

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).

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

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

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

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

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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Ravishankar Balasubramanian



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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

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 **Proceedings of the ASME Turbo Expo ...** ,2007 International Aerospace Abstracts ,1999 **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 *Scientific and Technical Aerospace Reports* ,1987 *Journal of Aircraft* ,1999 41st AIAA Aerospace Sciences Meeting & Exhibit ,2003 **SIAM Journal on Scientific Computing** ,2007 **Adjoint-based Error Estimation and Grid Adaptation for Functional Outputs from CFD Simulations** Ravishankar Balasubramanian, 2005 This study seeks to reduce the degree of uncertainty that often arises in computational fluid dynamics simulations about the computed accuracy of functional outputs An error estimation methodology based on discrete adjoint sensitivity analysis is developed to provide a quantitative measure of the error in computed outputs The developed procedure relates the local residual errors to the global error in output function via adjoint variables as weight functions The three major steps in the error estimation methodology are 1 development of adjoint sensitivity analysis capabilities 2 development of an efficient error estimation procedure 3 implementation of an output based grid adaptive scheme Each of these steps are investigated For the first step parallel discrete adjoint capabilities are developed for the variable Mach version of the U2NCLC flow solver To compare and validate the implementation of adjoint solver this study also develops direct sensitivity capabilities A modification is proposed to the commonly used unstructured flux limiters specifically those of Barth Jespersen and Venkatakrishnan to make them piecewise continuous and suitable for sensitivity analysis A distributed memory message passing model is employed for the parallelization of sensitivity analysis solver and the consistency of linearization is demonstrated in sequential and parallel environments In the second step to compute the error estimates the flow and adjoint solutions are prolonged from a coarse mesh to a fine mesh using the meshless Moving Least Squares MLS approximation These error estimates are used as a correction to obtain highly accurate functional outputs and as adaptive indicators in an iterative grid adaptive scheme to enhance the accuracy of the chosen output to a prescribed tolerance For the third step an output based adaptive strategy that takes into account the error in both the primal flow and dual adjoint solutions is implemented A second adaptive strategy based on physics based feature detection is implemented to compare and demonstrate the robustness and effectiveness of

the output based adaptive approach As part of the study a general element unstructured mesh adaptor employing h refinement is developed using Python and C Error estimation and grid adaptation results are presented for inviscid laminar and turbulent flows

Implementing a Linear Equation Solver in the CFD Code PHOENICS M. K. Boparai, Rutherford Appleton Laboratory, 1993

Krylov-subspace Methods with Dynamic Deflated Restarting for Solving Adjoint Systems of Equations for Aerodynamic Shape Optimization Chih-Hao Chen, 2020

Due to advances in computing engineers in the aerospace industry over the past decade have incorporated more advanced numerical algorithms into their computational fluid dynamics CFD codes These advancements have not only allowed routine numerical investigation on the aerodynamic performance of complete aircraft configurations but the redesign of aircraft geometries through aerodynamic shape optimization ASO A fundamental step required for ASO is the computation of gradients of objective functions with respect to design variables where adjoint based methods form the predominant choice An essential stage in adjoint based aerodynamic shape optimization is to obtain the Lagrange multiplier by solving a sparse linear adjoint system of equations based on the Jacobian matrices from the converged flow states Such an approach has been applied widely within the aerospace community for the design of aircraft and other optimization problems for aerospace applications However the need to resolve the flow over complex geometries often requires highly stretched grids and gives rise to anisotropic flow fields which increase the stiffness of the discrete Jacobian needed for the solution of the adjoint system When a generalized minimal residual GMRES algorithm preconditioned by an Incomplete LU factorization is used this stiff linear system requires the use of a large number of Krylov subspace vectors and a high level of fill in both require an increase in the amount of memory Deflated restarting which distributes spectral eigen pairs has proven to be an effective method to enhance the convergence rates when solving an ill conditioned linear system of equations In this thesis a novel adjoint solver based on the Krylov subspace method is proposed where Krylov subspace basis vectors are dynamically evaluated The solver is applied within two Krylov subspace solvers GMRES and the generalized conjugate residual method with an inner orthogonalization GCRO The efficiency of the solvers is demonstrated on a series of two dimensional and three dimensional benchmark test cases

Industrial Computational Fluid Dynamics of Single-phase Flows ,2013

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population of rabbits and grass increases

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