MULTI-DISCIPLINARY ANALYSIS AND DESIGN OPTIMIZATION

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Abstract Simultaneous numerical analyses of several interacting field problems (fluid mechanics, heat transfer, elasticity, electro-magnetism, etc.) are becoming a feasible practical tool for analyzing realistic engineering systems. It is also rapidly becoming popular to use optimization methods in design. Hybrid, semi-stochastic, and stochastic optimizers are becoming popular since they can handle several objectives simultaneously. Also, they can enforce several equality constraints, avoid local minima, and handle a large number of design variables. Examples of analysis and design optimization of multistage axial gas turbine, steady and unsteady flow linear airfoil cascades, magneto-hydrodynamic diffuser, and a freezing protocol for organ preservation, are sketched to illustrate the multi-disciplinary applicability of a variety of analysis and optimization algorithms.

Keywords: Multi-disciplinary Design Optimization, Gradient Optimizers, Genetic Algorithm, Hybrid Optimizers, Multi-objective optimization.

1. INTRODUCTION

The objective of this survey is to present a brief review of developments and applications of multi-disciplinary analysis and constrained optimization algorithms as practiced in our Multidisciplinary Analysis, Inverse Design and Optimization (MAIDO) Laboratory.

2. MULTI-DISCIPLINARY ANALYSIS

When several media are in contact, properties like temperature field, electric field, magnetic field, stress, deformation, etc. are distributed across the interface boundaries. The interface boundary conditions are simultaneously influenced by both of the domains in contact. To avoid speculating with the values of the interface boundary conditions, it is more

appropriate to solve all domains and fields simultaneously in a fully conjugate manner. **2.1 Conjugate Heat Transfer Analysis**

A three-dimensional conjugate heat transfer (convection-conduction) prediction code was developed where the compressible turbulent flow Navier-Stokes equations are solved simultaneously in the flow-field and in the solid material of the structure thus automatically predicting correct magnitudes and distribution of surface temperatures and heat fluxes (Han et al., 2000). This approach eliminates the need to specify temperature or heat flux distribution on the solid/fluid interface (Fig. 1 and Fig. 2). The conjugate codes use hybrid unstructured/structured grids throughout the flow-field and in the surrounding structure.





Fig. 1. Temperatures computed on the external and internal walls of an internally cooled axial flow gas turbine blade.

Fig. 2. Conjugate isotherms computed in the leading edge region of an internally cooled axial flow gas turbine blade.

2.2 Conjugate Heat Transfer and Magneto-Hydro-Dynamic (MHD) Flow Analysis

The problem of multi-disciplinary analysis of steady, incompressible magneto-hydrodynamic (MHD) flow with conjugate heat transfer in a two-dimensional straight wall channels was demonstrated (Dennis and Dulikravich, 2000) with a computer program based on a leastsquares finite element method (LSFEM). In this code, unstructured triangular grids were used to simulate MHD flows with conjugate heat transfer between the fluid and the wall. The LSFEM produces symmetric positive definite systems of algebraic equations that are solved efficiently by the preconditioned conjugate gradient method. Furthermore, the LSFEM can be applied to equations or systems of equations of any type without any special treatment. This makes it an ideal method for use in multi-disciplinary problems involving various types of physics. Results of the numerical simulations are shown (Fig. 3 and Fig. 4) that demonstrate the effect of applied external magnetic fields on an incompressible, electrically conducting, viscous, steady laminar fluid flow between two infinite parallel plates. The system of MHD equations was solved simultaneously in the fluid domain and in the solid wall where velocity was explicitly specified as zero. The effect on the conjugate heat transfer between the fluid and the solid wall are also shown demonstrating multiple flow separation regions due to MHD effects and the associated temperature field in both the fluid and the wall. In addition, the

conjugate MHD code predicted temperature and heat flux variation on the wall surface.



Fig. 3. Isotherms predicted in a conjugate solid wall/MHD flow-field.

Fig. 4. Multiple flow separation cells created by a strong external magnetic field.

3. MULTI-DISCIPLINARY DESIGN OPTIMIZATION

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. The design optimization approach is capable of achieving considerably more efficient designs than when using the best inverse design algorithms, since inverse methods utilize subjective (sub-optimal) specifications. However, design optimization is considerably more time-consuming than the inverse design, because it requires a large number of calls to the analysis algorithms and/or experimental data.

In typical transport processes, the main design objective should be minimization of entropy generation that is caused by viscous dissipation, heat transfer, internal heat sources, chemical reactions, and electro-magneto-hydrodynamic effects. This means that any reliable analysis code could be used to calculate entropy generation so that its minimization can be achieved by the proper variation of the domain and/or boundary and initial conditions.

