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PARAMETERIZED GEOMETRY FORMULATION FOR INVERSE DESIGN AND OPTIMIZATION

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ABSTRACT

This contribution focuses on the importance of preprocessing tools for successful design and optimization in practice of turbomachinery engineering. The development of problem-oriented computational geometry generation software is illustrated for the example of aerodynamic inverse design of transonic flow elements which define the compatible boundary conditions (surfaces) in detail. Resulting from learned sensitivity of high speed flows to small changes in airplane wing or turbomachinery blade geometry, preprocessing software is provided to create parametric shapes to be varied for optimization cycles or numerical simulation of mechanical adaptation processes. Supporting the need to design from a multidisciplinary viewpoint, parameterized geometry components for aerodynamic, as well as for thermal and structural considerations are defined. Examples for turbomachinery blade design and optimization are given.

INTRODUCTION

In the past years with rapid expansion of computer speed and storage, and improvements in algorithm speed and accuracy, optimization strategies have become affordable and reliable. Computational analysis and simulation of physical phenomena therefore become valuable design tools to improve technological performance of a product component. Here we focus on the complex technology of coupling the aerodynamics, structural and thermal loading as occurring in turbomachinery component design. In this situation we need realistic and flexible surface modelling to provide boundary conditions produced systematically and in rapid succession, with variations controlled by suitable and efficient sets of parameters.

High speed aircraft design is posing similar coupled problems, as outlined in [1]. Here we use some of the chapters in this book to be adapted and further developed for turbomachinery problems, like aerodynamic blade design with thermal and structural constraints.

With geometry data of a machine component being the common database for desirable aerodynamic, thermodynamic and structural considerations, to name only the most important of disciplines relevant for successful product development in the early engineering phase, we should explain some of the background of these fields as far as they have influenced parametrization of our geometry preprocessor.

GASDYNAMIC PHENOMENA, INVERSE AND DIRECT DESIGN TOOLS

Flow machinery, just like aircraft wings and other free form shapes with a need of refined surface quality is sensitive to the physical phenomena especially in the high speed domain. The knowledge base of transonic and supersonic gasdynamics tells us about regions of influence and

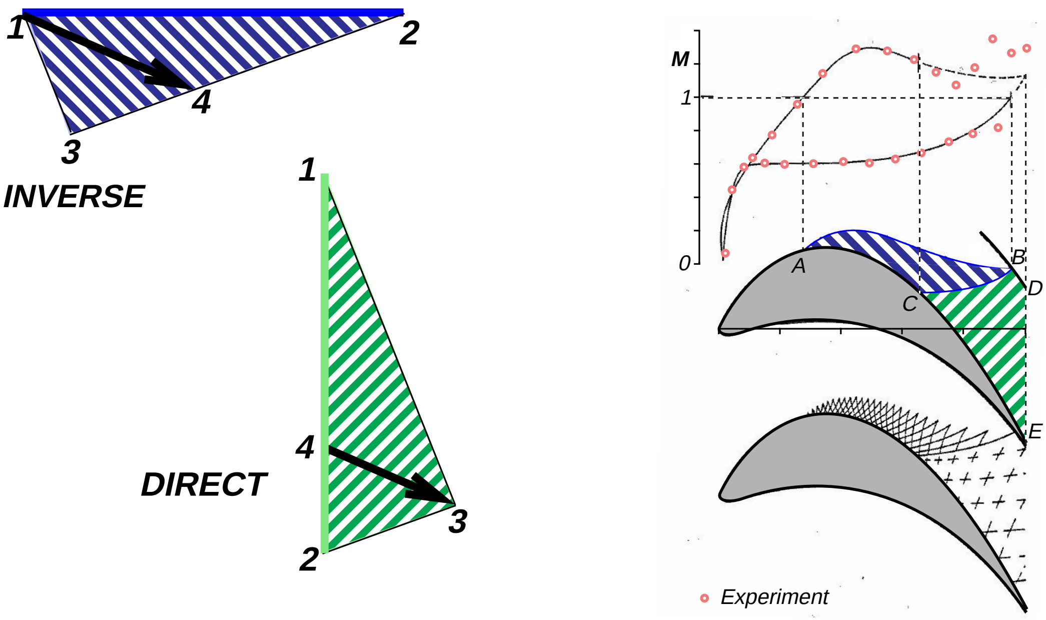

Figure 1: Principle of inverse and direct supersonic design; application of both inverse and direct methods to redesigning parts of the contour for a turbine blade test case.

dependence, this way suggesting the definition of section geometry definition observing the lack of upstream influence of any shape changes in certain regions.

