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PARALLEL THERMOELASTICITY OPTIMIZATION OF 3-D SERPENTINE COOLING PASSAGES IN TURBINE BLADES

ABSTRACT

An automatic design algorithm for parametric shape optimization of three-dimensional cooling passages inside axial gas turbine blades has been developed. Smooth serpentine passage configurations were considered. The geometry of the blade and the internal serpentine cooling passages were parameterized using surface patch analytic formulation, which provides very high degree of flexibility, second order smoothness and a minimum number of parameters. The design variable set defines the geometry of the turbine blade coolant passage including blade wall thickness distribution and blade internal strut configurations. A parallel three-dimensional thermoelasticity finite element analysis (FEA) code from the ADVENTURE project at the University of Tokyo was used to perform automatic thermal and stress analysis of different blade configurations. The same code can also analyze nonlinear (large/plastic deformation) thermoelasticity problems for complex 3-D configurations. Convective boundary conditions were used for the heat conduction analysis to approximate the presence of internal and external fluid flow.

The objective of the optimization was to make stresses throughout the blade as uniform as possible. Constraints were that the maximum temperature and stress at any point in the blade were less than the maximum allowable values. A robust semi-stochastic constrained optimizer and a parallel genetic algorithm were used to solve this problem while running on an inexpensive distributed memory parallel computer.

INTRODUCTION

With the continuing growth of computing resources available, the attention of design engineers has been rapidly shifting from the use of repetitive computational analysis, personal experience, and intuition towards a reliable and economical mathematically based optimization algorithms. Such algorithms have the potential to produce improved designs over a shorter period of time. In this prospect, the application of optimization to the design of passages for internally cooled 3-D realistic turbine blades is presented.

Internal cooling schemes of modern turbojet and turbofan engines bleed air from the compressor and pass this air into the serpentine coolant flow passages within the turbine blades. The maximum temperature within a turbine blade must be kept below a certain value in order to maintain blade life limited by creep, oxidation, corrosion, and fatigue. To achieve turbine blade durability requirements, section-averaged centrifugal stress limitations should be satisfied, concentrations of thermal stress should be limited in the cold areas to reduce low cycle fatigue, principal strains should be held below a given level in hot areas to reduce thermo-mechanical fatigue, and the maximum temperature in the blade metal and coating material must be below specified limits because of oxidation, corrosion and coating spallation concerns. These objectives can be obtained by the constrained optimization of the coolant passage shapes inside the turbine blade at a fixed level of coolant flow rate.

There is a strong interaction among a number of engineering disciplines when studying the design internally cooled gas turbine blades. The temperature and the associating stresses within the blade material are considered in detail. However, the effects of the hot gas flow and coolant flow will be treated in very approximate way. In the design process explained in this prospect, these individual disciplines will not be solved simultaneously in detail for 3-D designs, because this approach would take an unacceptably long time, even on a cluster of workstations running in parallel. For these pragmatic reasons a more approximate yet computationally affordable design approach was adopted.

In order to complete the design process in a reasonable amount of time, a parallel computer should be employed. Both the finite element analysis and the optimization codes used here were written to make full use of parallel computing resources.

OPTIMIZATION METHOD

In our experience, genetic algorithm (GA) variations and response surface methods based on Indirect Optimization based on Self Organization (IOSO) work well for 3-D turbine coolant passage design optimization.