3.1 Optimization of a Multi-Stage Axial Flow Gas Turbine

Very fast and accurate flow calculation and performance prediction of multi-stage axial flow turbines at design and off-design conditions can be performed using a compressible steady state inviscid axi-symmetric (through-flow) code with high fidelity loss and mixing models that account for turbulence, mixing, flow separation, etc. (Petrovic et al., 2000). An example of entropy minimization (efficiency maximization) optimizes hub and shroud geometry and inlet and exit flow-field for each blade row of a two-stage axial flow gas turbine. The optimization was performed using a hybrid constrained optimization code that performs automatic switching among genetic algorithm, simulated annealing, modified simplex method, sequential quadratic programming, and Davidon-Fletcher-Reeves gradient search algorithm (Dulikravich et al., 1999). The optimized shapes of hub and shroud indicate relatively minor differences as compared to the original shapes (Fig. 5a). 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. 5b).



This entire optimization process consumed less than two hours on a 500MHz processor.

3.2 Single-Objective Constrained Optimization of a Cascade of Airfoil Shapes

The shape design optimization algorithm was also applied in a redesign of an existing twodimensional cascade of turbine airfoils having supersonic exit flow (Dennis & Dulikravich, 1999). The single objective was to minimize the total pressure loss across the cascade row. A constrained micro-genetic optimizer was used for minimization of this single objective The following equality constraints were specified and iteratively enforced: function. 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 that the airfoil thickness should always be greater or equal than the specified minimum allowable thickness distribution. For enforcement of those equality constraints, like the specified airfoil cross-section area, that are inexpensive to compute a sequential quadratic programming optimizer was used. For the analysis of the performance of intermediate cascade shapes, an unstructured grid compressible Navier-Stokes flow-field analysis code with a k-E turbulence model was used. The airfoil geometry was parameterized using nine conic section parameters and eight B-spline control points, thus keeping the number of geometric design variables to a minimum while achieving a high degree of geometric flexibility and robustness.

The optimization code proved to be very robust since it found the narrow feasible domain and converged to a minimum that satisfied all the constraints within the tolerances specified (Fig. 6a). This type of shape design optimization is feasible on an inexpensive single processor workstation, it requires no changes to the existing flow-field analysis code, and can be operated even by a semi-skilled designer. The surface pressure distribution (Fig. 6b) that corresponds to the optimized airfoil cascade shape would be practically impossible to know in an *a priori* fashion even by the most experienced of the aerodynamics designers.



Fig. 6. a) Violation of constraints when using penalty function, and b) surface pressure distribution for the best airfoils of generations 1 and 11, with SQP, minimum thickness distribution constraint, and 9 conic sections with 8 B-spline geometry perturbation points.

4. ROTOR CASCADE OPTIMIZATION WITH UNSTEADY PASSING WAKES

An axial turbine rotor cascade shape optimization with unsteady passing wakes was performed to obtain an improved aerodynamic performance using an unsteady Navier-Stokes flow-field analysis code (Lee et al., 2002). 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. 7a). 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. Each individual's objective function was computed simultaneously by using a 32 processor distributed memory parallel computer. The optimization results indicate that only minor improvements are possible in the unsteady rotor/stator aerodynamics by varying these geometric parameters (Fig. 7b).



Fig. 7. Original DFVLR and optimized DFVLR (Case4) rotor linear cascade airfoil shapes (a) and time variation of lift and total pressure loss for these two cascades (b).

4.1 Multi-Objective Aerodynamic Shape Optimization

With the increased availability of inexpensive computing resources, the attention of design engineers has been rapidly shifting from the use of inverse shape design methods that require significant personal experience and intuition towards a reliable and less educationally demanding mathematically based optimization algorithms. This trend has also exposed the substantial weakness of traditional gradient-based optimization approaches that easily terminate in a local minimum, cannot efficiently produce multi-objective solutions, and require that the objective function and constraints satisfy continuity conditions. These facts, together with the growing need for the multi-disciplinary and multi-objective approach to design with a large number of design variables, resulted in an increased interest in the use of various versions of hybrid, semi-stochastic, and stochastic optimization algorithms.

In multi-objective optimization we strive to compute the group of the *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 is a modified version of the indirect method of optimization based upon self-organization (IOSO) and evolutionary simulation principles for parallel computation. 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. This approach allows for corrective updates of the approximation to make it more accurate in promising regions of the design space.

The distinctive feature of this approach is an extremely low number of trial points to build the initial approximation (30-50 points for the optimization problems with nearly 100 design variables). In the process of each iteration of IOSO, the optimization of the response function is performed only within the current search area. This step is followed by a direct call to the mathematical analysis model for the obtained point. During the IOSO operation, the information concerning the behavior of the objective function in the vicinity of the extremum is stored, and the response function is made more accurate only for this search area. Thus, during each iteration a series of approximation functions for a particular objective of optimization is built. These functions differ from each other according to both structure and definition range. The subsequent optimization of these approximation functions allows us to determine a set of vectors of optimized variables, which are used for the computation of optimization objectives on a parallel computer.