Applied to the design of turbine blades we use such phenomena to perform flow computations both in a direct (downstream) or an inverse (cross-flow) marching procedure (Fig. 1). The latter allows to use certain given starting data to compute the flow along with a compatible boundary condition: the shape results from this inverse approach which, in practice, means that we may control the flow quality to avoid or delay negative effects like separation and obtain design hints how to shape a blade to actually observe this desired flow quality.

Figure 1 shows the principle, infinitesimally starting from known data along ($\overline{12}$), finding the solution within a triangle ($\overline{123}$), for potential flow computation, or with entropy updates along streamlines ($\overline{14}$) for an Euler accurate CFD simulation. Also shown is the application to an experimentally tested turbine blade design: the supersonic domain is re-constructed by starting from the given sonic line ($\overline{AB}$) in the inverse mode, then continuing downstream of ($\overline{BC}$) in the direct mode.

This transonic design method has been used for turbomachinery cascades [2] and many airplane wing design examples [3].

In the following we may not need to use these methods but we use geometry preprocessors which use parametric airfoils and other component functions which have been tailored using experience with this design concept. So we ensure to be close to desirable conditions in the aerodynamic part of the many needed optimization steps in design practice.

GEOMETRY MODELS WITH PARAMETRIC SHAPE CONTROL

Results from the above cited inverse approach in aerodynamics have taught us about shape sensitivities [4] and consequently about the needed refined parameter definition for the following more recent and future optimization efforts. In practical design, there will be a more multidisciplinary approach trying to optimize aerodynamics, structure, thermal properties etc. in a synchronized way. Here we call for a setup of parameters for controlling the complete set of boundaries to vary the shape for each discipline effectively. Restricting our illustrations to turbine blade technology, which might be resulting from the above illustrated design process, now needs to be created including its structure of coolant passages to allow for a design optimization including structural and thermal loads.

Without knowledge of some physical properties of aerodynamics leading to a suitable parametrization, the size and shape of the mathematical space that contains all the design variables (for example, coordinates of all blade surface points) is very large and complex in a realistic cooled blade geometry. Only when it is possible to use fast flow-field analysis codes could it be affordable to have an ideal optimization situation where each surface grid point on the optimized configuration is allowed to move independently. Otherwise, the designer is forced to somewhat restrict the design space by working with a relatively small number of the design variables by performing parameterization - if not by a specialized software like the one introduced here, for example, by fitting polynomials - of either the 3-D surface geometry or the 3-D surface pressure. The optimization code then needs to identify the coefficients in these polynomials. Since it is often necessary to constrain and sometimes not allow motion of certain parts of the 3-D surface, the most promising choices for the 3-D parameterization appear to be different types of Bezier functions [5] and the geometry preprocessing tools used here which is based on a library of suitable analytical functions and successive manipulations and integrations in 3D cartesian coordinates ([1], pp 123-136).

This approach allows to vary the airfoil parameters as found suitable from 2D design (Fig. 1) into the third dimension, to compose a 3D blade with drastically changing sections as occurring between the root and tip sections of a realistic turbine blade. Moreover, mathematical description of every surface point without any interpolation and iteration to approximate given data, allows for an easy construction of parallel surfaces as needed to meet wall thickness constraints. These are crucial when the inner structure of the blade needs to house a coolant flow passage reducing the heat load on the blade and still maintain structural stiffness to support the forces produced by the flow and through structure transferred to yield shaft torque.

A starting geometry for subsequent simulations and optimization is illustrated in Fig 2.

