IDIHOM

Project N° : *ACP0-GA-2010-265780*

Project acronym : *IDIHOM*

Project title : *Industrialisation of Higher-Order Methods – A Top-Down Approach*

Instrument : *Collaborative Project*

Framework : *Seventh Framework Programme*

Publishable Summary Report

D1.1-36b

Period covered: from 01/10/2010 to 31/03/2014

Date of Preparation: 29 May 2014

Start date of project: 01/10/2010 *Duration: 42 months*

Project coordinator name: Dr. Norbert Kroll

Project coordinator organisation name: DLR

The IDIHOM project started in October 2010 as a Specific Target Research Project of the 7th EU Framework Programme. The main goal of the project was to mature high-order adaptive CFD methods for industrial applications.

The project was originally scheduled for 36 months with a total budget of about 4.2 Million Euro. It has been extended by 6 months and was completed by 31 March 2014. The consortium of 21 partners includes the European Airframe industry, the major Research centres, universities and SMEs. The list of partners is given below:

Participant no.	Participant organisation name	Short name	Country
1 (Coordinator)	Deutsches Zentrum für Luft und Raumfahrt	DLR	D
2	Dassault Aviation	DASSAV	F
3	Airbus Defense and Space (earlier: CASSIDIAN)	AIRBUS D&S	D
4	CENAERO	CENAERO	B
5	NUMECA	NUMECA	B
6	Aircraft Research Association Ltd.	ARA	UK
7	Swedish Defence Research Agency	FOI	S
8	Institut National de Recherches en Informatique et Automatique	INRIA	F
9	Nationaal Lucht- en Ruimtevaartlaboratorium	NLR	NL
10	ONERA	ONERA	F
11	Central Aerohydrodynamic Institute	TsAGI	RUS
12	Von Karman Institute for Fluid Dynamics	VKI	B
13	Laboratoire DynFluid, Arts et Métiers—ParisTech	ARTS	F
14	Imperial College London	ICL	UK
15	University of Bergamo	UNIBG	I
16	University of Brescia	UNIBS	I
17	Universität Stuttgart	USTUTT	D
18	Poznan University of Technology	PUT	PL
19	Warsaw University of Technology	WUT	PL
20	University of Linköping	LIU	S
21	Université catholique de Louvain	UCL	UCL

The IDIHOM project was co-ordinated by DLR.

Background, objectives, work description

Over the last two decades, computational fluid dynamics (CFD) has established itself to a point where it is widely accepted as an analysis and design tool complementary to theoretical considerations and experimental investigations. In aerospace, methods to solve the Navier-Stokes equations have matured from specialized research techniques to practical engineering tools being used on a routine basis in the industrial design process. Thus, numerical simulation has become one of the driving technologies for both, scientific discovery and industrial product development. Continuous development of physical models and numerical methods as well as the availability of increasingly powerful computers suggest using numerical simulation to a much greater extent than before, radically changing the way aircraft will be designed in the future.

On the other hand, despite the progress made, large aerodynamic simulations of viscous high Reynolds number flows around complex aircraft configurations are still by far too expensive in terms of turn-around time and computational resources. The requirement to achieve results at an engineering level of accuracy within wall-clock times that can be handled in the day-to-day procedure poses severe constraints on the application of CFD to aerodynamic design and data production. Improved flow physics modeling and the enormous increase in computer power is only one part of the solution. The other part is evidently dedicated to a necessary enhancement of the numerical methods themselves. The development of advanced CFD algorithms and their integration in an industrial environment to support multidisciplinary simulations and optimisation procedures and at the same time achieving high predictive accuracy will significantly reduce design cycle and cost and is therefore indispensable for industry.

The majority of the aerodynamic simulation tools currently used in the aeronautical industry for routine applications are mainly based on finite volume methods. Being bound in most of the cases to second order discretization of the underlying governing equations, real-life applications require tens or hundreds of million mesh points to enable accurate solutions and to provide deep insight into complex flow features. In recent years there has been worldwide an ever increasing effort in the development of high-order CFD methods because of their potential in delivering either improved predictive accuracy or reduced computational cost compared to their low-order counterparts. Many different strategies have been followed and their pros and cons have been evaluated for a diverse range of academic problems.

In Europe, the specific target research project ADIGMA (Adaptive Higher-Order Variational Methods for Aerodynamic Applications in Industry) was initiated within the 6^{th} European Research Framework Programme, in order to add a major step towards the development of next generation CFD tools with significant improvements in accuracy and efficiency for turbulent aerodynamic flows [1], [2]. The main objective of the ADIGMA project (2006-2009) was the development of innovative high-order methods for the compressible flow equations in combination with reliable adaptive solution strategies, enabling mesh independent numerical simulations for aerodynamic applications. The project concentrated on technologies showing the highest potential for efficient high-order discretization on unstructured meshes, namely the Discontinuous Galerkin (DG) methods and the Continuous Residual Distribution (CRD) schemes. Although significant progress has been made in ADIGMA, it was finally concluded that many of the achievements in high-order simulation methods are still far away from industrial maturity. In general, the high-order methods investigated within ADIGMA demonstrated the potential for reducing the size of the discrete system by a factor of about 5-10 for most of the considered aerodynamic test cases, however, the gain could not fully transferred to increased runtime performance as limited attention has been paid to efficient solvers for large scale applications. On a given mesh, high-order discretization involves more floating point operations than do their low-order counterparts. Strong, memory-efficient solution algorithms are required to outperform well-tuned low-order methods. Furthermore, the ability of generating coarse unstructured meshes suitable for high-order methods has been identified as a major bottleneck for industrial type applications. At the end of the ADIGMA research project it was recommended that further dedicated research effort is required to fully exploit the high-order methods for routine applications in aerospace industry.

In 2011 the follow-on project IDIHOM (Industrialization of High-Order Methods) was initiated within the 7th European Research Framework Programme. It was motivated by the increasing demand of the European aerospace industries to improve their CFD-aided design procedure and analysis by using accurate and fast numerical methods. IDIHOM follows a top-down approach. A comprehensive suite of challenging application cases proposed by industry was set up prior to the project to direct dedicated development and improvement of high-order solvers at hand. The test case suite includes turbulent steady and unsteady aerodynamic flows, covering external and internal aerodynamics as well as aero-elastic and aero-acoustic applications. The complete process chain of the high-order flow simulation capability was addressed, with focus on flow solver efficiency and mesh generation capabilities, but including also visualisation and coupling of CFD to other disciplines for multidisciplinary analysis. The challenging application cases defined by the industry formed the basis for the demonstration and assessment of the current status of high-order methods as a workhorse for industrial applications. IDIHOM was assigned to help to close the gap between current expectations of what high-order methods are capable of and their strongly required use for industrial real-world applications - reaching out for improved, more accurate and time-saving design processes.

The main objectives to be achieved by gathering expertise from European experts in the field of numerical analysis in aerodynamic and multidisciplinary design are summarized as follows:

- O1: Advance the maturity of current high-order methods, in particular Discontinuous Galerkin and Continuous Residual-Based approaches, and apply them to complex flows which are of particular interest for the aeronautical industry.
- O2: Demonstrate the capabilities of high-order methods in solving industrially relevant, challenging applications and achieving synergy effects by combining requirements from external and internal aerodynamic flows.
- O3: Investigate the capability of high-order methods to multidisciplinary topics as aero-acoustics & aero-elastics.
- O4: Extend high-order methods to advanced turbulence models.
- O5: For the adaptive high-order methods employed, advance the Software Technology Readiness Level from about 3 (status at the end of the ADIGMA project) to 5.
- O6: Facilitate co-operation between European industries, research establishments and universities and foster co-operation between different industries as there are airframe, turbo-engines, helicopters, and ground transportation.

