V European Conference on Computational Fluid Dynamics
ECCOMAS CFD 2010
J. C. F. Pereira and A. Sequeira (Eds)
Lisbon, Portugal,14-17 June 2010

RECENT PROGRESS IN A HYBRID-GRID CFD SOLVER FOR TURBOMACHINERY FLOWS

Kai Becker*, **Kathrin Heitkamp**, **Edmund Kügeler**

*Institute Of Propulsion Technology, German Aerospace Center (DLR)
Linder Höhe, D-51147 Cologne, Germany
e-mail: {Kai.Becker, Kathrin.Heitkamp, Edmund.Kuegeler}@dlr.de

Key words: turbomachinery, hybrid grids, transition model, zonal interface

Abstract. *In recent years, further developments in the computer technology have led to advanced CFD codes being able to analyze complex three-dimensional flow behavior of turbo-machines. At present, most components in regular shape can be meshed with high-quality structured grids. However, the generation of structured grids is very difficult for some parts or areas, such as casing treatments or coolant channels, even if multi-block topologies are applied. In these cases, unstructured grids have to be introduced. Therefore, a hybrid structured/unstructured solver should be favored supporting both grid topologies in the same modeling.*

This paper presents recent progress in the development of the hybrid CFD solver with regard to the transition modeling. In low pressure turbines, laminar boundary layers are usually encountered due to the prevalent low Reynolds numbers. On the one hand, they produce fewer losses in comparison with turbulent boundary layers. On the other hand, they are more sensitive to flow separation leading to higher overall losses. Therefore, appropriate transition models have to be included in the CFD solver to be able to predict the overall losses quantitatively. The CFD code is now able to reproduce transport phenomena and the transitional effects regardless of the used grid topology. To validate and demonstrate the efficiency of the advancements, two test cases are introduced, a three-dimensional planar turbine cascade and two-dimensional turbine profile for unsteady analysis.

1 INTRODUCTION

In the design process of modern aircraft engines, high performance levels have to be achieved while managing maintenance costs and weight issues. For high bypass ratio engines, these requirements cause high demands on the low pressure turbine component. The weight and cost considerations lead to a reduced number of turbine stages. In combination with a low speed parameter, this results in high stage loading requirements[1]. The raise may however create separation along the suction surface of the blade. Additionally, laminar boundary layers are usually encountered due to the prevalent low Reynolds numbers in low-pressure turbines. They produce fewer losses in contrast to turbulent boundary layers. However, they may cause higher overall losses due to their sensitivity to flow separation. Therefore, an accurate prediction of the transition and separation phenomena plays a major role in modern CFD solvers for turbomachinery since the successful design of LP turbines is accompanied by their ever-increasing aerodynamic loads.

As CFD has become a major element in the design of turbomachines and computing power as well as numerical techniques have been continually improved, the grid generation seems to be a bottleneck. At present, most components in regular shape can be meshed with high-quality structured grids. However, the generation of structured grids is very difficult for some parts or areas, such as casing treatments or coolant channels, even if multi-block topologies are applied. This problem can be alleviated remarkably if a CFD solver allows using any type of grid topology. The grid may consist of structured or unstructured blocks entirely or even a so-called hybrid structured-unstructured grid topology. The word hybrid implies here a combination of structured and unstructured grids, both of which are used to respectively discretize a portion of the flow domain where appropriate.

At the Institute of Propulsion Technology, such a three-dimensional, steady and unsteady flow solver for Favre- and Reynolds-averaged compressible Navier-Stokes equations has been developed for more than a decade, called TRACE. It can be used for both grid types, structured and unstructured. The different solver modules interact with a conservative hybrid-grid interfacing algorithm to allow mismatched abutting interfaces between the structured and unstructured grid blocks. The numerical features of the hybrid-grid CFD solver are its second-order-accurate Roe's upwind spatial discretization to the convective fluxes with MUSCL or linear reconstruction approaches and its first- or second-order accurate implicit predictor corrector formulation. A wide variety of models are integrated, e. g. implicit steady and unsteady nonlinear solvers, implicit non-reflecting boundary conditions, a two equation turbulence model based on Wilcox k-ω model, including special extension for rotating, compressible flows and streamline curvature, and transition models.

In this paper, recent progress in the development of the hybrid CFD solver TRACE is presented. A correlation-based transition model using local variables has been integrated in the structured solver. This transition model has been implemented in the unstructured solver as well. The fully conservative coupling algorithm for hybrid grids has been improved to use this transition model in every grid topology, structured, unstructured, or hybrid. Two test cases, a three-dimensional planar turbine cascade and two-dimensional turbine profile for unsteady analysis, are introduced to validate and demonstrate the efficiency of the advancements.

