EVOLUTIONARY METHODS FOR DESIGN, OPTIMISATION AND CONTROL
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MULTI-DISCIPLINARY DESIGN OPTIMIZATION

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Abstract. Hybrid, semi-stochastic, and stochastic optimizers are becoming popular since they can handle several objectives simultaneously, they can enforce several equality constraints, avoid local minima, and handle a large number of design variables. Examples of design optimization of a multistage axial gas turbine, steady and unsteady flow linear airfoil cascades, a magneto-hydrodynamic diffuser, and a freezing protocol for organ preservation, are sketched to illustrate the multi-disciplinary applicability of these algorithms.

Key words: multi-disciplinary design optimization, genetic algorithms, hybrid optimizers, semi-stochastic optimizers, multi-objective optimization.

1 INTRODUCTION

Design optimization has the objective to determine proper values for a large number of design variables that either minimize or maximize one or many global objectives while satisfying a number of user specified equality and inequality constraints. In transport processes, the main design objective should be the minimization of entropy generation caused by viscous dissipation, heat transfer, internal heat sources, chemical reactions, and electro-magneto-hydrodynamic effects. Entropy generation minimization can then be achieved by the proper variation of the domain size and shape, moving media properties and/or boundary and initial conditions. Gradient-based optimization algorithms are known for their inability to cope with multiple minima and for their inefficiency when dealing with a large number of design variables[1]. Genetic algorithms are known for their inefficiency especially when dealing with a relatively small number of design variables. A logical remedy is a hybrid constrained optimization package with automatic switching among different gradient-based and semi-stochastic optimization algorithms[2].

2. MULTI-DISCIPLINARY EXAMPLES OF DESIGN OPTIMIZATION

2.1 Optimization of a multi-stage axial flow gas turbine

An example of entropy minimization (efficiency maximization) optimizes hub and shroud geometry and inlet and exit flow-fields for each blade row of a multi-stage axial flow gas turbine by utilizing a fast compressible steady state inviscid axi-symmetric (through-flow) code with high fidelity loss and mixing models that account for turbulence, flow separation, etc.[3]. The optimization was performed using a hybrid constrained optimizer that performs automatic switching among genetic, simulated annealing, modified simplex method, sequential quadratic, and Davidon-Fletcher-Reeves gradient search algorithms[2]. The comparison of computed performance of initial and optimized designs shows significant improvement in the optimized two-stage turbine efficiency over the entire range of operating conditions (Fig. 1). This entire optimization process consumed less than two hours on a 500MHz processor.

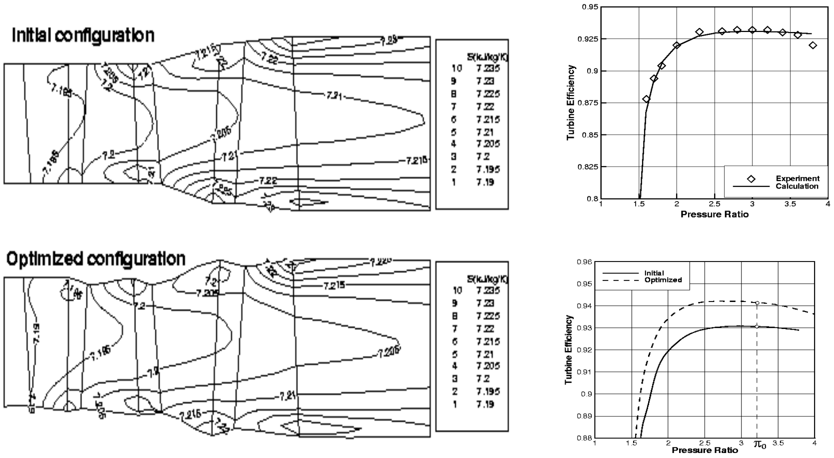


Figure 1. Entropy fields and total efficiencies before and after optimization of hub and shroud shapes using a hybrid optimizer[2] for a two-stage axial gas turbine[3].