Reaching these objectives shall enable industry to use high-order methods in their daily work. Improved accuracy coupled with a reduction of computation and hence turn-around time is a pre-requisite for a routine employment of novel methods in future aircraft design cycles.

The IDIHOM consortium was comprised of 21 organisations with well-proven expertise in higher-order methods or underlying technologies. Partners from European aircraft manufactures, small and medium enterprises, major European research establishments and universities were involved. The project was coordinated by the German Aerospace Center (DLR).

As mentioned already, the IDIHOM project followed a top-down approach to enhance the maturity of current high-order methods for routine use in aeronautical industry. Enhancement and improvement activities were identified which enable a robust, efficient and accurate computation of the comprehensive set of application challenges. The advancement of the complete set of the high-order environment was addressed to fulfil the industrial requirements, including mesh generation and adaptation, solver robustness and convergence acceleration, parallelization strategies for advanced computer hardware as well as flow visualisation.

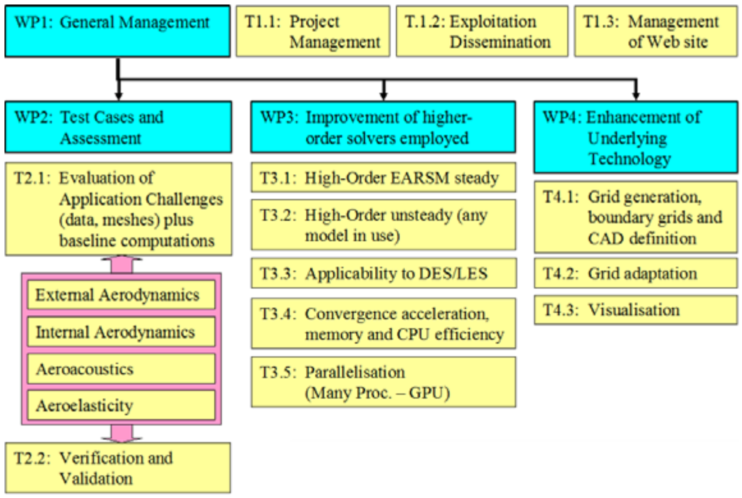

Figure 1. Work package structure of the project.

The technical work in IDIHOM was structured in three main work packages (WP), all of them split into specific work tasks. WP2 was the key driver of the project, as it demonstrated and steered the top-down approach of IDIHOM. In a first task the pre-selected test cases were further specified in terms of geometry, flow and boundary conditions. Reference solutions using second-order finite volume methods and baseline solutions employing high-order methods available at project start were computed. These results were then used in a second task for detailed comparisons with solutions obtained with the improved high-order methodologies available at the end of the project. Common test case templates were defined, ensuring that reference, baseline and final results are properly compared, allowing a thorough assessment of the achievements and advances gained through the IDIHOM project. Work package WP3 addressed the improvement of high-order solvers with regard to the IDIHOM application challenges and the underlying test cases. After successful completion of the precursor project ADIGMA, focus was not put on the general development of high-order approaches, but more on the maturity of the implementation of codes at hand, thus extending the available capabilities of the solvers with respect to physical modeling, the applicability to large-scale application cases and the treatment of time accurate simulations. In work package WP4 the enhancement of underlying technologies of high-order methods were addressed. Basically three aspects are of concern, in which high-order methods have special requirements. These are mesh generation, mesh adaptation and flow visualisation. Therefore, specific development actions were carried out to tackle the test cases considered in the project.

The test case suite selected for the IDHOM project can be split into four application areas: external and internal aerodynamics, aero-elastics and aero-acoustics. Two different types of test cases were defined. So-called application challenges were mainly defined by industry and they are characterized by complex three-dimensional flows around complex geometries. A few underlying test cases were provided with moderate geometrical and/or flow complexity to speed-up the process of method enhancement. The test case suite was selected prior to project start. During the course of the project, some modifications and adaptations were made due to lack of reference results and detailed geometry definitions.

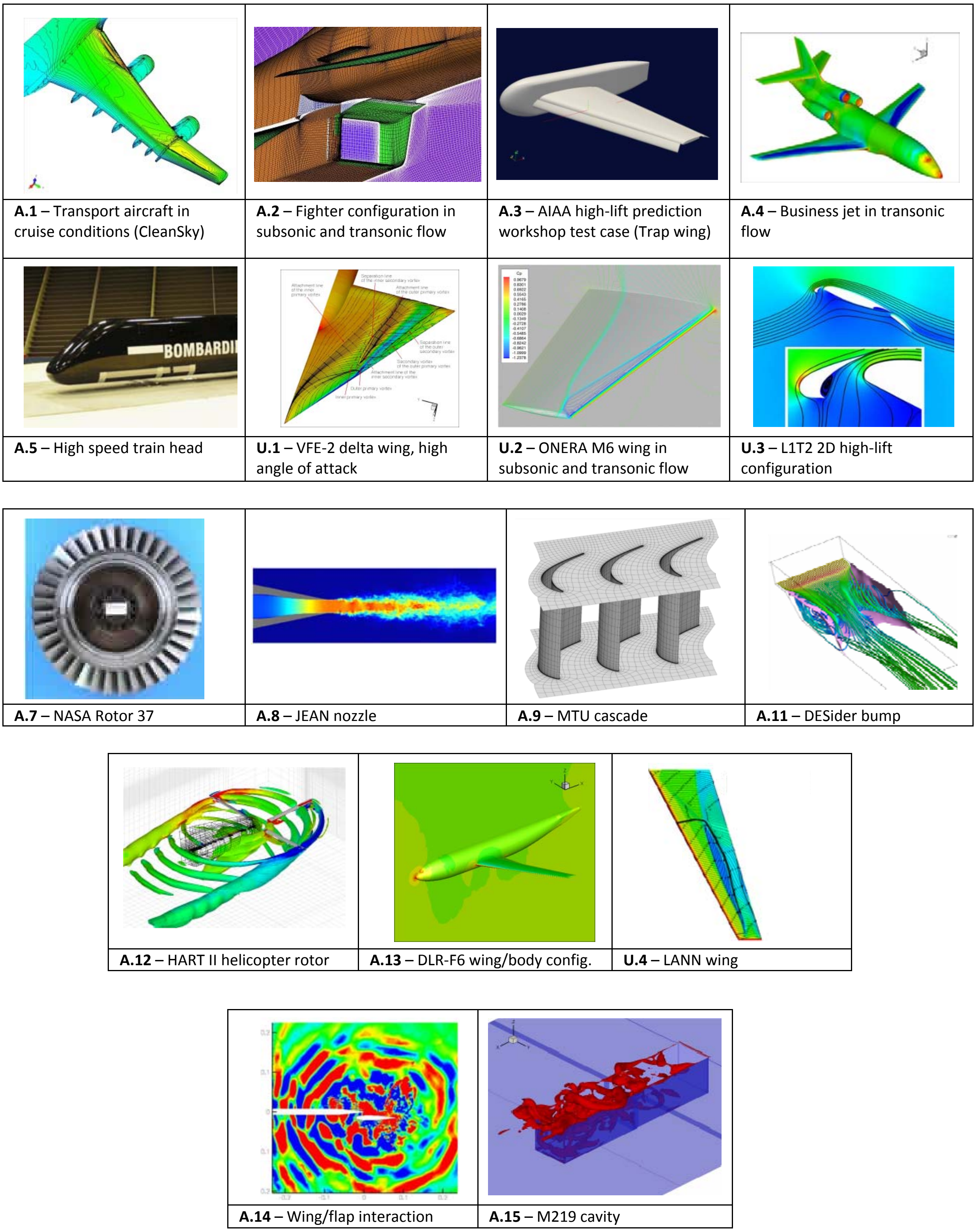

Figure 2. Test case suite of IDIHOM.