As a practical example, a constrained multi-objective shape optimization was performed on a linear cascade of gas turbine airfoils that had a finite length, thus a finite number of airfoils. The original airfoil shapes were designed at the von Karman Institute of Fluid Dynamics (VKI) using a highly sophisticated inverse shape design code. Thus, this initial airfoil cascade shape was already highly efficient. This way it is possible to observe if the multi-objective constrained optimization is capable of creating realistic results that are better than the initial finite cascade configuration. The objectives were to simultaneously minimize the total pressure loss, maximize total aerodynamic loading (aerodynamic force component that is tangent to the airfoil cascade), and minimize the number of airfoils in the finite cascade row. 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 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 analysis of the performance of intermediate airfoil cascade shapes were performed using an unstructured grid based compressible Navier-Stokes flow-field analysis code with a k- ϵ turbulence model.

It is interesting to notice that 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 are better than the inversely designed VKI airfoil cascade for all three objectives. Specifically, cascade No.1 offers reduction of 7% in total pressure loss, needs 1 airfoil less than the VKI cascade, and creates about 1% higher loading.

With such submit-and-forget automatic constrained multi-objective optimization software the role of the designer is to use a proven and robust flow-field analysis code and specify meaningful ranges of the design variables, the multiple objective functions, and the constraints. Finally, the designer ultimately must choose the best compromise solution among the optimized solutions that form the Pareto front. This multi-objective design optimization methodology can be readily applied to arbitrary three-dimensional configurations and to multidisciplinary problems.

This suggests that to make constrained optimization of a large system computationally feasible, one should make a judicious use of analysis tools of varying complexity and fidelity combined with a robust dynamically adaptive response surface formulation.



Fig. 8. Comparisons of total loading produced, total pressure loss generated, and number of airfoils for optimized finite length cascades and the original VKI airfoil cascade.

4.2 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 magnetohydrodynamics (Dennis & Dulikravich, 2001). When a viscous liquid flows from a narrow passage into a suddenly wider passage, there are significant flow separation zones that will significantly reduce the efficiency of such flow fields. One possibility to reduce and even completely eliminate 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 (Fig. 9a) 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 (Dennis & Dulikravich, 2001) that such optimized magnetic fields can be used to significantly reduce flow-field separation (Fig. 9b) and increase the static pressure rise for a fixed length of a diffuser.



Figure 9. Streamlines for diffuser flow without magnetic field (a) and with an applied magnetic field (b) optimized to suppress laminar steady incompressible flow separation.

5. OPTIMIZATION OF FREEZING 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 thus assuring that the heat transfer from the outer surface of the organ to such a medium will occur by pure conduction. A plausible 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 thermal stresses were determined at each point in the organ.

A nonlinear constrained maximization method based on a genetic algorithm (Dennis et al., 1999; Dulikravich et al., 1999) was used after a certain time interval to optimize these 26 parameters at each of the control points on the spherical container surface. Thus, such time

evolution of temperature distribution (Fig. 10a) on the container surface was determined that it maximizes the local cooling rates in the organ while keeping the local thermal stresses in the organ below user specified maximum allowable values (Fig. 10b).



Fig. 10. Temperature (a) and von Mises stresses (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.

6. SUMMARY AND RECOMMENDATIONS

Multi-disciplinary design methodologies are experiencing a general trend away from inverse design and gradient based optimization methods and towards multi-objective, multidisciplinary, semi-stochastic and stochastic constrained optimization. This trend is facilitated by the availability of inexpensive parallel computes 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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REFERENCES

- Dennis, B. H. and Dulikravich, G. S., 2001, Optimization of magneto-hydrodynamic control of diffuser flows using micro-genetic algorithm and least squares finite elements, Journal of Finite Elements in Analysis and Design, vol. 37, no. 5, pp. 349-363.
- Dennis, B. H., Dulikravich, G. S. and Han. Z.-X., 1999, Constrained optimization of turbomachinery airfoil cascade shapes using a Navier-Stokes solver and a genetic/SQP algorithm, ASME paper 99-GT-441, ASME Turbo Expo99, Indianapolis, Indiana, U.S.A., June 7-10, 1999; also in AIAA Journal of Propulsion and Power, vol., no., 2001.
- Dennis, B. H., Han, Z.-X., Egorov, I. N., Dulikravich, G. S. and Poloni, C., 2000a, Multiobjective optimization of turbomachinery cascades for minimum loss, maximum loading, and maximum gap-to-chord ratio, AIAA Multidisciplinary Analysis and Optimization Conference and Exhibit, Long Beach, CA, Sept. 5-8, 2000; also to appear in International Journal of Turbo & Jet-Engines, 2001.

