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THE FRENCH AEROSPACE LAB

PROPOSITION DE SUJET DE THESE

Intitulé : Vorticity Transport Model for Rotary Wings Aircraft : application to the predesign of Advanced hybrid VTOL aircraft

Référence : TIS-DTIS-2024- 03
(à rappeler dans toute correspondance)

Début de la thèse : September or October 2024	**Date limite de candidature :** May 2024

Mots clés

Predesign rotorcraft, helicopter, eVTOL, flight performances, Multidisciplinary Design Analysis and Optimization (MDAO), rotary wings and fixed wings aerodynamic interferences

Profil et compétences recherchées

Ecole d'ingénieur aéronautique ou M2R en mécanique des fluides, English – French speaking

School of aerospace engineering or Master in Applied mathematics, python programming

Présentation du projet doctoral, contexte et objectif

Context : With the new predesign paradigm based on Distributed Electric Lift and Propulsion, more and more aircraft concepts combine multi-rotors and wings for increasing the Air Mobility by bringing both the Vertical Take-Off and Landing capability and good cruising performance. The aerodynamic interaction between these close and numerous rotary and fixed wings have of course significant impacts: on the required powers, on the efficiency of the controls, on the aircraft trim and dynamics ... In hover and low speed flights as well as in nearly vertical climb and descent, the lifting propellers generate strong airwakes which remain close to the aircraft and induce significant velocities on their blades and on the other parts of the aircraft. In transition phases between hover and cruise, the rotors wakes are progressively skewed backwards which may induce strong velocity variation on some of the aircraft parts like the wings and empennage stabilizers. These interferences must be taken into account as soon as possible in the predesign and evaluation of a new aircraft concept.

ONERA is working on the development of models and methods to simulate and to assess these interferences both at DTIS/RFDS from the flight dynamics and controls point of view and at DAAA/H2T from the aerodynamic stand point. For the purpose of the preliminary concept studies requiring very numerous and thus rapid steady flight performance assessment, as well as for the purpose of flight dynamics and controls application, the models must be much more rapid than CFD approaches. Moreover these High Fidelity methods (including Lattice Boltzmann and Immersed Boundary) are not suited to preliminary conception at early stage when a fine geometrical description of the aircraft is not available for providing accurate meshes definition.

Objective: the main goal of the thesis will be to study the interest of the Vorticity Transport Method (VTM) for the predesign of Advanced VTOL air vehicles combining either multiple rotors or both rotary wings and fixed wings.

Compared to CFD approaches, more rapid and simpler methods in terms of both implementation, use and lower computational cost, have been studied at ONERA for the calculation of the rotor induced velocity field. The main examples are: the Finite State Unsteady Wake (FiSuW and now FSW3D in its last 3 Dimensional implementation), different kinds of Free Wake Models (FWM using vortex lines or lattices or sheets), Vortex Particle Model (VPM), Leading Edge Vortex Method (LDVM) …

The LDVM is in principle limited to 2D description of the airflow around a profile. The FSW3D is by principle based on a potential airflow assumption which can hardly be applied within the rotor wake (although Prof. Peters and his Ph.D. students found a way that we implemented in FSW3D). With respect to FWM and VPM, the most important difference is that VTM is an Eulerian description of the airflow field whereas FWM and VPM are Lagrangian methods. This has several important advantages.

First of all in VTM, the fluid is represented by its vorticity as a 3 Dimensional volumetric field described on a mesh with adaptable accuracy. In FWM and VPM, vortex singularities (2D with vortex sheets, 1D with vortex filaments, 0D with blobs) are emitted from the lifting elements in a time marching approach. So it takes a certain time to evacuate the first vortices which have been emitted in absence of a fully developed rotor wake and thus may “pollute” the airflow with some non-physical effects. A more physical topology of the vorticity distribution is obtained from the beginning and preserved by the VTM. In practice, this means that the vortex entities within FWM and VPM representation often do not evolve properly according to the underlying physics in certain critical circumstances, because they do not interact as they should.

