ΕΘΝΙΚΟ
ΜΕΤΣΟΒΙΟ
ΠΟΛΥΤΕΧΝΕΙΟ
ΣΧΟΛΗ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

Α.Π. : 3893
Αθήνα, 25/1/19

ΚΟΣΜΗΤΟΡΑΣ

Προς τα Μέλη ΔΕΠ της
Σχολής Μηχ/γων
Μηχ/κών

<u>ΠΡΟΣΚΛΗΣΗ</u>

Σας προσκαλούμε στην παρουσίαση της Διδακτορικής Διατριβής του Υ.Δ. **κ. ΤΣΙΑΚΑ Κωνσταντίνος** του Θωμά που εκπόνησε στον Τομέα Ρευστών, διπλωματούχος Μηχανολόγος Μηχανικός του ΕΜΠ καθώς και κάτοχος Μεταπτυχιακού Διπλώματος της ΣΗΜΜΥ στο αντικείμενο Παραγωγή & Διαχείριση Ενέργειας. Η Παρουσίαση θα πραγματοποιηθεί την *<u>Παρασκεύη 15 Φεβρουαρίου 2019</u>*, ώρα *<u>10:00π.μ.</u>* στην αίθουσα Τηλεκπαίδευσης (Πολυμέσων) του κτιρίου της Κεντρικής Βιβλιοθήκης του ΕΜΠ - Πολυτεχνειούπολη Ζωγράφου. Ο ελληνικός τίτλος της Διδακτορικής Διατριβής είναι ο εξής :

«ΑΝΑΠΤΥΞΗ ΤΕΧΝΙΚΩΝ ΠΑΡΑΜΕΤΡΟΠΟΙΗΣΗΣ ΕΠΙΛΥΤΗ ΡΟΗΣ ΚΑΙ ΤΟΥ ΣΥΖΥΓΟΥΣ ΤΟΥ ΓΙΑ ΤΗ ΒΕΛΤΙΣΤΟΠΟΙΗΣΗ ΜΟΡΦΗΣ ΣΕ GPUs. ΕΦΑΡΜΟΓΕΣ ΣΤΙΣ ΣΤΡΟΒΙΛΟΜΗΧΑΝΕΣ ΚΑΙ ΤΗΝ ΕΞΩΤΕΡΙΚΗ ΑΕΡΟΔΥΝΑΜΙΚΗ»

Και ο Αγγλικός ως εξής:

«DEVELOPMENT OF SHAPE PARAMETERIZATION TECHNIQUES, A FLOW SOLVER AND ITS ADJOINT, FOR OPTIMIZATION ON GPUs. TURBOMACHINERY AND EXTERNAL AERODYNAMICS APPLICATIONS»

Ο Κοσμήτορας της Σχολής

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Development of Shape Parameterization Techniques, a Flow Solver and its Adjoint, for Optimization on GPUs. Turbomachinery and External Aerodynamics Applications

Ανάπτυξη Τεχνικών Παραμετροποίησης, Επιλύτη Ροής και του Συζυγούς του για τη Βελτιστοποίηση Μορφής σε GPUs. Εφαρμογές στις Στροβιλομηχανές και την Εξωτερική Αεροδυναμική

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PhD Thesis Abstract

This thesis is concerned with the development of methods and numerical tools for fast and cost efficient aerodynamic/hydrodynamic shape optimization. Developments related to the ensemble of building blocks of a shape optimization framework, namely **a)** the Computational Fluid Dynamics (CFD) analysis software, **b)** the optimization methods and **c)** the shape parameterization techniques are performed. These reduce the overall optimization cost and make them appropriate for use in industrial design processes. Both Gradient-Based (GB) optimization methods assisted by the adjoint technique and Evolutionary Algorithms (EAs) are considered, with emphasis on the development of the former. Most of the proposed methods focus on turbomachinery design/optimization but, their range of applicability is much wider, including also external aerodynamics applications.

