NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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Parallel CFD & Optimization Unit

PhD Thesis

Adjoint methods for the design of shapes with optimal aerodynamic performance in laminar and turbulent flows

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Athens 2010

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Abstract

This PhD thesis focuses on the development, programming and assessment of adjoint methods for sensitivity analysis and optimization problems in aerodynamics/hydrodynamics. The thesis is exclusively concerned with continuous adjoint methods. Emphasis is paid to the accuracy of the computed sensitivity derivatives and, for this purpose, a solid mathematical background for developing adjoint formulations for both laminar and turbulent incompressible flows, is presented. The steepest descent method, supported by the exact gradient of the cost function, is used whenever an optimization problem is solved. Case studies related to turbomachinery blade airfoils and duct flows are presented. In addition, in the context of collaboration of the Parallel CFD & Optimization Unit of NTUA with a European automotive industry, the proposed methods and software were also applied in a real car configuration.

The developed continuous adjoint methods are utilised to produce sensitivity maps on aerodynamic bodies and in gradient-based optimization procedures. A secondary objective of this thesis is to propose adjoint methods that can be used for the computation of the Hessian matrix, in Newton optimization methods.

The developed adjoint methods are based on the continuous adjoint formulation proposed in a previous PhD thesis (by Dr. D.I. Papadimitriou) in the same Lab., which was however developed for compressible flows. That formulation was capable of computing accurate sensitivity derivatives in laminar flows, but this was not the case in turbulent ones, in which the usual assumption that the turbulence model quantities are not affected by the control vaiables was made. In view of the above, the present thesis proposes the development and additional solution of the adjoint to the turbulence model's equations. It is worth noting that the final adjoint sensitivity derivative expressions do not contain field integrals of mesh quantity variations, even if the cost function does, which is beneficial from the point of view of both accuracy and computing cost.

The proposed adjoint software was programmed on the basis of two different Navier-Stokes solvers, for incompressible flows. The first one uses the pseudo-compressibility method while the second one solves the flow equations in a segregated manner using the SIMPLE algorithm. Hence, two different adjoint solvers have been programmed, in Fortran77 and in C++, respectively. Furthermore, two different turbulence models have been utilized, the Spalart-Allmaras and the k-ε. The adjoint formulations that are presented in this thesis cover both low and high Reynolds number turbulence models. The low-Reynolds adjoint formulation relies on the Spalart-Allmaras turbulence model whereas the high-Reynolds one on the k-ε model. The first point of novelty of the thesis is that this is the first time the continuous adjoint to the turbulence model equation(s) is presented; though there exist a few similar research papers based on discrete adjoints, none of them deals with the continuous methods.

Regarding high-Reynolds number turbulence models, the mathematical formulation of the adjoint boundary conditions over the wall boundaries leads to the introduction of the adjoint friction velocity for the first time in the literature of adjoint methods. The latter is the second novelty of this PhD thesis. The adjoint friction velocity is related to the adjoint stress at the wall via the friction velocity of the primal problem and the normal to the wall gradients of the adjoint to the k and ε variables.

The proposed adjoint method is also used as the basis for developing optimization tools for the optimal placement of active flow control devices over an aerodynamic body. It is the sensitivity map produced from the adjoint method that indicates these positions. In such a case, the design variables of the control problem are the jet velocity components over the wall boundary. Methods for this kind of flow control applications is another point of novelty of this thesis.

Keywords: Computational Fluid Dynamics, Adjoint Methods, Adjoint Turbulence Models, Sensitivity Derivatives, Thermal Turbomachines, Optimization.