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HYBRID RANS/LES MODELLING OF SECONDARY FLOW IN AXIAL TURBINE STAGE

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Abstract: *The paper deals with application of hybrid RANS/LES model based on two-equation k–ω model in RANS mode and transport equation for the sub-grid scale turbulent energy in LES mode. Hybrid RANS/LES model is applied for computation of flow in an axial turbine stage with radial gaps under the stator and above the rotor blade. The model is implemented into the in-house numerical code which was originally designed for solution of RANS equation. Therefore the numerical inviscid fluxes are modified here in order to reduce a native numerical dissipation for use in LES approach.*

Keywords: hybrid RANS/LES, axial turbine stage, secondary flows.

1. Introduction

The contribution deals with simulation of flow in an axial stage of low power turbine (around hundreds kilowatts to units megawatts). To reduce of production costs this kind of turbines are often designed in a drum-type rotor configuration with prismatic blades, which are not equipped with a shroud. In that case there are radial gaps under the hub-end of the stator blade and above the tip-end of the rotor blade. Flow through these radial gaps leads to generation of large secondary flow structures which interact with following blade row. The interaction of blades with these secondary flow structures has major impact on the efficiency of the turbine stage. In paper (Straka et al., 2015) there was shown that drop in the efficiency due to interaction of the rotor blades with the secondary flows is up to ten percent.

Prediction of the blade/secondary flow interaction strongly depends on used turbulence model. In industrial applications, such as this, it is usual to solve system of RANS (Reynolds Averaged Navier–Stokes) equations, which is closed by two-equation turbulence model (such as k–ω). In paper (Straka & Němec, 2016) there was studied mechanism of the interaction between the rotor blades and the secondary vortices generated behind the radial gap under the stator blade using the k–ω model of Kok (2000). This model is based on linear relation for the Reynolds stress tensor. Although this model has provided interesting results, comparison with the experimental data revealed some differences in span-wise distribution of the efficiency behind the rotor blade. Therefore in paper (Straka, 2015) there was compared prediction of the secondary vortices development using the linear turbulence model of Kok (2000) and the nonlinear EARSM (Explicit Algebraic Reynolds Stress Model) model of Rumsey & Gatski (2001). It was found that the nonlinear EARSM model predicts deformation and unsteady behaviour of the secondary vortices, while the linear model doesn't have this capability. However, for better prediction of the interaction between the rotor blade and the secondary vortices generated behind the radial gap under the stator blade it is necessary to model not only deformation of large vortices but also their decay. Therefore, this contribution is focused on application of hybrid RANS/LES model for modeling of the rotor blade/secondary vortices interaction. In hybrid RANS/LES methods the flow field close to the wall is modeled via RANS approach, while the large detached eddies are simulated using LES (Large Eddy Simulation) approach which has capability to predict both deformation and decay of large secondary vortices. The hybrid RANS/LES model is implemented into the in-house RANS code described in (Straka, 2012; Straka, 2013) which was here modified with respect to requirements of the LES.

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2. Turbulence model

The hybrid RANS/LES method according to (Davidson & Peng, 2003; Kok et al., 2004) is used in this work. This model switches between the system of RANS equations closed by two-equation turbulence model of Kok (2000) and LES when computational mesh is fine enough to simulate of large turbulent eddies. The sub-grid scale model of LES is based on transport equation for the sub-grid scale turbulent energy.

The transport equations for the kinetic energy k and the specific dissipation rate ω read:

$$\frac{D(\rho k)}{Dt} = P_k - \max\left(\beta^* \rho k \omega, \frac{\rho\sqrt{k^3}}{C_{DES}\Delta}\right) + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_k \frac{\rho k}{\omega}\right)\frac{\partial k}{\partial x_j}\right], \tag{1}$$

$$\frac{D(\rho\omega)}{Dt} = \alpha \frac{\omega}{k} P_k - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_\omega \frac{\rho k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + C_D\,, \tag{2}$$

where ρ is the density, P_k is the production term, C_D is the cross diffusion term, α, β^*, β, σ_k and σ_ω are model constants. The local grid size Δ is defined by $\Delta = \max(\Delta_\xi, \Delta_\eta, \Delta_\zeta)$ where Δ_ξ, Δ_η and Δ_ζ are the distances between the cell faces in local ξ, η and ζ grid line directions. Constant $C_{DES} = 0.6086$ is chosen according to (Kubacki et al., 2013). Note that k is either the turbulent energy in RANS mode or the sub-grid scale energy in LES mode. The modeled stress tensor (Reynolds stress tensor in RANS mode, sub-grid scale stress tensor in LES mode) is given by $\tau_{ij}^t = 2\mu_t S_{ij} - 2/3\rho k \delta_{ij}$, where S_{ij} is the strain rate tensor and $\mu_t = \min(\rho k/\omega, \rho\beta^* C_{DES}\sqrt{k}\Delta_{LES})$ is either the turbulent viscosity in RANS mode or the sub-grid scale viscosity in LES mode according to (Davidson & Peng, 2003; Kok et al., 2004), $\Delta_{LES} = (\Delta_\xi \Delta_\eta \Delta_\zeta)^{1/3}$.