In the following chapter, some of our first results on optimization, will be commented, obtained prior to the availability of the fully parameterized blade geometry introduced here. The goal is, to learn from bi-disciplinary (aerodynamic-thermal, aerodynamic-structural, thermal-structural) optimization, before a truly multidisciplinary, automated optimization will be feasible.

Finally, the fully parameterized geometry of basic blade with coolant flow passages serves as a test bed for varying the parameters following the suggestions of a structural optimization strategy.

MULTIDISCIPLINARY DESIGN TASKS IN TURBOMACHINERY TECHNOLOGY

With presently available materials such as nickel-based alloys, gas turbine blades cannot withstand metal temperatures in excess of approximately 1300 K. Internal coolant flow passages augmented with heat transfer enhancements, such as trip strips or turbulators, impingement cooling, banks of pin fins and miniature heat exchangers can provide significant enhancements of convection heat transfer. For example, when needed in the initial turbine stages, cooling air can be made to impinge on the leading and trailing edge internal cooling passage surfaces in order to enhance convection. Impingement cooling schemes demand large leading and trailing edge diameters, but this creates thicker blades that can substantially increase aerodynamic losses. Complex heat exchangers have two major drawbacks. First, they induce early transition to turbulence and greatly increase the coolant passage effective friction, while moderately increasing the convective heat transfer. Second, manufacture of such complex internal configurations requires special machining processes.

The design variable set defines the geometry of the turbine blade including the external turbine airfoil shape definition, thermal barrier coating thickness, blade wall thickness distribution, and blade internal strut configurations. The blade stacking axis, twist, and taper are incorporated into the design variable set for three-dimensional blades. With the execution of this geometry generation program, a set of optimization design variables (the parametric model) is used to represent a virtual (electronic) prototype of the turbine blade or vane. The optimization design variable set controlled the internal coolant passage configuration, thickness variation of the coolant passage wall, positions and thicknesses of the internal ribs, and

