NOTES ON NUMERICAL FLUID MECHANICS AND MULTIDISCIPLINARY DESIGN · VOLUME 107

MEGADESIGN and MegaOpt – German Initiatives for Aerodynamic Simulation and Optimization in Aircraft Design

Results of the Closing Symposium of the MEGADESIGN and MegaOpt Projects, Braunschweig, Germany, 23–24 May, 2007

Norbert Kroll · Dieter Schwamborn
Klaus Becker · Herbert Rieger
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ISBN 978-3-642-04092-4 e-ISBN 978-3-642-04093-1

DOI 10.1007/978-3-642-04093-1

Notes on Numerical Fluid Mechanics
and Multidisciplinary Design ISSN 1612-2909

Library of Congress Control Number: 2009934349

Typeset & Cover Design: Scientific Publishing Services Pvt. Ltd., Chennai, India.

Printed in acid-free paper

5 4 3 2 1 0

springer.com

NNFM Editor Addresses

Preface

Over the last decade, Computational Fluid Dynamics (CFD) has become a mature technology for the development of new products in aeronautical industry. Aerodynamic design engineers have progressively taken advantage of the possibilities offered by the numerical solution of the Reynolds averaged Navier-Stokes (RANS) equations. Significant improvements in physical modeling and solution algorithms as well as the enormous increase of computer power enable high-fidelity numerical simulations in all stages of aircraft development.

In Germany, the national CFD project MEGAFLOW furthered the development and availability of RANS solvers for the prediction of complex flow problems significantly. MEGAFLOW was initiated by the first aviation research program of the Federal Government in 1995 under the leadership of the DLR (see Kroll, N., Fassbender, J. K. (Eds).: *MEGAFLOW – Numerical Flow Simulation for Aircraft Design*; Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Volume 89, Springer, 2005). A network from aircraft industry, DLR and several universities was created with the goal to focus and direct development activities for numerical flow simulation towards a common aerodynamic simulation system providing both a block-structured (FLOWer-Code) and a hybrid (TAU-Code) parallel flow prediction capability. Today, both codes have reached a high level of maturity and reliability. They are routinely used at DLR and German aeronautic industry for a wide range of aerodynamic applications. For many universities the MEGAFLOW software represents a platform for the improvement of physical models and for the investigation of complex flow problems. The network was established as an efficient group of very closely co-operating partners with supplementing expertises and experience. Focusing on common software, the process of transferring latest research and technology results into production codes used at industry has been considerably accelerated.

Despite the progress made in CFD, future demands of aircraft industry with respect to more environmentally friendly, safer and more economical aircraft require further improvement of simulation capabilities. The need to achieve reliable results at a high level of accuracy for complex configurations within short turn-around time places severe constrains on the application of CFD for aerodynamic data production and the integration of RANS methods into multidisciplinary simulation and optimization procedures. Consequently, enhanced CFD capabilities for reducing design cycle time and cost are indispensable for the industry.

In order to meet future requirements of German aircraft industry, two MEGAFLOW follow-on projects were set up, MEGADESIGN within the third aviation program of the Federal Government mid 2003 and MegaOpt as an internal DLR-project linked to MEGADESIGN. Based on the MEGAFLOW software, the main objectives of these four-year projects were to ensure the prediction accuracy with a guaranteed error bandwidth for certain aircraft configurations at design conditions, to reduce the simulation turn-around time for large-scale applications significantly, to improve the reliability of the flow solvers for full aircraft configurations in the complete flight regime, to extend the flow solvers to allow for multidisciplinary simulations and to establish numerical shape optimization as a vital tool within the aircraft design process. Partners of the MEGADESIGN consortium were DLR (Institute of Aerodynamics and Flow Technology), Airbus, EADS Military Air Systems, Synaps Ingenieur-Gesellschaft mbH, FastOpt, HPCC Space GmbH, RWTH Aachen University (Department of Mechanics), Berlin Technical University (Institute of Fluid Mechanics and Technical Acoustics), Braunschweig Technical University (Institute for Fluid Mechanics), Darmstadt University of Technology (Institute of Fluid Mechanics and Aerodynamics), Trier University (Department of Mathematics). The project was coordinated by DLR. Both the Institute of Aerodynamics and Flow Technology and the Institute of Aeroelasticity were involved in the complementary DLR-project MegaOpt.

This volume contains results presented during the closing symposium of the MEGADSIGN project which took place at DLR Braunschweig, Germany, on May 23rd and 24th 2007 and was jointly held with contributions from the MegaOpt project which finished at the end of 2007. Selected papers give an overview of the main activities and results achieved within both projects. Improvements and enhancements of the flow solvers are described, followed by new developments with respect to aerodynamic shape optimization and multidisciplinary optimization. Improved numerical simulation capabilities are demonstrated by several industrial applications.

Thanks are due to all partners and colleagues who have contributed in an open and collaborative manner. The knowledge and engagement of each individual contributed to the success and world wide appreciation of the MEGADSIGN project.

