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Effect of various boundary conditions on the supersonic flow through the tip-section turbine blade cascade with a flat profile

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Transonic flows through turbine blade cascades are usually connected with the shock-wave/boundary-layer interaction. This interaction mostly leads to the laminar/turbulent transition in separated flow. The flow through the tip-section turbine blade cascades is mainly supersonic due to a very high circumferential velocity. The stagger angle of the blade is large and so flow in the cascade is characterized by the supersonic inlet and outlet (see Synáč et al. [1]). In case of the tip-section turbine blade cascades with the inlet supersonic flow there are some further problems connected with numerical simulations. Partly it is necessary to modify the inlet part of the computational domain because of the suppression of parasitic shock waves arising by the reflection from boundaries of the domain. Further there is a relation between of the inlet Mach number and the inlet angle given by the unique incidence rule (see Lakshminarayana [2]). The inlet flow angle is prescribed in numerical simulations and corresponding inflow conditions are established in the distance about one chord upstream of the leading edge plane. The tip-section blade cascade was designed for two nominal regimes with the inlet Mach number M_1 = 1.2 and isentropic outlet Mach numbers M_{2is} = 1.7 and 1.9. Numerical simulations of 2D compressible flow through the tip-section turbine blade cascade with a flat profile were carried out at free-stream turbulence Tu = 1.5% for three regimes including nominal regimes. Further, the effect of inlet free-stream turbulence was studied. The Reynolds number related to the isentropic exit Mach number and the profile chord was $Re_c = 2\times10^6$.

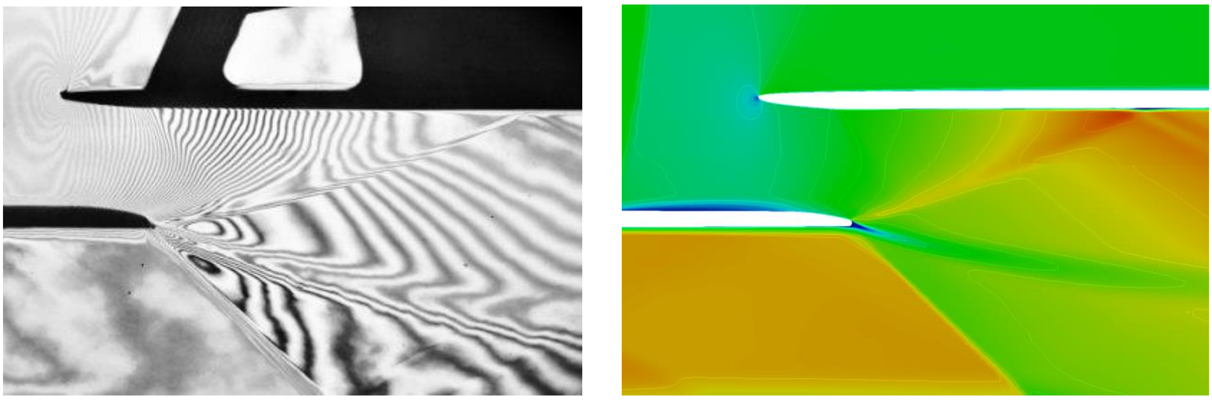
The OpenFOAM code was used for simulations based on the Favre-averaged Navier-Stokes equations completed by the two-equation SST turbulence model and the γ-$Re_{\theta t}$ transition model proposed by Langtry and Menter [3]. The transport equation for the intermittency coefficient γ is given by the equation

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial\left(\rho U_j \gamma\right)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\gamma}{\partial x_j}\right]$$

with production term P_γ and the destruction term E_γ. The onset and length of the transition region are expressed by means of the local Reynolds number given by the transport equation as well. The model is switched over to a simple algebraic transition model for the transition in separated flow. The only two-equation SST turbulence model was used for comparison.

The computational domain takes up one spacing of the blade cascade and it is extended up to 2.4t upstream of the leading edge plane. Similarly the outlet part is shifted downstream of trailing edges. The inlet boundary conditions are prescribed by the constant total pressure, total temperature and inlet flow angle. The outlet boundary condition is defined by the constant static pressure determined according to the outlet isentropic Mach number. Periodicity conditions were used on side boundaries of the computation domain. As the inlet Mach number is very sensitive to small changes of the inlet angle, the variation of M_1 with α_1 was studied. The presented numerical results were obtained for the inlet angle α_1 = 82.82° and the corresponding inlet Mach number M_1 = 1.135. Some numerical results for M_{2is} = 1.817 are described by Musil et al. [5]. Due to the geometrical configuration of blades and to inlet boundary conditions pressure and suction sides are on the inverse blade sides than usually. The evaluation of numerical results was carried out using the data reduction method proposed by Amecke and Šafařík [1]. Numerical results were compared with results of optical and pressure measurements, see Luxa et al. [4].

The field of Mach number isolines obtained by numerical simulation for the M_{2is} = 1.747 is compared in Fig. 1 with the interferometric picture for corresponding boundary conditions. The flow structure in the blade cascade is influenced particularly by the inner branch of the exit shock wave of the neighbouring blade and its interaction with the laminar boundary layer on the suction side of the blade resulting in the flow separation and the transition in separated flow. The separation on the blade suction side induced by the interaction begins at x/b ≈ 0.54. The length of the separation is $\Delta(x(b)_{sep} \approx 0.05$ for the M_{2is} =1.817 and slightly reduces with increasing free-stream turbulence. With diminishing entropic outlet Mach number the separation onset moves upstream equally as the position of the shock-wave interaction.



a) Interferometric picture b) Mach number isolines

Fig. 1. Flow field in the blade cascade

Due to the asymmetric blade trailing edge the supersonic expansion comes up on the pressure side leading to flow separation and to shifting of the near wake in the suction side direction with a very thick exit shock wave. Through different outlet isentropic Mach numbers at same boundary conditions due to the supersonic inlet the agreement of numerical simulations with experimental results is acceptable.

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