DESIGN ANALYSIS

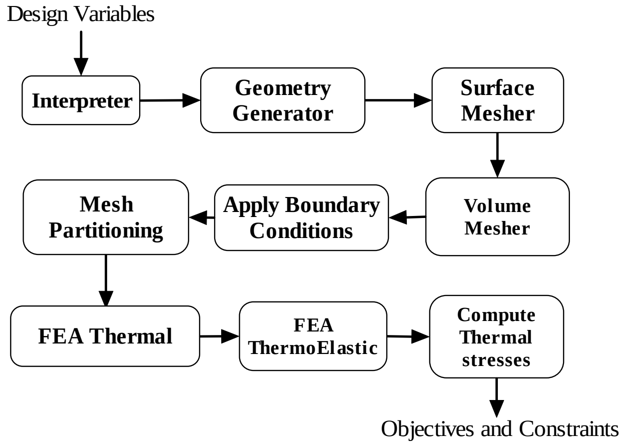
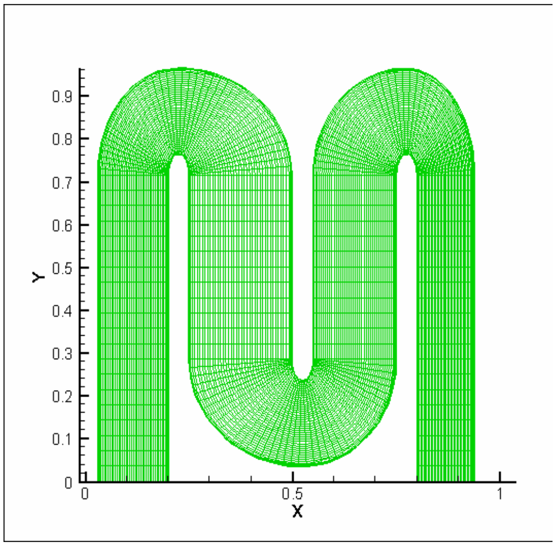


Figure 1: Modules used for automatic parallel FEA

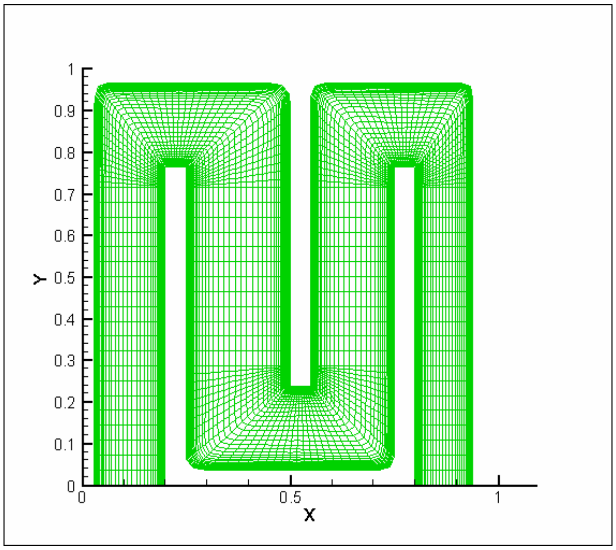
For each design, a series of modules is required to turn a given set of design variables into optimization objective and constraint function values. The flow of data between these modules is depicted graphically in Figure 1. The analysis process may need to be performed hundreds or thousands of times for a single optimization run so it is critical that each module be automatic, robust, and computationally efficient.

DESIGN PARAMETERIZATION

The outer blade shape was considered to be fixed and to be provided by the user at the beginning of the design optimization. The shapes of the internal coolant passages were parameterized using analytical shape functions.



R_{f1} =0.95, R_{f2}=0.95



R_{f1} =0.15, R_{f2}=0.15

Figure 2: Example passage shapes for variation parameters R_{f1} and R_{f2}

The shape parameterization code generates a block-structured grid that describes the shape of the blade (Figure 2).

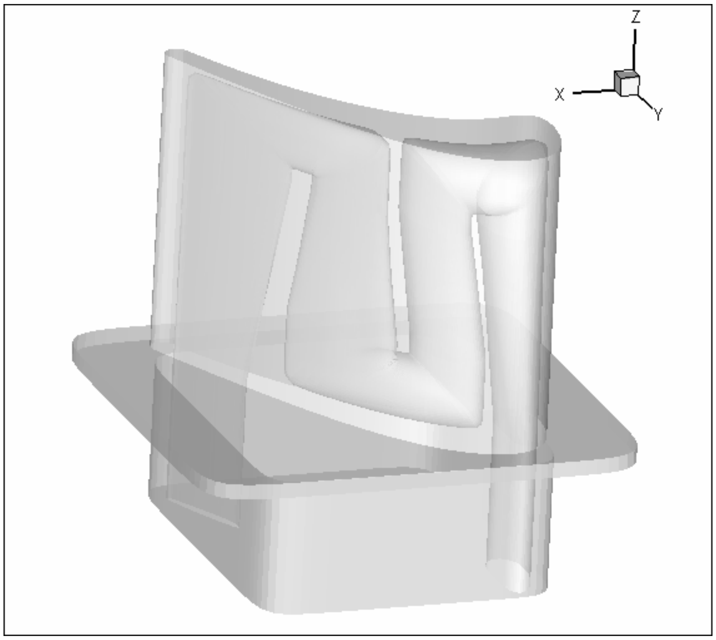


Figure 3: Internally cooled blade example.

