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Editorial

Rotary Wing Aerodynamics

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1. Introduction

Rotary wing aerodynamics represents a widely investigated topic due to this discipline's large number of applications in several fields of engineering and physics. Indeed, rotating lifting bodies provide quite complex and unsteady flow structures that have a robust influence in rotorcraft, aeronautical propulsion, turbomachinery and wind energy fields. Consequently, a deep knowledge of the main classical phenomena related to rotary wing aerodynamics, such as dynamic stall or blade–vortex interactions (BVI), to cite a few, is an essential step to improving the performance of helicopters or wind turbines.

In recent years, research effort in the field of rotary wing aerodynamics was focused on the study of rotor–rotor and rotor–body aerodynamic interactions. This interest was influenced in the aeronautical field by the recent great development efforts devoted to the design of unconventional vertical take-off and landing (VTOL) aircraft for urban air mobility (UAM). Indeed, recent improvements in electric motors and battery technologies present an opportunity for new concepts of personal aviation that will provide benefits to ground traffic in overcrowded metropolitan areas and will also improve the performance of logistics services. Distributed electric propulsion represents a key feature in the design of these new VTOL air vehicles, well-known as eVTOLs. Their architecture is characterised by multi-rotor and multi-wing configurations that highlight unprecedented aerodynamics challenges with respect to classical aircraft or rotorcraft configurations. Indeed, the occurrence of several different interactional effects between propellers and lifting bodies has a profound impact on aircraft performance and noise impact. Thus, a deeper understanding of the complex interactional aerodynamics features characterising eVTOL vehicles represents a milestone to be achieved before the next-generation UAM aircraft can soar through the skies of our metropolitan areas. In recent years, the field of wind energy research has also paid great attention to the phenomena of rotor–rotor interactional aerodynamics due to the great effort spent on the development of wind farms. Indeed, a thorough understanding of the complex aerodynamic interactions occurring between wind turbine wakes or the study of effective wake redirection techniques can be considered essential key points to improve power capture and reduce structural loading for wind farms application.

The desire to enhance our knowledge concerning the study of rotary wing aerodynamics has spurred researchers, scientists, and engineers to develop effective tools in both the experimental and numerical fields. These tools were essential to optimise the design process of novel machines or infrastructures characterised by configurations of single or multiple rotating lifting bodies, particularly aiming in improve their performance, structural dynamics, handling qualities, and acoustic impacts. Experimental activities in this research field were mainly based on wind tunnel tests performed over test rigs reproducing the dynamics of real rotors blades. Particular effort was devoted to the development of pitching airfoil test rigs capable of reproducing both the dynamics and the real flow conditions of a rotor blade section. Wind tunnel campaigns using these test rigs were highly useful for the study of the dynamic stall process, which represents a phenomenon that negatively influences both the aerodynamic performance characteristics and structural

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dynamics of helicopters and wind turbine rotors. A step forward concerning the investigation of classical aerodynamic phenomena characterising a rotor was achieved using whirl towers test rigs. These experimental rigs reproduced the complete mechanical system of real rotor hubs but on a smaller scale, thus showing a high manufacturing complexity related to the miniaturisation of their main constitutive parts, such as hinges, pitch rods, and actuators. Nevertheless, these test rigs enabled researchers to operate under monitored laboratory conditions, thus contributing to the achievement of more detailed insights with respect to real operative stands and to the highly unsteady flow features characterising rotating blades. A particular boost to the knowledge of flow physics in this research area was provided by recent developments in the field of optical measurement techniques. The use of Particle Image Velocimetry (PIV), particularly in stereoscopic or time-resolved modes, for instance, has enabled researchers to fully describe the fine details of the dynamic stall process over retreating rotor blades or to analyse several flow mechanisms typical of blade–vortex interactions (BVI). Moreover, recent advances in Pressure-Sensitive Paint (PSP) or Infrared Thermography (IR) measurements enabled researchers to accurately investigate transient aerodynamic phenomena, such as flow separation or the laminar to turbulent boundary layer transition, occurring over rotating blade surfaces without using intrusive probes.