IDIHOM

Work performed and results achieved within the project

In the following some results obtained in the project are highlighted. Detailed descriptions of the activities carried out by the different partners within the project and summaries of the results obtained for the various test cases are given in chapters below and in the dedicated book "IDIHOM - Industrialisation of High-Order Methods, A Top Down Approach" of the Springer Series *Notes on Numerical Fluid Mechanics and Multidisciplinary Design.*

Solver technologies

IDIHOM focused on two aspects, the implementation of advanced turbulence models and the efficiency improvement of solution algorithms for the nonlinear discrete systems for both steady and time-accurate applications.

In terms of advanced physical modeling Explicit Algebraic Reynolds Stress Models (EARSM) up to cubic terms of the anisotropy tensor coupled with the two-equation turbulence model was implemented in the frame of high-order Discontinuous Galerkin solvers. Reynolds stress turbulence models proved to be more reliable when being used for a wide range of applications compared to the classical one- or two-equation turbulence models. EARSM was selected because of the good compromise between improved modeling of turbulence and moderate associated cost. The advanced turbulence model was successfully applied to various underlying and challenging test cases. For some problems improved physical modeling was demonstrated resulting in a very small computational overhead compared to standard 2-equation turbulence models. However, it has been observed that for more complex applications often the EARSM approach was difficult to converge to a steady state solution.

Another area of research was the extension and adapation of high-order methods to scale resolving simulations. High-order methods are well suited since these simulations require high resolution in both space and time. Different approaches were followed within IDIHOM. In the frame of hybrid RANS/LES (DES), the X-LES approach was employed in a high-order block-structured code in combination with local block-wise grid refinement as well as in a high-order DG code. Impressive results were obtained for quite a number of test cases. Furthermore, high-order Discontinuous Galerkin and Residual Based Compact schemes were further developed and validated for LES and DNS. In particular, the quality of the implicit LES (ILES) approach in the frame of the DG discretization was demonstrated. The absence of tuning parameters and the robustness of DG methods with respect to mesh quality indicated industrial viability. For scale resolving simulations significant progress was made compared to start of the project.

As mentioned earlier, the construction of a robust and memory-efficient solver is a pre-requisite of efficient high-order methods. For steady state computations or unsteady phenomena which allow for rather large physical time steps, implicit formulations are generally preferred due to the fact that viscous terms, stretched meshes with very small mesh size in at least one direction and the high-order formulation all contribute to severe time step restrictions. Therefore, the research within IDIHOM concentrated on implicit solution methods. Due to the fact that additional, independent degrees of freedom are introduced to describe the high-order content of the solution, it is very difficult if not impossible to base the implicit treatment on just a lower-order approximation, as typically done for finite volume schemes. If the high-order content is not treated implicitly, the overall scheme becomes explicit. As a consequence, most implicit treatments make use of the full high-order Jacobian, resulting in considerable memory requirements. Although it is not possible to completely replace the implicit operator or preconditioner by a low-order approximation, an attractive alternative are so-called *p*-multigrid methods, variants of which were proposed by several partners. In spite of the name, these approaches approximate the numerical solution on single mesh, but with different order methods. While improvements over single-level computations were shown for a number of cases, there is still room for improvement. If for example, relatively fine meshes are used due to mesh generation restrictions, the effectivity of this approach might be rather limited. Therefore, alternative multigrid strategies based on agglomeration of meshes (*h*-multigrid) were developed and investigated. In the frame of DG methods, the corresponding discretizations require the use of non-parametric basis functions. The resulting hierarchy of levels can be exploited to use the nonlinear FAS multigrid approach or, alternatively, to formulate linear multigrid method to be used an effective preconditioner within a Krylov solver. The combination of both multigrid strategies proved to be the most robust and efficient approach for a wide range of applications. For the Residual Distribution methods a non-linear LU-SGS method was developed and successfully applied to 2D and 3D test cases. In addition, improvements of implicit methods for time-accurate computations were made.

Adaptive refinement techniques are essential for high-order methods to be competitive with standard finite-volume solvers. In the previous project ADIGMA substantial effort was devoted to the development of local refinement approaches related to both, mesh and discretization order refinement. Based on this work, limited activities were carried out within IDIHOM to further improve and mature the local refinement techniques for more complex applications.

High-order grid generation and visualisation

To fully exploit the capabilities of high-order methods, higher-order representation of the boundaries is required. Furthermore, for stretched elements often encountered close to the solid wall boundaries in aerospace applications, the volume mesh needs to be considered as curvilinear as well, at least close to the curved surfaces. Such high-order meshes are typically not readily available and the support in commercial grid generation software is not available. Based on the experience gained in ADIGMA, dedicated research activities were devoted to further development and enhancement of high-order mesh generation techniques. Focus was put on generation of coarse unstructured meshes for geometries of industrial interest. Different technologies were investigated and further enhanced including mesh adaptation techniques. Although some good progress towards this overall objective was made, the generation of usable grids for the most complex test cases considered in IDIHOM proved to be more difficult than anticipated when planning the project. In general difficulties were caused by problems in generating an initial coarse linear volume grid upon which most of the high-order grid generation algorithms depend. Usable capabilities were made available for 2D and simple 3D test cases. The use of mesh adaptation was successfully demonstrated for some of the IDIHOM 3D test cases.

With respect to visualisation limited effort was spent to investigate and further enhance existing open software tools following the super-sampling technique. This technique relies on a visualisation sub-mesh for each element in the underlying computational mesh, thereby approximating nonlinear data per element via a subdivision into several linear segments. Appropriate interfaces to the open source visualization tools were developed and integrated. In addition an alternative approach was investigated, in which the polynomial data are visualised directly.

Scope of applications

Higher-order computations of eight external aerodynamic test cases were performed in the IDIHOM project. Three of these cases are termed underlying as they involve geometries and physics that are not considered to be of industrial complexity. The remaining test cases consist of aircraft geometries at design point and high angle of attack/high-lift conditions, as well as a train configuration and a helicopter rotor case.

The first underlying test case considered was the VFE2 delta wing, included to enable a thorough analysis of the higher-order codes applied to vortex dominated flows. Even though there were significant problems in generating higher-order unstructured meshes for this geometry, a relatively large amount of data could be gathered, some of them illustrated in Figure 3. In general, it was shown for this test case, that higher-order approaches have the potential of reducing the discrete system size required for convergence within engineering accuracy with around one order of magnitude. In particular, adaptive strategies were found to be the most efficient way to reduce the overall problem size and thus alleviate the high computational cost per degree of freedom associated to high-order methods. Progress has been made in the robustness of higher-order codes, at least for subsonic conditions, and achieving converged results has become routine basis for this type of problems.

