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MULTIDISCIPLINARY AERO-MECHANICAL DESIGN OPTIMIZATION OF TURBINE BLADING

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ABSTRACT

The turbine airfoil design process is very complex and time-consuming, and it requires skilled aero/thermo designers to achieve the optimum balance between efficiency requirements, mechanical reliability, and manufacturing cost. This paper describes the use of an integrated, multidisciplinary, multi-objective optimization system for the aerodynamic and mechanical design of turbine blades. Process integration and design optimization software is used to link together commercially available simulation codes to automate airfoil shape generation, CFD analysis, stress and vibration analysis, and post-processing of results. Expert design rules and constraints are captured in the system, and various optimization strategies are employed to automatically search the design space to find optimal designs that meet goals for performance and stresses. The system produces substantial reductions in design cycle time, and it can be used to assess the trade-offs between multiple objectives.

INTRODUCTION

To remain competitive in the global power generation marketplace, turbine manufacturers must continually strive to develop highly efficient, reliable, and cost-effective machines in the shortest possible time. To meet these objectives, engineers face an inherently multidisciplinary optimization problem with many conflicting design objectives and constraints. Because traditional manual trial-and-error turbine design processes are no longer adequate to meet this challenge, many turbomachinery companies are working to automate their simulation-based design processes and use numerical optimization methods to develop better designs much faster than is possible with manual methods.

A key focus of these efforts is in blade design, because the blading is often the critical path item in a new design, and it has the greatest impact on overall machine efficiency and reliability. In the early 1990s, a number of turbomachinery companies began to automate their simulation-based blade design processes and apply numerical optimization methods to improve performance and reliability while at the same time reducing design cycle time and cost. Early examples that addressed the aerodynamic design process are presented in references 1-4.

Over the past five years, designers have expanded these systems to include mechanical design aspects to enable true multidisciplinary design optimization, or MDO (5-7). Recent efforts have focused on achieving robust designs (8), or designs that are insensitive to uncertainties and variability in such things as manufacturing tolerances, material properties, and loading conditions, and on tracking multiple objectives independently to better understand the tradeoffs and ensure that the best design decisions are made (9).

AUTOMATED BLADE DESIGN PROCESS

Most turbomachinery companies use a combination of in-house and commercial design and analysis codes, but it is becoming increasing difficult to maintain in-house codes, many of which are decades old. However, it is now possible to build a complete turbine airfoil design system using only commercial CFD and FEA codes integrated with commercial process integration and design optimization (PIDO) software. By using an automated design system that includes only commercial codes, which can be highly calibrated to historical design experience, engineers can focus on their key mission – designing better machines – and not have to worry about legacy code maintenance or the details of the data transfer between codes.

This paper describes an integrated, multidisciplinary, multi-objective optimization system for the aerodynamic and mechanical design of turbine blades, constructed entirely of commercial codes. The codes used are:

- **iSIGHT-FD** from Engineous Software Inc., a flexible framework for process integration, automation, and multidisciplinary, multi-objective optimization.
- **eBlade** from Engineous Software, a blade design environment that integrates tools for parametric airfoil shape generation, blade stacking, 3D viewing, and postprocessing in a common graphical user interface. It can be operated in manual mode or driven by the optimization algorithms in iSIGHT-FD.
- **MISES** from Analytical Methods Inc., 2D mesh generation and cascade flow analysis.
- **G/Turbo®** and **Fluent®** from Fluent Inc., or **FINE™/Turbo** from Numeca International s.a., 3D CFD mesh generation and analysis.
- Specialized finite element modeling mesh generation, and FEA postprocessing tools for turbine blading, available from several vendors.
- **MSC.NASTRAN™** from MSC.Software or **ANSYS™** from ANSYS Inc., finite element analysis.

The airfoil MDO process captured and automated in iSIGHT-FD is shown in Figure 1. This entire process is driven by optimization drivers to achieve specified design goals for aerodynamic performance, stress, and vibration. It is fairly representative of the MDO processes currently used for blade design by many steam and gas turbine manufacturers. The blade design tasks are:

1. Data defining the radial distribution of inlet and exit flow angles and thermodynamic operating conditions are extracted from the output file of a quasi-3D throughflow analysis at radial heights specified by the designer (i.e. for the "design sections"). Data defining the radial distribution of section properties such as axial chord, cross-section area, and moments of inertia are extracted from an external text file so that first-order mechanical requirements can be met.
2. An initial value for the optimum number of blades is calculated based on the Zweifel solidity criterion (10). The resulting blade throat is fixed during the optimization process.
3. eBlade is used to generate airfoil shapes for each design section using a variety of built-in parametric representations. For the example in this paper, typical high-turning steam turbine airfoil shapes are generated using the well-known Pritchard parametric model (11) modified to allow the optimizer more flexibility to fine tune the shape. The engineer can use the eBlade GUI in manual mode to load an existing blade to use as a starting point, to set constraints on the ranges of design variables, and to configure plots that are shown and updated during the optimization process.
4. Airfoil section properties are calculated to check if they meet the requirements defined in Task 1 within a specified tolerance.
5. If the requirements are not met, a new airfoil shape is chosen. If they are met, the process proceeds to Task 6.
6. The blade passage defined by the airfoil geometry generated in Task 3 is meshed and a 2D channel flow analysis is performed using the MISES code.
7. If the optimizer has achieved an optimum aerodynamic design for a given section, Tasks 3 through 7 are repeated for additional design sections. If not, the process returns to Task 3

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and a new shape is generated. The optimization objective is to maximize profile efficiency while meeting aerodynamic and mechanical design rules and constraints. Constraints are placed on geometric parameters such as stagger angle, maximum thickness, leading and trailing edge thicknesses, wedge angles, and unguided turning angle, as well as on aerodynamic output quantities such as incidence angle, the shape of the surface Mach number distributions on pressure and suction sides, and the amount of diffusion past the throat.