Numerical tools were also effective in recent studies concerning rotary wing aerodynamics. Indeed, the advances achieved in recent years in the field of high-performance computing has allowed an increase in the use of high-fidelity Computational Fluid Dynamics (CFD) solvers for investigating the complex interactional aerodynamics phenomena typical of rotary wing machines. These solvers, based on a finite-volume implementation of the Reynolds Averaged Navier–Stokes (RANS) equations, enables researchers to manage moving block-structured grids, particularly using the Chimera technique, thus easily performing complex simulations of vehicles characterised by multiple rotors and lifting bodies. Consequently, these numerical tools were successfully employed for aerodynamics studies of helicopters and complex rotorcraft vehicles, such as tiltrotors or compounds. Moreover, high-fidelity CFD tools were also widely used for wind turbines and turbomachinery simulations. High-fidelity solvers were thoroughly validated in the field of rotary wing aerodynamics research, as their solutions present a quite accurate agreement with wind tunnel measurements. Nevertheless, despite the advances in high-performance computing, time-accurate RANS simulations still require very high computational effort in terms of time and resources in applications of rotary wing machines. For this reason, high-fidelity CFD tools are usually employed for a limited number of simulations of a well-defined configuration of such complex vehicles. As a matter of fact, the high-fidelity numerical approach to aerodynamics is still not suitable for the preliminary design process of novel rotary wing machines which require a huge number of simulations. Consequently, in recent years, the attention to mid-fidelity numerical approaches to rotary wing aerodynamics, combining numerical models with different accuracy, is growing among researchers and engineers working in this field. Mid-fidelity solvers typically represent a combination of a boundary value problem based on potential methods and a vortex particles model of vorticity for the flow. In particular, the vortex particle method (VPM) is a grid-free model suitable to accurately reproduce the strong aerodynamic interactions occurring among wakes that are typical of complex rotary wing machines, such as eVTOLs or wind farms. Thus, a mid-fidelity numerical approach to rotary wing aerodynamics simulations represents an optimal trade-off between accuracy and computational effort. Indeed, the capability of mid-fidelity tools to obtain solutions for complex rotary wing vehicles in high agreement with experimental results, but with a limited computational time with respect to high-fidelity CFD solvers, have opened a new scenario in the design process of novel rotary wing machines.

The goal of this Special Issue is to collect experimental and numerical studies showing recent advancements in the study of rotary wing aerodynamics. Due to the transversal content of this topic, the Special Issue attracted works from both aerospace engineering and wind energy specialists. In particular, the Special Issue contains six articles. Three articles deal with rotorcraft aerodynamics applications, i.e., two numerical studies on innovative rotorcraft configurations such as eVTOL aircraft [1] and tiltrotors [2] and an experimental-numerical study aiming to study the fine wake details of a helicopter's main rotor [3]. Two articles deal with wind turbine aerodynamics applications, i.e., an experimental activity aimed to develop both aerodynamic and structural strategies to design an experimental model of a wind turbine rotor [4] and a numerical study aiming at the duct optimisation of a vertical-axis wind turbine finalised to power enhancement [5]. The last article describes a trade-off activity between rotorcraft and wind energy research fields, showing the results of piloted simulations to determine possible risks associated to wind turbine interactions in rotorcraft operations [6]. The next section includes a brief overview of these articles, pointing out their main findings and their novelties with respect to the state-of-the-art in the field of rotary wing aerodynamics research.

2. Special Issue Articles' Short Review

The first article collected in the Special Issue by Piccinini et al. [1] describes a numerical activity aimed at performing a systematic study of the aerodynamic interactions between two propellers, with applications to eVTOL aircraft flight conditions. As previously mentioned, these aircraft represent the greatest novelty in the aeronautical field developed in recent years. These aircraft configurations are widely investigated throughout the world, and even though very different layouts are under development, a common key feature of their architecture is represented by multiple propellers positioned in side-by-side and tandem configurations over single or dual-lifting surfaces. Consequently, a systematic study of the basic flow mechanisms involved in the aerodynamic interaction between two propeller represents a milestone in the development and optimisation of these novel aircraft configurations. This work provides interesting guidelines for eVTOL design. Indeed, the mid-fidelity numerical solver employed in this study was suitable to capture the fine details of the interactional flow field characterising the investigated propeller configurations. In addition, the numerical investigation provided a quantitative indication about the interactional effects on the propellers' aerodynamic performance by highlighting the propellers' performance losses due to their mutual separation distance and the different degree of overlap between their rotor disks. Moreover, this work showed that numerical results with a high level of accuracy compared to experiments could be obtained by a solver requiring a very low computational effort with respect to high-fidelity CFD tools. Thus, the outcomes of this activity confirmed for scientific and industrial communities the suitability of a mid-fidelity numerical approach to aerodynamics for the preliminary design and optimisation of novel eVTOL aircraft configurations which require a huge number of simulations to investigate the several phases characterising the flight mission of these vehicles.

The second article collected in this Special Issue by Muggiasca et al. [4] is focused on the investigation of "best practices" to be adopted to perform experiments on scaled wind turbine blade models. As a matter of fact, experimental activities have a key role in the investigation and development of wind energy technologies. In particular, the present article is focused on the strategies of designing a scaled wind turbine blade model suitable for obtaining a fluid–structure interaction comparable to real machine blades. In particular, applications to rotor blade models for wind tunnel tests as well as natural laboratory tests were considered by the authors. This work considers both the aerodynamic and structural design of a floating wind turbine blade model, showing that non-Froude performance scaling can favour the reproduction of the full-scale rotor's aerodynamic behaviour and can improve its agreement with the real wind turbine's thrust coefficient while also preserving the power coefficient shape.