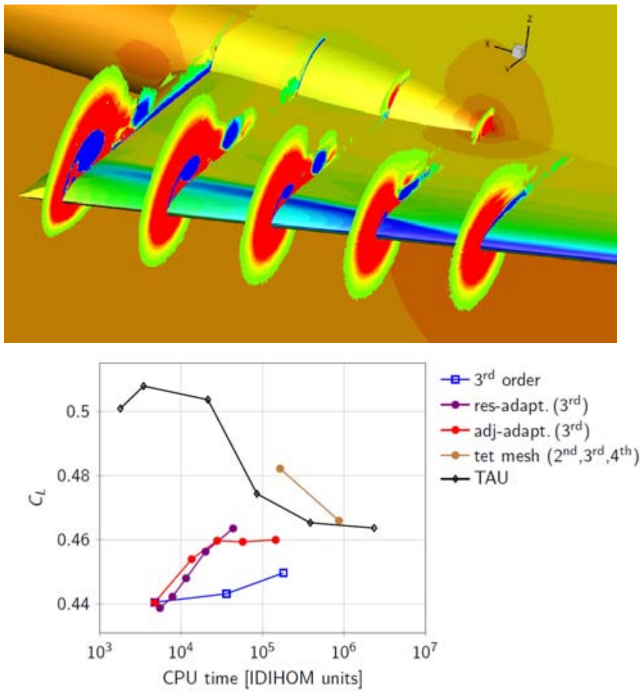

Figure 3. Mesh convergence for subsonic delta wing (M=0.4, α=13,3^0, Re=3x10^6) with higher-order adaptive DG method, comparison with state-of-the-art finite-volume solver (TAU), (DLR).

The second underlying test case was the ONERA M6 wing, considered as a simplified representative of typical aircraft cruise cases. For this case a series of unstructured higher order meshes could be generated. Unfortunately, however, the data made available were not sufficient for a stringent performance evaluation of the codes. The general impression was that little improvement could be achieved by the introduction of higher-order methods for this transonic test case. This maybe at least partially caused by the shock system dominating this particular case. It was however demonstrated that the higher-order approaches are capable of producing solutions for cases of this complexity.

The final underlying test case was the L1T2 three-element airfoil, serving as basis for high-lift applications. A large number of different high-order meshes were generated presenting progress in higher-order mesh generation capabilities. It however remains unclear, whether this progress is transferable to three dimensional complex geometries. In Figure 4 a higher-order solution obtained by DLR on an adapted mesh generated by the University of Warsaw is shown. The performance analysis of this test case again showed that reductions in discrete system size were obtainable. New developments in flow solver technologies have been successfully demonstrated for this test case. This includes the usage of agglomerated multigrid as well as the use of enhanced turbulence models. Despite the improvements made in terms of solver efficiency, however, for engineering accuracy the reduction in degrees of freedom did not result in increased overall runtime performance compared with the industrial reference.

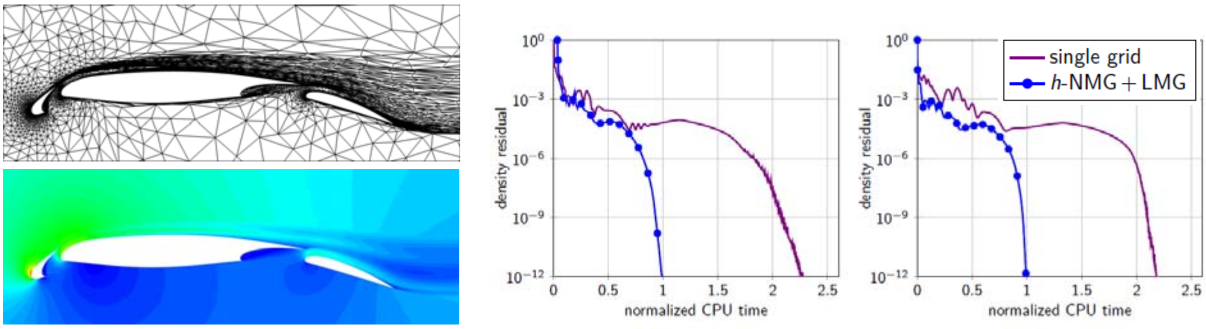

Figure 4. High-order adaptive mesh (University of Warsaw) for the L1T2 airfoil (M=0.197, α=20,18^0, Re=3.52x10^6), higher-order DG results with improved efficiency using agglomerated multigrid (DLR).

The first application test case computed consisted of the FA5 fighter aircraft configuration. For this test case, a thorough quantitative analysis related to improvements obtainable by higher-order discretization was not expected. The feasibility of higher-order computations on complex flows of this type was however demonstrated (Figure 5), also for unsteady hybrid turbulence modelling (RANS/LES).

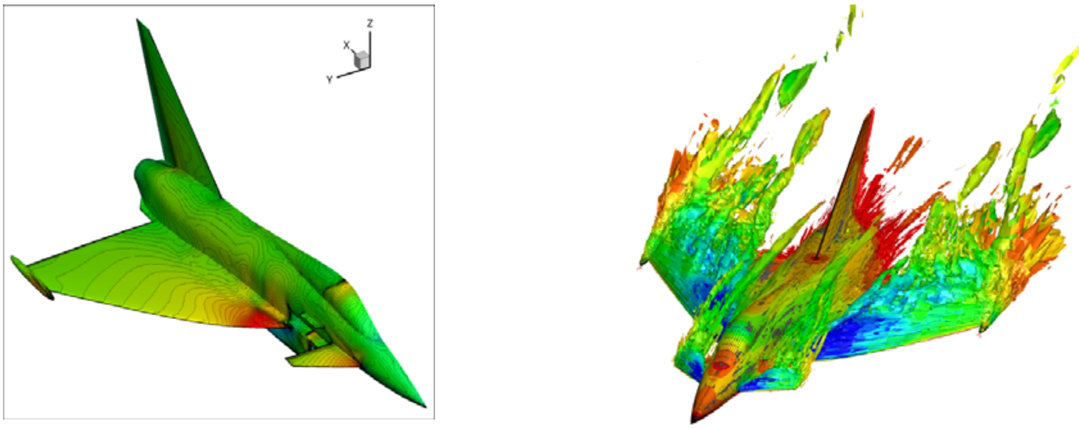

Figure 5. High-order DG results for FA5 fighter configuration, left: RANS P2 solution (pressure distribution) with algebraic Reynolds stress model (M=0.85, α=24^0, Re=4.65x10^7); right: X-LES P3 solution (M=0.125, α=15^0,78x10^6), (University of Bergamo).

The High Lift Prediction Workshop test case was also considered in the IDIHOM project (Figure 6). In general the applicability of high-order solvers to the challenge of 3D high-lift configurations was demonstrated. Even though a detailed performance analysis was planned, all partners involved experienced convergence problems and irregular asymptotic behavior. Further robustness improvements are necessary, in particular for angle of attack close to maximum lift.

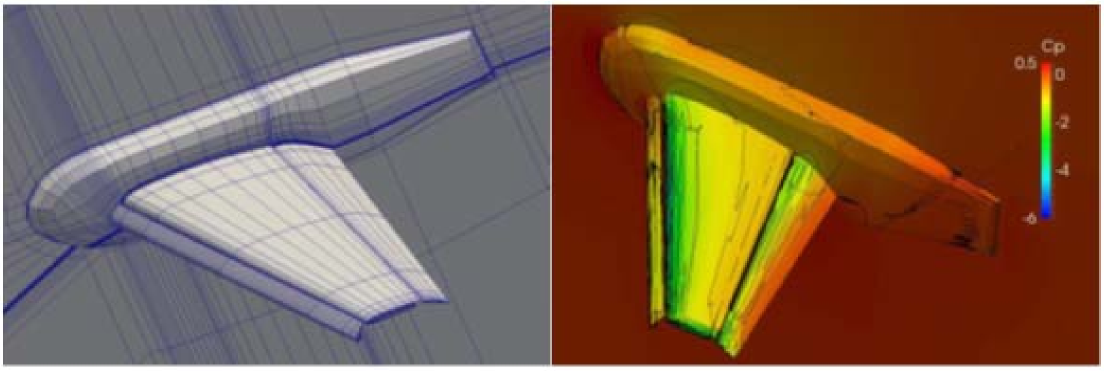

Figure 6. Grid and high-order DG results for the High Lift Prediction Workshop test case (M=0.2, $\alpha=13^0$, Re=4.3×10^6), (TsAGI).