2 NOMENCLATURE

k	turbulent kinetic energy	x_{ax}/l_{ax}	axial distance over axial chord
M	Mach number	y^+	distance in wall coordinates
p	static pressure	γ	intermittency
p_t	total pressure	Θ	momentum thickness
Re	Reynolds number	μ	molecular viscosity
Re_Θ	momentum-thickness Reynolds number	μ_t	eddy viscosity
$Re_{\Theta t}$	transition onset momentum-thickness Reynolds number	ρ	density
		ω	specific dissipation rate
Re_ν	vorticity Reynolds number	Ω	absolute value of vorticity
U	velocity		
x,y,z	cartesian coordinates		

3 NUMERICAL METHODS

Within the framework of the turbomachinery simulation system TRACE, a hybrid structured-unstructured Reynolds-Averaged Navier-Stokes solver is developed. The structured part of the solver has been evolved for longer period of time and is being applied by a growing user community. It is based on a block-structured grid topology and the mismatched abutting block interface managed by the conservative zonal approach in particular. The 3D RANS equations are integrated in time by a fully implicit formulation of the first- or second-order accurate scheme in the relative frame of reference in conjunction with the Wilcox k-ω two-equation turbulence model[2]. Compressible ideal gas or real gases can be analyzed[3].

The convective fluxes are discretized using Roe's TVD upwind scheme. Van Leer's MUSCL extrapolation is included to obtain second-order accuracy in space. The derivatives of the viscous fluxes are approximated by central differences. For a stationary multistage calculation, the non-reflecting formulation according to Giles[4] is applied at the inlet and outlet boundaries. The coupling of different stages is done by a mixing-plane approach. The time-accurate calculation through dual time stepping applies the non-reflecting boundary conditions of Acton and Cargill[5] at the inlet and outlet, while at the interface of sliding grids, the conservative zonal interface algorithm of Yang et al.[6] is employed. The solver has been parallelized based on domain decomposition using communication libraries so that it works on a wide variety of distributed or shared memory computer systems. More details can be found in Kügeler et al.[7].

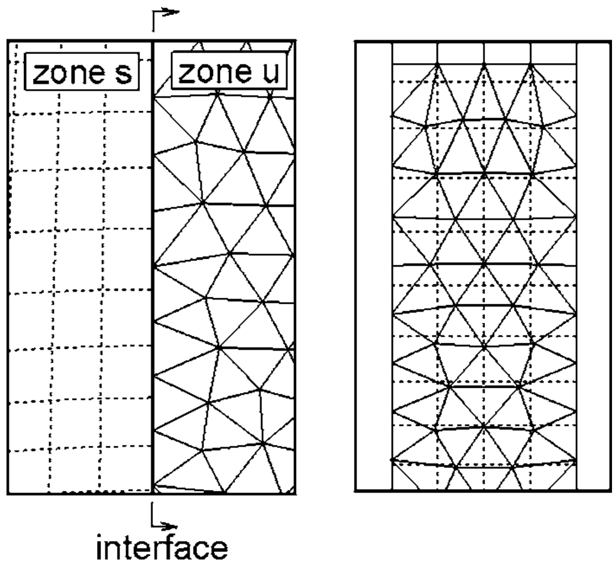

Figure 1: Schematic representation of structured/unstructured interface[11]

Two different models are available to predict the laminar-turbulent transition. On the one hand, Drela's formulation of Abu-Ghanam/Shaw AGS transition criterion[8] can be used, an integral method based on experimental correlations. On the other hand, a correlation-based transition model built strictly on local variables is implemented[9,10]. The second transition model is described in section 3.2.

3.1 Zonal Interface

The coupling of structured and unstructured grids plays a decisive role in the development of a hybrid structured/unstructured RANS solver. At the hybrid interface, the grid cells usually do not match between the two sides. Therefore, a fully conservative and secong-order-accurate coupling algorithm[11] has been developed for these hybrid grid interfaces. It is based on the conservative zonal approach previously applied on the structured grid and allows the interfaces to be of any shape.

The structured and unstructured grids need to be patched at their common boundary surface. In figure 1, a hybrid grid interface between the structured grid (denoted as zone s) and the unstructured grid (zone u) is depicted in a schematic manner. Consistent with the numerical schemes on the interior cells, the same Roe's upwind and central differencing formulations are applied to determine the convective and viscous fluxes, respectively. They are evaluated only at one side of the hybrid-grid interface (e.g. the structured side). Whereas, a conservative rezoning is performed for the other side of the interface (e.g. the unstructured zone) based on the known fluxes from its partner side and the grid overlapping relations between the two sides.

