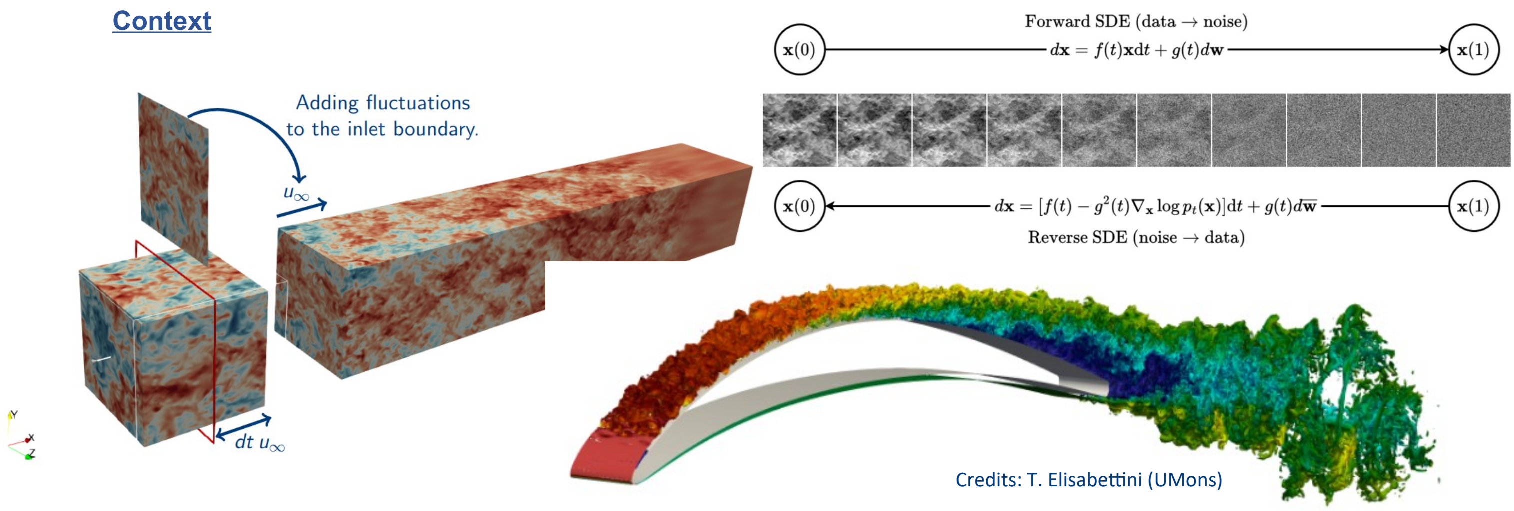
Ref.: BE-IP-2025-001

INTERNSHIP PROPOSAL

Scale-Resolving Simulations of a Low Compressor Cascade with Freestream Turbulence Injection supported by Diffusion Models

Cenaero is an applied research center that provides numerical simulation methods and tools to companies involved in a technology innovation process, allowing to invent and design more competitive products. Our ambition is to be internationally recognized as a technology leader in modeling and numerical simulation, to be a strategic partner of large global industries as well as a real support to regional companies including innovative SMEs. We are mainly active in the aerospace, process engineering, energy and building sectors, and provide expertise and engineering services in multidisciplinary simulation, design and optimization in the fields of mechanics (fluid, structure, thermal and acoustics), manufacturing of metallic and composite structures. Having a solid and recognized experience in numerical simulations and the development of methodologies and tools for turbomachinery applications, Cenaero is an official strategic R&D partner of the Safran group. In addition to providing engineering services and software development, Cenaero operates a Tier-1 supercomputing infrastructure. Our headquarters are located in Gosselies (Belgium), with a subsidiary office near Paris (France).

Context



Advances in computing power have made it possible to apply Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) techniques to more realistic compressible flow configurations, such as low-pressure compressor (LPC) cascades. In axial compressors, the occurrence of complex flow phenomena such as freestream turbulence, interaction with the upstream wake profile, and the limit of off-design conditions (e.g., flow reversal and strong pressure gradient) occur at the limit of the operating envelope, and their accurate prediction is crucial[1]. At the off-design angle of attack[2], the transition to turbulence is operated within a laminar separation bubble due to high incidence. Studying the interaction between the freestream turbulence and the laminar separation bubble is of paramount importance[3].