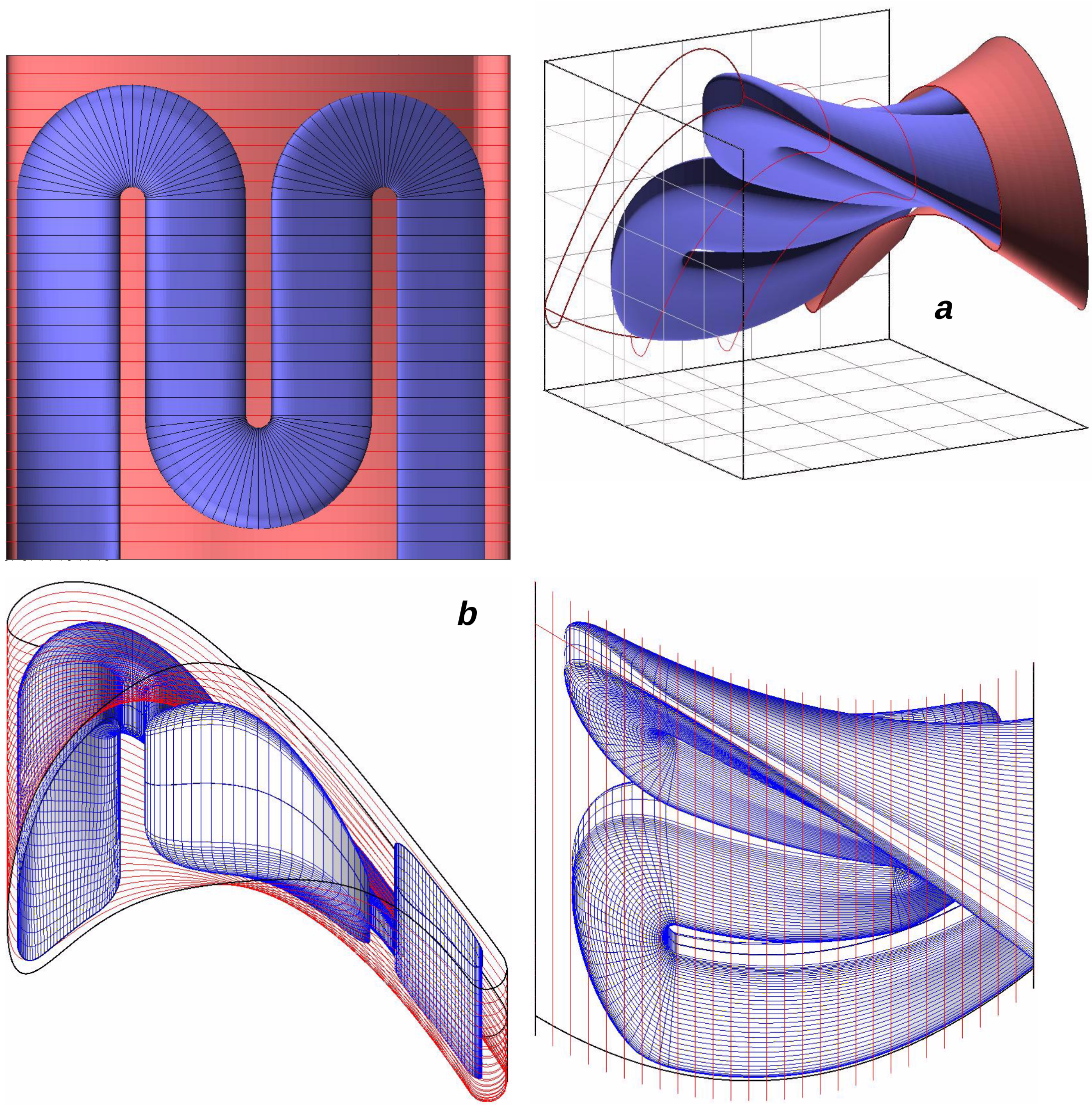

Figure 2: Turbine blade with coolant flow duct: Parametric outer shape definition plus meandering duct within the blade observing local shape control of duct cross section shape and wall thickness. Blade surface partly removed (a), three-view (b)

die pull angles of the ribs [6].

In our first exercise in multidisciplinary design optimization of internally cooled gas turbine blades, a turbulent compressible flow Navier-Stokes solver was used to predict the hot gas flowfield outside of the blade subject to specified realistic hot surface temperature distribution. As a byproduct, this analysis provides hot surface normal temperature gradients thus defining the hot surface convection heat transfer coefficient distribution. This and the guessed coolant bulk temperature and the coolant passage wall convection heat transfer coefficients create boundary conditions for the steady temperature field prediction in the blade and thermal barrier coating materials using fast boundary element technique. The quasi-one-dimensional flow analysis (with heat addition and friction) of the coolant fluid dynamics is coupled to the detailed steady heat conduction analysis in the turbine blade material. By perturbing the design variables (especially the variables defining the internal blade geometry) the predicted thermal boundary conditions on the interior of the blade will be changing together with the coolant flow parameters. As the optimization algorithm runs, it also modifies the turbine inlet temperature. Once the turbine inlet temperature changes significantly, the entire iterative procedure between the thermal field analysis in the blade material and the computational fluid dynamic analysis of the external hot gas flow-field will be performed again to find a better estimate for thermal boundary conditions on the blade hot surface. This global coupling process, so far, was performed only a small number of times during the course of the entire optimization. This semi-conjugate optimization uses sectional 2-D blade hot flow-field analysis and a simple quasi 1-D coolant flow-field analysis (Fig. 3).