To compute the left and right states at the interface boundaries, only one layer of ghost cells is needed to achieve second-order accuracy for the hybrid interface. By a simple extrapolation from the interior cells, the ghost cells are created from the interior cells in both zones. Their conserved variables are interpolated from the ghost cells on the opposing side. The same applies to the unknown states at one side of the interface. For instance, the left states at the interface boundary of zone s in figure 1 can be MUSCL extrapolated based on states of the interior cells and of the one-layer ghost cells from its own side, whereas its unknown right states can be interpolated from the known states at the interface boundary of the unstructured zone.

There are no restrictions concerning the grid topology at the interface for the generalized hybrid grid interfacing algorithm, i.e. all possible patterns of the grid topologies at the interface are supported, no matter in which combination, structured/unstructured, structured/structured, or unstructured/unstructured. The efficient and robust functionality of the hybrid grid interfacing algorithm is ensured by a sophisticated search algorithm based on the computational geometry and the clipping algorithm[12]. In addition, the hybrid grid interfacing algorithm has been parallelized as well. The communication to send and receive data between two patched zones is done asymmetrically.

3.2 Transition Model

For some turbomachinery components such as low pressure turbines, the low Reynolds numbers lead to significant effects of laminar and transitional boundary layers. If fully turbulent CFD simulations are applied the component performance, especially of viscous losses, may be predicted considerably incorrectly. The laminar boundary layers cause higher overall losses because of their sensibility to separation at adverse pressure gradients. However, they generate lower losses in comparison to the turbulent boundary layers. The quantitative prediction of these effects proves to be a very challenging task.

Transition occurs through different mechanisms[13]. In turbomachinery flows, the following modes are regarded as the dominant mechanisms.

- natural and bypass mode
  The natural mode usually occurs at low turbulence intensities. The laminar-turbulent transition is initialized by linear growth of disturbances and undergoes several manifestation levels (Tollmien-Schlichting waves, structures and turbulent spots) until the non-linear breakdown of a fully turbulent boundary layer. As the turbulence intensity is increased the intermediate levels become shorter, and are eventually bypassed in directly jumping to the non-linear amplification, leading to the so called bypass mode of transition[14].

- separation induced mode
  The separation-induced transition is detected by negative values of the wall shear stress. Due to the influence of an adverse pressure gradient, a laminar boundary layer separates. Thus, transition develops within the separated shear layer. In addition, turbulent boundary layers can relaminarize because of a strong favorable pressure gradient.

- wake induced mode
  Due to the relative motion between stators and rotors, unsteady wake-blade interaction is an inevitable consequence.

The transition model, applied in this paper, is a correlation-based approach specifically designed for modern CFD code architectures. It was first presented by Menter et al.[9,10] in 2004 and is called γ-Re_Θ transition model. Two additional transport equations are solved. This is required to capture the non-local influence of the turbulence intensity varying due to the changes in the freestream velocity outside the boundary layer and the decay of the turbulent kinetic energy in the freestream. The first transport equation is solved for the intermittency γ

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_f}\right)\frac{\partial \gamma}{\partial x_j}\right] \tag{1}$$

and the second one for the transition onset momentum Reynolds number $Re_{\Theta t}$

$$\frac{\partial(\rho \tilde{Re}_{\Theta t})}{\partial t} + \frac{\partial(\rho U_j \tilde{Re}_{\Theta t})}{\partial x_j} = P_{\Theta t} + \frac{\partial}{\partial x_j}\left[\sigma_{\Theta t}\left(\mu + \mu_t\right)\frac{\partial \tilde{Re}_{\Theta t}}{\partial x_j}\right]\,. \tag{2}$$

This second equation is an essential part of the model as it links the empirical correlation to the onset criteria in the intermittency equation. Therefore, it allows the model to be used in general geometries and over multiple airfoils, without additional information on the geometry.

The transition is triggered by a strain-rate Reynolds number

$$Re_\Theta = \frac{Re_{\nu max}}{2.193} = \frac{1}{2.193}\left(\frac{\rho y^2}{\mu}\Omega\right) \tag{3}$$

instead of the actual momentum thickness so that the use of non-local quantities can be largely avoided. The intermittency function is applied to turn on the production term of the turbulent kinetic energy downstream of the transition point. This is based on the relation between the transition momentum thickness and the strain-rate Reynolds number. Since the strain-rate Reynolds number is a local property, the present formulation avoids another very severe shortcoming of the correlation-based models, namely their limitation to 2D flows. Hence, the simulation of transition in 3D flows originating from different walls can be predicted. The formulation of the intermittency has also been extended to account for the rapid onset of transition caused by separation of the laminar boundary layer. In addition, the model can be fully calibrated with internal or proprietary transition onset and transition length correlations. The correlations can also be extended to flows with rough walls or to flows with crossflow instability. Menter et al.[9] stress the fact that the proposed transport equations do not attempt to model the physics of the transition process. Nevertheless, they form a framework for the implementation of correlation-based models into general-purpose CFD methods. A main advantage of this model in conjunction with the CFD solver TRACE is the potential to apply it to every possible grid topology, as it will be shown in the next sections.