The Dassault Aviation Falcon business jet was included as an industrially relevant transport configuration. Again, the generation of suitable higher-order meshes was found to be a major challenge and solutions could be produced only at the very end of the project

As a first internal aerodynamic test case the well-known NASA Rotor 37 [3] was computed. Although computed by a large community so far, it has proved notoriously difficult to match the experimental data, probably due to non-modeled leakage flow [4]. Also a large impact of turbulence models can be expected. Therefore the main aim of the exercise was rather to show fast grid convergence, more than correspondence to the experiments. Computations were run using Discontinuous Galerkin implementing Spalart-Allmaras turbulence model, DG implementing Explicit-Algebraic Reynolds Stress Model (EARSM) and Residual Based Compact (RBC) schemes implementing the Spalart-Allmaras model. Figure 7 shows an example of grid convergence of the flow pattern on the blade, computed with DG at different orders of interpolation. The mesh is very coarse, even considering that the high-order polynomial interpolation introduces internal subdivisions in each cell. It was shown that the fourth-order solution on the coarse mesh gives very similar results as a second-order solution on a fine mesh which has 8 times more cells. Figure 8 shows the grid convergence of two variants of the Residual Based Compact scheme compared to Jameson-type 2nd order finite volume scheme, all computed on the same sequence of meshes. Clearly, the increased order of accuracy enhances greatly the grid convergence.

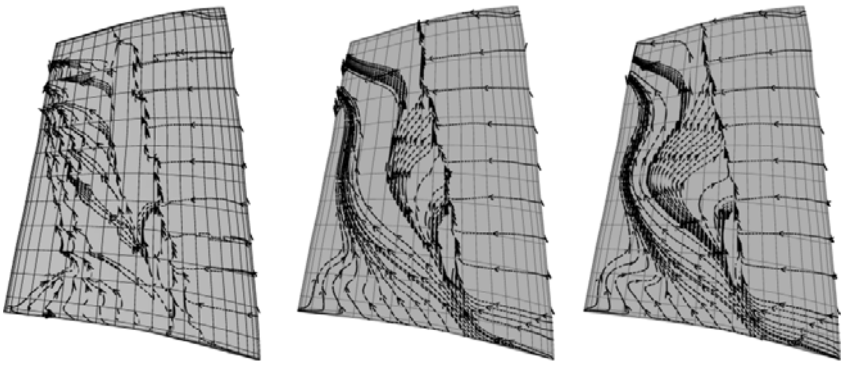

Figure 7. Skin friction patterns on the Rotor 37 blade computed on a coarse mesh with the EARSM turbulence model using 2nd, 3rd and 4th order DG method (University of Brescia).

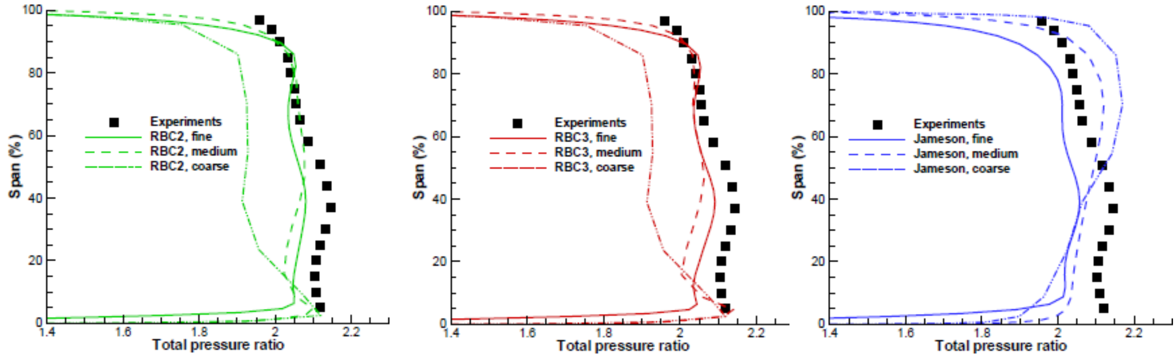

Figure 8. Grid convergence of the radial variation of the total pressure ration for the NASA rotor 37 computed with a 2nd and 3rd order RBC scheme in comparison to a 2nd order finite volume scheme (ARTS).

A second set of test cases concerns the MTU Cascade T106A representative of low pressure turbines, based on the same profile but with different pitch. Two configurations and flow conditions have been considered. The first concerns the low pitch version T106A at (nearly) fully turbulent conditions (Re=500.000). NUMECA and the University of Brescia carried out DG computations using EARSM for the full cascade including end walls. One of the objectives was to demonstrate the combined advantage of high-order convergence and anisotropic turbulence models to capture the complex secondary flow. Figure 9 depicts the computed near wall flow features together with the coarse mesh used for the simulation. From Figure 10 it can be seen that grid convergence, at least for the loading distribution, is obtained.

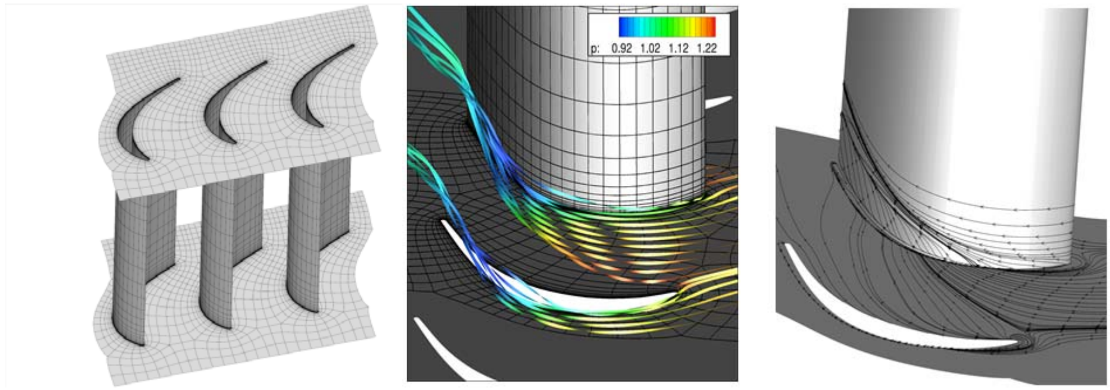

Figure 9. Computational geometry, mesh and visualisation of the computed secondary flows at the hub
for the T106A cascade at Re=500.000. 4th order DG computations using EARSM (University of Brescia).

