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OPTIMIZATION OF A LARGE NUMBER OF COOLANT PASSAGES LOCATED CLOSE TO THE SURFACE OF A TURBINE BLADE

ABSTRACT

A constrained optimization of locations and discrete radii of a large number of small circular cross-section straight-through coolant flow passages in internally cooled gas turbine vane was developed. The objective of the optimization was minimization of the integrated surface heat flux penetrating the airfoil thus indirectly minimizing the amount of coolant needed for the removal of this heat. Constraints were that the maximum temperature of any point in the vane is less than the maximum specified value and that the distances between any two holes or between any hole and the airfoil surface are greater than the minimum specified value. A configuration with maximum of 30 passages was considered. The presence of external hot gas and internal coolant was approximated by using convection boundary conditions for the heat conduction analysis. A parallel three-dimensional thermoelasticity finite element analysis (FEA) code from the ADVENTURE project at University of Tokyo was used to perform automatic thermal analysis of different vane configurations. In our experience, parallel genetic algorithm (PGA) 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

The thermal analysis was performed by parallel finite element analysis. The finite element analysis codes and tools for mesh generation, mesh partitioning, and others (Fig. 1) are freely available as a part of the ADVENTURE project lead by the University of Tokyo. The finite element solvers are geared towards large-scale parallel analysis and are well suited to the efficient analysis of complicated geometries.

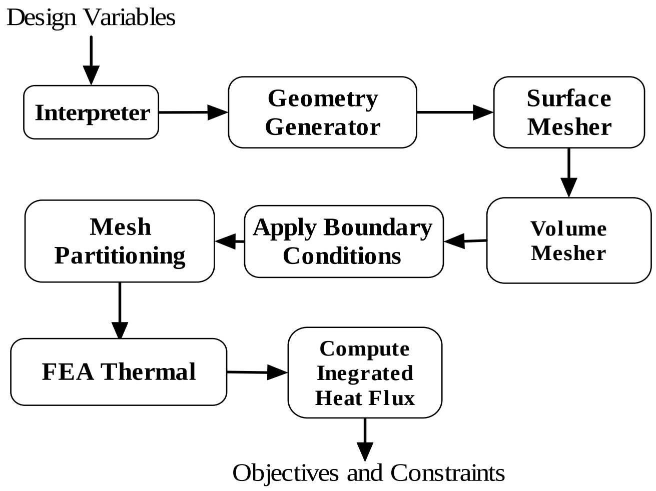

Figure 1: Modules used for automatic parallel FEA.

For each design, a series of modules is required to turn given set of design variables into an object and constraint function values. 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.

OBJECTIVE AND CONSTRAINTS

The objective is to minimize the total amount of heat transferred to the vane (integrated heat flux on the hot surface of the vane) while maintaining a maximum temperature, T_{max}, which is lower than the maximum allowable temperature, T_{allow}. This objective indirectly minimizes the amount of coolant required to cool the vane. The minimization of this objective could result in the reduction of the number of cooling passages as well.

DESIGN PARAMETERIZATION

The outer vane shape is considered to be fixed and to be provided by the user at the beginning of the design optimization. Presumably, this is the vane shape that has already been optimized for its aerodynamic performance. The design variables include the radius of each circular passage, r_i, and position of the passage center, $<x_i,y_i>$, in the vane cross-section. The passage center is allowed to move normal to the outer contour within a specific region as shown in Figure 2. The design variable x_i is a distance in the direction normal to the vane surface and is non-dimensionalized so that it always lies between the two dashed lines shown in Figure 3. The variable y_i is a non-dimensional distance in a surface following coordinate direction that is taken along the outer surface of the vane. The variable y_i is measured from the leading edge in the clockwise direction. **For 30 passages, this parameterization leads to a total 90 variables.**

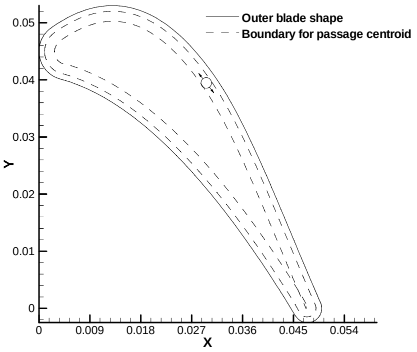

Figure 2. Region where coolant passage centers are allowed.

A triangular surface mesh and a tetrahedral volume mesh were generated automatically for each candidate design. The mesh generator did an adequate job of placing enough points between the passages and the vane surface, even when the passages were very close to the surface. Example meshes are shown in Figures 3 and 4. A typical mesh had around 80,000 nodes.

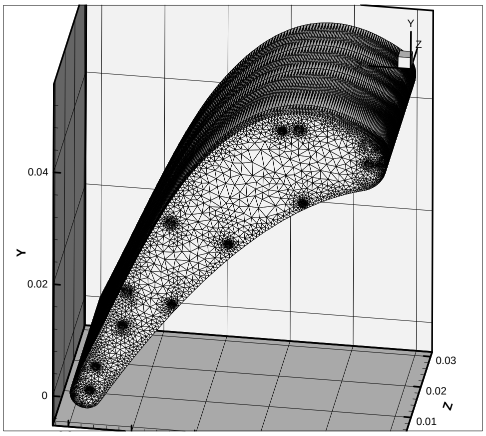

Figure 3: View of a surface mesh.