All details of the model framework have been given in the original paper[9,10]. However, some essential correlations were not published at that time. Since then, different research groups have published their conclusions for the remaining correlations as Malan et al.[15]. Their formulation is implemented in TRACE. In 2009, Langtry et al.[16] published their skipped correlations.

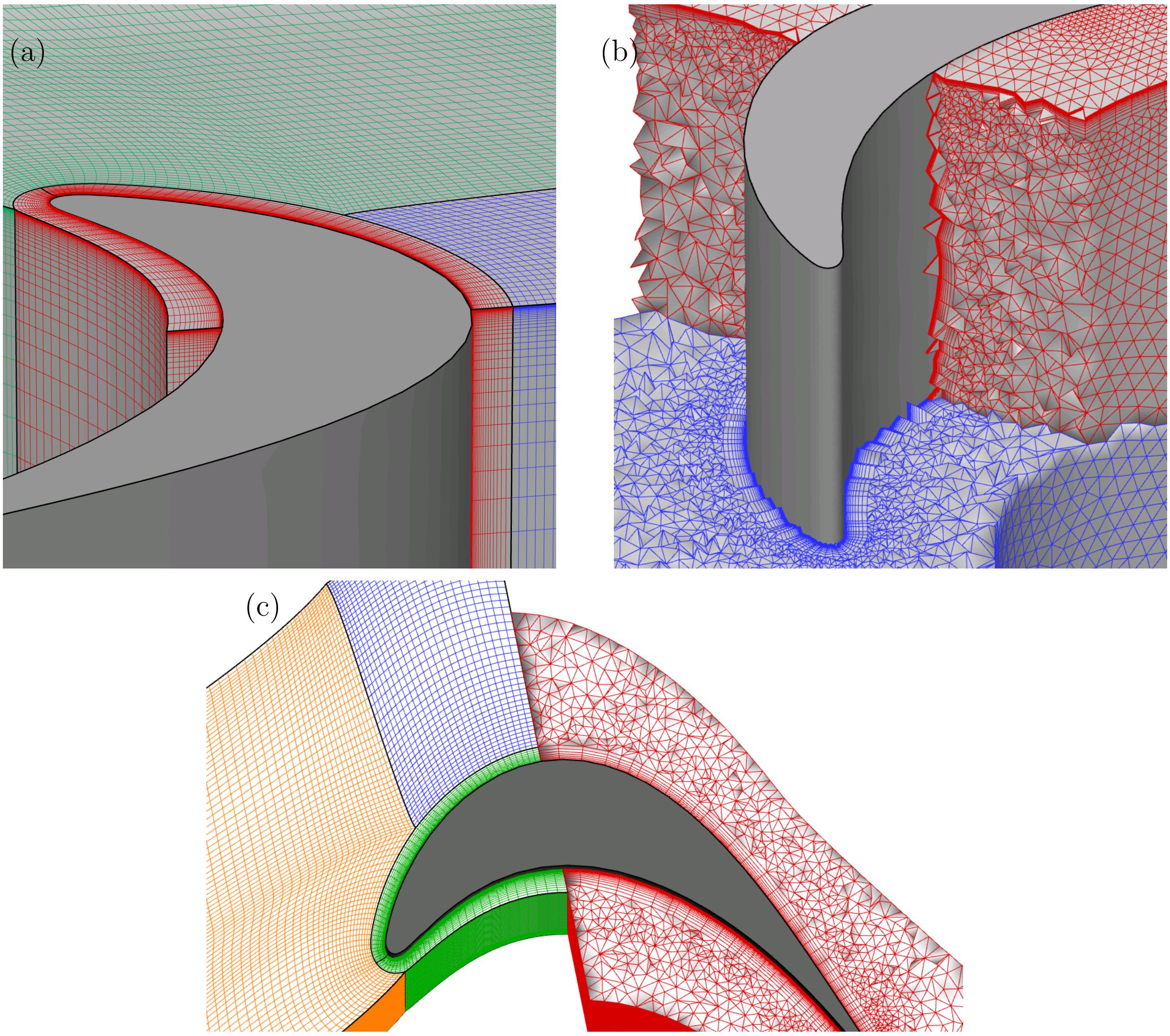

Figure 2: Grid topologies for T160 turbine cascade: (a) structured grid, (b) unstructured grid, (c) hybrid grid

4 CFD SIMULATIONS OF A PLANAR TURBINE CASCADE

The turbine cascade T160 exemplifies the present implementation of the γ-Re_Θ transition model in TRACE. The turbine represents a modern aerodynamic design, designed by MTU Aero Engines[1]. It has been mounted inside a diverging channel in order to reproduce authentic pressure gradients. The experimental investigations have been conducted at the University of Armed Forces, Munich[8]. Based on this cascade, the sensitivity of losses with respect to the more adverse aerodynamic boundary conditions can be studied. Furthermore, the data allow to check the quality of the boundary layer flow description in the analysis tools, especially in the transition modeling of the CFD code.