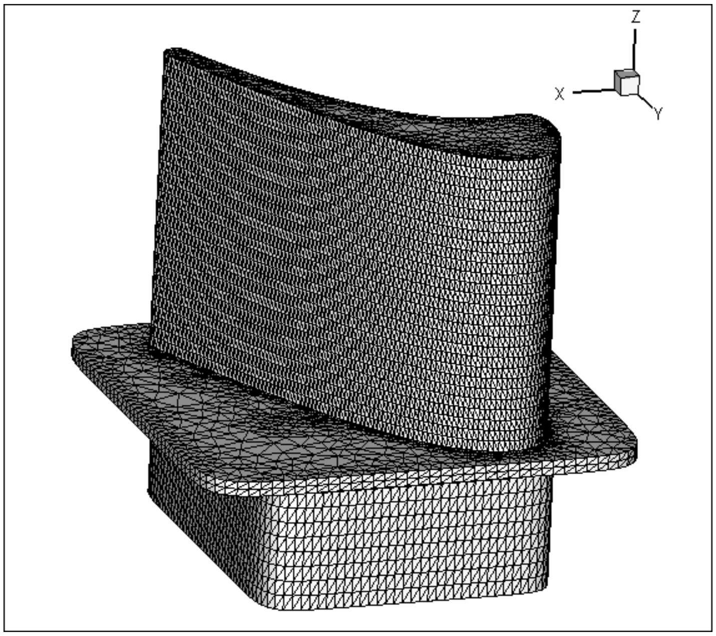


Figure 4: Triangular surface mesh for blade example.

An inner shroud and blade root geometry are generated separately and added to the base of the blade section. The block-structured grids for blade, shroud, and root are then used as the base geometry for generating a triangular surface grid. Sample geometry and the generated surface mesh are shown in Figures 3-4. The triangular surface mesh is then used as input to a tetrahedral mesh generation program.

DESIGN OPTIMIZATION EXAMPLE

Both PGA (Genetic Algorithm) and IOSO optimization methods were tested with this problem. A total of 12 analyses were performed per iteration for IOSO method. For PGA, 36 designs were evaluated per generation. For both cases each parallel thermoelastic FEM analysis used 4 processors. A typical analysis mesh contained over 150,000 degrees of freedom and required 4 minutes to complete a full thermoelasticity analysis. **A converged result was found by the IOSO optimizer in 70 iterations after consuming approximately 12 hours of total computer time. For PGA, the total computer time was more than 30 hours. The PGA run was terminated before a converged result was found.** The convergence history for the objective function for both PGA and IOSO is shown in Figure 5. The convergence history for the temperature constraint function is shown in Figure 6. **This figure shows that feasible region was found at iteration 12 for IOSO and iteration 68 for PGA. These convergence results clearly show the computational efficiency of the IOSO approach over the PGA method for this design problem.**

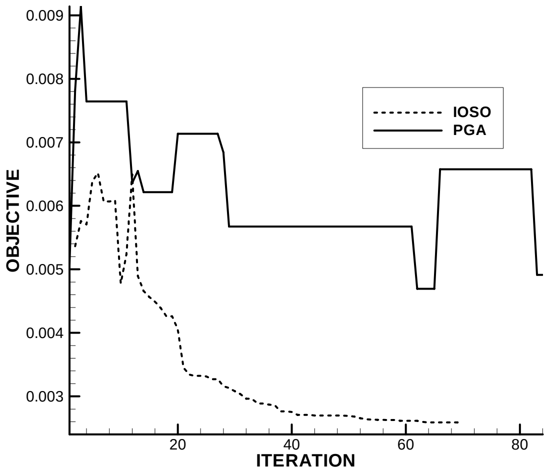


Figure 5: Objective function convergence history.

