Large Eddy Simulation of an axial compressor rotor passage: Preliminary comparison with experimental measurements

Alexis Giauque[a], Jérôme Boudet[a]
Hongwei Ma[b], Wei Wei[b]

(a) LMFA, Ecole Centrale de Lyon - Université de Lyon - UMR CNRS 5509, 69134
Ecully Cedex, France
(b) School of Jet Propulsion, Beihang University, Beijing, 100191, China

Mots clefs : Experience, Experiment, Simulation aux grandes échelles, Large Eddy simulation, Turbomachinery, Compressor, Secondary Flow, Tip-leakage Vortex

1 Introduction

In order to meet the European H2020 energy efficiency objectives in the transport industry, jet engines and therefore their sub-systems should be improved. The compressor is one of these key sub-systems. Its efficiency largely influences the overall performances and its stability is critical for obvious security reasons. Unfortunately, it can be shown by dimensional analysis that in the state space defined by the compression ratio and the flow coefficient, the operating area providing the highest efficiency is also close to the surge limit. Close to this limit, fluctuations uncorrelated with the BPF can be associated with localized unsteady boundary layer separation also denoted as stall. It has been shown that experimental control techniques can be used to mitigate these instabilities but such studies are scarce due to the high related cost. In this context, Large Eddy Simulation which is designed to capture the most energyetic turbulent scales, appears as a promising tool for numerical experiments.

In the context of turbomachines, the description of a tip-clearance flow using LES has been achieved by You et al.[1], on a cascade configuration with moving end-wall. Boudet et al.[2] carried-out a LES study on a single airfoil tip-clearance configuration with a particular interest in the noise generation. In the context of external aerodynamics, the Corner Separation phenomenon has been addressed by Gand et al.[3]. These studies consistently showed the superiority of LES with respect to RANS.

In the last five years, Large Eddy Simulation of compressor and turbine flows has received a lot of attention from various research institutions, confirming its potential for understanding complex unsteady phenomena responsible for losses such as secondary flows[4, 5, 6, 7, 8, 9, 10, 11]. On this matter, one should mention the detailed review published by Gourdain et al.[12]. The perspiration of Large Eddy Simulation in the industry is slowed down by two main factors. The first factor is its cost, which will most probably prevent it from entering the desired 24-hours design cycle in the next ten years. Yet, current research in HPC tries to answer this first point and will eventually make this tool affordable. The second reason is related to the modeling of turbulent flows in such geometries. Indeed, the capture of a larger part of the spectrum of fluctuations that LES provides also goes with a larger sensitivity to the numerical and physical models it relies on. Moreover, even when LES appears to compare favorably with the available experiments (see for example [13] on a single rotor configuration NASA 37), measurements are generally limited to averaged data, and detailed validation of LES is not possible.

This last point represents the main motivation for this study, which proposes to compare LES results to averaged and unsteady measurements obtained in the realistic configuration of a single rotor. As made clear in this introduction, Large Eddy Simulation still has to prove its point in the context of turbomachinery flow. This comparison will also enable to assess the shear-improved Smagorinsky subgrid model developed by Lévêque et al. [14] in this complex environment in which the entire "zoo" of turbulent structures are present.

2 Numerical setup

The general setup of the numerical simulation is shown in Figure 1. It represents one blade passage (1/17th of the full wheel). The hub and shroud are extended upstream from the rotor in order to let the boundary layers transition into turbulence. As pointed out by many authors [15, 11] a realistic representation of the incoming turbulent boundary layers is necessary in order for the turbulence to interact with developing structures around the blades. It was previously noted that it can (i) have a significant effect on the transition of the boundary layers on the blade and (ii) modify the location of the inception of the tip-leakage vortex.