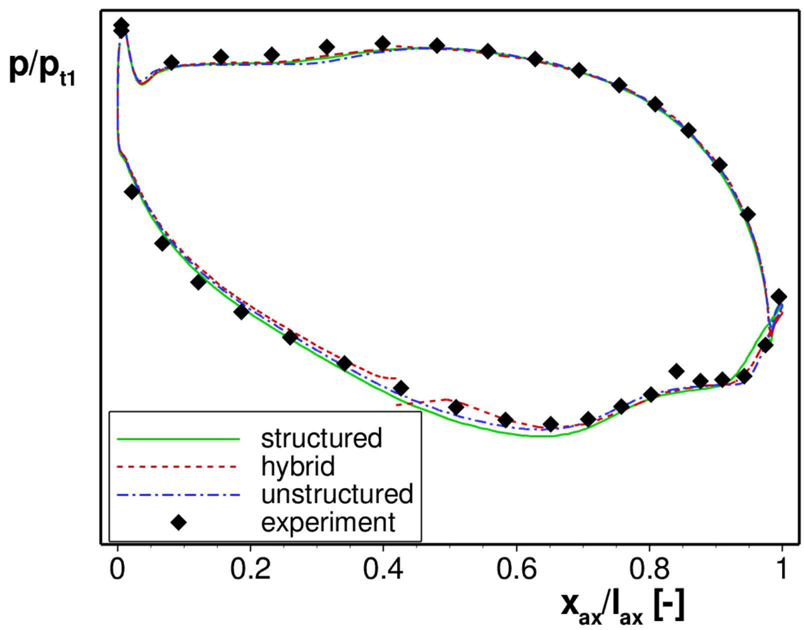

Figure 3: Pressure distribution of the T160 turbine cascade at 50% channel height

In contrast to the non-local transition model, the γ-Re_Θ model can be applied to structured and unstructured grids. Therefore, three different grid topologies are generated to demonstrate the validity of the implementation. In figure 2a, a cut of the structured grid in upstream direction is illustrated. The characteristics of a Low-Reynolds grid are obvious. The dimensionless wall distance of the wall adjacent cells is $y^+ \leq 1$ for blade surfaces and end walls. Figure 2b shows a comparable grid quality for the unstructured grid. Close to the end walls and the blade surface, prismatic layers are used to achieve the necessary grid resolution of the boundary layers. The third grid consists of a structured grid in the front part and an unstructured grid in the downstream area. A cross section is presented in figure 2c. All grids consist of at least 2.5 million grid points.

The three grids are evaluated for a Reynolds number of $Re = 70.000$ and an inlet

