WORKSHOP
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LARGE EDDY SIMULATION AND DIRECT NOISE PREDICTION OF A FAN STAGE IN TRANSONIC REGIME

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The broadband noise generated within a fan-OGV stage and partly caused by the interaction between shockwaves and turbulent structures cannot be easily modelled due to the stochastic nature of the flow. High fidelity numerical methods are able to simulate with sufficient accuracy the characteristics of the flow. LES of the ECL5 fan/OGV stage are performed using the AVBP solver developed by CERFACS. The purpose of those simulations is to locate and characterize broadband noise sources.

LES are performed on the ECL5 fan/OGV stage, an open test case designed at École Centrale de Lyon [1, 2, 3]. The stage is made of 16 rotor blades and 31 stator blades.

The computational cost of the LES is reduced by computing a periodic sector of the fan/OGV stage. In order to preserve the periodic extent for the rotor and the stator domains, the initial 31 vanes are adapted to 32 vanes. Fan stage performance is maintained by adjusting the chord length of the vanes [4]. The computational domain is represented in Figure 1.

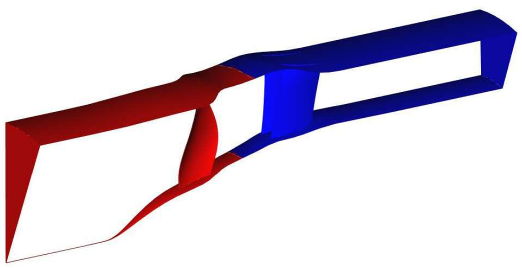

Figure 1: Computational domain of the ECL5 fan/OGV stage for the LES. Rotor domain is colored in red. Stator domain is colored in blue.

The present work is performed at the design point of the ECL5 at nominal speed ($\Omega = 11\,000$RPM). The corresponding inflow axial Mach number is 0.53 and the inlet relative Mach number at the fan blade tip is slightly above 1. The blade passage frequency is equal to 2933Hz.

Simulations of the ECL5 fan stage are performed using AVBP, an explicit unstructured fully compressible LES solver developed by CERFACS [5, 6, 7]. For turbomachinery applications, the resolution is performed over two domains: a rotating domain containing the rotor blade and a static domain containing the stator vanes. A third order interpolation is performed at every time-step to couple the domains. The coupling is ensured by the MISCOG methodology [8, 9]. Computational performance is preserved using the CWIPI library (ONERA) [10].

The computations are carried out using a third order Two-step Taylor Galerkin (TTGC) convection scheme [11]. Unresolved turbulent eddies are modelled using the SIGMA subgrid scale model [12]. Shockwaves are handled using Cook and Cabot hyperviscosity model [13]. Non-reflecting Navier-Stokes characteristic boundary conditions (NSCBC) are used both at the inlet and at the outlet [14]. A wall function (linear law below $y^+ = 11.45$, log law otherwise) is used near the walls in order to limit the computational cost [15, 16]. The time step for the simulation is slightly above $\Delta t = 1.6 \cdot 10^{-8}$s. The computational time is 200×10^3 CPUh for one rotation. The simulations are performed on a hybrid unstructured mesh. The mesh contains approximately 100 millions cells. It is designed to propagate acoustic waves one chord length upstream and downstream of the blade up to 15kHz [17]. The characteristic size of the elements is shown at 80% of the span in Figure 2. The dimensionless wall-normal distance y^+ of the first prismatic layer is under 35 on the blades skin.

Figure 2: Characteristic size of the elements in millimeters. The reference value for the refined area is 0.8 mm. The mesh is progressively coarsened in order to limit acoustic reflections.

Three full rotations of the rotor have been performed. An iso-surface of the Q-criterion, colored by the relative Mach number is represented in Figure 3. The boundary layer in the supersonic region remains mainly laminar, and the transition is induced by the shockwave. A corner separation is noticed near the hub. Intense turbulent structures are found in the tip region. The average axial velocity at 80% of the span is shown in Figure 4 as well as the sonic line near the suction side of the rotor blade. The shockwave thickens the boundary layer, leading to wide rotor wakes.

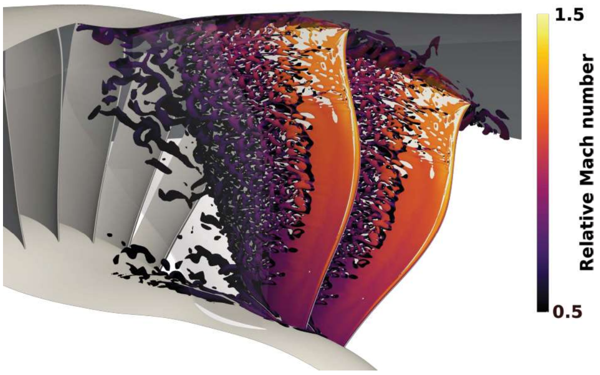

Figure 3: Isosurface of the Q-Criterion ($Qc^2/U^2 = 20$) colored by the relative Mach number.

Instantaneous pressure fluctuations at 80% of the span are shown in Figure 5 as well as the sonic line. Different noise sources are contributing to this acoustic field such as trailing edge noise, shockwave noise and interaction noise due to the rotor wakes interacting with the vanes leading edge. It can be observed that the acoustic waves propagating upstream, through the rotor, do not penetrate the supersonic regions and seem to be guided inbetween them.