The funding of partial activities through the German Government in the framework of the air transport research program is gratefully acknowledged. The editors would also like to express gratitude to M. Wagler and F. Prill for technical support in compiling this book. Finally, the editors are grateful to Prof. Dr. W. Schröder as the general editor of the Springer series "Notes on Numerical Fluid Mechanics and Multidisciplinary Design" and also to the staff of the Springer for the opportunity to publish the technical results of the German CFD projects in this series.

Braunschweig / Göttingen
May 2009

Norbert Kroll
Dieter Schwamborn

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Part I

Reduction of Simulation Time

Recent Developments of TAU Adaptation Capability

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Summary. We present an overview of the mesh adaptation facility of the DLR TAU code as well as details of improvements made to it in the recent MEGADESIGN project, in particular focusing on advances made in the core of the adaptation module (for example parallel (de-)refinement and other efficiency improvements) as well as a relatively new type of adaptation indicator based on the adjoint solution (among other things) for a goal-oriented mesh adaption.

These improvements to the existing algorithms already available in the TAU code allow us to produce improved computational meshes in a more distributed manner, which provide more accurate predictions for selected functionals of the flow solution such as drag or lift – in fact, for any for which the necessary adjoint solution can be computed.

1 Introduction

Today's computational fluid dynamics (CFD) solvers are used to solve problems of ever increasing size and complexity, with many industrial partners relying more and more on the predictions of their computations and less on actual testing until later development stages are reached.

A big improvement for complex configurations – although not the "panacea" it may once have been touted as – was the introduction of unstructured methods, which allow the cumbersome and time-consuming process of mesh generation for such computations to be largely automated. This was thought to reduce the reliance on experienced users for setting up such complicated computations. Unfortunately, the quality of the computational mesh is still directly related to the accuracy of the result.[1] The quality of the mesh is in turn often dependent on the experience of the user with similar flow configurations as it is usually not clear *a priori* where dominant flow features will occur, and even whether they will have an impact on the outcome of the computation.

[1] Or in some non-trivial cases, whether a result could be obtained at all, as a low quality mesh has a high impact on the robustness of the solver.

N. Kroll et al. (Eds.): MEGADESIGN and MegaOpt, NNFM 107, pp. 3–19.
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To remedy this and produce meshes that resolve each of the flow phenomena of interest, local mesh adaption was introduced (for examples in the DLR TAU code see [5]). This procedure takes an existing computational mesh and a flow solution thereon[2] to produce a new mesh that will in some sense yield a better result for the observed flow topology, usually by inserting additional points in "regions of interest" and sometimes removing points where they are not needed or moving existing points to improve element quality.

In order to isolate these regions, a so-called *adaption indicator* or *sensor* is computed for each point in the mesh to obtain a measure of the local mesh quality[3]. This is a non-trivial process as mesh quality is not a purely local phenomenon because it depends on how the flow solver itself operates – for example the size of the stencil of the scheme, the exact nature of its gradient computations, or the flux functions used all influence how accurate a solver can be on a particular mesh. For this reason, almost all mesh adaption indicators resort to computing gradients of the solution variables with the notion being that mesh regions where large changes in the solution occur (e.g. shocks/discontinuities) have a strong impact on the quality of the result. In a sense, this is certainly true as by Godunov's theorem such regions can only exhibit 1st order accuracy and as such, increased spatial resolution will improve the resolution of those discontinuities.

Unfortunately, the existence of such strong shocks can lead to a problem where most – if not all – of the added points during mesh adaption are spent over-resolving shocks all the while neglecting either weaker shocks or under-resolving smooth solution areas which nevertheless can have a larger impact on the accuracy of the computation, depending on how the "accuracy" is measured. This can result in solutions whose inaccuracy is *amplified* by the repeated application of local mesh refinement based on such a gradient-based indicator – a clear contradiction to the common opinion that using more points will always give a better solution.

2 TAU-Code Adaptation Overview

The adaptation module of the TAU-code consists of three different components for various grid manipulations to adapt a given grid to the solved flow field:

1. y^+ based grid adaptation to adjust the first wall distance over turbulent surfaces in hybrid grids,
2. hierarchical grid refinement and derefinement to introduce new grid points on a given egde-indicator function without producing hanging nodes,
3. surface approximation and reconstruction for curved surfaces after introduction of new grid points.

[2] As opposed to more dynamic methods that modify the mesh *during* the solver iteration itself and not as a separate post-process, for example [23].

[3] The quality of a mesh is not only dependent on the density of points, but also on the elements that are constructed out of them, but we presuppose that a good mesh adaption will produce adequate elements for the solver.

In this section we will give a brief description of the of grid refinement algorithm and of the implemented egde-indicator functions to detect regions of refinement and derefinement.

A detailed description of the capabilities of the y^+ based grid adaptation can be found in [1]. In [2] we have presented the hierarchical grid refinement and derefinement algorithm along with the requirements for a parallelization of the adaptation module on distributed memory machines. A brief overview of the algorithms used for the surface approximation may be found in [4].