2.1 Solver

Large-eddy simulation is carried out using Turb'Flow solver[16]. Turb'Flow uses a cell-vertex finite-volume discretization on block-structured grids. The turbulent subgrid viscosity is modeled using the shear-improved Smagorinsky model (SISM) [14]. A 4-point centered scheme is used for the interpolation of the inviscid fluxes, with a limited amount of fourth order artificial viscosity (coefficient: 0.0005, tuned according to [16]). The viscous fluxes are interpolated with a 2-point centered scheme. At the inflow, uniform density and velocity are imposed. Static pressure is imposed at the outlet, with a preservation of the radial equilibrium, and a partially non-reflecting treatment. Periodicity is used on the lateral boundaries. These conditions are consistent with those used in [17]. The simulation being an ideal description of the reality (no ingested turbulence, smooth walls...), grid steps are implemented to trip the transition to turbulence in the boundary layers (hub, casing, and blade surfaces), as explained in [16].

2.2 Mesh

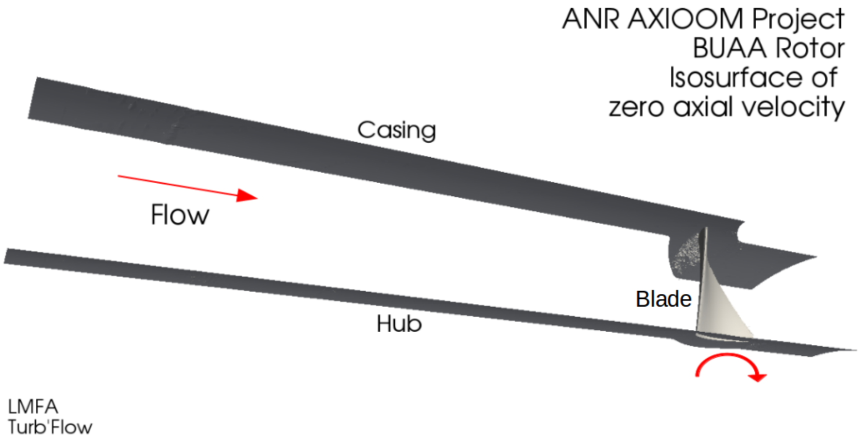


Figure 1: Schematics of the numerical setup

The computational grid encompasses 240 million nodes. A significant number of them (55 million) is devoted to the precise description of the hub and casing boundary layers, which influence the secondary flow structures (corner flow and tip-leakage). On the blade, the mesh is refined in order to capture the dynamic of the transition of the turbulent boundary layer without the need of a wall model. Grid sizes at the wall in wall units are as follow: y+ (perpendicular to the wall) is equal to 1.8 with an expansion ratio equal to 1.135. x+ and z+ (tangential to the wall) are equal to 40.

2.3 Subgrid-scale modeling

The closure of the LES equations, through the subgrid-scale model (SGS), requires a clear understanding of the physical interactions between the flow scales. Schumann [18] and Sullivan et al. [19] published pioneering works on this issue. Along the same line of idea, Shao et al.[20] made explicit from the Reynolds decomposition that the SGS stress tensor in complex flow simulations encompasses two types of interactions: the first one occurs between the mean flow (or coherent large structures) and the fluctuating velocities (=the rapid part of the SGS stress tensor), and the second one deals with triadic interactions among the fluctuating velocities (=the slow part of the SGS stress tensor). These two components have radically different properties, and must be modeled accordingly: the rapid part is related to the large-scale anisotropy, while the slow part is closely related to homogeneous and isotropic dissipative effects. Since these initial developments, efforts have been put at LMFA and with partners in order to reinforce the physical foundations of this approach and reduce empiricism in subgrid-scale modeling. These developments are gathered under the title: "Reynolds Decomposition Large Eddy Simulation" (ReDLES), whose main steps are:
Cui et al.[21, 22] consider the Kolmogorov equation for filtered velocities and derive the CZZS model.

Lévêque et al. [14] use the two-point energy equation derived from the Navier-Stokes equations (in physical space), i.e. the exact generalized Kolmogorov equation, and introduce the Shear-Improved Smagorinsky Model (SISM).
Cahuzac et al. [23], address a practical point of crucial importance in ReDLES: the separation between large scales and turbulence (i.e. filtering) at moderate cost. In the present case, the scale separation is achieved by an exponential smoothing (cut-off frequency: $F_c = U/c$ =213Hz) as described by Cahuzac et al. [23]. In brief, the ReDLES approach accounts for the mean flow (including the near-wall shear) and the large coherent structures (numerous in turbomachines: tip-leakage vortex, corner separation, etc), in a physically sound manner and at a moderate computational cost.