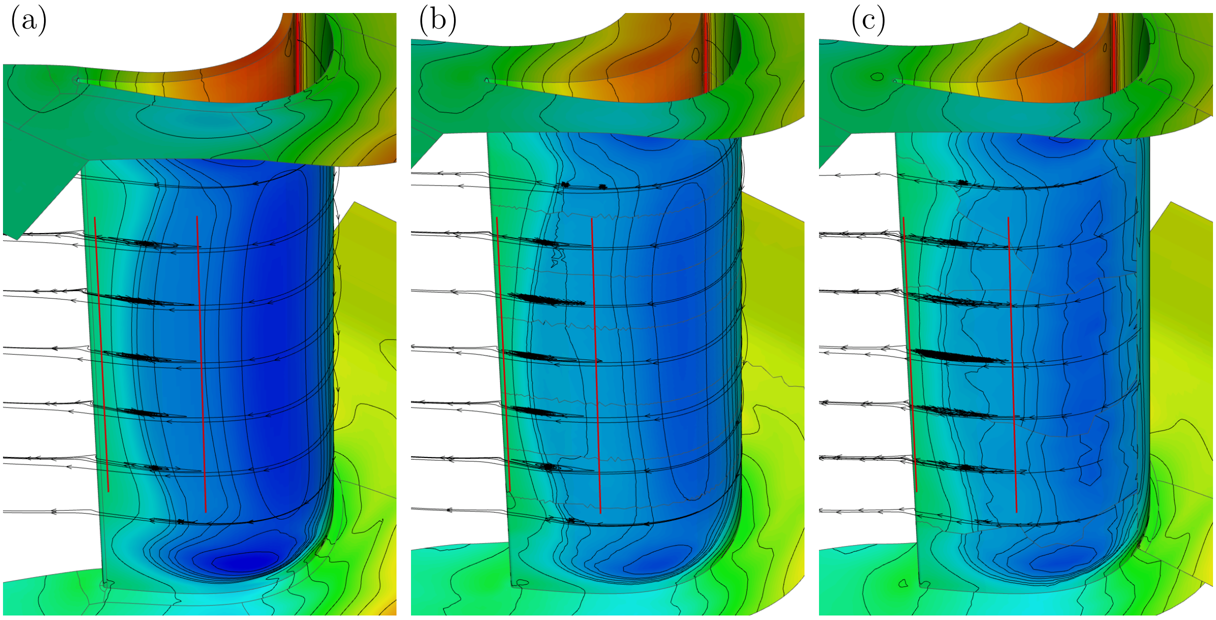

Figure 4: Schematic representation for the turbine T160: (a) structured grid, (b) unstructured grid, (c) hybrid grid

Mach number of $M = 0.6$. In figure 3, the pressure distributions of all grids are compared to the experimental data. Along the pressure side, all three CFD calculations display the same characteristics. On the suction side, the solutions differ quite a bit from each other. Although they all predict the separation bubble, they show differences in the locations of separation and reattachment of the flow. These minor differences depend on the varied grid topologies and a dissimilar formulation of the turbulence model between the structured solver and the unstructured one. In the case of the hybrid grid, discontinuities at the interface between the structured and the unstructured part can be observed. They can be ascribed to the interpolation routines inside the visualization software Tecplot. Altogether, the three CFD simulations agree fairly well with the measurements.

In figure 4, the pressure distribution at all viscous walls is illustrated for the three grid topologies. Figure 4c does not reveal the discontinuties in the static pressure as shown in figure 3. Additionally, streamlines are plotted at several channel heights to depict the separation area. The red lines are drawn in as reference to approximately depict the locations of separation and reattachment. A comparison of the three pressure distributions evidences that the separation bubble in the structured grid is located further upstream in contrast to the other ones. This characteristic is consistent with the conclusions of figure 3.

The distribution of the eddy viscosity is plotted in figure 5 for the structured and the unstructured grid. In both pictures, the wakes are clearly defined. The values in the structured case (figure 5a) agree with the results of the unstructured grid (figure 5b). Therefore, the implementation of the transition model results in the same flow character-

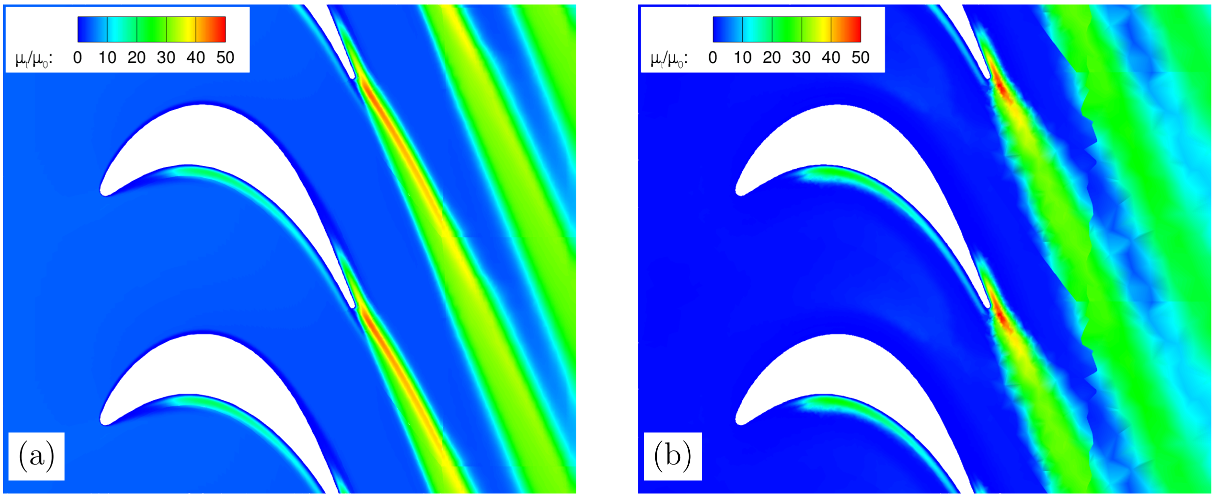

Figure 5: Distribution of eddy viscosity at 50% channel height of T160 turbine cascade: (a) structured grid, (b) unstructured grid

istics for the structured and unstructured grid.

