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Introduction: Rotor Wakes

THIS special issue of the *Journal of Aircraft* concerns the improved understanding and prediction of rotor wake aerodynamics of helicopters and tilt rotors. This task continues to be of fundamental importance in defining blade aerodynamics, and in evaluating new and improved rotor designs that are more efficient in hover and forward flight, show lower vibration levels, and are also acoustically quieter. The papers emphasize that the proper understanding and modeling of the flow field surrounding a rotor still remains a terribly difficult problem. Yet, success is fundamentally important to the accurate prediction of blade airloads and rotor performance, and absolutely critical for the design of better performing rotors. Furthermore, the increasing emphasis on designing rotors for reduced noise has made it necessary to develop wake methods that must provide for substantially increased spatial and temporal fidelity over what was considered acceptable just a few years ago.

The topology of a rotor wake is dominated by strong vortices, trailed from the tips of each blade. The nature of the rotor wake, in terms of its structure and the aerodynamic effects, is sensitive to the operating state and flight condition of the rotorcraft. In hovering flight, the tip vortices follow interlocking, nominally helical, trajectories below the rotor. During forward flight, the vortices are skewed back behind the edgewise moving rotor, and a more complicated wake is produced. In descending and maneuvering flight, or when landing or taking off, more of the wake may remain near the rotor, producing further distortions to its evolving topology, which can be a source of increased unsteady, aperiodic, three-dimensional airloads, and also leads to the production of obtrusive rotor noise. In most flight conditions, it is the sustained proximity of the wake to the rotor blades that is the key factor that makes the wake analysis much more complicated compared to a fixed-wing aircraft. Most rotor analysts would argue that the airplane people have it easy!

The papers in this special issue of the journal represent work in a variety of areas of rotor wake analysis, using a number of different techniques, including analytical, numerical, and experimental approaches. The papers by no means represent every facet of ongoing work, but they do represent a fair sample of the approaches being used and developed. Some of the papers contain reviews of techniques that have matured over time, whereas other papers report on newer developments. It will be clear to the reader, however, that a better understanding of rotor aerodynamics remains a truly challenging effort that must be approached from several complementary modeling and experimental perspectives.

The tremendous advances in computers over the last 20 years have played a large part in the development of better and more complete computational techniques for rotorcraft aerodynamics analysis. Problems that were considered intractable, or were relegated to super-computers, are now solvable on desktop workstations. Yet, bigger problems and more ambitious numerical techniques continue to challenge the limits of computer speeds and memory capabilities, with the ultimate (albeit elusive) goal to predict the aerodynamics around an entire rotorcraft in an arbitrary flight condition. Modern Navier–Stokes methods, solved numerically on Eulerian grids, have made great inroads toward this goal, but for many practical problems the nonphysical numerical diffusion of wake vorticity produces errors in the wake solution. This has led to the development of adaptive gridding or vorticity capturing schemes. Lagrangian based vortex methods also circumvent these problems, at the expense of some fidelity, but retain the accuracy and high numerical efficiency that is necessary for detailed rotor design work. Still other wake methods, although parsimonious, are often required in some rotor applications because of their efficiency and attractive mathematical structure.

The highly three-dimensional nature of a helicopter rotor wake, as well as the sensitivity of the wake to the geometric and operational parameters of the rotorcraft, means that measuring faithfully the details of what actually happens at the rotating blades is rather daunting. Advances in experimental techniques such as three-component laser Doppler velocimetry and particle image velocimetry have been substantial, and now allow better measurements to be made with a fidelity that was impossible even just a few years ago. However, there are still many challenges in the development of better instrumentation, specialized measurement techniques, and in the assessment of measurement accuracy and uncertainty. The continued acquisition of high quality experimental data inside the rotor wake is essential for the thorough validation of mathematical models.

There are many unanswered questions in understanding the formation and evolution of the blade tip vortices themselves, especially in terms of their induced velocity field, their laminar/turbulent structure, and the effects of blade and vortex Reynolds numbers. Because of the proximity of blades to tip vortices and the mutual interactions between the vortices, the validity of extrapolating results measured in simplified, sub-scale laboratory experiments is still open to question. The dearth of quality empirical data, and data that can be independently corroborated, continues to impede the development of properly validated vortex models. Another complication is that the blade tip shape, such as sweep, taper, and anhedral, is known to affect the structure of the blade tip vortex as it is trailed off into the wake, and a better understanding of these effects poses a significant challenge to the analyst.

As this special issue shows, the field of rotorcraft aerodynamics, particularly the subject of rotor wakes, will continue to challenge the rotorcraft analysts of the future with some of the most fascinating problems in fundamental fluid dynamics and applied aerodynamics.

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