NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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PhD Thesis

APPLICATION OF EVOLUTIONARY ALGORITHMS, COMPUTATIONAL INTELLIGENCE AND ADVANCED COMPUTATIONAL FLUID DYNAMICS TECHNIQUES TO THE OPTIMIZATION – INVERSE DESIGN OF TURBOMACHINERY CASCADES, USING PARALLEL PROCESSING

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Abstract

The main intent of this work was the research, development and evaluation of a complete design procedure for optimum aerodynamic shapes using Evolutionary Algorithms (EA) and advanced Computational Fluid Dynamics (CFD) techniques. These techniques constitute the software tools for the analysis of candidate solutions with respect to a number of specified objectives. Even though the design procedure was used mainly in the area of thermal turbomachines, a main characteristic of the proposed optimization method is its general applicability.

The optimization method is based on a unified and generalized formulation of EA for single and multi-objective problems. The proposed algorithm keeps and constantly updates three population sets and combines evolutionary operators and coding techniques which are part of the well known Genetic Algorithms and Evolutionary Strategies. In multi-objective problems the Pareto optimal front is computed and the fitness score of each individual is assigned using a plethora of alternative techniques.

The generalized EA formed the basis upon which additional techniques for the reduction of the computational cost were built. These techniques originate from the computational intelligence area and their combination with EA leads to a significant cost reduction (up to one order of magnitude). The optimization method originally proposes the direct and dynamic cooperation of the exact analysis model (costly CFD techniques) with a surrogate, inexact model (metamodel, mainly Artificial Neural Netwoks (ANNs) or Kriging techniques) for the evaluation of the candidate solutions. Thus, at the beginning of each generation the so-called Inexact Pre-evaluation Phase of all individuals belonging to the offspring population set takes place and, subsequently, only a very small number of the most promising individuals is exactly evaluated (using costly CFD techniques). The inexact model is locally trained before each and every prediction to keep its training cost low (negligible) and to increase its predictive capabilities.

A new idea for further improving the prediction capabilities of ANNs was the introduction of importance factors for every design variable in order to pin-point and degrade the effect of noisy design variables. The role of importance factors is considered as autocatalytic since they are computed during the training phase of an ANN and, at the same time, they are used by it to increase its predictive capabilities.

The elapsed, wall-clock time of the proposed optimization method is reduced using parallel processing with open message passing protocols (primarily PVM) which support the majority of modern parallel distributed or shared memory computers. The parallelization technique is based either on the concurrent evaluation of the most promising individuals designated during the Inexact Pre-evaluation Phase or on a distributed EAs model. This model increases the number of individuals that may be concurrently evaluated and additionally improves the convergence rate of the whole optimization method. All parallel computations were executed on the cluster of personal computers at the Lab. Of Thermal Turbomachines which was initially set up by the author.

In a distinct part of this dissertation all modifications made to the CFD software which numerically solves the Navier-Stokes equations on unstructured grids are presented. The major change is related to the parallelization technique which is based on the unstructured grid partitioning to subdomains. The computations within each subdomain are assigned to a different processor. A new method for the load balancing of processors after each grid adaptation phase is proposed. This method statically and optimally repartitions the grid after grid adaptation using a new, generalized and fast graph partitioning method based on Genetic Algorithms, a multilevel coarsening technique and heuristics.

The design procedure consisting of the optimization method and aerodynamic shape parameterization tools was evaluated and ‘calibrated’ initially in a number of external aerodynamics problems, for instance, at the optimum positioning of the slat and flap of a three element airfoil, at the inverse design and shape optimization of airfoils in multiple operating points with single and multi-objectives (drag or/and lift coefficients at each operating point). During the next essential evaluation phase the method was applied in a series of turbomachinery problems. In all these problems the flow is considers viscous and thus, the Navier-Stokes equations are numerically solved. The main application area was the constrained shape optimization of 2D linear cascade airfoils of compressors and turbines aiming at the reduction of the coefficient of total pressure losses at one and up to five operating points. Designing turbomachinery components for more than one operating points is a state of the art problem and the results of this work are very satisfactory. Besides 2D airfoils, the shape optimization of a 3D rotating axial compressor cascade blade was presented. This is a computationally expensive industrial test case which demonstrates the benefits of combining computational intelligence, parallel processing and Evolutionary Algorithms in a robust optimization method. Finally, the multi-objective design of optimal combined cycle power plants with supplementary firing aiming at minimizing the capital cost and maximizing the efficiency and power was presented.

Closing, over and above the particular aerodynamic or turbomachinery test cases, the developed optimization method may be applied to a broad range of problems. Under this perspective, a general, user friendly technological product named EASY (The Evolutionary Algorithms SYstem) originated out of this work.