2.1 Grid Refinement Algorithm

The basic concept of the local grid refinement and derefinement is similar to the red/green refinement in [7, 16]. The main requirements of a local refinement strategy are the detection of grid areas which will be refined and a method of element subdivisions, which results from insertion of new points to these areas. A basic algorithm for the grid refinement reads as follows:

I. Build edge list and element to edge reference.
II. Evaluate edge indicators I_{e}.
III. Refine edge list considering:
  a. the edge indicators,
  b. the target point number and
  c. the grid conformity.
IV. Calculate coordinates of new points.
V. Construct new elements.
VI. Interpolate solution to new points.

The refinement module (2.) uses an edge based approach. The refinement indicators are therefore evaluated for all edges in the grid and new points are inserted at the edge mid points. The element subdivisions can then be determined from the configuration of refined edges [5]. Therefore, the edge list and the element to edge reference has to be build up first (I.). In stage II. all edges (N_{e}) are evaluated by the use of one of the sensor functions described in the next section.

2.2 Edge-Indicator Sensor Functions

The definition of a useful edge-indicator for local refinement depends on the investigated problem. Some approaches use a residual-based indicator or an adjoint approach (see for details Sect. 3) while other make use of gradients or differences of any suitable flow variable. The letter is the default setting for the refinement module (2.) of the TAU-code adaptation.

The approximated gradient $G_{(\Phi)}$ of a variable Φ in discrete form is $\Delta\Phi/h$ with $\Delta\Phi = \Phi_{p_1} - \Phi_{p_2}$, i.e. the difference between the point values of the two points p_1 and p_2 connected by one edge, where h is the length of the edge. We write the indicator function as

$$I_{\mathrm{e}} = \Delta\Phi h^{\alpha} \ . \tag{1}$$

A widely used formulation is $\alpha = 1$, i.e.: $G_{(\Phi)} h^2$. The advantage of scaling the indicator with a positive value of α is that the refinement stops automatically in the corresponding area after several cycles.

Our choice of $\Delta\Phi$ for the indicator function is

$$\Delta\Phi_{\mathrm{e}} = \max_{i=0,\dots N_\phi} \left(c_{\phi_i} \frac{(\Delta\phi_i)_{\mathrm{e}}}{(\Delta\phi_i)_{\max}} \right) \tag{2}$$

with N_ϕ being the number of different flow variables considered and e the edges in the grid.

The weights c_{ϕ_i} are scaling parameters which enable the choice of different combinations of the single parts of the indicator (to be set to zero in order to turn off ϕ_i).

The reference values $(\Delta\phi_i)_{\max}$ are for a balanced scaling of each part of the indicator function with

$$(\Delta\phi_i)_{\max} = \max_{\mathrm{e}=0,1,\dots N_{\mathrm{e}}} ((\Delta\phi_i)_{\mathrm{e}}) \;, \tag{3}$$

for all edges e in the grid. For the standard usage we have implemented three sensors functions for the edge-indicator

A. The differences (Δ_{d}) of the flow values

$$(\Delta_{\mathrm{d}}\phi_i)_{\mathrm{e}} = |\phi_i(x_{p_1}) - \phi_i(x_{p_2})| \;. \tag{4}$$

B. The differences of the gradients (Δ_{g}) of the flow values

$$(\Delta_{\mathrm{g}}\phi_i)_{\mathrm{e}} = |\partial(\phi_i(x_{p_1})) - \partial(\phi_i(x_{p_2}))| \;. \tag{5}$$

C. The differences of the reconstructed flow values (Δ_{r}) to the edge midfaces

$$\begin{aligned}(\Delta_{\mathrm{r}}\phi_i)_{\mathrm{e}} = |(\phi_i(x_{p_1}) + \tfrac{x_{\mathrm{e}}}{2}\partial(\phi_i(x_{p_1}))) - \\ (\phi_i(x_{p_2}) - \tfrac{x_{\mathrm{e}}}{2}\partial(\phi_i(x_{p_2})))| \;.\end{aligned} \tag{6}$$

with ϕ_i the flow value, p_1 and p_2 the two edgepoints of edge e and $x_{\mathrm{e}} = x_{p_1} - x_{p_2}$.

2.3 Target Point Number Iteration

In stage III. of the basic refinement algorithm we calculate an initial limit

$$L_0 = c\,(\max_{I_{\mathrm{e}}} + \min_{I_{\mathrm{e}}}) \;, \tag{7}$$

with $\max_{I_{\mathrm{e}}} = \max_{e=0,1,\dots N_{\mathrm{e}}}(I_{\mathrm{e}})$ and $\min_{I_{\mathrm{e}}} = \min_{e=0,1,\dots N_{\mathrm{e}}}(I_{\mathrm{e}})$ for the indicator I_{e} which results in the target number of new points if all edges with

$$I_{\mathrm{e}} > L_i \;,\; i = 0, 1, \dots \tag{8}$$

are marked for refinement. The variable c depends on the distribution of I_{e} and the desired target point number. This data is used to modify the default value of $c = \frac{1}{2}$ in order to speed up the target point number iteration.