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A STUDY ON DESIGN AND OPTIMIZATION OF ADVANCED HIGH- LOADED TRANSONIC TURBINE AIRFOILS

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Abstract
Today the earth's global warming is an undeniable phenomenon, confirmed by studies of several independent scientific organizations. At present there is stronger evidence that most of the warming observed over the last 50 years is of anthropogenic nature (Folland et al., 2001), deriving from increased emissions of greenhouse gases. This evidence has launched major intergovernmental efforts over the last two decades in order to address the problem. At the beginning of the nineties the United Nations General Assembly initiated negotiations leading to a framework convention on climate change.

Key Words: Design, Optimization, Turbine.

1. Introduction

Over time various innovative technologies can be listed, which allow major improvements in the energy conversion efficiency. Among these the so-called hybrid-processes, consisting of a combination of high temperature fuel cells and combined gas cycle power plants seem to be the most promising today. Combined cycles on coal basis like pressurized fluidized-bed combustion with partial gasification, externally fired combined cycles, pressurized pulverized combustion and integrated gasification combined cycles are being currently tested and appear to be a possible solution for the medium term. In a short period perspective, however, substantial progresses can be only achieved by improving existing advanced technologies like steam and gas combined power plants. In the nineties, in fact, extensive research efforts have been performed in this field and great advances have been achieved already. Moreover the components used within steam and gas combined cycle power plants present reliability, availability and maintainability (RAM) which are in line with the market expectations for energy production (Steel et al., 2004). Today combined gas cycle processes show efficiencies slightly below 60%. By 2010 an efficiency increase of combined gas and steam turbine power plants to 62% is expected (BMWA, 2003). This is a very challenging task which requires significant multidisciplinary efforts both in the fluid mechanics research field and in the field of material technology. Major improvement potential for increasing the efficiency is to be found in the gas turbine. One of the key factors is the turbine inlet temperature. Figure 1.3 presents the development trend of the maximum turbine inlet temperature as reported today by a leading original equipment manufacturer (OEM) like Siemens Power Generation (Thien et al., 2004).This denotation indicates power plants which release less than 0,1 kgCO_2/kWh in the atmosphere by applying CO_2 retention measures (BMWA, 2003).

2. Objectives of The Study

a. To study theoretical background about the boundary layer development in turbo machinery blades.

b. To know the numerical environment where the aerodynamic optimization procedure and structure of the automatic design method.

3. Scientific Background and Motivation

Today the components of modern gas turbines feature high aerodynamic efficiencies, so that a further improvement represents a very challenging task for the turbo machinery aerodynamics designer. The introduction of multidisciplinary aspects and of a three dimensional way of thinking in the design process of the blading is fundamental for better engineered and more clearly understood components. Moreover advanced methods are required which permit higher levels of automation within the design process in order to reduce the development time and costs. Over the last decades, the extraordinary development and improvement of computing resources has been offering an ideal terrain for the design process to develop in this direction. The use of Computational Fluid Dynamics (CFD) has been gaining even more importance and covers a fundamental part within the aerodynamic design process today. A fundamental aspect for the successful application of Navier-Stokes codes within the aerodynamic blade design process is an extensive validation work based on experimental data for operating conditions and aerodynamic loadings similar to those encountered in modern turbo machinery blades. Moreover, the development of advanced optimization techniques handling large numbers of design parameters and eventually contrasting objectives could be observed and a large amount of applications of these methods can be found in the literature. The invention of splines in the 1960s followed by the introduction of more advanced geometrical description systems based on spline- and Bezier-curves in the 1980s should not be underestimated as this opened the way for the use of non conventional profile forms for gas turbine blades.

In fact the knowledge of the boundary layer development is a fundamental aspect for the design of turbine blade profiles with reduced losses. Furthermore reliable numerical tools predicting with a reasonable accuracy the transition phenomena and the turbulent boundary layer are the backbone for an accurate assessment of the results obtained within the optimization cycle. The question of the optimal profile velocity distribution on high pressure turbine blade profiles for heavy duty gas turbine applications and the question of the optimal turbine blade spacing will be discussed as well. In fact, the former aspect is strictly associated to both the boundary layer development and to an efficient blade cooling. The choice of the blade spacing is of major importance for the improvement of the aerodynamic design of gas turbines components, featuring a reduced number of parts. The blade spacing influences the profile Mach number distribution as well. After the discussion of these fundamental physical aspects, a survey of recent progresses in the area of automatic optimization methods for aerodynamic blading design is illustrated. The application of these procedures within the industrial design process is discussed as well. Finally, a short overview about conventional aerodynamic design systems is given for a better identification of the potentials offered by automatic methods for increasing the efficiency of the design process.