From equations (1) it is evident that the solution is independent on equation (2) in LES mode although equation (2) is solved.

3. Numerical method

Flow through the axial turbine stage is modeled as unsteady, 3D, compressible, viscous, fully turbulent flow of the perfect gas. System of governing equations is discretized by the cell-centered finite-volume method on multi-block structured mesh of hexahedral elements. The inviscid numerical fluxes are calculated using the exact solution of the 1D Rieman problem in normal direction to the cell edges. The viscous numerical fluxes are calculated using the central scheme using the Green-Gauss theorem on a dual cells. Higher order of accuracy in space is obtained using linear reconstruction with the Van Leer's slope limiter. Temporal discretization is performed using the second-order backward Euler formula in implicit form, which is realized through a dual iterative process. The resulting numerical method is second order of accuracy in both time and space.

Although numerical methods based on exact or approximate solution of the Riemann problem have good features for RANS modelling, they are too dissipative for using in LES approach. Therefore a "centralization" of the numerical inviscid fluxes was used in this work for suppression of the native numerical dissipation. Let $F(W_{i+1/2}^L, W_{i+1/2}^R)$ is the inviscid numerical flux through cell face between i-th and (i+1)-th cells which is based on the Riemann problem solution. $W_{i+1/2}^L$ and $W_{i+1/2}^R$ denotes state vectors extrapolated to the cell face from the left and right in means of linear reconstruction with the slope limiter. The numerical dissipation is related to rate of difference between $W_{i+1/2}^L$ and $W_{i+1/2}^R$. Let $W_{i+1/2}^C$ is the state vector at the cell face computed as an average value of the state vectors in centers of i-th and ($i+1$)-th cells. The "centralization" of the inviscid numerical fluxes means replacing of $W_{i+1/2}^L$ and $W_{i+1/2}^R$ by $W_{i+1/2}^{CL}$ and $W_{i+1/2}^{CR}$, where $W_{i+1/2}^{CL} = \psi W_{i+1/2}^C + (1-\psi)W_{i+1/2}^L$ and $W_{i+1/2}^{CR} = \psi W_{i+1/2}^C + (1-\psi)W_{i+1/2}^R$. Parameter ψ is given as

$$\psi = \begin{cases} 0 & \text{for } L_t < L_{DES} \quad \text{(RANS mode)}, \\ \left[0.5 - 0.5\cos\left(2\pi\left(1 - L_{DES}/L_t\right)\right)\right]^2 & \text{for } L_t \geq L_{DES} \quad \text{(LES mode)}, \end{cases} \tag{3}$$

where $L_t = \sqrt{k} / \beta^* \omega$ is the turbulent length scale and $L_{DES} = C_{DES} \Delta_{DES}$ is the sub-grid length scale.

4. Computational results

In left part of figure 1 there is shown scheme of the computational domain which contains one stator and one rotor blade. The chord of the stator and rotor blade is ≈30 mm. The hub diameter is 330 mm and diameter of the outer casing is 430 mm. The size of both radial gaps is 1.4 mm. The axial distance between the stator trailing edge and the rotor leading edge is 8 mm. The inlet boundary is placed 24 mm before the stator leading edge and the outlet boundary is placed 15 mm behind the rotor trailing edge. The sliding mesh interface between stator and rotor parts of the computational domain is placed in the middle of the axial gap between the stator and the rotor blades.

Presented results were calculated for the isentropic outlet Mach number $M_{is} = 0.7$, the outlet isentropic Reynolds number based on blade chord $Re_{is} \approx 3\times10^5$. The rotor blade and the hub-wall rotate at 7430 RPM.

In right part of figure 1 there is shown a distribution of the parameter ψ in meridian section. Red indicates areas where the inviscid numerical flux is fully centralized while in blue domains it remains in original form. In figure 2 there are shown instantaneous isosurfaces of $(|\Omega|^2 - |S|^2)$ which are colored with local turbulence intensity. It is evident that the "centralized" inviscid numerical fluxes allow to resolve more details in flow field. Figure 3 shows instantaneous distribution of the total-total efficiency behind the rotor blade and the time averaged span-wise distribution in section 11 mm behind the trailing edge. The total-total efficiency is defined as $\eta_{TT} = (T_{T0} - T_T) / (T_{T0} - T_{Tis})$ where T_{T0} is the inlet total temperature, T_T is local total temperature and T_{Tis} is the total isentropic temperature. The experimental data in figure 3 are from (Straka & Němec; 2016).