8. Once all of the individual design sections have been optimized, they are stacked relative to one another to create a 3D shape using utilities in eBlade. An optimizer-driven smoothing process is invoked to make small adjustments to the profile shapes to eliminate ripples in the 3D surface.
9. If desired, a full 3D Navier-Stokes solution can be performed to check the final 3D stackup using the G/Turbo mesher and the Fluent solver or the FINE/Turbo suite of codes.
10. If all aerodynamic and first-order mechanical requirements have been met, the process proceeds to Task 11 for a more detailed mechanical analysis. If they are not, the process returns to Task 3 and a new stackup is generated.
11. Geometries for the shroud, platform, fillets, and dovetail or fastener are parametrically generated and attached to the main airfoil shape generated by eBlade to create a model of the complete blade. Aerodynamic loads and boundary conditions for the FEA analysis are captured from the CFD results, and material properties are selected.
12. A structured mesh is generated and a NASTRAN or ANSYS input file is created. A typical blade model and mesh is shown in Figure 2.
13. The FEA solver is run to perform a detailed structural analysis.
14. The blade postprocessing tool reads the FEA code output files and generates a Goodman diagram to assess cyclic stresses, and a Campbell diagram to assess blade vibration.
15. iSIGHT-FD assesses output data to determine if detailed stress and vibration requirements have been met. Many specific requirements can be included, such as bending stresses, centrifugal stresses, vibratory stresses (axial, tangential, torsional), thermal stresses, response to stimulus (nozzle passing frequency, low per rev), damping (shrouds, lacing/tie wires, mid-span snubbers), and high and low cycle fatigue.
16. If all requirements are met, the design is completed. If not, the process returns to Task 2 for further iterations.

DESIGN EXAMPLE

To be shown in presentation.

CONCLUSIONS

Automated blade design processes such as the one described here give designers the flexibility to approach the design problem from many angles. During preliminary design, the engineer can use Design of Experiments techniques with lower fidelity codes to identify the critical design parameters that have the most impact on meeting the objectives, so that the optimizer does not waste its time when using the higher fidelity CFD and FEA codes. Approximation models can be invoked to reduce the number of runs of the high fidelity codes. Multi-objective optimization algorithms can be used in conjunction with sophisticated postprocessing tools to allow the engineer to thoroughly understand the design space and assess the tradeoffs between often conflicting objectives. This will help to ensure that the best design decisions are made to meet customer requirements for performance, cost, and reliability.

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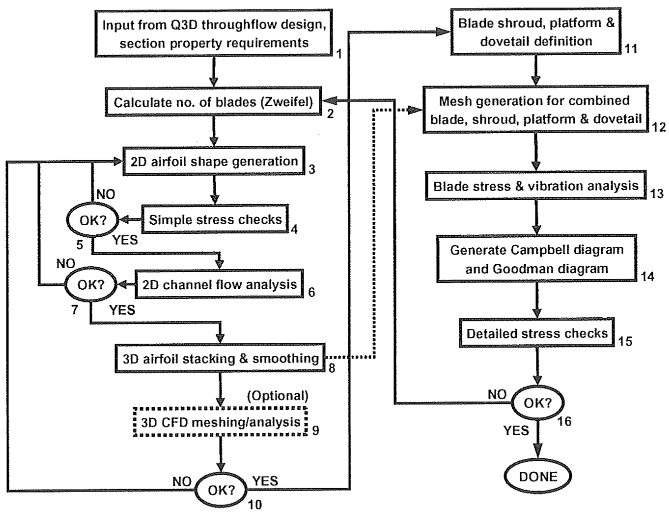

Figure 1. Turbine airfoil MDO process

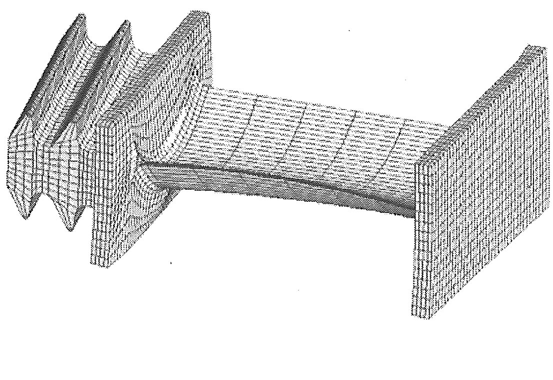

Figure 2. Finite element model of complete blade