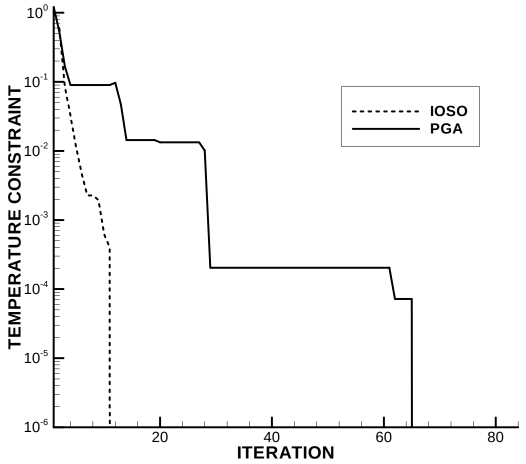


Figure 6: Temperature constraint function.

The initial and the IOSO optimized passages configurations are shown in Figures 7 and 8. Principal stresses on the surface of the blade with the initial shape of the coolant passage is shown in Figure 9, while the IOSO optimized coolant passage offers lower and more uniform stress field (Figure 10).

Temperature distributions for the initial design and the IOSO optimized design are shown in Figures 11-12. The temperature patterns on the surface of the blade follow the shapes of the passage inside the blade. This shows that the passage shape will have a strong impact on the temperature distribution and hence the thermally induced stresses. The temperature distribution on the surface of the IOSO optimized blade is considerably lower and smoother compared with that of the initial design.

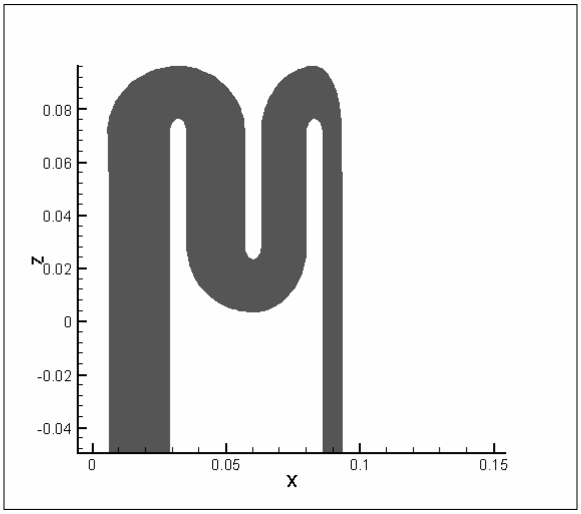


Figure 7: Passage shape in *x-z* plane for initial design.

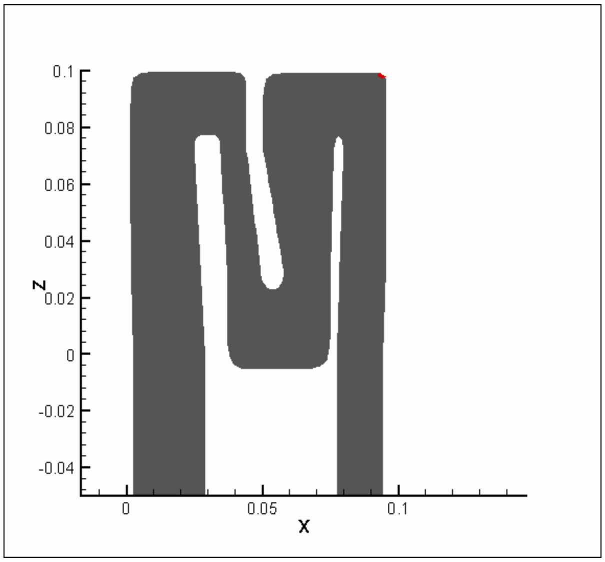


Figure 8: Passage shape in *x-z* plane for IOSO optimized design.

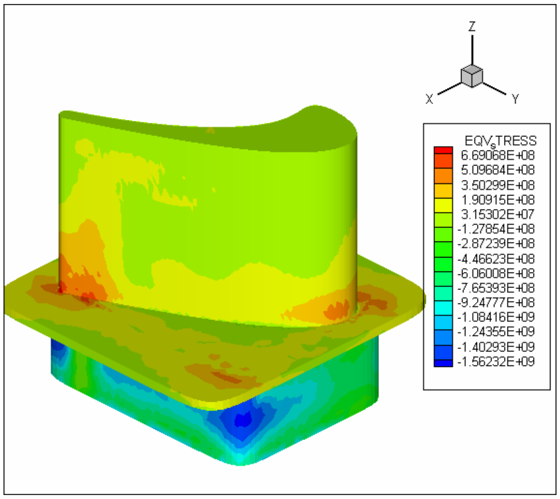


Figure 9: Principal stress contours for initial design.

