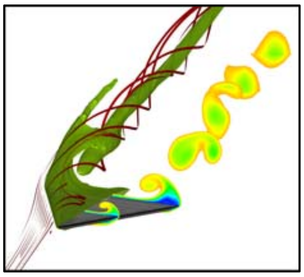
ADIGMA – Adaptive Higher-Order Variational Methods for Aerodynamic Applications in Industry



Specific Target Research Project of the 6th EU Framework Programme

Duration: September 2006 – December 2009

Publishable summary

The main goal of the project was to further strengthen Computational Fluid Dynamics (CFD) as a key enabler for meeting the goals of future air transportation by developing innovative numerical simulation techniques with significant improvements in efficiency, accuracy and reliability.

The consortium consisted of 22 partners from the European aircraft industry, the major research establishments and several universities. The project was coordinated by DLR.

Participant name	short name	Ctry
Deutsches Zentrum für Luft- und Raumfahrt e.V.	DLR	DE
Alenia Aeronautica	ALA	I
Airbus Deutschland GmbH	A-D	DE
Airbus France SAS	A-F	F
Dassault Aviation	DASSAV	F
EADS Deutschland GmbH, Military Aircraft	EADS-M	DE
CENAERO	CENAERO	B
Aircraft Research Association Ltd	ARA	UK
Uppsala University	UNUP	S
Institut National de Recherche en Informatique et en Automatique	INRIA	F
Nationaal Lucht- en Ruimtevaartlaboratorium	NLR	NL
Office National d'Etudes et de Recherches Aérospatiales	ONERA	F
von Karman Institute for Fluid Dynamics	VKI	B
Università degli Studi di Bergamo	UNBG	I
Ecole Nationale Supérieure d'Arts et Métiers, Paris	SERAM	F
University of Nottingham	UNNO	UK
Charles University Prague	UNPR	CZ
University of Wales Swansea	UNSW	UK
University of Stuttgart	UNST	DE
University of Twente	UNTW	NL
Warsaw University of Technology	UNWA	PL
Nanjing University	NJU	CN

Background, objectives, work description

Computational Fluid Dynamics (CFD) has become a key technology in the development of new products in the aeronautical industry. Significant improvements in physical modelling and solution algorithms as well as the enormous increase of computer power have enable numerical simulations in all stages of aircraft development. However, despite the progress made in CFD, in terms of user time and computational resources, large scale aerodynamic simulations of viscous high Reynolds number flows are still very expensive and time consuming. The requirement to reliably achieve results at a sufficient level of accuracy within short turn-around times places severe constraints on the application of CFD for aerodynamic data production and the integration of high-fidelity methods in multidisciplinary simulation and optimization procedures. The limitations of today's numerical tools reduce the scope of innovation in aircraft development, keeping aircraft design at a conservative level. Consequently, enhanced CFD capabilities for reducing the design cycle and cost are indispensable for industry. Moreover on a longer term, advanced physical models like DES and LES will be used for evaluating the complete flight envelope of the final design, but it becomes clear that current results too often depend on the computational mesh which cannot be tuned sufficiently well, once more stressing the need for novel methods.

The main objective of the ADIGMA project was the development and utilization of innovative adaptive higher-order methods for the compressible flow equations enabling reliable, mesh independent numerical solutions for large-scale aerodynamic applications in aircraft design. A critical assessment of the newly developed methods for industrial aerodynamic applications should allow the identification of the best numerical strategies for integration as major building blocks for the next generation of industrial flow solvers.