To ensure physically representative simulations and accurate simulation of the separation bubble, the injection of a high-quality, time-dependent inflow that mimics freestream turbulence should be implemented as a high-quality and realistic boundary condition. Since such an inflow varies stochastically and continuously in space and time, defining an ideal turbulent inflow remains a complex task. The fluctuations must mimic real turbulence, as they will affect the downstream flow dynamics. The constructed turbulent flow field should satisfy statistical turbulent characteristics in both space and

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time, be fully developed as quickly as possible after the inlet[4], and should be divergence-free to avoid the injection of spurious pressure waves (i.e., acoustic effects).

A variety of methods have been proposed in the literature to obtain such a high-quality fully turbulent inflow data with prescribed properties. They can be divided into four groups: transition-inducing methods, turbulence library-based methods, recycling-rescaling methods, and synthetic inflow generators. However, these methods can be computationally intensive, often require long inlet domain length, and introduce spurious low-frequency oscillations or unrealistic inflow characteristics. Recent advances in Machine Learning offer promising solutions to these limitations and have led to the emergence of a new category of turbulence injection.

In the class of deep generative models, Diffusion Models (DM) have recently emerged as powerful tools for generating high-quality images, while being simpler to define and more efficient to train. A novel data-driven turbulence injection method has been developed at Cenaero for the generation of three-dimensional boxes of velocity fluctuations of Decaying Homogeneous Isotrpic Turbulence (DHIT) conditioned by a Turbulent Kinetic Energy (TKE) level[5]. The physical representativeness of the generated samples was assessed both *a priori* and *a posteriori* using first and second order statistics such as the energy spectrum, the autocorrelation functions, the vorticity distribution and the anisotropic state of the Reynolds stress tensor. The '*fake*' fluctuations were injected in a free domain (i.e., without solid walls) and good agreement with the original library-based method, already implemented in Argo-DG, Cenaero's flow solver, was observed.

Objectives

The aim of this work is to extend the *a posteriori* evaluation of the novel data-driven turbulence injection to a more complex and realistic configuration, a low-pressure compressor cascade designed by Safran Aero Boosters and measured at the Von Karman Institute, aiming at investigating fine grained flow mechanisms resulting from solidity variations. Blade solidity is indeed an important design parameter for the axial flow defined as the ratio of blade chord length to spacing. This linear cascade features a laminar separation bubble on the suction side, that interacts with the freestream turbulence. This one-year project can be divided into two main objectives. The first goal is to retrain a diffusion model on several DHIT boxes with a wide range of turbulence intensity (TI). Second, the student will be asked to inject the generated samples into the main computational domain and evaluate the sensitivity of the separation to different levels of TI. The ability of the diffusion model to generate realistic turbulent fluctuations without spurious artifacts in the context of turbomachinery will also be investigated.

Profile

- ***Required: Bachelor + ongoing Master's studies in Fluid Mechanics, or Aeronautical Engineering or data science.***
- *Languages: English and/or French.*
- *Pre-requisites: notions of aerodynamics and/or turbulence and/or Machine Learning + programming (Python)*
- *Motivation, creativity and team spirit!*

Duration

The length of the internship can vary from 4 months to 6 months, depending on your university or school regulations.

Contact

Interested candidates should send a cover letter, quoting reference number of the offer, and a resume to rh_be-ip-2025-01@cenaero.

References

[1] Leggett, S. Priebe, R. Sandberg, V. Michelassi, and A. Shabbir. *Detailed investigation of RANS and LES predictions of loss generation in an axial compressor cascade at off design incidences.* In Proc. of the ASME Turbo Expo 2016. American Society of Mechanical Engineers. DOI: 10.1115/GT2016-57972

[2] D. Papadogiannis, S. Mouriaux, J-S. Cagnone, K. Hillewaert, F. Duchaine, S. Hiernaux. *Influence of the numerical strategy on wall-resolved LES of a compressor cascade.* Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics ETC13, April 8-12, 2019. DOI: 10.29008/ETC2019-418

[3] M.S. Istvan and S. Yarusevych. *Effects of free-stream turbulence intensity on transition in a laminar separation bubble formed over an airfoil.* Experiments in Fluids, 59 (52), 2018. DOI: 10.1007/s00348-018-2511-6

[4] Dhamankar, Blaisde, and Lyrintzis. *An Overview of Turbulent Inflow Boundary Conditions for Large Eddy Simulations.* 22nd AIAA Computational Fluid Dynamics Conference, 2015. DOI: 10.2514/6.2015-3213

[5] Boxho, Dominique, Benarama, Rasquin, Salesses, Sainvitu, Louppe and Toulorge. *Turbulent Injection assisted by Diffusion Models for Scale Resolving Simulations.* Physics of Fluids. (currently being submitted)

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