Institut des Sciences du Calcul et des Données

PhD Proposal
Machine-learning-assisted wall-modelled large eddy simulations of transitional flows in turbomachinery

PhD directors
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1 Context and participants

P. Cinnella is a professor of Fluid Mechanics at Institut Jean Le Rond D'Alembert, and she coordinates a new project team, **LearnFluidS**, focused on the use of machine learning components for improving the modelling of turbulent flows. The team is composed by researchers specialized in fluid dynamics, numerical methods flow fluid flows, and machine learning.
X. Gloerfelt is a professor of Fluid Mechanics at DynFluid Laboratory, and an expert in high-performance computing and high-fidelity simulations of turbulent flows. The PhD candidate will be mainly hosted at d'Alembert, and she/he will be regularly involved in the activities of LearnFluidS (seminars, brainstorming sessions, interactions with postdoc and PhD researchers in the team). Additionally, a collaboration agreement will be set so that the PhD will be granted regular access to the DynFluid Laboratory (15 minutes walk from Jussieu Campus), and benefit of additional expertise and infrastructures.

2 Motivations

Turbomachinery flows are of crucial importance for a range of engineering applications, including aeronautic and naval propulsion and ground power generation. The quest for designs with drastically reduced environmental impact requires significantly improved understanding of physical phenomena and computational models of significantly increased accuracy with respect to the existing ones. The latter rely largely on so-called RANS, Reynolds-Averaged-Navier-Stokes, approaches, alongside significant technical know-how, which become unreliable for new, uncharted designs. The understanding and modelling of flows in turbomachines raises several challenges due to the passing-wake/boundary-layer interaction, shock/boundary-layer interaction, rotation, tip and passage vortices, separation, and **transition**.
The present research is focused on the latter. Three types of transition are commonly observed in turbomachines: 1) so-called 'bypass transition', in which Tollmien-Schlichting waves are completely bypassed and turbulent spots are directly produced within the boundary layer by the influence of free-stream turbulence; 2) 'separated-flow' transition, which occurs in the free shear layer close to the reattachment point of a laminar separation bubble; 3) 'wake-induced' transition, related to the periodic excitation of the passing wakes from the upstream blades in relative motion. Furthermore, strong pressure gradients are present in turbomachines and affect significantly the evolution of transition, with favorable pressure gradient tending to delay transition and/or promoting relaminarization, and adverse pressure gradient tending to promote transition.
Transition is particularly difficult to compute and it is very sensitive to many factors, such as Reynolds number, pressure gradients, curvature, intensity and scales of the freestream turbulence, roughness, unsteadiness, etc. Most transition models employed in numerical simulations strongly rely on empirical correlations and are subject to significant uncertainties. Prediction tools vary from linear stability theories, impractical for real-world applications, to Direct numerical simulation (DNS) that resolves all flow scales but is too costly for high-Reynolds flows of engineering interest. Large Eddy Simulation (LES) can reproduce transition mechanisms accurately in presence of low upstream perturbations; on the other hand, the LES of freestream transition, remains very challenging because of the effort for resolving the external turbulence. On the RANS modeling side, some sophisticated transition models involving the solution of additional transport equations for an intermittency function or a "laminar kinetic energy" have been proposed to improve the predictions, but they still rely on

a significant amount of empiricism and tunable parameters. More recently, so-called hybrid RANS-LES approaches and Wall-Modeled-LES (WMLES) have received increasing interest, with the promise of alleviating the computational cost of LES. Unfortunately, such methods inherit the deficiencies of the underlying RANS model in transitional flows. **The development of hybrid RANS/LES and WMLES able to predict transition is then an open and very active research field**. A recent review can be found in [1].

3 Objectives

In the proposed research we plan to use accurate wall-resolved LES for investigating transition mechanisms (with focus on free-stream turbulence induced, FST, and separation induced, SEP, transition) in turbomachinery configurations. Second, we will explore the potential of machine learning techniques for producing accurate and generalizable transition models for WMLES.

