

# An Adjoint Solver for an Industrial CFD Code via Automatic Differentiation

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## 1 Introduction

Industrial use of CFD is now routine and the current challenge is to incorporate large scale CFD codes into the engineering design cycle via design optimisation. The associated use of gradients is non-trivial and is the subject of the monograph [6]. Aerodynamic designs may have 100's of design variables making adjoint methods, which compute gradients in time proportional to the (small) number of design objectives [4], attractive. Here we concentrate on discrete adjoint methods, in which the discretised flow solver is adjointed, since it may be generated and maintained by automatic differentiation (AD) [5] tools. Previously [7] we described using the Odyssey AD tool [3] to obtain and validate a discrete forward sensitivity version of the BAE SYSTEMS/AIRBUS UK unstructured mesh CFD code FLITE3D. In this paper we report on the generation, validation and performance optimisation of the corresponding adjoint solver.

## 2 The Flite3D CFD Package

Neglecting RK time-stepping and multigrid, FLITE3D's solver is described by (1–4).

$$\left. \begin{array}{l} \textbf{Surface Mesh Generator} \\ \text{Given design parameters } \underline{\beta} \\ \text{Surface mesh generation } \mathbf{x}_S = \mathbf{X}_S(\underline{\beta}) \end{array} \right\} \quad (1)$$

$$\left. \begin{array}{l} \textbf{Volume Mesh Generator} \\ \text{Volume Mesh generation } \mathbf{x} = \mathbf{X}(\mathbf{x}_S) \end{array} \right\} \quad (2)$$

$$\left. \begin{array}{l} \textbf{Geometric Pre-Processor} \\ \text{Calculate point and face surface normals } \mathbf{n}(\mathbf{x}_S, \underline{\beta}), \mathbf{n}(\mathbf{x}_S) \\ \text{Calculate Volume Mesh normals } \mathbf{w}(\mathbf{x}, \mathbf{x}_S) \end{array} \right\} \quad (3)$$

$$\left. \begin{array}{l} \textbf{Flow Solver} \\ \text{Initialise flow variables } \mathbf{u}^0 \\ \text{Do} \quad \mathbf{n} = 0, n_{\max} - 1 \\ \quad \text{Finite volume residual } \mathbf{r}^n = \mathbf{R}(\mathbf{u}^n, \mathbf{x}, \mathbf{w}, \mathbf{n}) \\ \quad \text{If (converged) Exit Do Loop} \\ \quad \mathbf{u}^{n+1} = \mathbf{u}^n - \mathbf{P}_L(\mathbf{u}^n, \mathbf{x})\mathbf{r}^n \\ \quad \text{Aerodynamic Coefficients } [C_L, C_D, M_Y] = C(\mathbf{u}^n, \mathbf{x}, \mathbf{n}) \\ \text{EndDo} \end{array} \right\} \quad (4)$$

Given design parameters  $\underline{\beta}$ , for example B-spline coefficients, a surface mesh  $\mathbf{x}_S(\underline{\beta})$  is generated, followed by the volume mesh  $\mathbf{x}$  using Delaunay techniques. A geometric pre-processor then calcu-

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**Charles Hirsch, Dirk Wunsch, Jacek Szumbariski, Łukasz Łaniewski-Wołk, Jordi Pons-Prats**

## **An Adjoint Solver For An Industrial Cfd Code Via Automatic:**

**Computational Fluid Dynamics 2002** Steve Armfield, P. Morgan, Karkenahalli Srinivas, 2012-12-06 We are pleased to present the Proceedings of the Second International Conference on Computational Fluid Dynamics held at the University of Sydney Australia from July 15 to 19 2002 The conference was a productive meeting of scientists mathematicians and engineers involved in the computation of fluid flow Keynote lectures were presented in the areas of optimisation algorithms turbulence and bio fluid mechanics Two hundred and fifty abstracts from many countries were received for consideration The executive committee consisting of A Lerat M Napolitano J J Chattot N Satofuka and myself were responsible for the selection of papers Each of the members had a separate subcommittee to carry out the evaluation One hundred and seventy papers were selected of which one hundred and fifty two were presented at the conference All papers that appear in the proceedings have been peer reviewed by a panel of experts with a minimum of two for every paper before publication The conference was attended by 160 delegates with a minimum of late with drawals The informal and friendly atmosphere provided by the university surroundings was highly appreciated and the technical aspects of the conference were stimulating It is appropriate here to thank Alain Lerat the retiring secretary of the international scientific committee of the conference