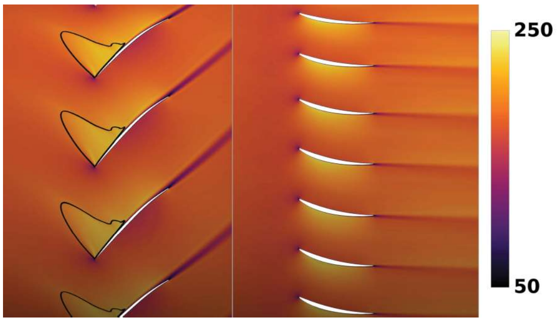

Figure 4: Average axial velocity at 80% of the span. The sonic line in the relative mean flow is represented in black.

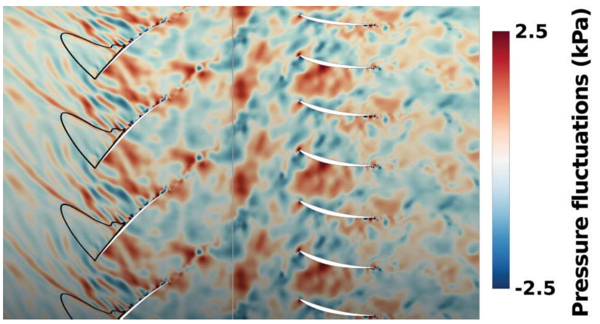

Figure 5: Instantaneous pressure fluctuations in both rotor and stator domains. Only a radial slice at 80% of the span is represented. The sonic line in the relative mean flow is represented in black.

Beyond the average and instantaneous fields, the simulation is monitored with over 4 000 unsteady probes recording thermodynamic and velocity variables with a sampling frequency around 97kHz. Those probes are located all over the blade skin, in the tip region, in the wakes, and in planes upstream the rotor blades, downstream the stator vanes and in the interstage.

The purpose of the study is to assess acoustics models using LES data and suggest modifications to take into account the presence of the shockwave. For this purpose, 8 full rotations of the ECL5 fan stage are planned. The resulting analysis including converged and well resolved acoustic spectra will be presented at the conference.

REFERENCES

[1] V. Pagès, P. Duquesne, S. Aubert, L. Blanc, P. Ferrand, X. Ottavy, and C. Brandstetter, "UHBR Open-Test-Case Fan ECL5/CATANA," *IJTPP*, May 2022.

[2] C. Brandstetter, V. Pagès, P. Duquesne, X. Ottavy, P. Ferrand, S. Aubert, and L. Blanc, "UHBR Open-test-case fan ECL5/Catana, Part 1: Geometry and aerodynamic performance," ETC, 2021.

[3] V. Pagès, P. Duquesne, X. Ottavy, P. Ferrand, S. Aubert, L. Blanc, and C. Brandstetter, "UHBR Open-test-case fan ECL5/Catana, Part 2: Mechanical and aeroelastic stability analysis," ETC, 2021.

[4] M. M. Rai and N. K. Madavan, "Multi-Airfoil NavierStokes Simulations of Turbine RotorStator Interaction," *Journal of Turbomachinery*, July 1990.

[5] T. Schonfeld and M. Rudgyard, "Steady and Unsteady Flow Simulations Using the Hybrid Flow Solver AVBP," *AIAA Journal*, Nov. 1999.

[6] S. Moreau, "Turbomachinery-related aeroacoustic modelling and simulation," Conference on Modelling Fluid Flow, Sept. 2018

[7] J. Al-Am, V. Clair, A. Giauque, J. Boudet, and F. Gea-Aguilera, "Direct noise predictions of fan broadband noise using LES and analytical models," AIAA, June 2022.

[8] G. Wang, F. Duchaine, D. Papadogiannis, I. Duran, S. Moreau, and L. Y. M. Gicquel, "An overset grid method for large eddy simulation of turbomachinery stages," *Journal of Computational Physics*, Oct. 2014.

[9] J. de Laborderie, F. Duchaine, L. Gicquel, O. Vermorel, G. Wang, and S. Moreau, "Numerical analysis of a high-order unstructured overset grid method for compressible LES of turbomachinery," *Journal of Computational Physics*, June 2018.

[10] F. Duchaine, S. Jauré, D. Poitou, E. Quémerais, G. Staffelbach, T. Morel, and L. Gicquel, "Analysis of high performance conjugate heat transfer with the OpenPALM coupler," *Comput. Sci. Discov.*, July 2015.

[11] O. Colin and M. Rudgyard, "Development of High-Order Taylor-Galerkin Schemes for LES," *Journal of Computational Physics*, Aug. 2000.

[12] F. Nicoud, H. B. Toda, O. Cabrit, S. Bose, and J. Lee, "Using singular values to build a subgrid-scale model for large eddy simulations," *Physics of Fluids*, Aug. 2011.

[13] A. W. Cook and W. H. Cabot, "Hyperviscosity for shock-turbulence interactions," *Journal of Computational Physics*, Mar. 2005.

[14] T. J. Poinsot and S. K. Lelef, "Boundary conditions for direct simulations of compressible viscous flows," *Journal of Computational Physics*, July 1992.

[15] P. Schmitt, T. Poinsot, B. Schuermans, and K. P. Geigle, "Large-eddy simulation and experimental study of heat transfer, nitric oxide emissions and combustion instability in a swirled turbulent high-pressure burner," *Journal of Fluid Mechanics*, Jan. 2007.

[16] F. Jaegle, O. Cabrit, S. Mendez, and T. Poinsot, "Implementation Methods of Wall Functions in Cell-vertex Numerical Solvers," *Flow Turbulence Combust*, Sept. 2010.

[17] J. Al-Am, V. Clair, A. Giauque, J. Boudet, and F. Gea-Aguilera, "A Parametric Study on the LES Numerical Setup to Investigate Fan/OGV Broadband Noise," *IJTPP*, May 2021.