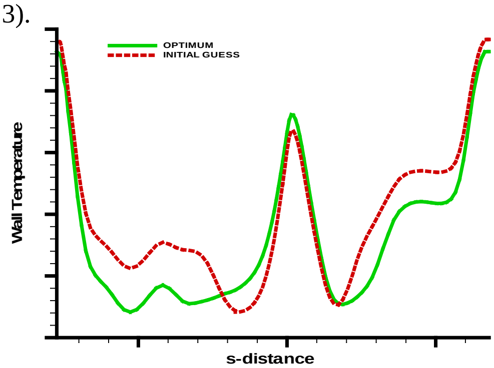

Figure 3. Comparison of external wall temperature variations computed at the quarter-root span of the second HPT blade of the F100 engine

This design methodology was successful at generating a wide range of realistic internally cooled turbine blades and vanes, while the surface meshing, grid generation, and boundary conditions were automatically mapped between the interfacial surfaces. This information was transferred between the various design, optimization, and numerical analysis tools without user intervention. A constrained hybrid optimization algorithm [7] controls the overall operation of the system and guides the multidisciplinary internal turbine cooling design process towards the objectives of cooling effectiveness and turbine blade durability. Design variable sets which had generated an infeasible or impossible geometry, were restored to a feasible shape automatically using a constraint sub-minimization.

There are also possibilities for further improvement in the design of cooled turbine blades. The external turbine blade shape could be modified in an effort to make the external aero-thermodynamics reduce the amount of heat absorbed by the blade. Each new design of the external airfoil would require a fully conjugate viscous three-dimensional steady-state CFD analysis of the hot gas flow field and the temperature field inside the blade [8]. This CFD solution would then be used to predict new external heat transfer coefficients, as well as provide an aerodynamic constraint function so that the efficiency and work of the turbine row could be fixed [9], [10]

RESULTS ON TURBINE BLADE STRUCTURAL ANALYSIS

The geometry preprocessing tool based on analytical functions was already used to model boundary conditions for the automatic structural analysis of internally cooled turbine blades. The preprocessing tool can quickly generate realistic coolant passage shapes within a specified outer blade. The passage shapes are controlled by a set of parameters that the users provide as input. When combined with automatic grid generation and finite element analysis tools, the system is ideal for automatic parameter studies as well as for design optimization. In the current structural analysis system, the geometry preprocessing tool generates a multiblock structured grid that represents the turbine blade geometry. Another program then automatically generates a surface triangulation [11] and then another code makes a volume grid composed of tetrahedrons [12]. A typical surface mesh is shown in Fig. 4. Once a mesh is generated, a structural analysis is performed. The current structural analysis system uses a parallel finite element analysis (FEA) code that can do both linear and nonlinear structural analysis [13]. This code also has the capability of doing automatic partitioning of the mesh as well as automatic FEA. Figure 5 shows an example finite element linear stress analysis result for a turbine blade with coolant passages spinning at 3000 RPM. In this case, the number of degrees of freedom was around 100,000. Two Pentium II 333 MHz processors were used to compute the solution in roughly 15 minutes. With this system, the user only needs to input the parameters that govern the shape of the blade and start the system. Once completed, the system provides the detailed stress and displacement field for the turbine blade without any further interaction with the user. It is hoped that when combined with optimization this automatic geometry generation/analysis system will be a powerful tool for turbine blade design.