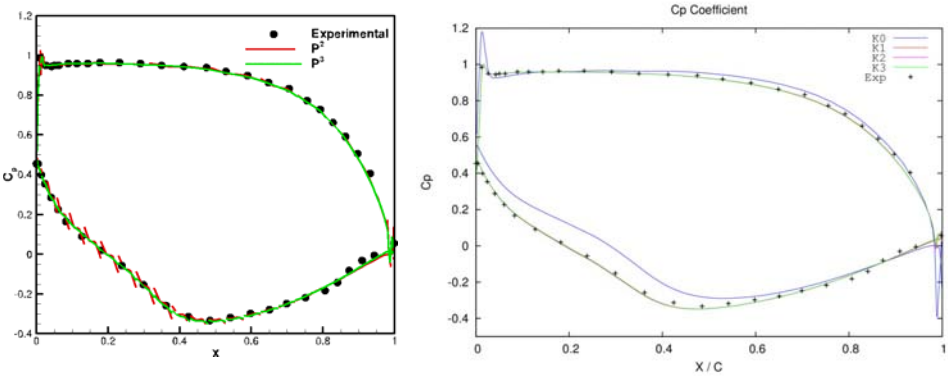

Figure 10. Computed pressure distribution at mid-span for the T106A cascade using DG methods at different orders and EARSM, computations by University of Brescia (left) and NUMECA (right).

The second variant is the high-lift configuration T106C at transitional conditions (Re=80.000), for which LES simulations were performed by Cenaero on a representative span-wise section. This test case was also part of the 2nd International Workshop on High-Order Methods for CFD [5]. Preliminary results are shown in Figure 11. Unfortunately, no good comparison with respect to measurements was obtained. Due to the high level of similarity between the different simulations, in particular in the front section, this difference can probably be attributed to the difficulty to master the experimental conditions at this low Reynolds numbers and match those in the computations. Research on this case is ongoing in collaboration with the von Karman Institute, who performed the measurements.

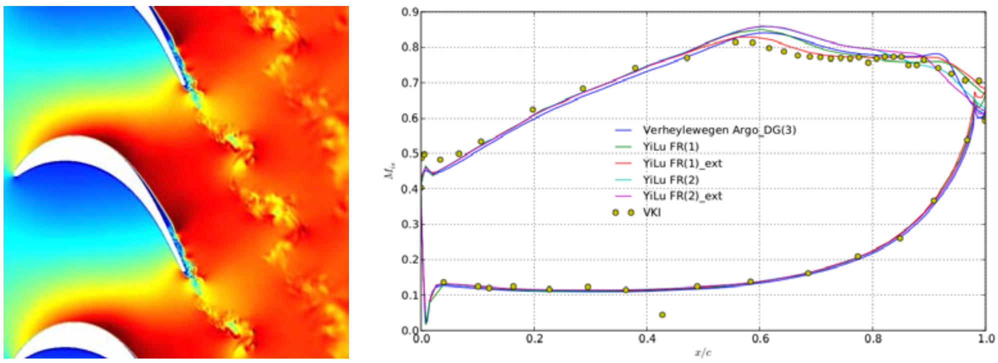

Figure 11. Simulations of the T106C cascade section, instantaneous Mach number distribution (Cenaero) and isentropic Mach number distribution computed by Cenaero (Verheylewegen) and workshop participants compared to experimental results.

In order to validate the scale-resolving capabilities of the high-order codes, two simple separating flow benchmarks are considered. The first is the bump benchmark of the Desider project, consisting of a smooth expansion in a wide channel, illustrated in Figure 12. Due to the very high Reynolds number, hybrid RANS-LES approaches are taken. Figure 12 shows the comparison between experimental values and computations using a fourth-order finite volume code, implementing the XLES approach (NLR). In addition, computations with a 4th order DG code using the Spalart-Allmaras DES model (University of Bergamo). Both computations provide roughly the same differences with respect to the experimental data. It is however not clear whether these can be attributed to insufficient resolution or the models.

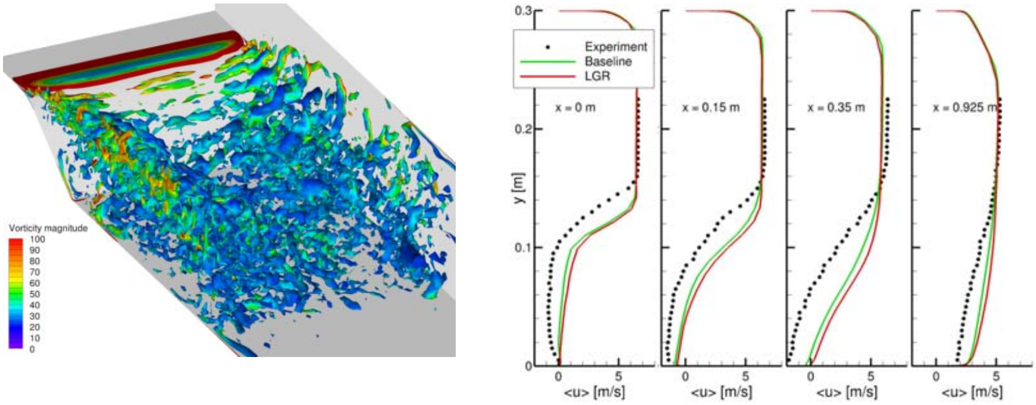

Figure 12. Simulation of the DESider bump, visualization of the Q-criterion and comparison of velocity profiles between computations and experiments using the XLES approach, 4th order computation on baseline structured grid (647,000 cells), LGR: 4th-order computation on block-wise refined grid (356,00 cells) (NLR).

The second baseline test case is the periodic flow over a 2D periodic hill, which is part of the ERCOFTAC QNET-CFD data base [6]. The test case has also been taken up in the International Workshop on High-Order Methods for CFD. Computations have been performed, namely DNS at Re=2.800 and LES at Re=10.595 (see Figure 13). Various high-order methods have been uses on the same meshes. In general, good agreement is obtained with the reference solutions.

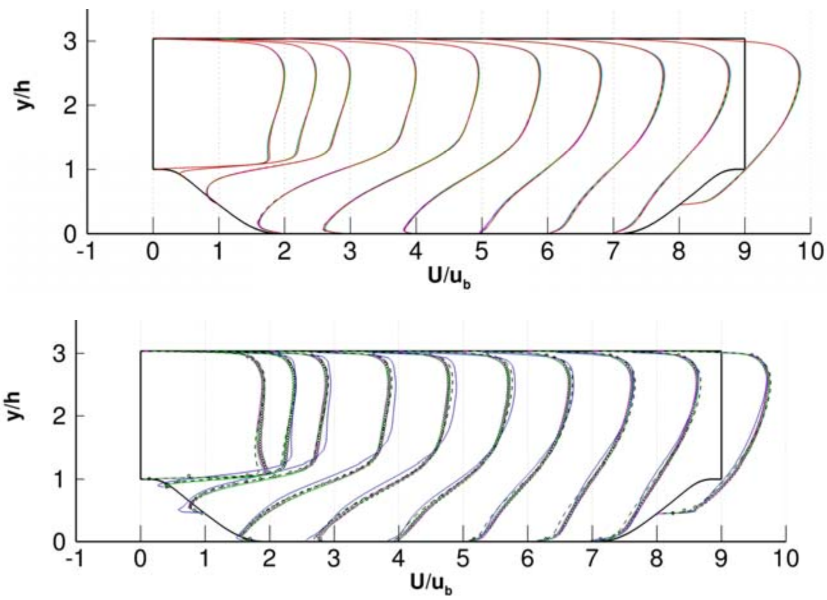

Figure 13. Comparison of the computed velocity profiles for the 2D hill with respect to reference computations (black line) and experiments (dots) at Re=2800 and Re=10595, simulations performed with DG methods (Cenaero, University of Stuttgart), RBC (ARTS), spectral element method (Imperial College London).

The last test case concerns the subsonic, isothermal jet of the JEAN project [7]. Both RANS and LES have been performed for Re=50.000 on the basis of high-order DG methods, respectively by ONERA and Cenaero. In particular for the LES simulations good correspondence with experiments was found (Figures 14 and 15), especially considering that these have been obtained at Re=900.000.