The ADIGMA project concentrated on technologies showing the highest potential for efficient higher-order discretizations. These are Discontinuous Galerkin (DG) methods and Continuous Residual Distribution (CRD) schemes. The main scientific objectives of the ADIGMA project were:

- Further development and improvement of key ingredients for higher-order space discretization methods for compressible Euler, Navier-Stokes and RANS equations
- Development of higher order space-time discretizations for unsteady flows including moving geometries
- Development of novel solution strategies to improve efficiency and robustness of higher-order methods, enabling large-scale aerodynamic applications
- Development of reliable adaptation strategies including error estimation, goal-oriented isotropic and anisotropic mesh refinement and the combination of mesh refinement with local variation of the order of accuracy (*hp*-refinement)
- Utilization of innovative concepts in higher-order approximations and adaptation strategies for industrial applications
- Critical assessment of newly developed adaptive higher-order methods for industrial aerodynamic applications; measurement of benefits compared to state-of-the-art flow solvers currently used in industry
- Identification of the best strategies for the integration as major building blocks for the next generation industrial flow solvers

The technical work in ADIGMA was split into 5 work packages (WP). In WP2 industrial partners specify the requirements and the evaluation procedure for the methods newly developed. A test case suite of increasing complexity was specified including the necessary data in order to provide a firm basis for comparison at midterm and the end of the report. Work package WP3 aimed at the improvement and enhancement of higher-order methods for aerodynamic applications. Several alternative strategies were investigated. Shortcomings and limitations of these rather new methodologies for industrial use were addressed. Since computational efficiency is a crucial aspect for higher-order methods, work package WP4 was dedicated to the development of solution strategies which meet the industrial requirements in terms of memory storage, computing time and efficient utilization of parallel low cost computers. Work package WP5 addressed the effectiveness and reliability of adaptation techniques in combination with higher-order methods developed in the previous work

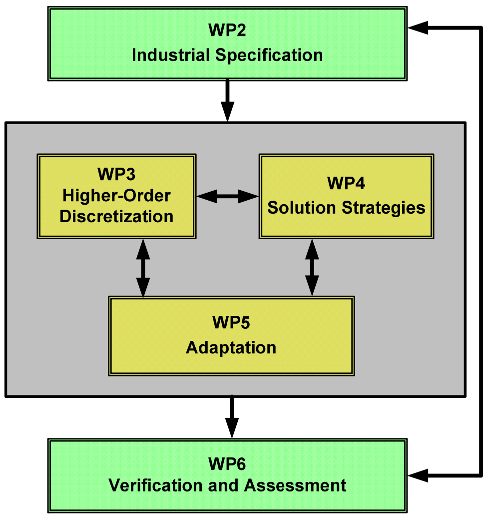


Fig. 1 Work package structure of the ADIGMA project

packages. New approaches were developed in order to achieve accurate flow features and flow quantities with minimal amount of degrees of freedom and computation time. Finally, work package WP6 dealt with the critical assessment of the methods and technologies developed in ADIGMA under the specific aspect of a future industrial use for complex aerodynamic problems. The assessment was based on the evaluation plan and the test case suite defined in WP2. Identification of the best strategies and best practice guidelines should ensure technology transfer to industry. Work package WP1 was dedicated to the management activities.

The ADIGMA project focused the up to now fragmented research in higher-order methods in Europe. It fostered the scientific co-operation between the universities, research establishments and the aeronautical industry. The transfer from innovative upstream technologies in CFD into the industrial design cycle was significantly improved. The novel higher-order adaptive methods developed within ADIGMA are expected to yield essential progress on several items:

- Improved simulation accuracy in reduced time and at lower cost
- Enabling automatic and reliable shape optimization and multi-disciplinary simulation and optimization through improved flow solvers
- Enabling accurate flow control simulations based on advanced physical modeling of flow control phenomena e.g. controlled flow, receptivity issues
- Mesh independent predictions of aerodynamic forces through error estimation and goal-oriented adaptation
- Automatic and reliable resolution of physical effects that have become relevant to aerodynamic design (confluent boundary layers, vortex sheets, trailing vortices, etc.)
- Provision of highly accurate aerodynamic input for aeroacoustic simulations

In summary, the ADIGMA project was expected to be an essential and indispensable brick to fully exploit the potential of Computational Fluid Dynamics as the major source for determination of data required to drive the aerodynamic design process and a key enabler for meeting the strategic goals of future air transportation as specified in the ACARE Vision 2020 Report.

