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Multidisciplinary Inverse Design and Optimization of Turbine Blades

George S. Dulikravich
The Pennsylvania State University

Abstract: This proposed three-year research project will deliver a multidisciplinary design optimization package that will provide the designer with a tested and portable tool to guide the development of innovative designs of internally cooled, thermally coated or non-coated gas turbine blades that will cost less to manufacture, have a longer life span, be easier to repair, and sustain higher turbine inlet temperatures without contributing to air pollution.

Background: Increased thermodynamic efficiency in gas turbines can be achieved by allowing higher temperature combustion gases to enter the blade row. This process, however, is limited by the material properties of the blade. A typical remedy is to cool the blade by pumping a cooling fluid through passages manufactured inside the blade and by ejecting the coolant through a large number of very small holes on the surface of the blade. This method of blade cooling known as film cooling, significantly increases blade manufacturing costs, makes blades difficult to repair, interferes with the aerodynamic performance of the blade, and enhances the generation of air pollutants at higher gas temperatures. Consequently, optimized designs of internally cooled blades without film cooling are becoming interesting because of their lower cost and easier maintainability.

Objectives: We propose to develop, implement, and verify a multi-disciplinary combined inverse design/constrained optimization algorithm that will maximize 3-D cooled turbine blade efficiency while simultaneously accounting for external aerodynamics, conjugate heat transfer, and elasticity issues.

Approach: This research project focuses on providing an advanced integrated method of coupling aerodynamic, thermal and structural design of internally cooled gas turbine blades. It utilizes various inverse design concepts and constrained hybrid optimization algorithms implemented on distributed parallel and massively parallel computing facilities. The optimization of the 3-D cooled turbine blades will be accomplished through the use of a hybrid optimizer combined with a thermal field inverse boundary element code, thermo-elasticity finite element analysis and inverse design code, viscous compressible hot gas flow analysis and inverse design finite volume code, viscous incompressible coolant flow finite volume analysis and inverse design codes, and a hybrid constrained optimization code that incorporates a quasi-Newtonian gradient search, a genetic algorithm, Nelder-Mead simplex method, simulated annealing, and random searches guided by probability density distribution about feasible designs [1].

Heat Transfer: We have developed and thoroughly tested a new non-iterative fast 3-D boundary element inverse boundary condition code capable of determining temperatures and heat fluxes on the surfaces of 3-D multidomain objects where such boundary conditions are unknown [2].

Thermo-Elasticity: Our finite element code solves the unsteady and steady Navier equations of 3-D elasticity and Poisson equation of 3-D heat conduction using nonisoparametric quadratic tetrahedrons. All integrals are evaluated analytically. Temperatures, heat fluxes, and convective heat transfer can be specified on the boundaries of the domain. The code has support for discrete and distributed tractions (Fig. 1 and Fig. 2) and several types of body forces including gravitational, centrifugal, and thermal loads. Damping is provided through a structural damping matrix and thermal stresses are calculated using temperatures determined by the heat transfer section of the code. The code is written in C++ and utilizes an efficient sparse matrix data structure and preconditioned iterative solvers allowing for the solution of large problems on inexpensive workstations. A separate non-iterative boundary element elastostatic code was developed for inverse determination of unknown boundary deformations and loads [3].

Aerodynamics: A robust, constrained and fully automated design system has been developed for the aerodynamic shape optimization of turbomachinery cascade airfoils (Figs. 3-5). This design system has been incorporated into the existing design system at Pratt & Whitney Company to provide for faster optimization convergence histories [4].

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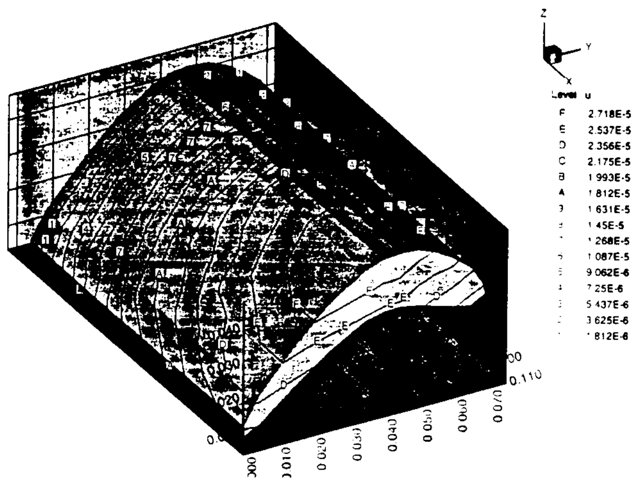
Fig. 1 Computed Axial Displacements in meters