2.2 Single-objective constrained optimization of cascade of airfoil shapes

The single objective was to minimize the total pressure loss across an existing two-dimensional cascade of gas turbine airfoils having supersonic exit flow. A constrained micro-genetic optimizer was used for minimization of this single objective function[4]. The following equality constraints were specified and iteratively enforced: aerodynamic lift force, mass flow rate, exit flow angle, and airfoil cross-section area. In addition, axial chord and gap-to-axial chord ratio were kept fixed, while enforcing an inequality constraint where the airfoil thickness was greater than or equal to the specified minimum allowable thickness distribution. For the analysis of the performance of intermediate cascade shapes, an unstructured grid compressible Navier-Stokes flow-field analysis code with a k-ε turbulence model was used. The airfoil geometry was parameterized using nine conic section parameters that guarantee realistic airfoil shapes without a possibility of overlap of the upper and lower surface of the airfoil. Eight B-spline control points were superimposed, thus keeping the number of geometric design variables to a minimum while achieving a high degree of geometric flexibility and robustness. The sequential quadratic programming was used for enforcement of the computationally inexpensive equality constraints like the specified airfoil cross-section area (Fig. 2).

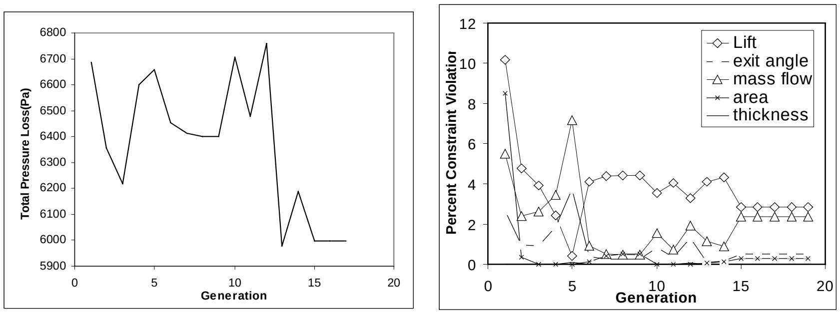


Figure 2. Convergence history of total pressure loss for best designs and violations of constraints when using penalty function with SQP, minimum thickness distribution constraint, and nine conic sections with eight-point B-spline geometry perturbation[4].

2.3 Rotor cascade optimization with unsteady passing wakes

An axial turbine rotor cascade shape optimization with unsteady passing wakes was performed to obtain improved aerodynamic performance using an unsteady Navier-Stokes flow-field analysis code[5]. The objective function was defined either as minimization of total pressure loss or as maximization of lift, while the mass flow rate was fixed during the optimization. The design variables were geometric parameters characterizing airfoil leading edge, camber, stagger angle, and inter-row axial spacing (Fig. 3a). Penalty terms were introduced for combining the constraints with the objective function. A genetic algorithm with a population of 32 designs was used as the optimizer. During each optimization iteration, the objective functions of the 32 new population members were computed simultaneously by using a 32 processor distributed memory parallel computer. The optimization results indicated that only minor improvements were possible in the unsteady rotor/stator aerodynamics by varying these geometric parameters (Fig. 3b).

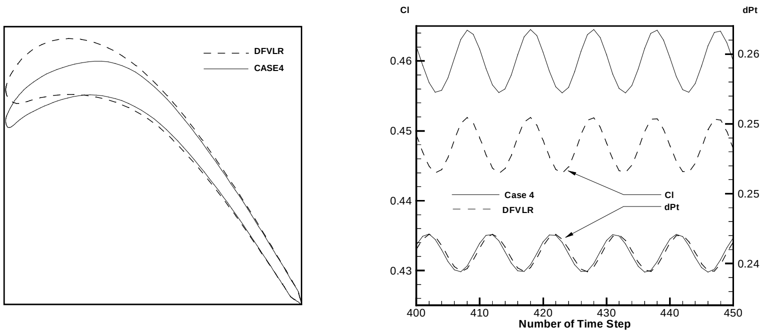


Figure 3. Original DFVLR and optimized[5] DFVLR rotor linear cascade airfoil shapes (a) and time variation of lift and total pressure loss for these two cascades (b).