Work performed and results achieved within the project

Higher-order disretization

Throughout ADIGMA, the state-of-the-art of Discontinuous Galerkin (DG) methods was further improved from the solution of viscous laminar flows for simple configurations to turbulent flows around aerodynamic configurations of moderate complexity (University of Bergamo, ONERA).

University of Bergamo demonstrated its capability to successfully conduct RANS simulation for the DLR-F6 wing/body configuration up to 4th-order (see Fig. 2). Moreover, they showed that in contrast to standard finite-volume solvers, DG methods can be used on high-aspect ratio meshes without severe convergence degradation as long as sufficient integration is employed. Some novel formulations for DG discretization methods were investigated such as edge-based formulation (University of Uppsala), semi-implicit discretization (University of Prague) and space-time discretization strategies (University of Stuttgart, University of Twente). Since high-order DG discretization raises many efficiency issues in terms of CPU and memory usage, several aspects, that should have a significant impact on the code complexity and efficiency, were studied. These include efficient ways of implementing DG methods by mitigating the increased cost of higher-order discretizations by casting the method in terms of global linear algebra operations (CENAERO). Other partners explored the type of shape functions, the choice of quadrature formulae or the use of reduced quadrature rules (zonal strategy, CENAERO). The results achieved were not always conclusive.

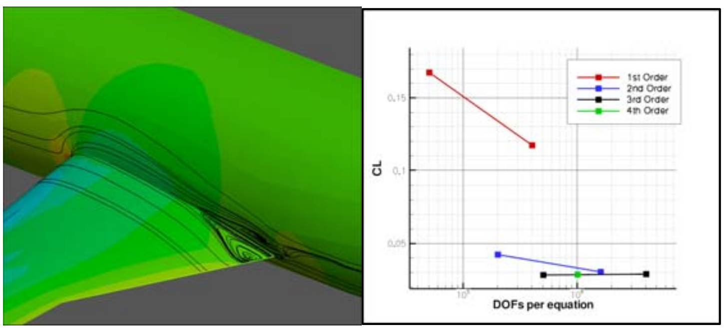


Fig. 2 Higher-order DG simulation of turbulent flow around DLR F6 wing-body configuration (University of Bergamo)

However in many test cases it was shown that, although harder to optimize, higher-order DG methods are competitive to industrial base line simulation codes, when targeting the same accuracy threshold.

The continuous high-order formulations were less mature and understood at the start of the project than their discontinuous counterparts. Within ADIGMA the continuous high-order formulations were further developed up to maturity for computation of aerodynamic configurations of moderate complexity. High-order accuracy was demonstrated on a series of test cases on external aerodynamic configurations, from subsonic to transonic flow regimes, both for inviscid and laminar flows. Promising preliminary results were shown for RANS simulations (Dassault Aviation, SERAM), but these methods still need a better understanding of the discretization of the turbulence equations. Both VKI and INRIA developed Residual Distribution (RD) methods starting from scalar equations up to laminar Navier-Stokes equations and demonstrate some first RANS capabilities, with VKI focusing on multidimensional upwind schemes and INRIA on simpler, non-upwind, artificially stabilized methods.

One of the challenges in higher-order methods is the preservation of monotonicity over discontinuities. It is a crucial requirement for the methods concerning robustness for industrial aerodynamic applications.

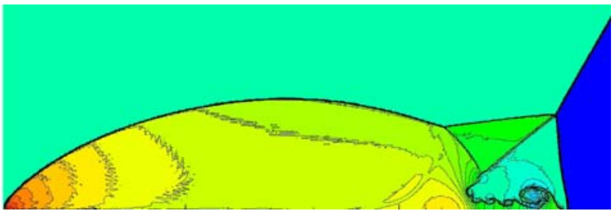


Fig. 3 Double Mach reflection problem, 5th order DG simulation (University of Stuttgart)

Many different shock capturing techniques were investigated within the project. Some partners focused their activities on finding so-called “troubled cell indicators” (University of Stuttgart, Nanjing University, VKI), while others relied on a global shock-sensing schemes (INRIA, Dassault Aviation). An extensive comparison of the different shock capturing procedures, both for continuous and discontinuous methods, was performed under the same test case conditions. No uniform solution to the problem of high-order shock capturing was found. However, the comparisons helped to identify some techniques which perform better for steady cases while others perform better for unsteady cases.

