National Technical University of Athens

School of Mechanical Engineering

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Parallel CFD & Optimization Unit

Adjoint Methods for Turbulent Flows, Applied to Shape or Topology Optimization and Robust Design

PhD Thesis

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Athens, 2013

The present thesis deals with the mathematical formulation, programming and validation of adjoint methods for the computation of (first and higher-order) sensitivity derivatives for objective functions related to aerodynamics/hydrodynamics and the utilization of the latter in optimization algorithms. Methods based on both the discrete and continuous adjoint approaches are presented with emphasis laying on the latter. Academic and industrial cases are tackled in the fields of shape optimization (including, among others, the design/optimization of passenger cars and turbomachines), topology optimization and optimization under uncertainties (robust design).

Regarding shape optimization in fluid dynamics, the importance of differentiating the turbulence model equations is demonstrated for low- and high-Re number turbulence models for steady, incompressible flows. Particularly, the continuous adjoint method is extended to cover flows governed by the low-Re number Launder-Sharma turbulence model for the first time in the relevant literature. The implications of neglecting this differentiation (the widely used “frozen turbulence” assumption) on the optimization process are investigated. Moreover, the continuous adjoint method for the differentiation of the high-Re number Spalart-Allmaras model is mathematically developed and implemented for the first in the literature. In addition, the eikonal equation, used to compute the distance field, and its adjoint are utilized in order to make the final sensitivity derivatives expression independent from the distance variation, for flows governed by the low- and high-Re number variants of the Spalart-Allmaras model.

A significant part of the thesis is the subsequent application of the developed methods to industrial shape optimization problems. Specifically, the drag minimization of a concept car is tackled, using the exact continuous adjoint method for the low-Re number Spalart-Allmaras model and mesh-morphing techniques. In addition, surrogate aeroacoustic problems of the automotive industry, dealing with the noise perceived by the driver, are faced using the developed software. Moreover, driven by the industrial use of the computationally demanding

DES Spalart-Allmaras model, an industrially feasible continuous adjoint formulation for drawing lift and rear lift sensitivity maps, based on this model, is proposed. Emphasis is given to the reduction of the CPU and memory requirements in order for the method to be industrially applicable. To facilitate the application of the continuous adjoint method to industrial problems, two new coupled adjoint solution algorithms are presented, targeting increased numerical robustness and convergence acceleration.

In addition, the developed software is applied to the design/optimization of a Francis turbine runner. In detail, the continuous adjoint method is used to compute the sensitivity derivatives of various cost functions, with respect to the normal displacement of the boundary wall nodes. The cost functions include target velocity distributions at the outlet of the runner, changes in the hydraulic head to match the operating point and cavitation suppression. The computed sensitivities are then used in an optimization loop to optimize the performance of the runner in hand.

Regarding topology optimization, which leads to the initial design of a shape by searching for the optimal values of an artificial porosity field, the present thesis extends the mathematical formulation to cover 3D incompressible flows governed by the high-Re number Spalart-Allmaras model for the first time in the relevant literature. Moreover, frequently used industrial constraints are tackled, making the procedure more user-friendly and requiring less (or no) trial-and-error iterations. The developed software is used for designing an air conditioning duct placed on a passenger car as well as a plenum chamber mounted on a school formula car.

Despite using the low-cost adjoint methods, the optimization process may become time-consuming due to the number of optimization cycles required to obtain a converged solution. Aiming at lower turn-around times, a truncated-Newton algorithm is developed for the first time in the literature of topology optimization methods. The proposed algorithm makes use of Hessian-vector products to approximate the second-order correction of the design variables, at a feasible computational cost. The method is applied to 2D topology optimization problems with encouraging results for the acceleration of the optimization algorithm.

Robust design is the process of designing aerodynamic shapes with acceptable performance, not only at the design point, but in a range of operating conditions. The Second-Order Second-Moment method is used to compute the mean value and standard deviation of an objective function, requiring the computation of first- and second-order sensitivities of this function with respect to the uncertain variables. If the minimization of these metrics through a deterministic algorithm is targeted, derivatives up to third-order must be computed. The optimal combination of direct differentiation and the discrete adjoint method to compute the necessary derivatives is proposed and applied for the first time in the literature.

Key words: Computational Fluid Dynamics , Continuous and Discrete Adjoint Methods, Adjoint Turbulence Models, Shape and Topology Optimization, Truncated Newton Methods, Robust Design, High-Order Sensitivity Derivatives

Publications related to the PhD Thesis

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