The GPU-enabled in-house (U)RANS solver PUMA (Parallel Unstructured Multi-row Adjoint), previously developed only for steady and unsteady compressible flows, is enriched with an incompressible flow solver based on the Artificial Compressibility (AC) approach. The RANS equations for both compressible and incompressible flows are expressed in a relative frame of reference although they are solved for the absolute velocity components, using the Multiple Reference Frame (MRF) approach. To enable the simulation of multi-row turbomachinery configurations, Rotor-Stator Interaction techniques, such as the mixing interface, frozen rotor and sliding interface approaches are employed. GPU-specific programming techniques and numerical schemes, developed in previous works on the PUMA software, are revisited, upgraded and re-evaluated, resulting in a GPU implementation which is up to 40x faster than the equivalent CPU one. This is achieved by careful code re-structuring, delicate GPU memory handling, the use of Mixed Precision Arithmetics (MPA) and efficient utilization of the NVIDIA CUDA programming environment, in order to optimally exploit the SIMD architecture and hardware characteristics of modern GPUs. Especially, MPA is a technique according to which, when solving for the update of flow quantities, double precision storage is used for the right-hand-side (r.h.s.) terms, while single precision storage is employed for the left-hand-side (l.h.s.) ones, reducing the overall memory usage and increasing GPU memory bandwidth. The PUMA solver is also capable of running in parallel on multiple GPUs, using overlapping domains. Communications among GPUs of the same computational node are carried out through the shared on-node CPU memory, while the MPI protocol is employed for communications among different computational nodes. A series of test cases are studied for validation and verification purposes of the PUMA compressible and incompressible flow solver. These concern the turbulent flow around two isolated airfoils, the flow through a convergent-divergent transonic diffuser and over a backward-facing step and the flow around a Horizontal Axis Wind Turbine (HAWT) blade, with published results to compare with. Furthermore, the solver is also validated/verified on the prediction of the flow field around the ONERA M6 wing, inside a propeller type water turbine and a high pressure turbine stator.

Throughout this thesis, the continuous adjoint method is exclusively used and its development for both the compressible and the AC-based incompressible flow solver is proposed. The method allows the computation of the sensitivity derivatives of several objective functions (like the lift and drag forces, the torque, the total pressure losses and the turbomachinery row efficiency) with respect to the aerodynamic shape at a cost independent of the number of design variables controlling the shape, enabling the efficient use of Gradient-Based (GB) optimization methods.

Two different expressions for the sensitivity derivatives are developed, namely the Surface Integral (SI) and Field Integral (FI) adjoint formulations. The former makes use of the Leibniz rule and, usually neglecting surface integral terms containing the residuals of the state equations (referred to as Severed-SI), results in a series of surface integrals that constitute the sensitivity derivatives expression. The latter, on the other hand, results in sensitivity derivatives expressed as the sum of surface and volume integrals. Though mathematically equivalent, numerically these expressions result in sensitivity derivatives of potentially different accuracy and computational complexity. The FI approach is more accurate, especially in turbulent flows, compared to the Severed-SI one but requires a properly differentiated grid displacement model and more arithmetic operations in order to compute the volume integrals involved in the sensitivity derivatives expressions. Conversely, the SI approach results in potentially less accurate but, also, computationally cheaper sensitivity derivatives.

In both formulations, the variations of the eddy viscosity due to shape changes are taken into account by differentiating the Spalart-Allmaras turbulence model for both compressible and incompressible flows. The variations of the distance from the nearest wall are also taken into account, through the differentiation of the Eikonal equation, i.e. a PDE computing distances from the walls. Proper consideration of these variations results in a complete and consistent expression for the sensitivity derivatives enhancing the convergence and robustness of the GB optimization method.

In the field of shape parameterization for aerodynamic optimization, a parametric modeler for turbomachinery blade rows is developed, namely the GMTurbo software. A bottom-up strategy is followed, where the meridional outline is constructed, camber lines of the blade at several spanwise positions are built using metal and other angles, thickness is added normal to them and the blade sections are interpolated to yield the 3D blade shape. With the GMTurbo, a wide range of blade shapes can be generated parametrically, while maintaining a compact CAD-compatible representation of the geometry. The GMTurbo software, together with the PUMA flow solver and the in-house evolutionary algorithm based optimization tool (EASY software), is employed for the optimization of a propeller type water turbine. Both the inlet guide vanes and the runner shape are optimized for maximum efficiency. In this case, the interaction between the stationary and rotating blades is taken into account through the mixing plane technique. The advantage of jointly optimizing the two rows is demonstrated.

Additionally, a Free Form Deformation technique, based on Volumetric NURBS, is developed to support optimization loops. According to this technique a NURBS volume is defined by means of a control point lattice, in which the aerodynamic shape under consideration is embedded together with parts of the CFD domain. Displacements of the control points lead to displacements of any entity embedded in the NURBS volume allowing for a monolithic approach for simultaneously displacing the aerodynamic body and the CFD mesh around it. A new strategy for extending the applicability of this technique to the shape optimization of turbomachinery components, based on intermediate coordinate system transformations, is proposed.

The Volumetric NURBS parameterization is differentiated to provide the grid sensitivities needed by the FI continuous adjoint method. Then, it is used for the GB shape optimization of a 2D transonic airfoil and that of a linear compressor cascade. The method is also applied to the shape optimization of a 3D transonic wing and, finally, that of a peripheral high pressure turbine nozzle guide vane.

Keywords: Computational Fluid Dynamics, Graphics Processing Units, Continuous Adjoint Method, Shape Optimization, Thermal and Hydraulic Turbomachines, Wind Turbines, Shape Parameterization, NURBS, External and Internal Flows, Evolutionary Algorithms.

Athens, 2019