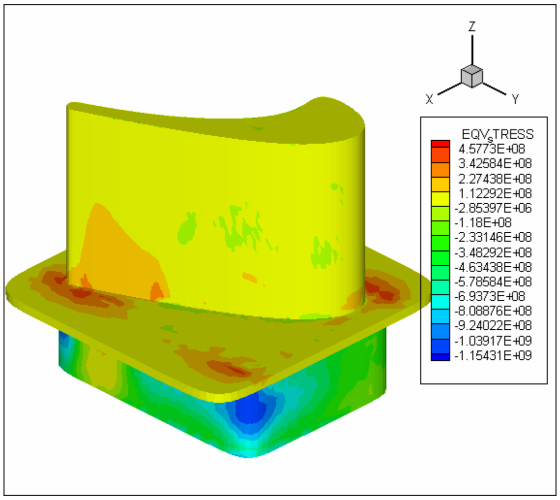


Figure 10: Principal stress contours for IOSO optimized design.

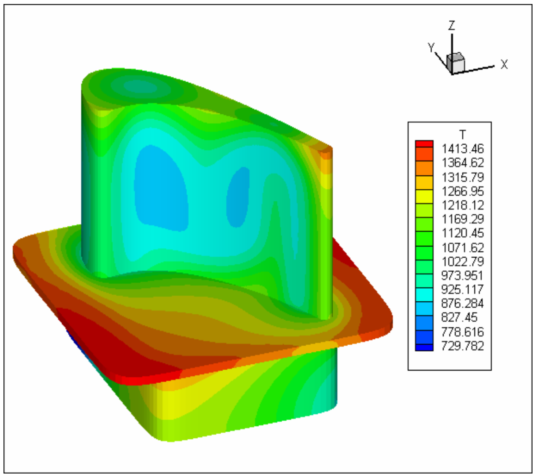


Figure 11: Temperature contours for initial design on pressure side.

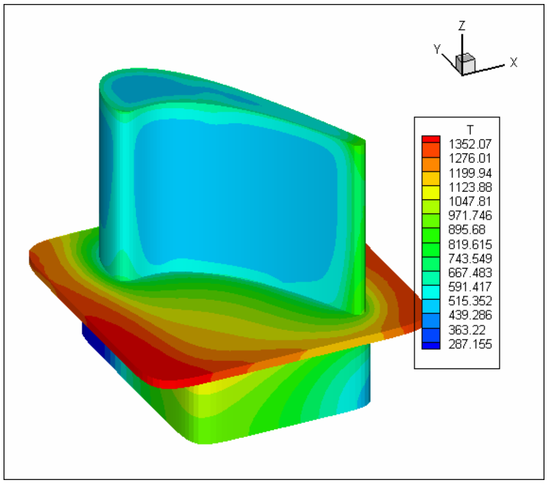


Figure 12: Temperature contours on pressure side for IOSO optimized design.

Table 1 gives a quantitative comparison between the initial and optimized passage designs. The initial design exceeds the maximum allowable temperature while satisfying the stress constraint. However, the optimized blade is clearly feasible with respect to the temperature and stress constraints.

Table 1: Comparison of initial and optimized cooling passage design

Quantity	Initial	Optimized
Maximum Temperature, T_{max}	1333.8 ^{o}C	894.6 ^{o}C
Volume	9.64×10^{-4} m^3	8.46×10^{-4} m^3
Maximum Principal Stress, σ_{max}	668.9 MPa	425.1 MPa
Coolant bulk temperature, T_C	600.0 ^{o}C	158.0 ^{o}C
Objective function value, F	6.80×10^{-3} Pa	2.59×10^{-3} Pa

CONCLUSIONS

A software system for the design of turbine blade coolant passages has been developed using powerful optimization algorithms and efficient parallel finite element analysis codes. The automatic parametric shape design of an internal serpentine coolant passage was demonstrated. **A performance comparison was made between PGA and IOSO optimization methods. For this design problem, the IOSO approach was found to be more efficient by finding better designs with fewer function evaluations.**