In order to achieve the full potential of higher-order methods, the mesh needs to represent the underlying geometry and in particular to resolve regions of high curvature. However, several important bottlenecks exist in the creation of such a boundary representation, particularly in case of highly stretched boundary layer meshes around 3D configurations. Some aspects were tackled within ADIGMA including the treatment of curved wall boundary conditions, as well as solution adaptive meshing, the development of mesh deformation strategies to provide curved higher-order elements close to the wall boundary and the specification of a set of mesh quality metrics for higher-order simulations. ARA extended its hybrid grid generation system SOLAR to a higher-order meshing capability. An initial implementation of such a capability was successfully demonstrated for the ONERA M6 wing. It is clear though, that this puts an increased onus on the mesh generation procedure.

Solver efficiency

Computational efficiency is a crucial aspect for higher-order methods. Within ADIGMA solution strategies were identified and further developed towards having the potential to meet the industrial requirements in terms of memory storage, computing time and efficient utilization of parallel low cost computers. According to the literature two major research lines were followed, namely capable multigrid strategies (p-multigrid, h-multigrid) on the one side and efficient and robust implicit Newton-type techniques with particular focus on linearization, linear solvers and suitable preconditioners on the other side.

For the Discontinuous Galerkin discretizations a detailed two- and three-level h-multigrid analysis was conducted both for the advection-diffusion and the linearized Euler equations in two space dimensions (University of Twente, NLR). These analysis tools were successfully used to optimize Runge-Kutta type smoothers, which resulted in a significant improvement in convergence rate. A spectral p-multigrid DG algorithm for the solution of the steady state Euler and Navier-Stokes equations was investigated by the University of Bergamo. Care was taken to design efficient smoothers, in particular for viscous flows.

Compared to classical implicit schemes this approach provides similar efficiency along with significant memory savings of about 75%. A hybrid multigrid approach was proposed by ONERA in the frame of a 3D multiblock structured solver using second- or third-order Discontinuous Galerkin discretizations on the fine grid and classical second-order finite volume formulations on the coarser grids. NLR extended the h-multigrid algorithm to four-dimensional (space-time DG discretization) time-accurate simulations targeted at helicopter applications including locally refined meshes.

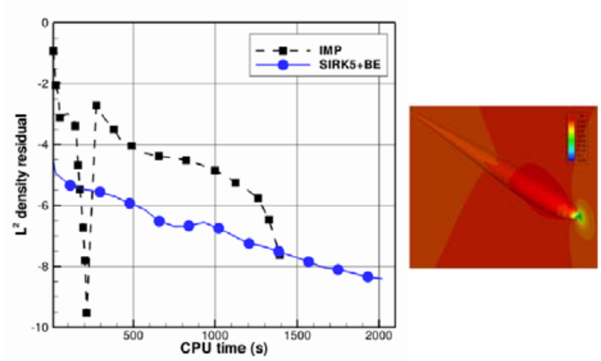


Fig. 4 Comparison of convergence behavior of implicit scheme (black line) and p-multigrid (blue line) for a 5th order DG method of a 3d turbulent flow (University of Bergamo)

With respect to fully implicit methods based on Newton-type iterations, various aspects crucial for higher-order discretizations were investigated. Particular focus was put on linearization and efficiency of the linear solvers associated with each Newton step using GMRES (University of Bergamo, University of Prague). The research covered e.g. the choice of preconditioners, the dimension of the Krylov subspaces and the number of iterations and the relative tolerance for GMRES. Although in many cases progress was achieved in reducing the computational effort of higher-order methods, the findings were not always conclusive, in particular with respect to viscous turbulent flow problems.