The third article collected in this Special Issue by De Gregorio et al. [3] describes an experimental and numerical activity aimed at investigating the wake of a helicopter rotor in the hovering condition in detail. This article represents a successful attempt to combine a quite modern experimental technique such as PIV with a classical numerical method, i.e., the free-wake Boundary Element Methodology (BEM), to study a complex problem in the field of rotary wing aerodynamics, i.e., the investigation of the vortex decay process during the downstream convection of a rotor wake in hovering conditions. In particular, the thorough comparison between experimental and numerical results highlights the degree of accuracy provided by a lower-order numerical method such as BEM to capture the trajectory of the filament vortex and in the interest of the complex interactions occurring between the tip vortices issued by rotating blades. Consequently, the outcomes of this article provide quite interesting indications to validate low-order numerical methods for the investigation of complex aerodynamics problems typical of classical rotary wing applications. Indeed, as previously stated, the validation of low-order numerical tools with increasing accuracy represents an essential task for the development of novel rotorcraft vehicle configurations.

The fourth article collected in this Special Issue by Ranjbar et al. [5] turns readers back to the investigation of wind turbine aerodynamics. In particular, the article is focused on the aerodynamic performance optimisation of a quite interesting machine in the wind energy field, i.e., a vertical-axis-ducted wind turbine. The article illustrates in detail a successful numerical activity aimed to optimise the duct's geometry used to collect the flow over a wind turbine rotor for the purposes of power enhancement. This work illustrates an effective example of the capabilities of a modern numerical tool to perform all the steps required for an aerodynamics geometry optimisation problem, from geometry and mesh generation to solver setup and simulations execution. In particular, the numerical results presented in this article clearly highlight the need for a high-fidelity aerodynamic solver based on Navier–Stokes equations equipped with a suitable turbulence model to properly describe the vortical structure's evolution typical of the deep dynamic stall phenomena occurring on wind turbine rotor blades.

The fifth article collected in this Special Issue by Savino et al. [2] turns the reader's attention back again to the rotorcraft research field, particularly with a focus on an interdisciplinary activity connecting aerodynamics to structural dynamics. The main goal of this work is to underline the importance of a more accurate aerodynamic numerical model for aeroelastic studies of complex rotary-wing aircraft. The article illustrates a novel numerical tool obtained by coupling a VPM-based, mid-fidelity aerodynamic solver to a multibody dynamics code. This tool is completely open source. The numerical results shown in this article, obtained by coupled simulations reproducing a full tiltrotor during a transient rolling manoeuvre, confirm that the use of VPM for the modelling of rotating blade wakes introduces an apparent benefit for the evaluation of rotor aerodynamic loads and consequently improves the aeroelastic assessment of rotary-wing aircraft configurations typically characterised by complex interactional aerodynamic features. Moreover, the quite limited computational effort shown by this coupled numerical tool supports the suitability of this enhanced approach to aerodynamics finalised to obtain higher accuracy in the preliminary design of novel rotary-wing vehicles.

The sixth article by Strbac et al. [6] brings readers to an interdisciplinary scenario where wind turbine aerodynamics plays a significant role in rotorcraft piloting. This work deals with helicopter operations within an offshore wind farm environment, with particular focus on the interaction between wind turbine wakes and helicopter flight paths. The approach used to investigate this problem is quite novel and interesting. Indeed, the use of high-fidelity CFD methods for modelling the far- and near-wake flow field of a wind turbine superimposed as input to a flight simulator campaign enabled the authors to obtain realistic information for piloting helicopters in the maritime environment of a wind farm. As a matter of fact, the outcomes of this work provide significant and appreciable indications for avoiding potential risks for helicopter operations in these complex scenarios by suggesting the proper size of the flight corridor and a sufficient lateral safety clearance near offshore wind turbines.

3. Conclusions

The articles published in this Special Issue cover a wide range of research topics in the main key areas of rotary wing aerodynamics. High-quality experimental and numerical techniques highlighted how to deal with such complex physical problems in a modern and effective way. Furthermore, these works provide insights that must be considered very useful to enhance knowledge in this discipline and to favour innovative developments both in rotorcraft and wind energy research areas. Indeed, the investigated topics are widely investigated by the scientific and industrial research community, and I thoroughly believe that the collected works will spur further authors to deepen the findings disseminated by the present Special Issue.

Generally, I would like to thank all the authors for the precious work devoted to the activities disseminated in the present Special issue and to the manuscript's preparation. The collected works meet the high-quality standard of *Energies*, and I hope that future Special Issues of this journal could consolidate the interest of the research community concerning rotary wing aerodynamics, particularly deepening topics related to electrical air mobility and wind farms applications.

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