3 Preliminary results

An instantaneous view of the flow is shown in Figure 2. A vorticity iso-surface is plotted, colored by axial momentum. The transition to turbulence is clearly observed on the blade suction side. Turbulence is also vigorous in the casing corner, influenced by the tip-leakage vortex. The turbulent boundary layers at the hub and casing are still under transition, which has not yet reached the rotor as no significant vorticity is visible upstream of the blade passage.

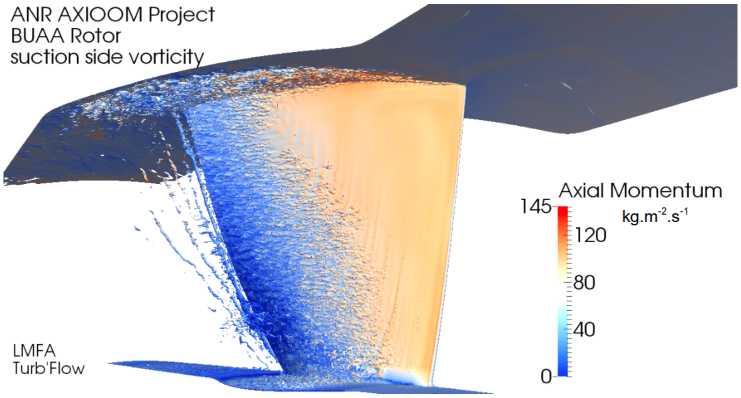


Figure 2: Isosurface of vorticity ($\Omega * \frac{c}{u} = 47$)

3.1 Comparison with experimental results

This configuration is the subject of a detailed experimental campaign considering:

- The compressor aerodynamic performances: Rotation speed, mass flow, classical mean pressure and temperature measurements are used to assure the control of the inlet and outlet flow conditions.
- Inlet conditions: Experimental investigation will provide the spectral energy distribution of the turbulence in the end-wall boundary layers and in the free stream

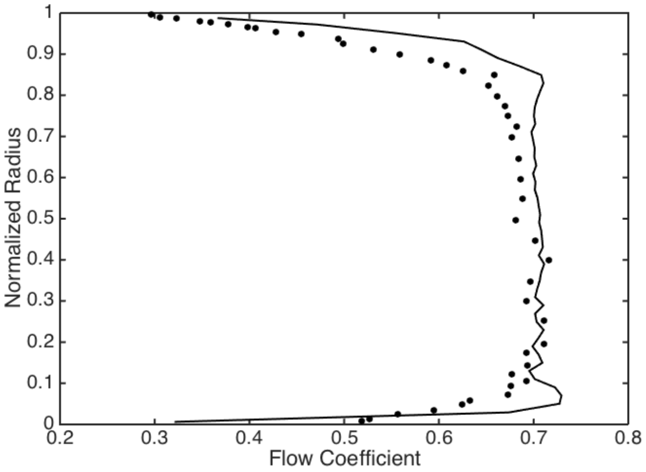


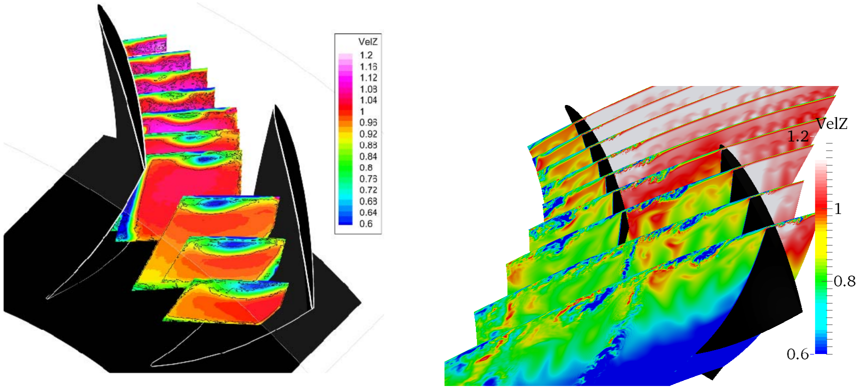
Figure 3: Evolution of the flow coefficient with respect to the normalized radius at outlet station ($x = x_{\text{trailing edge}} + 0.1 * \text{chord}$). Experiment: ●, LES: ▬