Efficient parallelization of the higher-order methods was another research topic within ADIGMA. Parallel versions of discontinuous Galerkin methods (e.g. University of Bergamo) and Residual Based Distribution Schemes (INRIA, VKI) were developed and analyzed. Research work was devoted to dynamic load balancing allowing for proper parallel efficiency, particularly in case of local grid refinement (Warsaw University of Technology). It was demonstrated that good parallel performance can be achieved with higher-order methods; however, the tests were limited to a rather small number of processors.

Finally, hybrid techniques based on the heterogeneous domain approach coupling different discretization and integration strategies were investigated within ADIGMA as a means to cut computational cost while maintaining improved accuracy of higher-order discretization. A hybrid Discontinuous Galerkin/finite volume solver was investigated by ONERA. First results for 2D turbulent flows look promising but evaluation on more complex configurations is required in order to assess the benefit compared to a full discontinous Galerkin approach. A hybrid parallel framework connecting different classes of methods (DG, FV, FD) on structured and unstructured grids for the solution of different governing equations (linearized Euler, nonlinear Euler and Navier-Stokes equations) was investigated by University of Stuttgart. This capability was successfully demonstrated by the simulation of laminar vortex shedding. An alternative approach was proposed by University of Wales Swansea and EADS-MAS. Higher-order discretizations and improved equation solution was attempted within wall boundary layer regions based on standard finite volume solvers. The benefit of this methodology was demonstrated for a number of examples.

Adaptation

Local grid refinement is an essential ingredient for higher-order methods to be competitive with standard finite volume solvers. Traditionally, mesh adaptation for flow problems is based on feature-based sensors, which refine the computational mesh based on flow features such as shocks and vortices. The mathematical framework of finite-element methods allows sensors targeted at reducing the error in computed quantities, so-called goal-oriented adaptation. Within ADIGMA existing goal-oriented algorithms for the Euler equations were extended to the laminar and turbulent Navier-Stokes equations (Dassault Aviation, DLR).

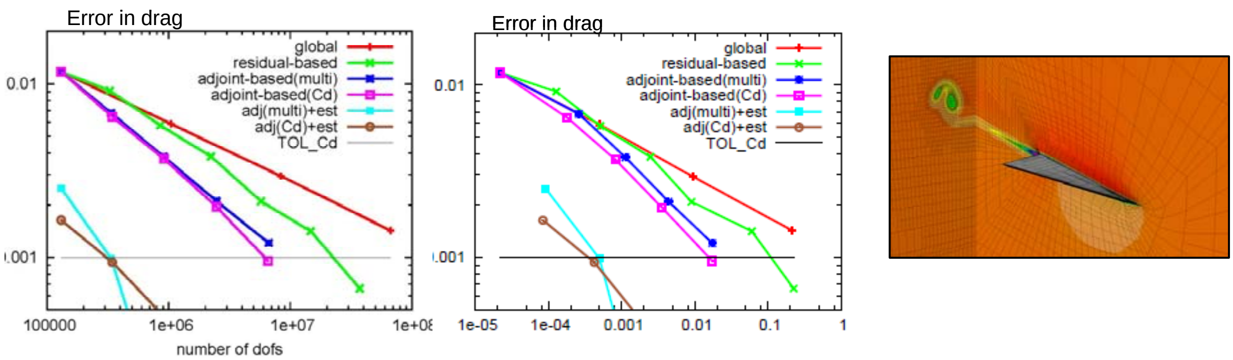


Fig. 5 Residual-based, adjoint-based and error estimation for 2nd order DG simulation for laminar flow around delta wing, left figure: error in drag versus number of degrees of freedom, middle figure: error in drag versus normalized CPU time, right figure: solution on residual-based adapted grid (DLR)