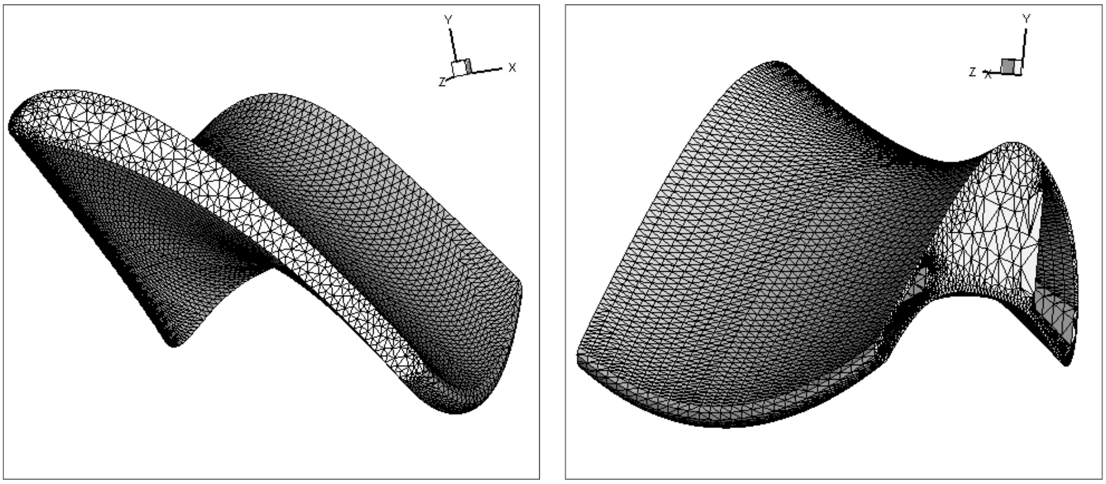

Fig. 4. View of triangular surface mesh from blade tip and from blade root

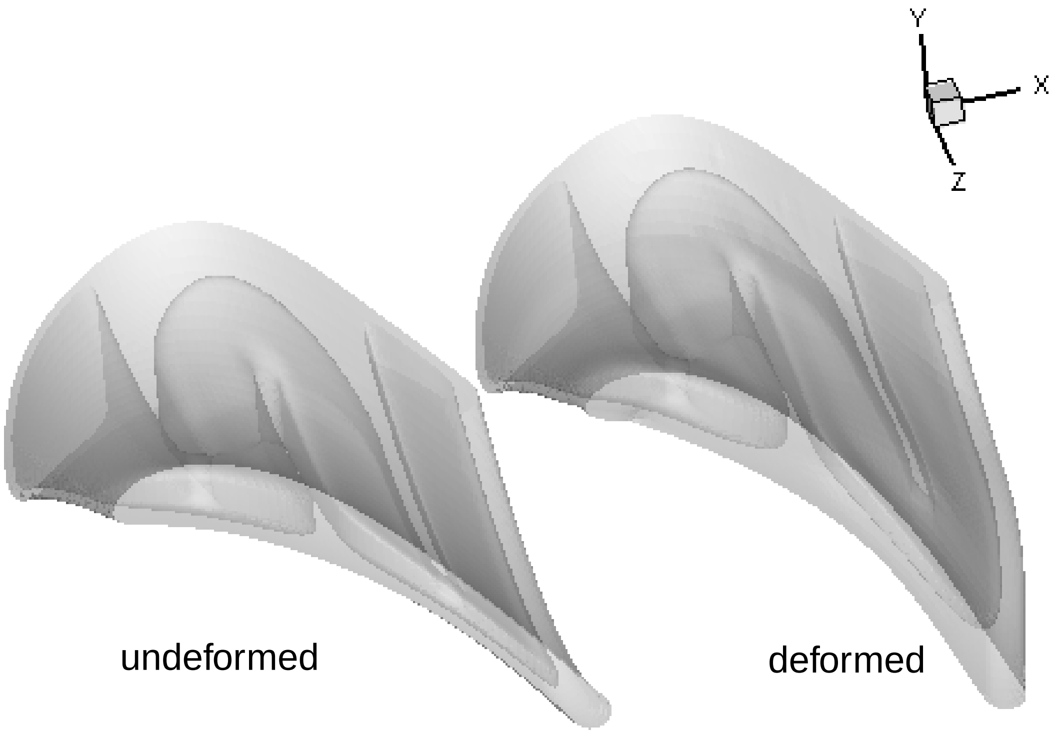

Fig. 5. Result from linear stress analysis of spinning turbine blade with passages,
(for illustration, deformations have been multiplied by a factor of 20)

CONCLUSION

We have shown some first results of what is going to be a software system for multidisciplinary optimization for turbomachinery components like cascades, stators and rotors. Other applications for aerospace and ground vehicle design seem straightforward and rather may be less complicated: A very close coupling of high speed areodynamics, thermal and extreme structural loading may occur only in high speed aircraft design. While showing several results for monodisciplinary design and first results of bidisciplinary optimization, we come to the conclusion and have stressed the fact that fast, flexible and realistic surface modelling for practical components is effectively supporting any future multidisciplinary approach to optimize product components observing advantages and constraints of all mayor disciplines involved in the operation of the component. Optimization of turbomachinery blades poses first, but strong test cases challenging all aspects of the simulation software.

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