5 UNSTEADY ANALYSIS OF THE T106C CASCADE

The T106C turbine cascade with upstream moving bars ($M_{2th} = 0.65$, $Re_{2th} = 140000$) is utilized to compare the structured part of the solver with the unstructured one with

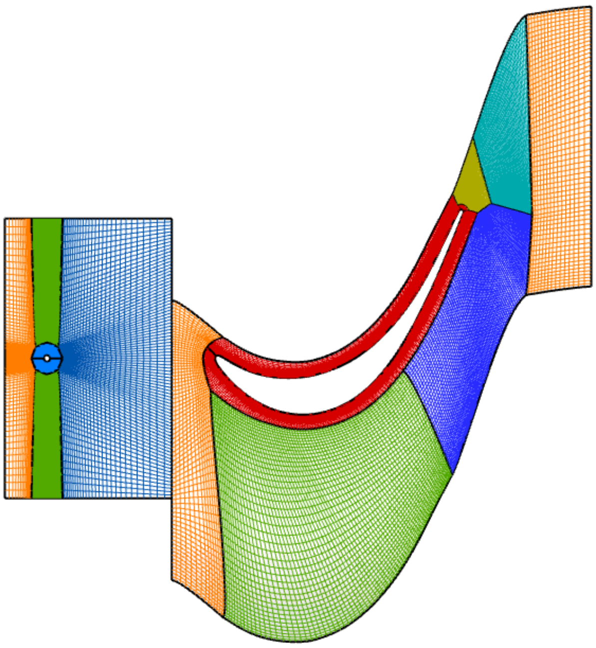

Figure 6: Quasi-3D structured grid of the T106C turbine

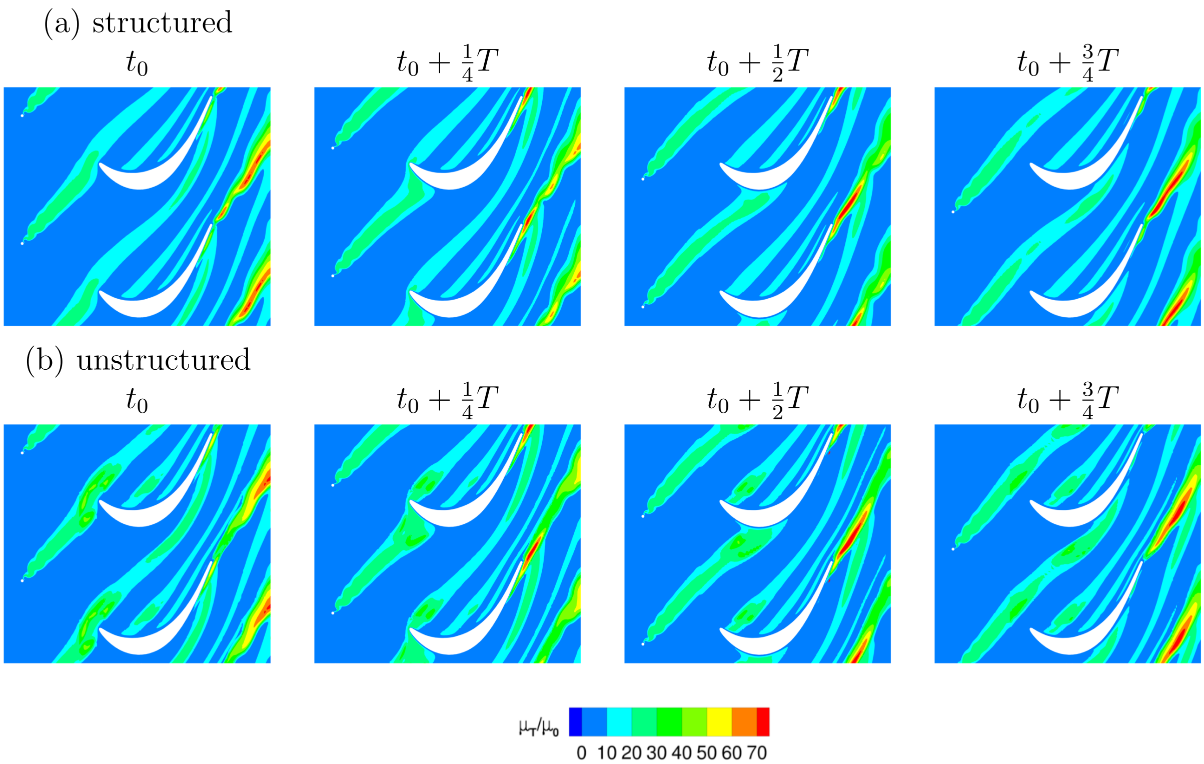

Figure 7: Eddy-viscosity contours at four instances in time.

regard to the prediction of unsteady transitional flows. For the simulations, a quasi-3D structured grid, consisting of 28,000 cells, is used as shown in figure 6. For the unstructured caculation, this structured grid is applied. Only the blocks belonging to the turbine profile are considered as unstructured to achieve a good comparison between the structured and unstructured solver.