4. Experimental Investigations

After a brief introduction of the reference geometries and the background leading to the design of these cascades, the experimental setup will be presented. The main features of the High Speed Cascade Wind Tunnel will be outlined as well as the applied measurement techniques. The results obtained with the reference turbine cascade blades will be discussed in order to identify detriments and benefits of the different design strategies.

The reference turbine cascades T150, T151 and T152

The datum profile, named T150, represents the mid-span section of a typical turbine rotor blade for high pressure stages of large scale stationary gas turbines. The aerodynamic loading of this profile is moderate. Starting from this reference profile, two further design approaches were investigated. The resulting turbine cascade blades were indicated as T151 and T152. Two different design strategies were strived for. While for the design of T151 the objective was the reduction of the number of parts with a consequent increase of the blade spacing, for T152 instead an optimization of the profile Mach number distribution was pursued to enable favorable conditions for the blade cooling. The reduction of the number of blades within the stage is associated with reduced wetted surface, friction losses and reduced cooling air mass flow per stage. Therefore the design strategy for T151 strived for the aerodynamic optimum.

On the other hand it must be kept in mind that increasing the aerodynamic loading produces an increase of the cooling air mass flow per blade pitch since the increase of the adverse pressure gradients influences the efficient action of the profile film cooling. This increases the mixing flow losses. Furthermore, a reduced number of blades is associated with higher blade sections for mechanical reasons. Thus, the internal cooling channels of the blade have to be modified as well, with a consequent increase of the number of blade cooling channels (Lötzerich, 2004b). As a consequence manufacturing costs increase. Furthermore, an excessive increase of the blade aerodynamic loading is associated with higher pressure gradients over the blade passage, which would lead to an undesirable increase of secondary flow structures and leakage losses. These negative aspects deriving from an excessive increase of the aerodynamic loading were considered for the design of T152, reducing the blade loading to the level featured by the datum profile. Favorable conditions for the optimal profile cooling were strived for as well. The gradients in the back diffusion region of the suction side were reduced, the velocity magnitude on the whole pressure side was increased and a continuous acceleration over the entire blade surface was realized. The design operating conditions for the three cascades are quite similar. The design exit Reynolds number exceeds two million and the design exit Mach number is slightly below 0.80. For the experimental investigations the nominal reference exit Reynolds number and nominal reference exit Mach number were fixed at Re_{2th}=1 200 000 and Ma_{2th}=0.75 respectively. The definition of the theoretical exit Mach and Reynolds number is given by Ladwig (1989).

5. Numerical Optimisation Environment

The present chapter illustrates the numerical environment where the aerodynamic optimization procedure was developed. The structure of the automatic design method is shown in Figure 1.1. The optimization loop consists of three major components: parametric geometry generator, Navier-Stokes flow solver and optimization algorithm. The aim of the optimization process is to find the n-dimensional vector of design variables $\boldsymbol{X}=(x_1, x_2, \ldots, x_n)$ which minimizes a scalar function, indicated as the objective function $F(\boldsymbol{X})$, and respecting a set of m constraints expressed by the vector function $\boldsymbol{B}(\boldsymbol{X})=(b_1, b_2, \ldots, b_m)$. The generic i^{th} constraint $b_i(\boldsymbol{X})$ is violated, if $b_i(\boldsymbol{X})$ is located outside a specified range. For the present application, the design variables correspond to the parameters describing the blade profile geometry. The objective function is set up by combining various aerodynamic performance coefficients which result from the flow simulation of the actual blade profile. Thereby the main optimization target is the reduction of the cascade total pressure losses by imposing a fixed operating point. Requirements on the profile velocity distribution with regard to cooling demands were integrated into the objective function as well. Furthermore, some major mechanical and geometrical constraints were specified in order to restrict the search to a subset of realistic geometries. In this way the optimization task is reduced to a single-objective, constrained approach.