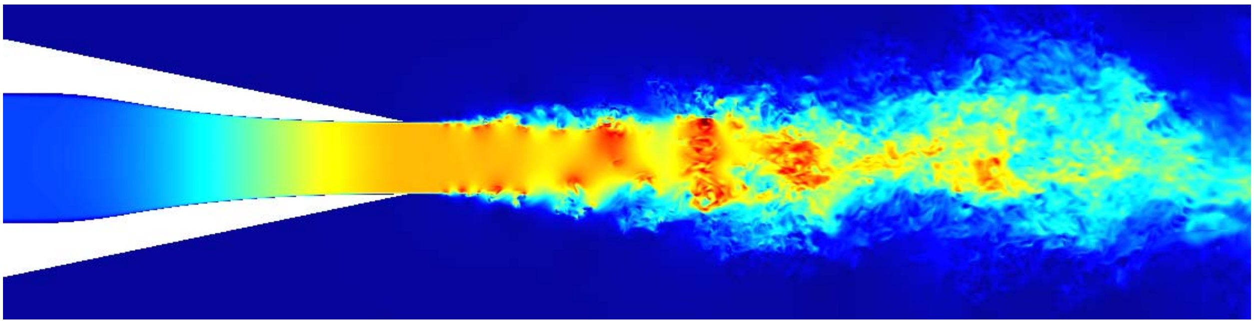

Figure 14. Instantaneous Mach number of the JEAN nozzle jet computed by a 4th order accurate DG method (Cenaero).

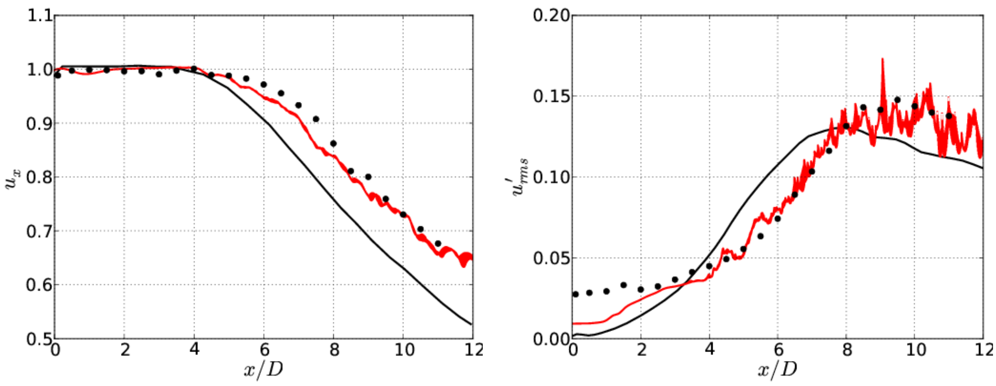

Figure 15. Comparison of axial profile of the axial velocity of the JEAN nozzle, experimental results (black circle), reference LES of Andersson [8] (black line) and 4th order DG results (red line) from Cenaero.

The external and internal aerodynamic test cases computed in the project served to illustrate the capabilities of current higher-order schemes, but also the challenges facing the approaches. A large variety of underlying and application test cases covering high geometrical and flow complexity as well as coupling to other disciplines were successfully computed. In general, it can be said that many flows of industrial interest can now be computed in a routine manner using higher-order schemes, although in some cases problems are still reported regarding flow features such as shocks. Even though there are indications of favorable aspects of the new approaches, it was proven whether for typical RANS-type application problems the approaches evaluated have the potential of improving the overall efficiency of the industrial codes in current use. A major problem for the project was the lack of appropriate higher-order meshes made available, reducing the amount of quantitative data produced. Nevertheless, the IDIHOM project provided strong indications that higher-order methods have the potential to reduce the discrete system size required for mesh convergence within industrial accuracy for many cases. For smooth flow fields this reduction typically seems to reach around one order of magnitude. However, despite the significant improvements achieved related to flow solver technologies, for most cases the reduction in problem size did not translate to significantly reduced overall computational time. Adaptive strategies were found to be an important ingredient to reduce the overall problem size and thus alleviate the high computational cost per degree of freedom associated to high-order methods. Moreover, the project indicates that future computer hardware developments may increase the attractiveness of higher-order methods since the data locality support extreme parallelization for large scale applications. This might be in particular pay-off for unsteady scale-resolving simulations in which high resolution is required in both space and time. The high potential of high-order methods for scale-resolving simulations has been clearly demonstrated in IDIHOM. In particular, the unstructured high-order methods are of great interest for industry. Similar to highly specialist academic high-order codes used for fundamental research, they offer low-dissipative, low-dispersive schemes on unstructured grids allowing scale resolving simulations (hybrid RANS/LES, LES/DNS) for applications which are of industrial interest.

Finally, high-order multidisciplinary simulations were successfully demonstrated in the IDIHOM project including aero-elastic and aero-acoustic problems.

Objectives achieved

The main technical objectives of the project were achieved. Referring to page 5 the following conclusions can be drawn:

O1: *Advance the maturity of current high-order methods and apply them to complex flows which are of particular interest for the aeronautical industry.*

This objective was fully achieved. Except the transport aircraft test case (A.1) all application challenges (see Figure above) were successfully computed.

O2: *Demonstrate the capabilities of high-order methods in solving industrially relevant, challenging applications.*

This objective was partly achieved. For a few underlying and application challenges reduction in degrees of freedom (Dofs) and overall CPU-time was achieved compared to the state-of-the-art second-order finite volume codes. However, not for all cases considered in IDIHOM the reduction in Dofs could be transferred to an increase of overall efficiency of the high-order approaches.

O3: *Extend high-order methods to multidisciplinary applications as there are aero-acoustics and aero-elastics, improving future cost-effective industrial designs.*

This objective was fully achieved, since the multidisciplinary test cases defined prior to the project were successfully computed with high-order simulation approaches.

O4: *Extend high-order methods to advanced turbulence models*

This objective was fully achieved. Computations with algebraic Reynolds stress models and scale-resolving simulations (DES, X-LES and ILES) were successfully carried out. In particular, the benefit of high-order methods for scale-resolving applications compared to the low-order counterparts was demonstrated.

O5: *For the adaptive high-order methods employed, advance the Software Technology Readiness Level from about 3 (status at the end of the ADIGMA project) to 5.*

This objective was partly achieved. Based on a given description of the main features of the different phases of the Capability Readiness Level (CRL) used in aerospace industry, the readiness level of higher-order methods was judged to be CRL=4.

O5: *Facilitate co-operation between European industries, research establishments and universities and foster co-operation between different industries as there are airframe, turbo-engines, helicopters, and ground transportation.*

This objective was fully achieved through exchange of tools and transfer of know-how between the partners.

Dissemination and exploitation

The knowledge gained in the IDIHOM project, the computational methods developed and the particular results generated were disseminated in various forms. Important means are publications in journals, technical papers and presentations at national and international conferences. In particular, the dedicated mini-symposia held at various international CFD conferences, the VKI Lecture Series course on high-order methods and the final IDIHOM report being published as a dedicated book in the Springer Series "Notes on Numerical Fluid Mechanics and Multidisciplinary Design" are seen as important channels to disseminate the project results. Within the project a comprehensive data base for the evaluation of higher-order methods was created. The data base includes specification of test cases, computational grids, solutions of higher-order obtained with various approaches as well as reference solutions of standard industrial second-order methods. This test case suite is of high interest to the CFD community to promote the further development and application of high-order CFD tools. As a consequence, the IDIHOM consortium was heavily involved in the organisation of the 1st and 2nd International Workshop on High-Order CFD Methods held in 2011 (US) and in 2013 (Germany).