2.4 Multi-objective aerodynamic shape optimization

In multi-objective optimization we strive to find a group of not-dominated solutions, which is known as the Pareto optimal set, or Pareto front. These are the feasible solutions found during the optimization that cannot be improved for any one objective without degrading another objective. The multi-objective constrained optimization algorithm that we used was a modified version of an indirect method of optimization based upon self-organization (IOSO)[6] and evolutionary simulation principles. Each iteration of IOSO consists of two steps. The first step is the creation of an approximation of the objective functions. In this step, the initial approximation function is constructed from a set of simple approximation functions resulting in a final response function that is a multi-level graph. The second step is the optimization of this approximation function. The distinctive feature of this approach is an extremely low number of trial points to build the initial approximation. A constrained multi-objective shape optimization was performed using IOSO on a linear cascade of gas turbine airfoils. The objectives were then to simultaneously minimize the total pressure loss, maximize total aerodynamic loading, and minimize the number of airfoils in the finite cascade row[7]. The equality constraints were: fixed mass flow rate, axial chord, inlet and exit flow angles, and blade cross-section area. The inequality constraints were the minimum allowable airfoil thickness distribution, minimum allowable aerodynamic lift force, and a minimum allowable trailing edge radius. This means that the entire airfoil cascade shape was optimized including its stagger angle, thickness, curvature, and solidity resulting in 18 design variables, 5 nonlinear constraints, and 3 objectives. The performances of the intermediate airfoil cascade shapes were analyzed with an unstructured grid based compressible Navier-Stokes flow-field analysis code with a k-ε turbulence model. Although the VKI airfoil was designed by experienced aerodynamicists using sophisticated inverse shape design software, the optimizer found an entire family of feasible solutions that were better than the inversely designed VKI airfoil cascade for all three objectives (Fig. 4).

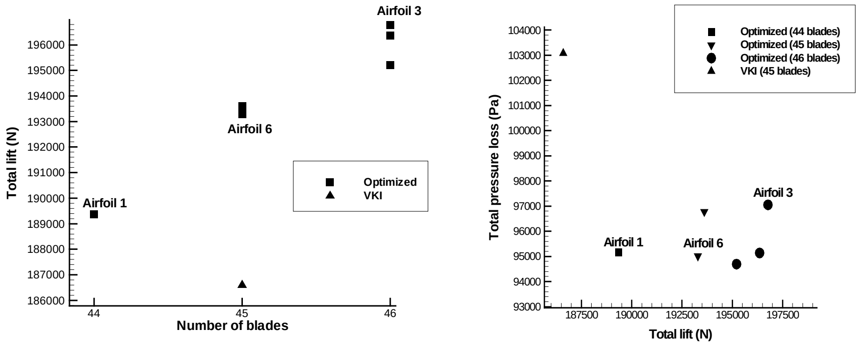
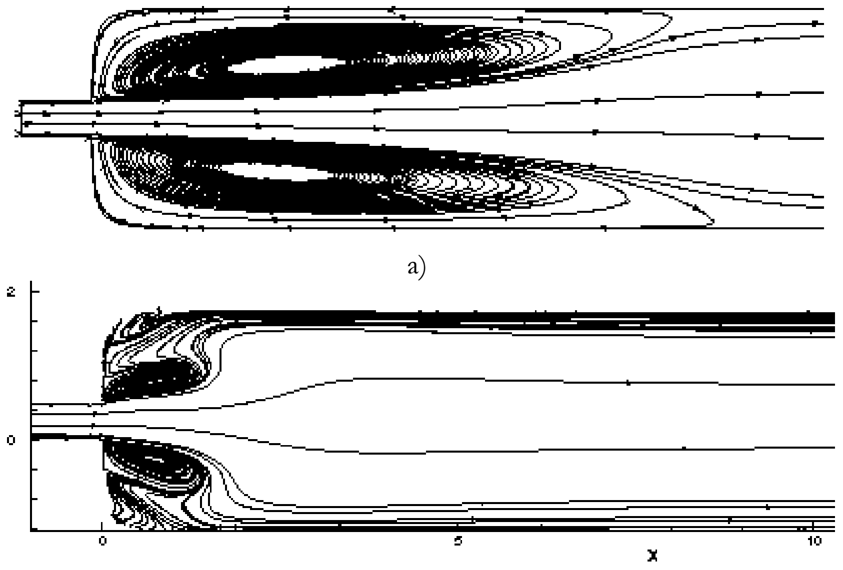


Figure 4. Comparisons of total loading produced, total pressure loss generated, and number of airfoils for optimized finite length cascades and the original VKI airfoil cascade[7].