region of the inlet flow. A particular care is needed for the description of the end-wall boundary layers.

- The characterization of the flow structures in the rotor passage: Measurements of the flow field in the rotor passage will show the structures of the corner separation and the tip leakage vortex, as well as their interaction, which is very useful for validating the ReDLES simulation.

Figure 3 presents a comparison of the evolution of the average flow coefficient along the radial coordinate at an axial position located 10% of the axial chord downstream of the trailing edge. A reasonable agreement is achieved for normalized radii lower than 0.6. Above this value some discrepancies appear between experimental and numerical results. These discrepancies are under investigation and could be due to a transient overestimation of the flow coefficient upstream of the rotor.

Figure 4 presents a qualitative comparison of the flow in the blade passage. For the LES results, the plane cuts are normal to the blade at the tip. They are designed in order to follow the development of the tip-leakage vortex. Both experimental and LES views present a strong tip-leakage vortex with an inception point located at roughly 30% of the chord. Again the nondimensional velocity is overestimated by LES in the upper part of the sections when compared to the experiments.



a) b)

Figure 4: Visualisation of the normalized "normal to plane" velocity in the blade-to-blade passage: a) Averaged experimental results , b) Instantaneous LES results

4 Concluding remarks

Preliminary results for the comparison of a detailed Large Eddy Simulation of a rotor passage with experimental measurements are presented. They show qualitative evidence that LES reproduces the main features of the flow.

Statistical convergence is not reached yet and numerical results are still being gathered at the time of submission of this extended abstract. A more detailed picture of the comparison with experimental results will be available for the conference.

Acknowledgements

This study is part of the Sino-French project AXIOOM, funded by ANR and NSFC, and leaded by X.Ottavy. The simulations are performed using HPC ressources from GENCI-CINES (Grant #c2015-2a5039).

References

[1] D. You, M. Wang, P. Moin, and R. Mittal, “Large-eddy simulation analysis of mechanisms for viscous losses in a turbomachinery tip-clearance flow,” *Journal of Fluid Mechanics*, vol. 586, pp. 177–204, 2007.

[2] J. Boudet, J. Caro, B. Li, E. Jondeau, and M. C. Jacob, “Zonal large-eddy simulation of a tip-leakage flow,” *Submitted to International Journal of Aeroacoustics*, 2015.

[3] F. Gand, S. Deck, V. Brunet, and P. Sagaut, “Flow dynamics past a simplified wing body junction,” *Physics of Fluids*, vol. 22, no. 11, p. 115111, 2010.

[4] W. McMullan and G. Page, "Towards Large Eddy Simulation of gas turbine compressors," *Progress in Aerospace Sciences*, vol. 52, pp. 30–47, 2012.

[5] G. Wang, D. Papadogiannis, F. Duchaine, N. Gourdain, and L. Y. M. Gicquel, "Towards Massively Parallel Large Eddy Simulation of Turbine Stages," *Volume 6C: Turbomachinery*, p. V06CT42A021, 2013.

[6] B. J. Joo, G. Medic, and D. A. Philips, "Large-eddy simulation of a compressor rotor," in *Summer Program 2014*, (Stanford), Center for Turbulence Research, 2014.

[7] C. Hah, M. Hathaway, and J. Katz, "Investigation of unsteady flow field in a low-speed one and a half stage axial compressor, part 2: Effect of tip gap size on the tip clearance flow structure at near stall operation," in *ASME Turbo Expo*, (Dusseldorf), 2014.