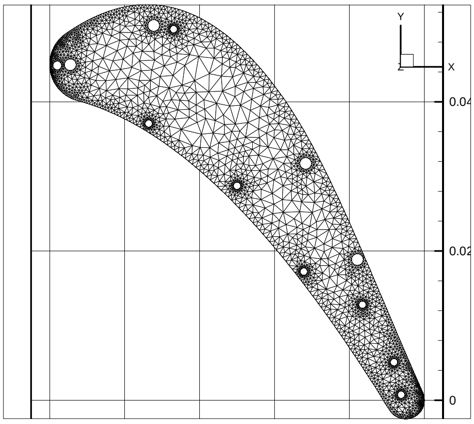

Figure 4: View of mesh on a vane cross-section.

DESIGN OPTIMIZATION EXAMPLE

An example design optimization was performed. The maximum number of coolant passages was set to 30. **The total number of design variables was 90.** This problem was solved using both PGA and IOSO algorithms. For both PGA and IOSO method, 40 simultaneous analyses were run per iteration. Each finite element heat conduction analysis used 2 processors. The same initial design was given to both optimizers at the start of each run. The following PGA parameters were used: 5.0 percent mutation rate, 50.0 percent chance of uniform crossover, 7 bit binary encoding for y_i and 5 bit encoding for x_i, r_i.

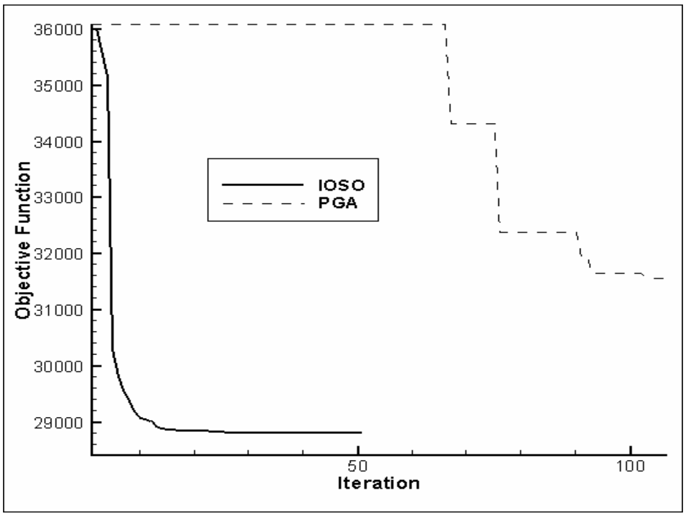

Figure 4: Objective function convergence history.

The convergence history in Figure 4 shows that for this example the IOSO method outperforms the PGA method. Both IOSO and PGA methods reduced the total heat flux from the initial design as shown in Table 1. The passage size and position for the IOSO result is more uniform than the PGA result.

The outer surface temperature on the optimized design is much closer to T_{allow} than in the initial design as shown in Figure 5.

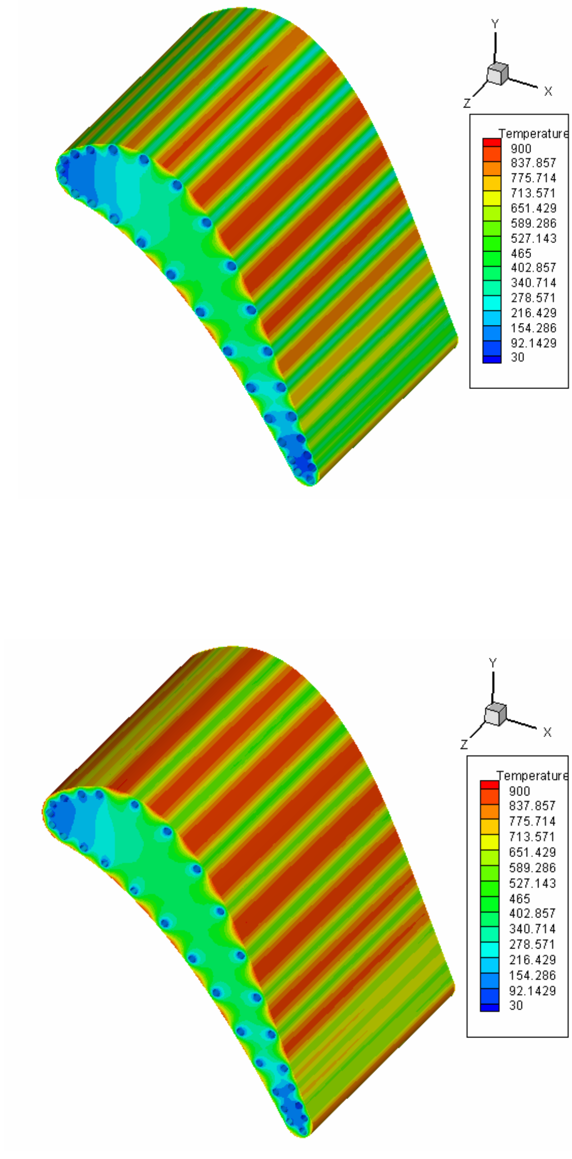

Figure 5: Temperature distribution on suction side for initial design (top) and IOSO optimized best design (bottom).

Table 1: Optimization results.

Result	Initial guess	PGA best design	IOSO best design
nholes	30	30	30
T_{max}	892.6 ^{o}C	899.1 ^{o}C	902.3 ^{o}C
F	36099.8 W	31563.0 W	28808.2 W

CONCLUSIONS

A software system for the design of turbine vane coolant passages has been developed using powerful optimization algorithms and efficient parallel finite element thermal field analysis code. The automatic parametric shape design of many internal coolant passages was demonstrated. A typical design optimization can be completed within a few hours using an inexpensive cluster of personal computers. The IOSO optimization method was found to produce better results with fewer iterations than the PGA method. The IOSO method is also more robust and easier to use since it requires fewer tuning parameters than the PGA method.