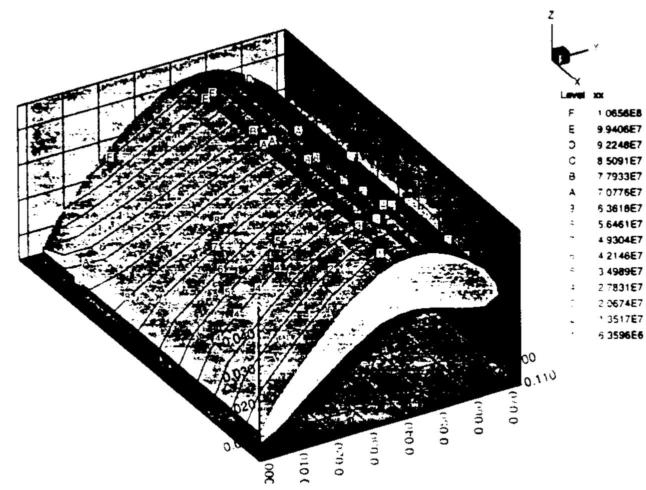
Fig. 2 Computed Axial Stresses in Pascals

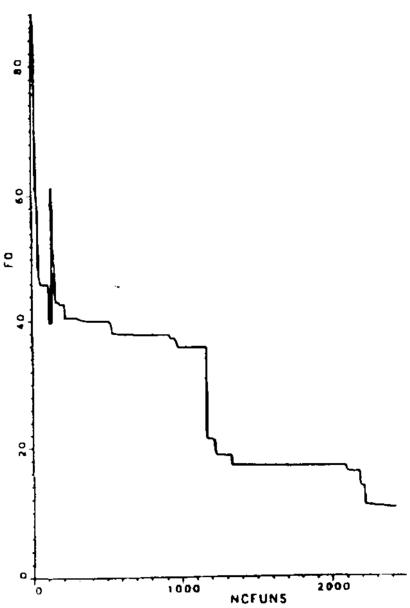

Fig. 3 Convergence History (Aerodynamic Optimization)

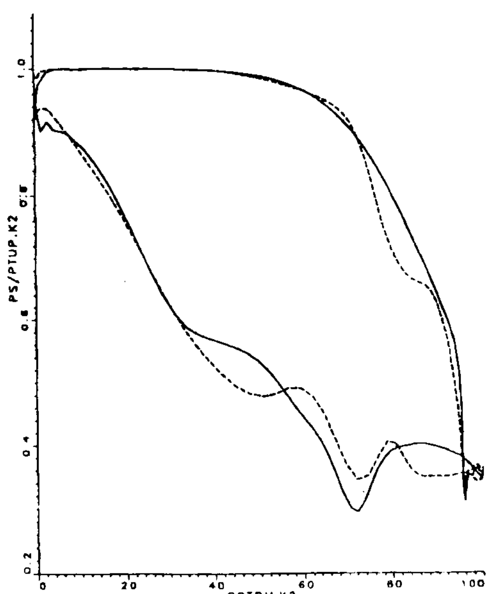

Fig. 4 Navier-Stokes Results: Initial (dashed line) and Optimized (full line) Pressures

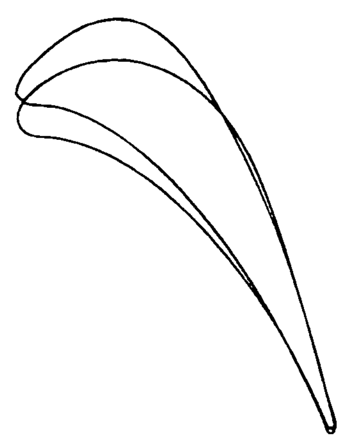
Fig. 5 Blade Airfoil Shapes: (a) Initial and (b) Optimized