[8] D. Papadogiannis, F. Duchaine, F. Sicot, L. Gicquel, G. Wang, and S. Moreau, "Large eddy simulation of a high pressure turbine stage: Effects of sub-grid scale modeling and mesh resolution," in *ASME Turbo Expo*, (Dusseldorf), pp. 1–13, 2014.

[9] J. Marty and L. Castillon, "Zonal Detached Eddy Simulation of Tip Leakage Flow," in *ASME Turbo Expo*, 2014.

[10] N. Gourdain, "Prediction of the unsteady turbulent flow in an axial compressor stage. Part 1: Comparison of unsteady RANS and LES with experiments," *Computers & Fluids*, vol. 106, pp. 119–129, 2015.

[11] N. Gourdain, "Prediction of the unsteady turbulent flow in an axial compressor stage. Part 2: Analysis of unsteady RANS and LES data," *Computers & Fluids*, vol. 106, pp. 67–78, 2015.

[12] N. Gourdain, F. Sicot, F. Duchaine, and L. Gicquel, "Large eddy simulation of flows in industrial compressors: a path from 2015 to 2035," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 372, no. 2022, p. 20130323, 2014.

[13] C. Hah, *Large eddy simulation of transonic flow field in NASA rotor 37*. National Aeronautics and Space Administration, Glenn Research Center, 2009.

[14] E. Lévêque, F. Toschi, L. Shao, and J.-P. Bertoglio, "Shear-improved smagorinsky model for large-eddy simulation of wall-bounded turbulent flows," *Journal of Fluid Mechanics*, vol. 570, pp. 491–502, 2007.

[15] F. Gao, *Advanced Numerical Simulation of Corner Separation in Advanced Numerical Simulation of Corner Separation in a Linear Compressor Cascade*. PhD thesis, Ecole Centrale de Lyon, 2014.

[16] J. Boudet, J.-F. Monier, and F. Gao, "Implementation of a roughness element to trip transition in large-eddy simulation," *Journal of Thermal Science*, vol. 24, no. 1, 2015.

[17] J. Boudet, A. Cahuzac, P. Kausche, and M. C. Jacob, "Zonal large-eddy simulation of a fan tip-clearance flow, with evidence of vortex wandering," *Journal of Turbomachinery*, vol. 137, no. 6, 2015.

[18] U. Schumann, "Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli," *Journal of computational physics*, vol. 18, no. 4, pp. 376–404, 1975.

[19] P. P. Sullivan, J. C. McWilliams, and C.-H. Moeng, "A subgrid-scale model for large-eddy simulation of planetary boundary-layer flows," *Boundary-Layer Meteorology*, vol. 71, no. 3, pp. 247–276, 1994.

[20] L. Shao, S. Sarkar, and C. Pantano, "On the relationship between the mean flow and subgrid stresses in large eddy simulation of turbulent shear flows," *Physics of Fluids*, vol. 11, no. 5, pp. 1229–1248, 1999.

[21] G. Cui, H. Zhou, Z. Zhang, and L. Shao, "A new dynamic subgrid eddy viscosity model with application to turbulent channel flow," *Physics of Fluids*, vol. 16, no. 8, pp. 2835–2842, 2004.

[22] G. X. Cui, C.-X. Xu, L. Fang, L. Shao, and Z. Zhang, "A new subgrid eddy-viscosity model for large-eddy simulation of anisotropic turbulence," *Journal of Fluid Mechanics*, vol. 582, pp. 377–397, 2007.

[23] A. Cahuzac, J. Boudet, P. Borgnat, and E. Lévêque, "Smoothing algorithms for mean-flow extraction in large-eddy simulation of complex turbulent flows," *Physics of Fluids*, vol. 22, no. 12, p. 125104, 2010.

[24] J. Boudet, J. Caro, and M. C. Jacob, "Large-eddy simulation of a single airfoil tip-clearance flow," in *Proceedings of 16th AIAA/CEAS Aeroacoustics Conference, Stockholm, Nederlands*, 2010.