- Dennis, B. H., Dulikravich, G. S. and Rabin, Y., 2000b, Optimization of organ freezing protocols with specified allowable thermal stress levels, ASME IMECE-2000, Orlando, FL, November 5-10, 2000, HTD-Vol. 368/BED-Vol. 47, pp. 33-48.
- Dennis, B.H. and Dulikravich, G.S., "Simulation of Magneto-Hydro-Dynamics with Conjugate Heat Transfer," ECCOMAS2000 (European Congress on Computational Methods in Applied Sciences and Engineering), Barcelona, Spain, September 11-14, 2000.
- Dulikravich, G. S. (editor), 1987, Proceedings of the Second International Conference on Inverse Design Concepts and Optimization in Engineering Sciences (ICIDES-II), The Pennsylvania State University, University Park, PA, October 26-28, 1987.
- Dulikravich, G. S. (editor), 1991, Proceedings of the Third International Conference on Inverse Design Concepts and Optimization in Engineering Sciences (ICIDES-III), Washington, D.C., October 23-25, 1991; also NASA CR-188125, January 1992.
- Dulikravich, G. S., Nov./Dec. 1992, Aerodynamic shape design and optimization: status and trends, AIAA Journal of Aircraft, vol. 29, no. 5, pp. 1020-1026.
- Dulikravich, G. S., January 1995, Shape inverse design and optimization for three-dimensional aerodynamics, AIAA invited paper 95-0695, AIAA Aerospace Sciences Meeting, Reno, NV.
- Dulikravich, G. S., 1997, Design and optimization tools development, Chapters no. 10-15 in New Design Concepts for High Speed Air Transport, (ed: H. Sobieczky), Springer, Wien/New York, pp. 159-236.
- Dulikravich, G. S. and Martin, T. J., Nov. 1996, Inverse shape and boundary condition problems and optimization in heat conduction, Chapter no. 10 in Advances in Numerical Heat Transfer - Volume I (eds: W. J. Minkowycz and E. M. Sparrow), Taylor and Francis, pp. 381-426.
- Dulikravich, G. S., Martin, T. J., Dennis, B. H. and Foster, N. F., 1999, Multidisciplinary hybrid constrained GA optimization, Chapter 12 in EUROGEN'99 - Evolutionary Algorithms in Engineering and Computer Science: Recent Advances and Industrial Applications, (eds: K. Miettinen, M.M. Makela, P. Neittaanmaki and J. Periaux), John Wiley & Sons, Ltd., Jyvaskyla, Finland, May 30 - June 3, 1999, pp. 231-260.
- Egorov, I. N., 1998, Indirect optimization method on the basis of self-organization, Curtin University of Technology, Perth, Australia, Optimization Techniques and Applications (ICOTA'98), vol.2, pp. 683-691.
- Fujii, K. and Dulikravich, G. S. (eds), April 1999, Recent development of aerodynamic design methodologies - inverse design and optimization, Vieweg Series on Notes on Numerical Fluid Mechanics, Vol. 68, Springer.
- Han, Z.-X., Dennis, B. H. and Dulikravich, G. S., 2000, Simultaneous prediction of external flow-fields and temperature in internally cooled 3-d turbine blade material, International Journal of Turbo & Jet-Engines, 2000, vol. 17, pp. 267-278.
- Lee, E.-S., Dulikravich, G. S. and Dennis, B. H., 2002, Rotor cascade shape optimization with unsteady passing wakes using implicit dual time stepping and genetic algorithm, Proceedings of the 9th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC-9), Honolulu, HI, February 10-14, 2002.
- Martin, T. J., Dulikravich, G. S., Han, Z.-X. and Dennis, B. H., 1999, Minimization of coolant mass flow rate in internally cooled gas turbine blades, ASME paper 99-GT-146, ASME Turbo Expo, Indianapolis, IN, June 7-10, 1999.
- Martin, T. J. and Dulikravich, G. S., 2001, Aero-thermo-elastic concurrent design optimization of internally cooled turbine blades, Chapter 5 in Coupled Field Problems, Series on Advances in Boundary Elements (eds: Kassab, A. J. and Aliabadi, M. H.), WIT

Press, Boston, MA, pp. 137-184.

Petrovic, M. V., Dulikravich, G. S. and Martin, T. J., 1999, Maximizing multistage turbine efficiency by optimizing hub and shroud shapes and inlet and exit conditions of each blade row, International Journal of Turbo & Jet-Engines, 2000, vol. 17, pp. 267-278.