In figure 7, an unusual flow condition is analyzed to evaluate the numerical stability of the CFD solver. In this setup the bar is moving in the opposite direction. Therefore, the wake hits the turbine profile on the suction side. The results of the unsteady unstructured simulation are still in good agreement with the structured calculation.

6 CONCLUSIONS

The latest progress for the 3D hybrid structured-unstructured RANS solver TRACE is presented and validated in this paper. To ameliorate the prediction of transition and separation phenomena, the γ-Re_Θ transition model has been implemented requiring two additional transport equations, one for the intermittency and one for a transition onset criterion in terms of the momentum-thickness Reynolds number. This model combines the benefits of physical information within empirical correlations and locally formulated transport equations so that non-local operations are avoided.

In this regard, a general formulation for transport equations has been realized for the structured part of the solver as well as the unstructured one. So the CFD code is now able to capture the transition regardless of the grid topology. This conclusion is proved by the two described test cases showing corresponding results for the structured, unstructured, and hybrid grids.

REFERENCES

[1] Gier, J., and Hübner, N., 2005. "Design And Analysis Of A High Stage Loading Five-Stage LP Turbine Rig Employing Improved Transition Modeling". In ASME Turbo Expo, no. GT2005-68971.

[2] Wilcox, D., 1988. "Reassessment of the Scale-Determining Equations for Advanced Turbulence Models". *AIAA Journal,* ***26***(11), pp. 1299–1310.

[3] Kügeler, E., Fakhari, K., Mönig, R., and Engel, K., 2008. "Influence of Real Gas Phenomena in a Multistage Gas Turbine Compressor". In 12th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, no. ISROMAC12-2008-20029.

[4] Giles, M. B., 1988. Non-Reflecting Boundary Conditions for the Euler Equations. Tech. Rep. CFDL-TR-88-1, CFD Lab., MIT.

[5] Acton, E., and Cargill, M., 1988. "Non-Reflecting Boundary Conditions for Computations of Unsteady Turbomachinery Flow". In 4th Int. Symp. Unsteady Aerodynamics and Aeroelasticity of Turbomachines and Propellers, pp. 211–228.

[6] Yang, H., Nürnberger, D., and Weber, A., 2002. "A conservative zonal approach with application to unsteady turbomachinery flows". In DGLR Jahrestagung.

[7] Kügeler, E., Weber, A., Nürnberger, D., and Engel, K., 2008. "Influence of Blade Fillets on the Performance of a 15 stage Gas Turbine Compressor". In ASME Turbo Expo 2008: Power for Land, Sea and Air, no. GT2008-50748, Proceedings of ASME Turbo Expo 2008: Power for Land, Sea and Air.

[8] Kozulovic, D., Röber, T., and Nürnberger, D., 2007. "Application to a Multimode Transition Model to Turbomachinery Flows". In Seventh European Turbomachinery Conference.

[9] Menter, F. R., Langtry, R. B., Likki, S. R., Suzen, Y. B., Huang, P. G., and Völker, S., 2004. "A Correlation-Based Transition Model Using Local Variables Part 1 - Model Formulation". In ASME Turbo Expo, no. GT2004-53452.

[10] Menter, F. R., Langtry, R. B., Likki, S. R., Suzen, Y. B., Huang, P. G., and Völker, S., 2004. "A Correlation-Based Transition Model Using Local Variables Part 2 - Test Cases And Industrial Applications". In ASME Turbo Expo, no. GT2004-53454.

[11] Yang, H., Nürnberger, D., and Kersken, H.-P., 2006. "Toward Excellence In Turbomachinery Computational Fluid Dynamics: A Hybrid Structured-Unstructured Reynolds-Averaged Navier-Stokes Solver". *Journal Of Turbomachinery,* ***128***, pp. 390–402.

[12] Newman, W. M., and Sproull, R. F., 1979. *Principles of Interactive Computer Graphics.* McGraw-Hill, New York.

[13] Mayle, R. E., 1991. "The Role of Laminar-Turbulent Transition in Gas Turbine Engines". *Journal Of Turbomachinery,* ***113***, pp. 509–537.

[14] Kozulovic, D., Röber, T., Kügeler, E., and Nürnberger, D., 2004. "Modifications of a Two-Equation Turbulence Model for Turbomachinery Fluid Flows". In DGLR Jahrestagung, no. DGLR-JT2004-229a.

[15] Malan, P., Suluksna, K., and Juntasaro, E., 2009. "Calibrating the γ-Re_Θ Transition Model for Commercial CFD". In 47th AIAA Aerospace Sciences Meeting, no. AIAA-2009-1142.

[16] Langtry, R. B., and Menter, F. R., 2009. "Correlation-Based Transition Modeling for Unstructured Parallelized Computational Fluid Dynamics Codes". *AIAA Journal,* ***12***, December, pp. 2894–2906.