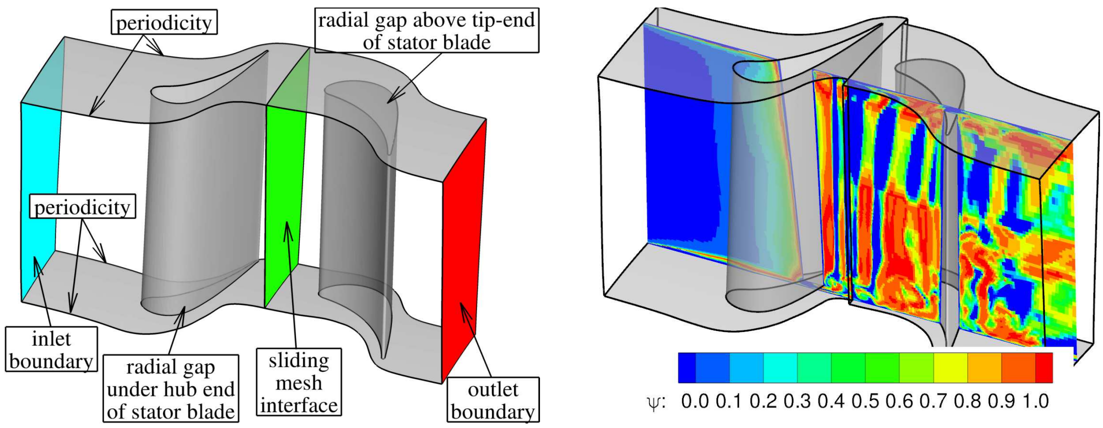

Fig. 1: Computational domain (left), distribution of parameter ψ in meridian section (right).

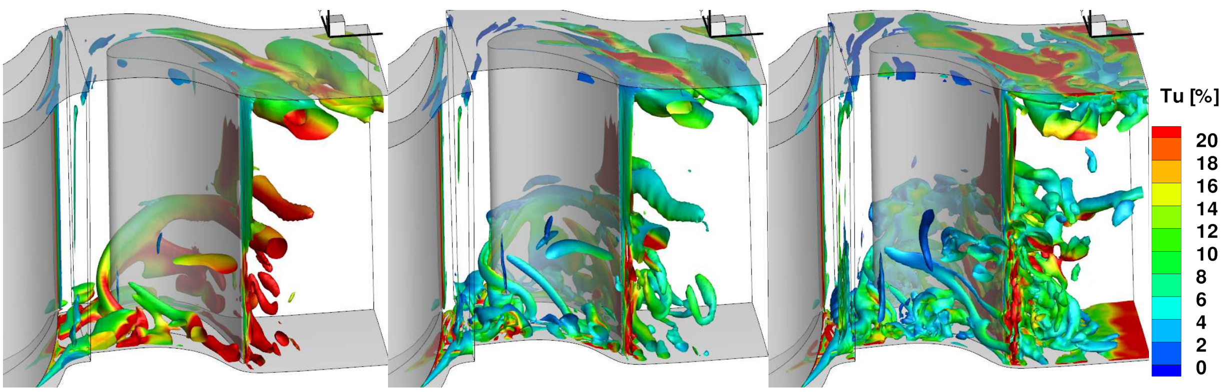

Fig. 2: Isosurfaces of $(|\Omega|^2 - |S|^2)$ colored by local turbulence intensity; RANS (left), RANS/LES with original inviscid numerical fluxes (middle), RANS/LES with centralized inviscid numerical fluxes (right).

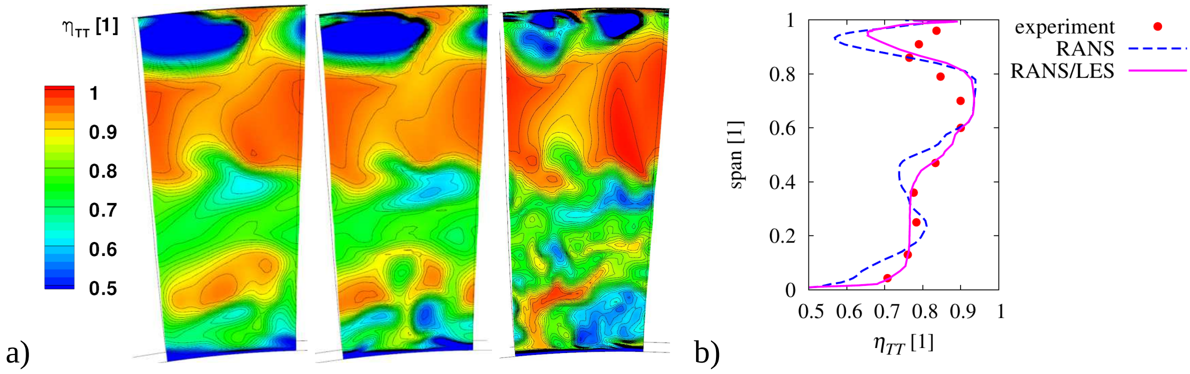

Fig. 3: Distribution of the total-total efficiency behind the rotor blade; a) instantaneous distribution in axial section: RANS (left), RANS/LES with original inviscid numerical fluxes (middle), RANS/LES with centralized inviscid numerical fluxes (right); b) time averaged span-wise distribution..

5. Conclusions

Hybrid RANS/LES model was implemented into the in-house numerical code which was here modified for using in LES approach. The model was applied for computation of flow in the axial turbine stage. Computational results shows that hybrid RANS/LES model predicts the interaction of the rotor blade with the secondary vortices much better then RANS model.

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