllability characteristics, and evaluating their performance. Depending on the level of fidelity used, flight simulation models, methods, and tools make it possible to characterize the aeromechanical behavior of aircraft at any stage of the design process, from the initial conceptual stages to the most advanced detailed analysis. Such models are relevant to the advancements of different fields of transport aeronautics, such as the enhancement of flight safety, the optimization of mission performance, the development of new concepts for aircraft operations (e.g., urban air mobility), and the establishment of virtual certification methods. These areas are crucial for the aeronautical sciences, driving the development of new technologies that will define the future of aviation.

As the industry continues to evolve, research in these domains must remain a priority to ensure that civil and commercial aviation can meet the demands of tomorrow's challenges with safety, efficiency, and ingenuity. For this reason, the second edition of the Special Issue "*Flight Dynamics, Control & Simulation*" of the *Aerospace* journal has been opened and is available here: [32]. This Special Issue is intended to be a platform for the most up-to-date research on the subject, in continuity with what is proposed in this editorial. All researchers involved in these topics and enthusiastic to share their latest findings are cordially invited to contribute to this Special Issue.

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