The same holds for a posteriori error estimation algorithms and the extension to anisotropic refinement (DLR, University of Nottingham). The goal-oriented adaptation and error estimation were also extended to multiple target quantities (DLR). The developed algorithms were successfully applied to laminar delta wing (see Fig. 5), turbulent 2D high-lift test case, turbulent 3D streamlined body and wing-body configuration, clearly showing the fast convergence of the goal-oriented refinement strategy, especially when combined with error estimation. An important result was that the method is more efficient than performing a grid convergence study in terms of turnaround time, even though it requires the additional solution of an adjoint problem. As DG methods allow variation of the polynomial order on a cell-to-cell basis, hp-refinement strategies were developed in the same context as the above h-refinement strategies. For p-refinement both feature-based sensors (University of Stuttgart) and sensors based on the smoothness of the solution were developed (University of Nottingham). The efficiency of the anisotropic hp-refinement algorithm was demonstrated for 2D laminar flow problems (University of Nottingham).

Industrial assessment

The assessment of the developed methods and technologies in an industrial setting was a central issue in the ADIGMA project. A specific activity was devoted to the specification of requirements that industrial aerodynamic applications will be putting on future numerical simulation tools. Industrial partners expressed their needs in terms of accuracy, efficiency, robustness, ease of use, applicability and implementation issues among others.

A test case suite of increasing complexity was specified together with clearly defined reporting templates in order to put the comparison of newly developed methods with traditional industrial flow solvers on a firm basis.

The large amount of test cases considered in the industrial assessment activity was a result of considerable differences in the maturity of the codes developed in ADIGMA. Many of the partners had to limit their studies to 2D flows and more importantly, a few codes were capable to treat turbulent flows. For some test cases (especially for the more complex ones) just one partner contributed with a newly developed method, and so the conclusion was somehow limited to this specific run. Furthermore, the thorough asymptotic analysis on order of accuracy was restricted to rather simple cases. In general, the higher-order methods investigated within ADIGMA showed a high potential for reducing the discrete system size by a factor of about 5-10 for most of the test cases and accuracy levels considered. At the same time,

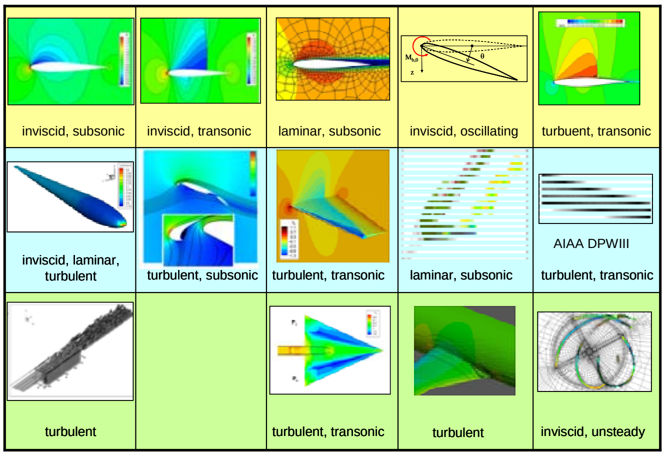


Fig. 6 ADIGMA test case suite, 1st row: Mandatory Test Cases (MTC), 2nd row: Baseline Test Cases (BTC), 3rd row: Complex Test Cases (CTC)

the memory usage of the examined codes is typically at least one order of magnitude higher. On the other hand the potential of the higher-order methods for industrial applications were tested by successfully computing most of the baseline and complex test cases (see Fig. 7 and Fig. 8).

The gain in discrete system size, however, is not yet fully transferred to increased runtime performance as available solver technologies are not adequate for large scale applications. The treatment of flow discontinuities in transonic flow problems does not seem to be a major problem regarding robustness or efficiency and turbulence modelling does not represent a principal hindrance to the higher-order approaches. The codes that were used in ADIGMA appear to be readily parallelizable and some of them appear to be suitable for enhancements to a competitive code for industrial use within the next few years. The solver part of the codes turned out to be the largest bottleneck and require future research activities.

