Abstract

The anticipated growth in commercial aviation, combined with increasing environmental constraints, has intensified the need for effective decarbonization strategies. Among these, improving energy efficiency through enhanced propulsive performance remains a priority. This trend has led to the development of Geared-TurboFan (GTF) architectures, in which the Low-Pressure Turbine (LPT), a key component of the engine, drives the fan through a gearbox and therefore operates in a complex environment characterized by transonic flow conditions and low Reynolds numbers. Under such conditions, the boundary layer on High-Speed Low-Pressure Turbine (HS-LPT) blades becomes particularly prone to instabilities that can compromise aerodynamic performance. A detailed understanding of these turbines, and especially their boundary layer dynamics, is therefore essential.

Investigating such flows requires high-fidelity numerical simulations to complement advanced experimental measurements, which remain limited for studying boundary layer mechanisms under compressible flow conditions. This thesis focuses on Wall-Resolved Large-Eddy Simulations (WR-LES) of HS-LPT cascades to analyse boundary layer and wake dynamics in the presence of compressibility effects and realistic inflow turbulence. WR-LES is made feasible by the moderate Reynolds numbers considered and by the use of the massively parallel CFD code YALES2. All simulations rely on the explicit compressible solver ECS, which enables high-order numerical schemes even in the presence of discontinuities such as shock waves.

Two LPT cascades were investigated. The well-documented T106C cascade was first studied to validate the computational workflow. ECS predictions showed good agreement with numerical results from the recent literature and with experimental measurements, both in the boundary layer and in the wake. The second configuration, SPLEEN C1, a next-generation HS-LPT tested on the transonic linear cascade rig S-1/C at the von Karman Institute (VKI), was simulated at its nominal isentropic exit Reynolds number of $Re_{out,is} = 70\,000$ and for isentropic Mach numbers covering subsonic and transonic regimes: $M_{out,is} = 0.70$, 0.80, 0.90, and 0.95.

The first simulation campaign, performed without freestream turbulence, showed substantial agreement with available experimental data. The wake was observed to thin and losses to increase with Mach number, a trend also present in the measurements. Discrepancies in peak losses for $M_{out,is} > 0.70$ were attributed to the absence of turbulence in the simulated inflow, whereas the experimental freestream turbulence intensity was 2.5%. Compressibility effects were also observed: a weak compression wave appeared in the region of the cascade throat for $M_{out,is} = 0.90$, and a shock formed at $M_{out,is} = 0.95$, with the cascade choked. The impact of these features on suction-side separation and transition was analysed.

The realistic representation of inflow turbulence is a major challenge in turbomachinery simulations, as transition mechanisms and separation behaviour are highly sensitive to upstream flow conditions. This thesis proposes an original turbulence injection strategy for compressible flows by numerically replicating the experimental turbulence generation device through a Dynamic Actuator Line Method (DALM). Applied to the transonic wind-tunnel setup S-1/C at VKI, DALM successfully reproduced inflow turbulence levels consistent with SPLEEN C1 measurements under nominal conditions ($TI_x = 2.5\%$, $\Lambda_{int} = 13$ mm).

Accounting for this realistic freestream turbulence in the SPLEEN C1 simulations under nominal and off-design conditions significantly improved the reliability of boundary-layer and wake predictions. In particular, the pressure-side separation bubble and the wake losses were predicted with much higher accuracy than under clean-inflow conditions. Freestream turbulence was found to delay suction side separation, promote earlier transition, and facilitate reattachment at low Mach numbers. Velocity and turbulence predictions within the blade-to-blade passage and in the wake showed good agreement with PIV measurements. The combined effects of turbulence and compressibility were also analysed.

Keywords: High-speed low-pressure turbine, Wall-resolved large-eddy simulations, Compressible flows, Boundary-layer separation and transition, wake dynamics, Freestream turbulence, Dynamic Actuator Line Method, Mach-number effects.