PROPOSITION DE SUJET DE THESE

Intitulé : Data-driven turbulence modeling for rotor-stator cavity flows in space turbopumps

Référence : **MFE-DAAA-2026-11**
(à rappeler dans toute correspondance)

Début de la thèse : Automne 2026	**Date limite de candidature : 30/06/2026**

Mots clés

Data assimilation, linear mean-flow analyses, machine learning, rotating flows, optimal sensor placement

Profil et compétences recherchées

Master 2/diplôme d'ingénieur en mécaniques des fluides et/ou mathématiques appliquées. Expérience en simulation numérique pour la mécanique des fluides souhaitée.

Présentation du projet doctoral, contexte et objectif

Unsteady flow phenomena within rotor–stator cavities are recognized as critical contributors to detrimental vibrations in space turbopumps, an example of which is shown in Figure 1. Although various palliative strategies are typically incorporated during the design phase, experimental investigations frequently reveal persistent high-amplitude flow oscillations capable of compromising the structural integrity of turbomachinery components and, in severe cases, the rocket engine as a whole. These cavity flows are characterized by rotating, three-dimensional turbulent boundary layers that are inherently unstable and prone to the development of complex flow structures, such as spiral and annular modes. Traditional computational approaches, such as Reynolds-Averaged Navier–Stokes (RANS) simulations, have demonstrated significant limitations in accurately capturing these unsteady dynamics. In contrast, Large Eddy Simulation (LES) has emerged as a more promising methodology, offering improved fidelity in predicting such flow behaviors under variable operating conditions, albeit at a substantially higher computational cost [2,3].

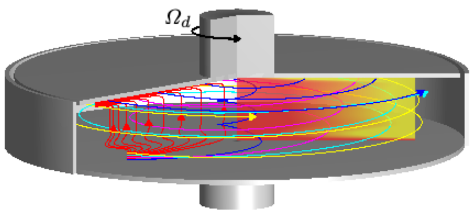

Figure 1: Schematic from [1].

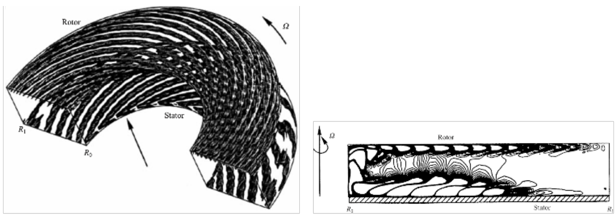

Figure 2: LES simulations of rotor-sator cavity [2].

In this project, we aim to obtain RANS-based flow predictions whose fidelity is comparable to that in more expensive approaches such as LES. To this end, it is proposed to rely on the following two-step approach. In a first step, reference data, which may come from either high-fidelity simulations or experiments, are assimilated to correct the steady RANS equations and the associated mean-flow solution. In a second step, linear mean-flow analyses are performed to give access to the unsteady content of the flow. Compared to previous studies [4], one of the main challenges of the present project is to extend the above-described methodology to the prediction of complex flow dynamics as present in rotating cavity systems. To achieve this, we will in particular consider the use of non-intrusive, ensemble-based variational techniques [5] to perform the first, so-called data-assimilation step of the above methodology. A key advantage of this non-intrusive approach lies in its avoidance of direct solver differentiation, which is typically required to compute gradients in the data-assimilation procedure. Instead, gradient information is approximated through ensembles of forward RANS evaluations, making the approach both computationally efficient and compatible with legacy solvers.

Once the considered RANS turbulence model has been calibrated for a reference configuration, the next phase of the study will focus on strategies for generalizing the model to other design conditions through machine-learning techniques. While such generalization techniques have already demonstrated significant promise in simpler flow scenarios [6], their application to the more complex, highly anisotropic environments that are characteristic of turbomachinery remains largely unexplored. This work aims to extend these methods to rotor–stator cavity flows, thereby enabling the development of robust, transferable turbulence models capable of maintaining predictive accuracy across a broader range of operating regimes.

Finally, to facilitate the transition from high-fidelity simulation-based workflows to experimental applications, this study will investigate strategies for reducing the number of required measurement locations and optimizing sensor placement. In practical experimental setups, access to flow measurements is inherently limited; thus, developing a methodology that can operate effectively under sparse data conditions is essential. In the present context, we will thus here investigate the development of an optimal sensor placement strategy that should ensure a reliable estimation of both mean [7] and fluctuating flow quantities through the data-assimilated RANS model, possibly exploiting sparse sensing concepts [8]. The proposed approach will serve a dual purpose: (i) it will enable turbulence model design using limited observational data, thereby making the method directly transferable to experimental contexts, and (ii) it will provide a systematic framework for guiding experimental design. This capability holds strong potential for informing and enhancing future experimental campaigns intended to support turbulence model validation and development.

In summary, this PhD project focuses on the rotor–stator cavity flows within space turbopumps, with the objective of developing predictive and generalizable data-driven-assisted RANS models tailored to such complex configurations. The work builds upon existing collaborations with CNES and ONERA, leveraging flexible, non-intrusive methodologies to enhance model fidelity and adaptability. By combining advanced data-driven modeling techniques with high-fidelity simulation data and experimental constraints, the proposed research aims to contribute to the design of more robust, transferable turbulence models for next-generation propulsion systems.

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Collaborations envisagées

CNES

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