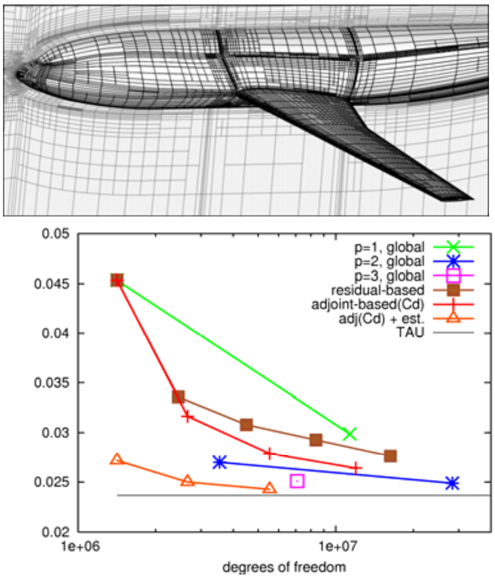


Fig. 7 Effect of higher-order DG method and adjoint-based adaptation with error estimation on convergence of error for DLR-F6 wing/body-configuration (DLR)

Although the evaluation was not as rigorous as planned resulting in somewhat limited conclusion, a first attempt was made in an EU-funded CFD project to conduct a careful and thorough assessment of new technologies with the current industrial standard. This approach on the one hand allows industry to gain insight in new CFD technologies developed in academia and on the other hand provides universities and research institutions industrial needs and performance levels to be tackled.

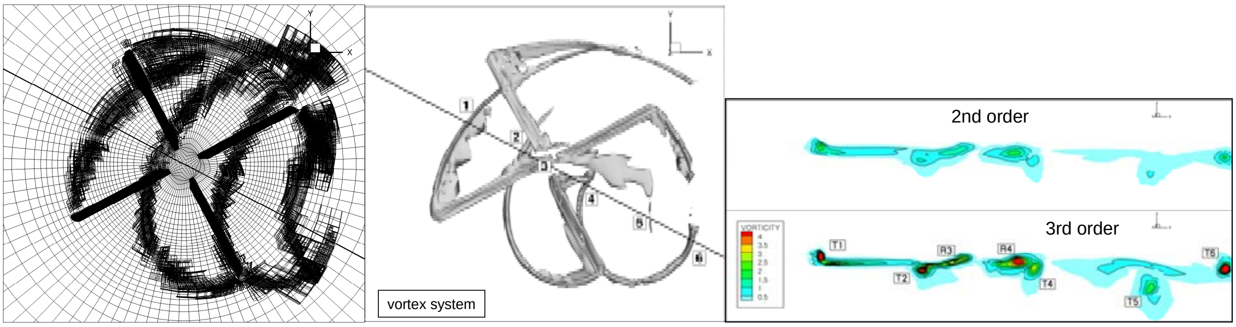


Fig. 8 Results for helicopter in forward flight, left figure: adapted grid, middle grid: vortex system, right figure: comparison of vortex resolution in cross-sectional vertical slice obtained by 2nd and 3rd order DG solution (NLR)

Dissemination and exploitation

The knowledge gained in the ADIGMA project, the computational methods 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 two ADIGMA VKI Lecture Series courses, the publicly open final workshop and the final report 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 adaptive 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 proliferation of high-order CFD tools.

The ADIGMA objectives enabled a strong cooperation between universities (upstream research), aircraft industry (end user) and research establishments (bridge between basic research and application). According to their role the organizations applied different dissemination and exploitation strategies.

The aircraft industry is directly involved in the transfer process from basic research and development into industrially applicable simulation methods and tools. The newly developed discretization schemes and numerical solution algorithms were explored on industrially relevant test cases. With the help of the research establishments as central providers of highly sophisticated CFD simulation tools for the aircraft industry the most promising methods will be further explored on even more complex cases from daily aerodynamic work.

The research organizations participating in ADIGMA will directly exploit the knowledge gained in the project by improving their numerical tools. In particular, ADIGMA was an important step towards the establishment of the next generation of CFD tools which can cope with the future requirements of the aeronautical industry. By providing improved CFD codes to their customers and partners in industry and academia, the research organizations actively contribute to the dissemination of the ADIGMA results.