Secondly, the use of the underlying mesh in the VTM means that one can use rigorous metrics to make sure that the method maintains its accuracy and stability throughout a calculation. For long calculations, such is always required when dealing with the Vortex Ring State (VRS) on rotors in descending flights, this can be crucial. If errors build up in the numerics, then the representation of the physics deteriorates as the vorticity gets older and older, and if this vorticity is close to the rotor (in VRS some of the vortices near the rotor have been there for dozens of rotor revolutions) then the accuracy of the calculation suffers very badly.

This need of having a significant long description of the rotor wake in terms of rotor wake revolutions conserved within the wake is critical and recurrent in many cases, e.g. : in hover and even more in hover or low speed flights near the ground or obstacles, in descending flights and especially in VRS or autorotation ... The VTM is able to keep in the rotor wake simulation hundreds of rotor revolutions while still keeping a good control over the numerical space and time steps.

Therefore the two main big advantages of VTM are:

+ a direct representation of the whole flow field through the topology of its vorticity distribution,

+ the mathematical control over accuracy and stability of this structure.

Another one is that the method is conservative, meaning that a calculation run at low resolution just gives low-resolution results compared to one run at high resolution, not fundamentally different answers. This can be a big problem with FWM and VPM, which are more sensitive in the sense the wake geometry can sometimes "jump" from one type of solution to another as the number of elements in the calculation is increased.

Regarding the interferences between a rotor wake and other parts of the air vehicle, some issues can raise with FWM when some vortex elements (like lines or sheets) are stretched or cut or deformed by another physical part of the aircraft (e.g. blades, wings, fuselage etc.). The advantages of the VTM come again from the grid-based representation of the vorticity (the surface of the wing or fuselage is known accurately with respect to the vorticity in the flow) and the accurate and stable treatment of the physics. For example reference [2] examined the effects of rotor wake interaction with the fuselage and tail of a compound helicopter on various issues including trim, performance, vibration and acoustics.

The **main tasks** will be:

- A careful and comprehensive state of the art comparing the different methods for the modeling of the rotor induced velocities field,
- The implementation of the VTM method into the ONERA flight dynamics code DynaPyVTOL,
- The study of the interest of this approach on critical phenomena affecting the eVTOL predesign and mission profile definition, mainly regarding interferences and VRS through their impact on safety, performance, control …

References:

R.E. Brown, “Efficient high-resolution wake modeling using the vorticity transport equation", AJ Line, AIAA journal 43 (7), 1434-1443.

Kim, H.W. and Kenyon, A.R. and Duraisamy, K. and Brown, R.E. (2008) “Interactional aerodynamics and acoustics of a propeller-augmented compound coaxial helicopter”, 9th American Helicopter Society Aeromechanics Specialists' Meeting, 23-25 January 2008, San Francisco, California

R.E. Brown, “Are eVTOL Aircraft inherently more susceptible to the Vortex Ring State than Conventional Helicopters ?”, 48th European Rotorcraft Forum, Winterthur, Switzerland, 6-8 Sept. 2022.

P.M. Basset, R. Perret: “Failure Analysis Method for the Presizing of Multi-Rotors eVTOL”, 48th European Rotorcraft Forum, Winterthur, Suisse, 6-9 September 2022.

J.M. Vegh, P.-M. Basset, N. Beals, R. Scott, R. Perret, R. Singh : “A comparison of three conceptual design approaches applied to an electric distributed lift aircraft”, 49th European Rotorcraft Forum, Bückeburg, Germany, September 2023.

Collaborations envisagées

Richard E. Brown qui est le meilleur spécialiste de cette approche VTM et de son application aux voilures tournantes est d’accord pour nous apporter son expertise et son soutien technique dans cette thèse. Ancien Professeur à l’université de Glasgow, il travaille actuellement à : Sophrodyne Aerospace (United Kingdom) https://sophrodyne-aerospace.com

Laboratoire d’accueil à l’ONERA	**Directeurs de thèse**
Département : Traitement de l'information et systèmes	Nom : P.M. Basset & Thomas Leweke
Lieu (centre ONERA) : Salon-de-Provence	Laboratoire : DTIS/RFDS & IRPHE-CNRS
Contact : Pierre-Marie Basset	Tél. : +33 4 1355 2061
Tél. : 04 90 17 01 13 Email : basset@onera.fr	Email : thomas.leweke@cnrs.fr

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