The LES will rely on the in-house, high-resolution, massively parallel multiblock finite-difference solver MUSICAA (recent advances are described in [2]). The solver will be used to investigate in fine details FST and SEP transition in presence of various effects (external turbulence characteristics, pressure gradients, interaction with shock waves. . .) and for generating reference databases. The latter, along with additional databases from previous work by the same team, will constitute a unique resource for the subsequent modeling task. For such intensive computations (about 10 computations requiring $O(10^9)$ mesh points) we will further optimize the numerical strategy and develop efficient online processing tools. The calculations will be run on the MESU clusters and on the national GENCI supercomputing centers. ISCD 3D visualization facilities will be be exploited for in-depth analysis of the databases.

Subsequently, we will use the high-fidelity databases to inform data-driven transition models for WMLES. For that purpose, we will rely on a Sparse-Bayesian-Learning (SBL) algorithm recently proposed by our team for data-driven modeling of turbulent stresses [3]. The algorithm will be first extended to transition modeling problems. Afterwards, transition models learned for different transition scenarios will be fused together by using a Bayesian mixture-of-experts approach [4]. The data-driven transition model performances will be assessed for flows not employed for training, and compared in detail to standard transition models from the literature.

Previsional work

1. **First year :** Bibliography on laminar/turbulent transition in turbomachinery, and on transition models. Training to HPC flow simulations with MUSICAA. Generation of wall-resolved LES of selected transitional flow cases in turbomachinery. Parallel post-processing and analysis of transition mechanisms..
2. **Second year:** Development of SBL symbolic identification of transition models. Model training and testing. Validation against models from the literature. Writing of papers.
3. **Third year:** Machine-learning-assisted WMLES investigation of the effects of free-stream turbulence characteristics and pressure gradients on FST and SEP. Writing of papers and of the PhD manuscript.

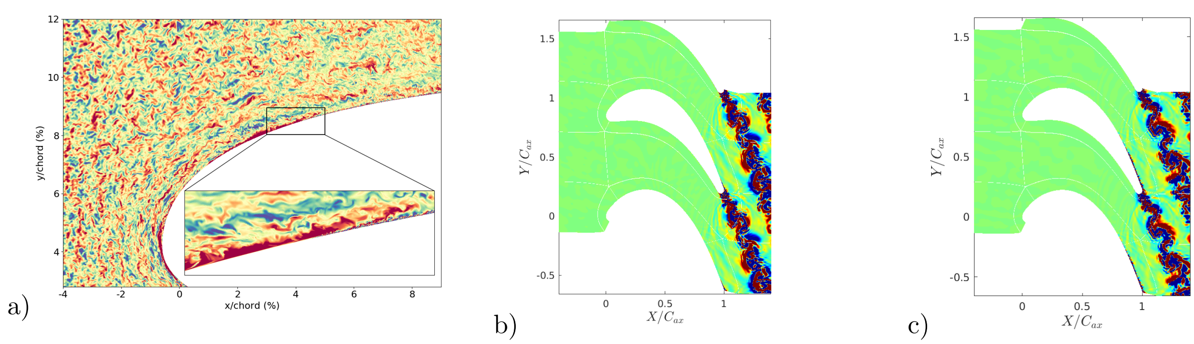

Figure 1: a) Free-stream transition over a turbine leading edge, with the transition region highlighted in the inset. b)-c) Snapshots of transverse velocity w at two instants showing the back and forth appearance of a turbulent boundary layer on the suction side of a transonic turbine with zero inlet turbulence.

References

[1] E. Dick and S. Kubacki. Transition models for turbomachinery boundary layer flows: A review. *Internationa Journal of Turbomachinery Propulsion & Power*, 2(4), 2017.

[2] A. Bienner, X. Gloerfelt, and P. Cinnella. Assessment of a high-order implicit residual smoothing time scheme for multiblock curvilinear meshes. In *Eleventh International Conference on Computational Fluid Dynamics (ICCFD11)*, Maui, USA, July 11-15 2022.

[3] S. Cherroud, X. Merle, P. Cinnella, and X. Gloerfelt. Sparse bayesian learning of explicit algebraic reynolds-stress models for turbulent separated flows. *International Journal of Heat and Fluid Flow*, 98:109047, 2022.

[4] S Cherroud, X Merle, P Cinnella, and X Gloerfelt. Spatial model aggregation (x-ma) of stochastic explicit algebraic reynolds stress models. In *2022 Symposium on Turbulence Modeling: Roadblocks, and the Potential for Machine Learning. Suffolk, VI*, 2022.