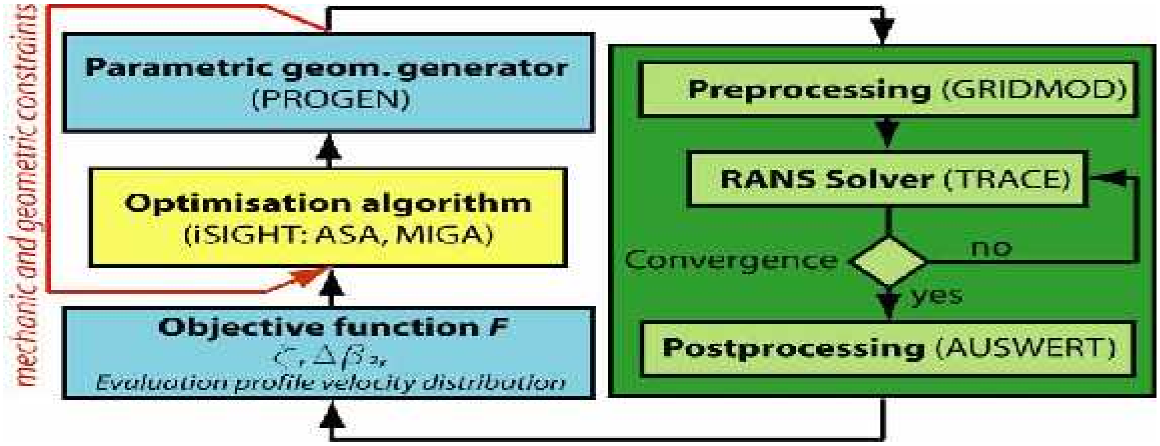

Fig 1.1: Schematic representation of the optimization loop and connections of the components

As illustrated in Figure 1.1, the optimization algorithm represents the core of the whole process. It modifies the design parameters according to the information obtained by the already evaluated parameter datasets. If the parameters satisfy the specified mechanical and geometrical constraints, the corresponding blade geometry is transferred to the flow simulation process. Otherwise the present parameter dataset is associated with an appropriately high value of the objective function. The flow simulation process is performed in a sequence of automatic steps. The first step is the grid generation. In this work a method was implemented which ensures reduced dependence of the flow solution on the mesh by maintaining a fixed grid topology and modifying, mainly, the mesh in the boundary layer region (Niß, 2002). The flow simulation is performed using the Reynolds averaged Navier-Stokes solver TRACE developed by the DLR in Cologne (Eulitz, 2000) in a quasi three dimensional version. In order to reduce the code running time, each simulation restarts from a well converged solution on a reference mesh of the reference geometry T150. Furthermore, a convergence criterion based on monitoring the cascade total pressure losses, the exit flow angle and the total pressure ratio inlet/outlet during the flow simulation was integrated within the solver. The third step of the flow simulation process consists in the evaluation of the results obtained for the present set of design parameters.

The evaluation process (Jogwitz, 2002b and Groth, 2004) takes place both in a plane downstream of the cascade and on the blade profile. The results are then used to build the objective function, whose value is then computed by the optimization algorithm. The whole procedure is set up within the commercial software package iSIGHT (Engineous Software, 2002). This facilitated the use of various optimization techniques. The present investigations were carried out using a probabilistic heuristic optimization approach as the adaptive simulated annealing algorithm ASA. Further investigations were performed using the multi island genetic algorithm MIGA. Another major advantage of implementing the optimization procedure within iSIGHT was the reduced efforts to interface the single components, thanks to the file parsing capabilities of this software package.

