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Simulation of supersonic flow through the tip-section turbine blade cascade with a strong shock-wave/boundary-layer interaction

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The numerical simulation of compressible flow including the laminar/turbulent transition through the turbine blade cascade with strong shock-wave/boundary-layer interactions presents a great challenge. The flow field structure depends to a large degree on the character of the boundary layer during the interaction. In case of the laminar boundary layer, the flow separation usually will come out connected with the transition in the separated flow. Therefore, the Favre-averaged Navier-Stokes equations should be completed not only by the turbulence model, but by adequate models of the laminar/turbulent transition and turbulent heat transfer as well. The numerical simulation was carried out by means of the EARSM turbulence model according to Hellsten [1] completed by the transition model with the algebraic equation for the intermittency coefficient proposed by Straka and Příhoda [5] and implemented into the in-house computational programme (see Straka and Příhoda [6]). The transition model considers two parts of the intermittency coefficient γ in the boundary layer γ_i and in the free stream γ_e. The intermittency in the boundary layer is expressed by the relation

$$\gamma_i = 1 - \exp\left[-\hat{n}\sigma\left(Re_x - Re_{xt}\right)^2\right]$$

where the transition onset is given by the Reynolds number Re_{xt} expressed by the momentum Reynolds number $Re_{\theta t}$ and the transition length by the spot generation rate $\hat{n}$ and spot propagation rate σ. Empirical correlations for $Re_{\theta t}$ and $\hat{n}\sigma$ are given by means of the pressure-gradient parameter and the free-stream turbulence for attached and separated flows as well. Using the vorticity Reynolds number instead of the momentum Reynolds number, the transition model is based on local parameter only and so it can be used for modelling of transitional flows in complex geometries like turbomachinery applications.

The numerical simulation of transonic flow through the tip-section turbine blade cascade was focused on the adequate simulation of the shock-wave/boundary-layer interaction. The flow field at the high inlet Mach number is influenced mainly by the interaction of inner branch of exit shock wave with boundary layer on the suction side of neighbouring blade. Numerical simulations were carried out for nominal conditions given by the inlet Mach number M_1 = 1.68 and the isentropic outlet Mach number M_{2isSC} = 2.05 corresponding to the pressure in the settling chamber. The isentropic outlet Mach number in the traversing plane is M_{2is} = 1.97 and the isentropic outlet Reynolds number $Re_{2is} = 1.98\cdot10^6$. The inlet free-stream turbulence was considered Tu = 1.5 % in the distance about one spacing upstream the blade cascade according to experimental data. Numerical results were compared with results of optical and pressure measurements, see Luxa et al. [4], [3].

Due to supersonic inlet and outlet flow conditions the computational domain was extended upstream and downstream to suppress reflections of parasitic shock waves. The outlet boundary condition is prescribed usually from experimental data in the traversing plane behind the cascade. The outlet boundary condition given the outlet isentropic Mach number was optimised according to angle of the exit shock wave and the blade chord.

The interferometric picture obtained for nominal regime is shown in Fig. 1. The interaction of the inner branch of the exit shock wave with the boundary layer on the suction side is connected with the separation on the laminar boundary layer. The detail of Mach number isolines showing the interaction of the inner branch of the exit shock wave with the boundary layer on the suction side of the blade is presented in Fig. 2. The best agreement was achieved for the isoentropic Mach number M_{2is} = 1.78 at the traversing plane behind the blade cascade. The field of Mach isolines well corresponds with the interferometric picture.

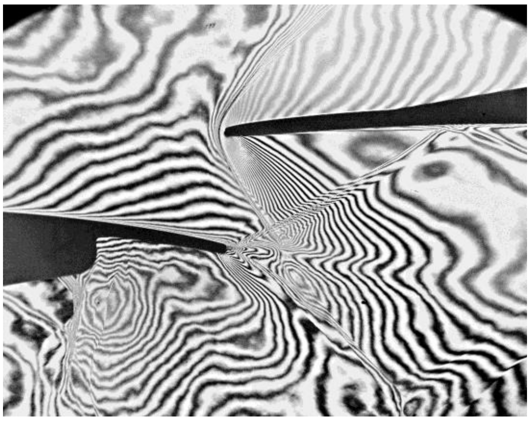

Fig. 1. Interferometric picture for M_{2is} = 1.97

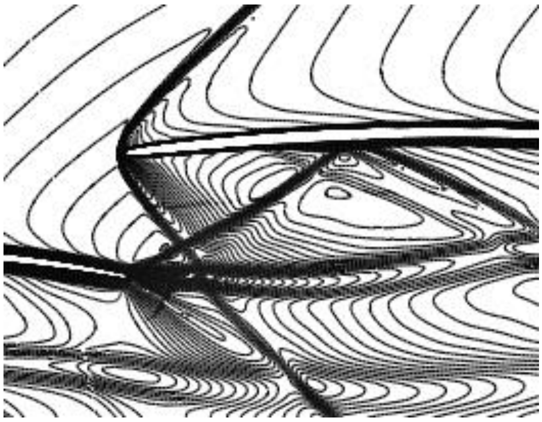

Fig. 2. Detail of Mach number isolines

Numerical simulations of the supersonic flow have shown the significant effect of the prescription of the outlet boundary condition. Simulations carried out for the standard computational domain with the output behind the blade cascade and/or for the computational domain corresponding to the experimental arrangement have shown that numerical results obtained on the basis of the numerical optimization correspond quite well to experimental data (see Louda et al. [2]). The agreement of predicted flow fields and main parameters including energy losses is acceptable.

Acknowledgements

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