We also wish to welcome J J Chattot who is the incoming secretary

**Computer Algebra in Scientific Computing** Vladimir P. Gerdt, Wolfram Koepf, Ernst W. Mayr, Evgenii V. Vorozhtsov, 2013-08-15 This book constitutes the proceedings of the 14th International Workshop on Computer Algebra in Scientific Computing CASC 2013 held in Berlin Germany in September 2013 The 33 full papers presented were carefully reviewed and selected for inclusion in this book The papers address issues such as polynomial algebra the solution of tropical linear systems and tropical polynomial systems the theory of matrices the use of computer algebra for the investigation of various mathematical and applied topics related to ordinary differential equations ODEs applications of symbolic computations for solving partial differential equations PDEs in mathematical physics problems arising at the application of computer algebra methods for finding infinitesimal symmetries applications of symbolic and symbolic numeric algorithms in mechanics and physics automatic differentiation the application of the CAS Mathematica for the simulation of quantum error correction in quantum computing the application of the CAS GAP for the enumeration of Schur rings over the group A5 constructive computation of zero separation bounds for arithmetic expressions the parallel implementation of fast Fourier transforms with the aid of the Spiral library generation system the use of object oriented languages such as Java or Scala for implementation of categories as type classes a survey of industrial applications of approximate computer algebra

*Computational Fluid Dynamics 2004* Clinton Groth, David W.

Zingg, 2006-09-27 Those interested in state of the art in computational fluid dynamics will find this publication a valuable source of reference The contributions are drawn from The International Conference on Computational Fluid Dynamics ICCFD held in 2004 The conference is staged every two years and brings together physicists mathematicians and engineers who

review and share recent advances in mathematical and computational techniques for modeling fluid dynamics      **Advances in Automatic Differentiation** Christian H. Bischof, H. Martin Bückner, Paul Hovland, Uwe Naumann, Jean Utke, 2008-08-17

The Fifth International Conference on Automatic Differentiation held from August 11 to 15 2008 in Bonn Germany is the most recent one in a series that began in Breckenridge USA in 1991 and continued in Santa Fe USA in 1996 Nice France in 2000 and Chicago USA in 2004 The 31 papers included in these proceedings reflect the state of the art in automatic differentiation AD with respect to theory applications and tool development Overall 53 authors from institutions in 9 countries contributed demonstrating the worldwide acceptance of AD technology in computational science Recently it was shown that the problem underlying AD is indeed NP hard formally proving the inherently challenging nature of this technology So most likely no deterministic silver bullet polynomial algorithm can be devised that delivers optimum performance for general codes In this context the exploitation of domain specific structural information is a driving issue in advancing practical AD tool and algorithm development This trend is prominently reflected in many of the publications in this volume not only in a better understanding of the interplay of AD and certain mathematical paradigms but in particular in the use of hierarchical AD approaches that judiciously employ general AD techniques in application specific algorithmic harnesses In this context the understanding of structures such as sparsity of derivatives or generalizations of this concept like scarcity plays a critical role in particular for higher derivative computations      *Optimization and Computational Fluid Dynamics* Dominique Thévenin, Gábor Janiga, 2008-01-08

The numerical optimization of practical applications has been an issue of major importance for the last 10 years It allows us to explore reliable non trivial configurations differing widely from all known solutions The purpose of this book is to introduce the state of the art concerning this issue and many complementary applications are presented

**Optimal Design and Control of Multibody Systems** Karin Nachbagauer, Alexander Held, 2024-01-04 This book presents the proceedings of the IUTAM Symposium on Optimal Design and Control of Multibody Systems 2022 covering research papers in the realm of optimal structural and control design for both rigid and flexible multibody systems It delves into the application of the adjoint approach enabling the undertaking of extensive topology optimizations to unearth body designs that excel under time and design dependent loads Encompassing presentations on adjoint sensitivity analysis structural optimization optimal control robust optimization artificial intelligence machine learning and computational methods and software development the IUTAM Symposium 2022 showcased the latest breakthroughs and innovative methodologies This book presents 14 meticulously peer reviewed proceedings papers from the event evenly split between the Optimal Design and Optimal Control panels      **More UK Success Stories in Industrial Mathematics** Philip J. Aston, 2025-04-22

This volume highlights successful projects in which academic mathematicians in the United Kingdom got involved with solving problems in industry for which mathematics was essential It contains a wide range of articles in areas ranging from music composition to climate change which describe successful collaborations between mathematicians

statisticians and industry The impact that the work had on the companies involved and on people's everyday lives is included in each article The book conveys to the non expert some of the many ways that mathematics and statistics have contributed to economic growth and societal well being