The IDIHOM objectives enabled a strong cooperation between universities, research establishments and aircraft industry as well as software vendors. According to their role the organisations will apply different dissemination and exploitation strategies. The universities taking part in IDIHOM will directly exploit the project findings for teaching and training students and researchers in advanced high-order methods. The close cooperation with research organisations and industry will lead to the training of qualified personnel with knowledge of the industrial requirements, thereby increasing the potential of graduates for employment within industry. The project outcome will allow universities to pursue their goals in the field of applied mathematics and computational fluid dynamics, both in research and education. The research organisations participating in IDIHOM will directly exploit the knowledge gained in the project by improving their numerical tools for complex aeronautical applications. Bases on results of the comprehensive test case suite, the potential and limits of these methods for tackling challenging applications were highlighted and future research directions were identified. The aircraft industry was directly involved in the transfer process. With the help of the research establishments as central providers of highly sophisticated CFD methods, aircraft industry will further explore the most promising methods for selected applications for aerodynamic and multidisciplinary design work.

General conclusions and recommendations

In the IDIHOM project significant progress in the development of high-order CFD methods and their application to cases which are of interest to the aerospace community was made. Dedicated research activities further enhanced the maturity of the methods and helped to enable a critical assessment of the potential and current limits of the novel high-order approaches for applications in aerospace industry.

Despite the progress, the current status of the technology seems to prohibit an immediate incorporation of these tools into routine industrial processes. Even though a large range of simulation scenarios were covered within the project, no single existing implementation is capable of covering the whole spectrum of applications which is offered by established lower order codes. Certainly, the time frame for development of high-order methods is much shorter than was invested into classical approaches, e. g. 2nd order finite volume schemes. However, additional reasons for a slowdown of the progress can also be observed. High-order methods are, in general, less forgiving than low-order approaches. If any ingredient in the overall process is done slightly incorrect, the order can easily be destroyed and the overall efficiency of the approach is significantly reduced. In contrast to that, for state-of-the-art second-order methods, there is a certain tolerance for simplified treatments allowing a relatively easy extension of the methods to a large variety of applications covering e.g. complex geometries, flow fields with strong shock waves, bodies in relative motions and coupling of CFD with other disciplines.

In the short term, there is a high potential for high-order methods in the area of scale-resolving simulations as demonstrated in the project. In these scenarios resolution requirements are particularly high, which yields a large benefit for high-order approaches. Due to resolution requirements in time, explicit time integration is often a viable choice. This greatly simplifies solution algorithms and increases robustness of the methods. Furthermore, massively parallel implementations are almost trivial for explicit time integration schemes. In the frame of fundamental research, high order methods are already in use for scale-resolving simulations. However, they are often dedicated to structured grids and are therefore limited to problems with simple to moderately complex geometries. Recent developments of high-order finite element approaches allow the construction of low-dissipative, low-dispersive methods on unstructured grids enabling scale-resolving simulations for more complex geometries. This type of simulation scenarios is of increasing interest to aerospace industry as it greatly reduces (or even overcomes) the issues of physical modeling in certain applications.

Currently, high-order meshing for complex geometries seems to be the most severe restriction in the overall simulation technology tool chain, in particular if considering meshes with high aspect ratio stretched elements as typically used in RANS or DES-type applications in aerospace. Undeniably, progress has been achieved through IDIHOM and other research projects over the last years. The generation of 2D unstructured high-order meshes might be considered as manageable. However, for 3D cases it is already very difficult to generate appropriately coarse meshes at all, and the modification to high-order is expensive and error-prone. Many difficulties might be related to technical issues with the implementation rather than fundamental problems. However, in the long run, considerable progress will have to be made in this area if high-order methods shall ever be available for general purpose aerospace applications. Until then, simplified procedures based on local surface reconstructions or the exploitation of structured mesh blocks can be used to further exploit the potential of the underlying CFD methods.

For many routine use cases in aerospace industry, e. g. steady-state RANS computations for cruise conditions, state-of-the-art second order methods are very mature and thus fairly competitive, in particular as the absolute accuracy requirements might not be too demanding. Thus, the potential for improvement with high-order methods is limited in this area. The benefit will be larger for unsteady simulations in which spatial errors can accumulate over time, such that spatial accuracy is more important than for steady state simulations. In this class of problems, the benefit might be particularly large for interaction phenomena, typically including the resolution of vortices over long distances. Another example might be the simulation of local effects for (active) flow control. The latter scenario has the additional advantage that the simulation of basic effects is typically associated to relatively simple geometries, which eases the meshing.

As it seems unlikely even in the long run that all numerical simulations in industry will be performed with high-order approaches, it might be wise to develop a common code framework based on unstructured methods that can handle low- and high-order approaches and features a close integration of both. Good candidates are general implementations of continuous or discontinuous finite element methods since these approaches coincide with the highest flexibility concerning solution algorithms and offer a large amount of intensive experience. As demonstrated in the IDIHOM project, an important ingredient is adaptivity, in particular for high-order methods. The additional availability of reliable error estimators is an essential aspect for the management of uncertainties, which is of increasing importance in industrial applications. With these ingredients, a successful incorporation of high-order numerical methods into aerospace CFD codes for industrial use seems possible. In the long run, the method of choice can then be selected case by case based on the application and simulation intent. In order to achieve this goal, a continuation of the current efforts is required. The European research project IDIHOM focused development on the applicability of high-order approaches to industrially relevant simulations and the required supporting technologies. Even though this work was successful, there is need for further progress in order to transfer the current demonstration of applicability to a status, where the associated tools can be used on a routine basis with a minimal amount of user interaction.

References

[1] Kroll, N, "ADIGMA - A European Initiative on the Development of Adaptive Higher-Order Variational Methods for Aerospace Applications" AIAA-2009-0176, 2009.

[2] Kroll, N, Bieler, H., Deconinck, H., Couallier, V., van der Ven, H., Sørensen, K. (Eds), "ADIGMA - A European Initiative on the Development of Adaptive Higher-Order Variational Methods for Aerospace Applications: Results of a Collaborative Research Project Funded by the European Union, 2006-2009" Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 113, Springer, 2010.

[3] AGARD Advisory Report 355, "CFD Validation for Propulsion System Components", Report of the Propulsion and Energetics Panel Working Group 26, 1998.

[4] Shabbir, A., Celestina, M.L., Adamczyk, J.J, Strazisar, A.J., "The effect of hub leakage on two high speed axial flow compressor rotors", ASME Paper 97-GT-346, 1997.

[5] Second International Workshop on High-Order CFD Methods. Cologne, Germany, 27-28 May 2013, http://www.dlr.de/as/desktopdefault.aspx/tabid-8170/13999_read_35550/

[6] ERCOFTAC QNET-CFD wiki, Test case UFR 3-30: 2D periodic hill flow, http://qnet-ercoftac.cfms.org.uk/w/index.php/UFR 3-30.

[7] Jordan, P., Gervais, Y., Valire, J.-C., Foulon, H., "Final results from single point measurements", Project deliverable D3.4, JEAN EU 5th Framework Programme, G4RD-CT-2000-00313, 2002.

[8] Andersson, N., Eriksson, L.-E., and Davidson, L., "Large-Eddy Simulation of a Mach 0.75 Jet", AIAA paper 2003-3312, 2003.

Contact: Prof. Dr. N. Kroll, DLR, Norbert.kroll@dlr.de