2.5 Multi-disciplinary design optimization applied to magneto-hydrodynamics

Most realistic design problems involve not only aerodynamics, but also other interacting disciplines. One such multi-disciplinary design optimization example involves magneto-hydrodynamics[8]. When a viscous liquid flows from a narrow passage into a suddenly wider passage, there are significant flow separation zones (Fig. 5a). One possibility to reduce the flow separation would be to perform a straightforward wall shape optimization. But, if the shape of the passage walls is not to be altered for whatever reason, it is still possible to affect the flow-field pattern if the fluid is electrically conducting. It is well known that electrically conducting fluids respond to externally applied magnetic or electric fields. In this situation, the objective is to find the proper distribution and orientation of the externally applied magnetic field along the passage walls so that the fluid flow separation is minimized.

Using a two-dimensional magneto-hydrodynamics analysis code based on the least squares finite element method and a parallel micro-genetic optimizer, it was recently shown[8] that such optimized magnetic fields can be used to significantly reduce flow-field separation (Fig. 5b) and increase the static pressure rise for a fixed length of a diffuser.



a)

b)

Figure 5. Streamlines for diffuser flow without magnetic field (a) and with an applied magnetic field (b) optimized to suppress laminar steady incompressible flow separation[8].

2.6 Optimization of freezing protocols for preservation of organs

One concept that offers a possible practical solution to freezing and thawing of organs is to immerse them in a cryo-protective gelatin in order to assure that the heat transfer from the outer surface of the organ to the gelatin occurs by pure conduction. The optimization objective is then to find the proper time variation of thermal conditions on the surface of the freezing container so that the optimal local cooling rates are achieved at each instant of time at every point inside the heterogeneous organ. Transient temperature distribution was computed at every point of the organ using a three-dimensional linear thermo-elasticity finite element method analysis code subject to initially guessed 26 parameters describing temperature distribution on the spherical freezing container surface. From this, the actual local temperature gradients and the resulting thermal stresses were determined at each point in the organ.

A nonlinear constrained maximization method based on a genetic algorithm[9] was used after each specified time interval to optimize the 26 parameters at each of the control points on the spherical container surface. Thus, such time evolution of temperature distribution on the freezing container surface was determined that it maximizes the local cooling rates in the organ while keeping the local thermal stresses in the organ below the user specified maximum allowable values. The resulting thermal stresses are non-uniform because of different physical properties of the organ's tissues (Fig. 6a).

The kidney was located in the region –0.5 < x < 0.5 (Fig. 6b).

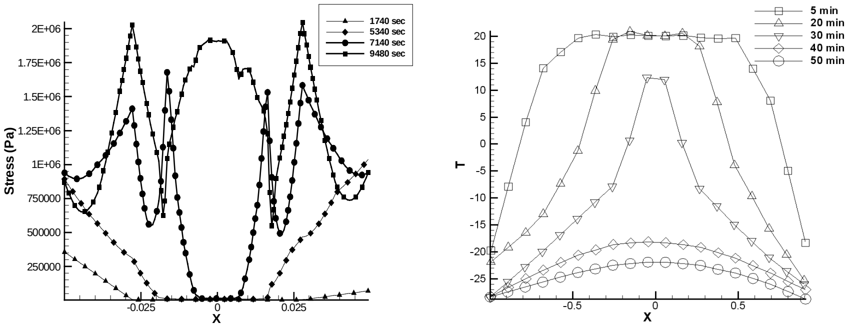


Figure 6. von Mises stress (a) and temperature (b) time evolutions along the intersections of x-y plane at z = 0 and x-z plane at y = 0 using periodic optimization of a spherical container wall temperature distribution during optimized freezing of a dog kidney[9].

3 SUMMARY AND RECOMMENDATIONS

Multi-disciplinary design methodologies[10] are experiencing a general trend away from inverse design and gradient based optimization methods and towards multi-objective, multi-disciplinary, semi-stochastic and stochastic constrained optimization. This trend is facilitated by the availability of inexpensive parallel computers based on commodity PC components. Multidisciplinary design and optimization technology will likely result in a decreased need for highly educated, experienced, and expensive designers.

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