**Engineering Applications of Neural Networks** Lazaros Iliadis, Ilias Maglogiannis, Serafin Alonso, Chrisina Jayne, Elias Pimenidis, 2023-06-06 This book constitutes the refereed proceedings of the 24th International Conference on Engineering Applications of Neural Networks EANN 2023 held in Le n Spain in June 2023 The 41 revised full papers and 8 revised short papers presented were carefully reviewed and selected from 125 submissions The papers are organized in topical sections on artificial intelligence computational methods ethology classification filtering genetic algorithms complex dynamic networks optimization graph neural networks convolutional neural networks spiking neural networks deep learning modeling deep machine learning in engineering LEARNING reinforcement federated adversarial transfer natural language recommendation systems

**Uncertainty Management for Robust Industrial Design in Aeronautics** Charles Hirsch, Dirk Wunsch, Jacek Szumbarski, Łukasz Łaniewski-Woŋk, Jordi Pons-Prats, 2018-07-21 This book covers cutting edge findings related to uncertainty quantification and optimization under uncertainties i e robust and reliable optimization with a special emphasis on aeronautics and turbomachinery although not limited to these fields It describes new methods for uncertainty quantification such as non intrusive polynomial chaos collocation methods perturbation methods as well as adjoint based and multi level Monte Carlo methods It includes methods for characterization of most influential uncertainties as well as formulations for robust and reliable design optimization A distinctive element of the book is the unique collection of test cases with prescribed uncertainties which are representative of the current engineering practice of the industrial consortium partners involved in UMRIDA a level 1 collaborative project within the European Commission's Seventh Framework Programme FP7 All developed methods are benchmarked against these industrial challenges Moreover the book includes a section dedicated to Best Practice Guidelines for uncertainty quantification and robust design optimization summarizing the findings obtained by the consortium members within the UMRIDA project All in all the book offers a authoritative guide to cutting edge methodologies for uncertainty management in engineering design covers a wide range of applications and discusses new ideas for future research and interdisciplinary collaborations

AIAA Journal American Institute of Aeronautics and Astronautics, 2008

*New Results in Numerical and Experimental Fluid Mechanics VI* Cameron Tropea, 2007-10-26 This volume features the contributions to the 15th Symposium of the STAB German Aerospace Aerodynamics Association Papers provide a broad overview of ongoing work in Germany including high aspect ratio wings low aspect ratio wings bluff bodies laminar flow control and transition active flow control hypersonic flows aeroelasticity aeroacoustics mathematical fundamentals numerical simulations physical fundamentals and facilities

International Aerospace Abstracts , 1999

**Innovative Tools for Scientific Computation in Aeronautical Engineering** Jacques Periaux, 2001

Proceedings of the ASME Turbo Expo ... , 2007

**Aerospace America** , 1992

**ADIGMA - A European Initiative on the Development of Adaptive Higher-Order Variational Methods for Aerospace Applications** Norbert Kroll,Heribert Bieler,Herman Deconinck,Vincent Couaillier,Harmen van der Ven,Kaare Sorensen,2010-09-18 This volume contains results gained from the EU funded 6th Framework project ADIGMA Adaptive Higher order Variational Methods for Aerodynamic Applications in Industry The goal of ADIGMA 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 industry The ADIGMA consortium was comprised of 22 organizations which included the main European aircraft manufacturers the major European research establishments and several universities all with well proven expertise in Computational Fluid Dynamics CFD The book presents an introduction to the project exhibits partners methods and approaches and provides a critical assessment of the newly developed methods for industrial aerodynamic applications The best numerical strategies for integration as major building blocks for the next generation of industrial flow solvers are identified Evolutionary and Deterministic Methods for Design Optimization and Control With Applications to Industrial and Societal Problems Esther Andrés-Pérez,Leo M. González,Jacques Periaux,Nicolas Gauger,Domenico Quagliarella,Kyriakos Giannakoglou,2018-09-06 This book contains thirty five selected papers presented at the International Conference on Evolutionary and Deterministic Methods for Design Optimization and Control with Applications to Industrial and Societal Problems EUROGEN 2017 This was one of the Thematic Conferences of the European Community on Computational Methods in Applied Sciences ECCOMAS Topics treated in the various chapters reflect the state of the art in theoretical and numerical methods and tools for optimization and engineering design and societal applications The volume focuses particularly on intelligent systems for multidisciplinary design optimization mdo problems based on multi hybridized software adjoint based and one shot methods uncertainty quantification and optimization multidisciplinary design optimization applications of game theory to industrial optimization problems applications in structural and civil engineering optimum design and surrogate models based optimization methods in aerodynamic design NASA Tech Briefs ,2016-12 **Research and Technology 1998** ,1999 41st AIAA Aerospace Sciences Meeting & Exhibit ,2003

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