The universities taking part in ADIGMA will directly exploit the ADIGMA findings of advanced numerical algorithms and procedures for teaching and training students and researchers. The close cooperation with 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.

General conclusions and recommendations

The competitiveness of higher-order methods to standard finite volume solvers was demonstrated for airfoil computations and 3D inviscid or laminar flows around rather simple configurations. Only limited research activities were devoted to the discretization of the RANS equations with higher-order methods, and it became clear that this effort is still in its infancy. A dedicated effort towards the industrialization of the different higher-order methods is required and in particular the understanding of the discretization procedure needs to mature. Moreover, although work was carried out to mitigate the resource usage of higher-order methods, further research needs to be invested in the area of algorithm optimization and complexity reduction. Finally, as high-order methods target same accuracy levels with coarser and coarser meshes as the approximation order increases, the quality of the mesh generation becomes more important. Care must be placed into generating meshes where higher-order elements with high aspect ratio have valid curved geometries. Achieving this on arbitrarily complex geometries is a challenge for the future. Additionally, the interface with the underlying CAD model information should not be lost, in order to support possible adaptation procedures.

Although within ADIGMA various methods and strategies were investigated and further enhanced to improve the solver efficiency of higher-order methods, the development of memory and CPU efficient solvers for large-scale industrial relevant applications still remains a major challenge. The techniques developed were mainly tested and adjusted for inviscid and laminar flows with moderate geometric complexity. The results achieved so far are not conclusive for turbulent complex flow problems. Further research work including efficient adaptation to the new type of processors and computer architectures is required in order to mature higher-order methods for industrial use.

In order for local refinement strategies to be efficient, the starting mesh for the computations should be as coarse as possible, but also represent the geometry accurately. This poses different requirements on grid generation than the classical finite volume methods do. In case of turbulent simulations, an additional complication is that the curvature of the geometry must be extended into the flow domain in order to avoid grid folding. In ADIGMA only a small portion of the research effort was devoted to this problem. There are currently no grid generators available which can be routinely used for this task. Thus the development of such grid generators is highly recommended. The goal-oriented sensors and error estimation developments showed good progress. Nonetheless, maturation of the algorithms is required for routine industrial use, especially for turbulent flow and/or p-refinement. Another consideration in the application of goal-oriented adaptation and error estimation to turbulent flows is the balance between numerical and modelling error. The error estimation algorithms will reduce the numerical error, but will not improve upon the turbulence model. There will be a cross-over point where the numerical error drops below the modelling error and further reduction of the numerical error does not make sense. This cross-over point is unknown and application-dependent. It is recommended to develop best practices for stopping criteria for turbulent flows.

It was realized during the execution of the test cases that, at the start of the project, rather ambitious test cases were intended to be investigated. In order to keep the test case suites manageable for the majority of the consortium members, adjustments and redefinitions were necessary. In some cases this raised questions, whether the simplified test cases were still close enough to industrial needs to raise the industrial awareness for this project. Based on the experience gained in ADIGMA it is highly recommended to include a rigorous well defined industrial assessment in any future planning of adaptive higher-order R&T projects.

In summary, the main achievements of the collaborative research project ADIGMA are

- significant progress in the development of adaptive higher-order methods for aerodynamic applications with high scientific output
- unique approach for critical assessment of innovative methods for industrial use,
- creation of a comprehensive data base for performance assessment of advanced CFD methods,
- successful demonstration of the potential and capabilities of higher-order methods,
- identification of limitations and research directions for further industrialization of higher-order methods as well as
- significant improvement of the collaboration between academia, research organizations and industry on advanced CFD methods.

Despite the significant progress, it has to be mentioned that many achievements are still far from industrial use. In order to realize the full potential of adaptive higher-order methods, further concentrated research effort is required. Particular research areas to be addressed are generation of coarse higher-order meshes and memory-efficient solver strategies for large-scale simulations for turbulent flow problems.

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