6. Results and Discussion

The present section contains the results obtained applying the automatic design procedure at different aerodynamic loadings. The investigations were run fixing the cascade deflection to the value of the datum profile T150 and optimising the profile shape for various blade spacings. The main target of the optimisation process was the reduction of the cascade total pressure losses considering the discussed requirements on the profile velocity distribution for an efficient cooling of the blade. The search space was restricted constraining the profile area and section modulus according to the indications given at the end of the previous section. The present investigations were performed using a set of 15 parameters for the description of the blade geometry within the geometry generator PROGEN. The form of the objective function *F* and the parameters used are described in the previous chapter as well. The trailing edge thickness to pitch ratio and the axial chord were fixed at the values of the datum profile T150. The influence of the trailing edge thickness on the cascade aerodynamic behaviour was quantified by performing additional investigations presented at the end of this chapter.

Results at the spacing of turbine cascade blade T151

Firstly the results of the automatic procedure for the re-design of cascade T150 at the blade spacing of T151 are presented. The profile Mach number distribution obtained in this case is compared with the reference distributions in Figure 5.4. The velocity distribution on ASA_{T151} is represented by the continuous line, the Mach number distribution on the turbine cascade blade T151 is represented by the dashed line and the dash-dotted line corresponds to the datum profile T150. The results on an additional reference profile called $T150_B$ correspond to the dash-dotted-dotted line. This profile was obtained from T150 by reducing the blade stagger angle and the exit blade metal angle in order to ensure the same deflection as T150 at the pitch ratio of T151. Turbine cascade T151 features ten degrees higher deflection than cascade $T150_B$, but somewhat lower mass flow capacity. Nevertheless its profile velocity distribution features smooth acceleration both on the suction and on the pressure surface and a comparison with the optimisation results is useful to assess the efficiency of the present method. The comparison shown in Figure 5.4 indicates that the optimisation procedure is able to locate blade geometries featuring smooth profile Mach number distributions and at the same time reduced total pressure losses. The optimised geometries respect the specified geometric and mechanic requirements and ensure the required cascade deflection. Extensive preliminary investigations were performed at this blade to pitch ratio in order to test different formulations of the objective function *F*. These calculations were performed at a lower inlet turbulence intensity Tu_1 = 1.5%. The weighting coefficient for the total pressure losses in the objective function was reduced from 50 to 1 in order to limit the weight of the total pressure losses on the optimisation results. This gave the possibility to investigate in more detail the behaviour of the other terms related to cascade deflection and profile Mach number distribution.

7. Summary and Conclusions

The design of turbine cascade blades for heavy duty gas turbines has to take into account various often counteracting aspects deriving from the interaction of different disciplines. A major aim pursued in the development of modern turbine bladings is a reduced number of blades. In fact, even if the maximal temperature in heavy duty gas turbines is somewhat lower than in aero engines, life expectations and maintenance intervals are expressed here in thousands of hours instead of hours (Madfeld et al., 2004). This corresponds to a demanding challenge for the materials applied in the high pressure components, which can be met only making use of advanced materials (e.g. Nickel based super alloys or ceramic composite matrix) in combination with expensive casting techniques for obtaining single crystal structures, advanced thermal protection coatings and extensive cooling procedures. All these aspects contribute to increased manufacturing costs. Thus, the reduction of the number of blades represents a possible way for limiting costs. Furthermore, this design strategy is associated with beneficial effects under an aerodynamic point of view like reduced wetted surface and reduced quantities of cooling air mass flow per stage. Nevertheless, the resulting increase of the aerodynamic lift coefficients produces unfavourable effects like increased secondary flow losses, highly convex profile curvatures and undesired supersonic flow regions over the blade suction surface. Moreover, the increased profile aerodynamic loading makes the cooling efforts per unit pitch higher as well and the beneficial effects of a reduced number of parts could be even suppressed.

In this context the development of reliable and fast automatic tools assume major importance for the designer, facilitating a rapid reaction to continuously changing boundary conditions specified during an iterative process in which different goals from different disciplines have to be accounted for. In the present work an automatic design method for the aerodynamic optimisation of two-dimensional turbine blade profiles for the application in the front stages of heavy duty gas turbines was developed and validated. The design process consists mainly of three major components: a flow simulation procedure (TRACE, DLR Cologne), a parametric geometry generator (PROGEN) and an optimisation algorithm. The whole procedure was set up within the commercial software package iSIGHT. Since both the operating and the geometric conditions of turbine blade for these applications can significantly differ from the conditions at which the flow solver was validated, an extensive experimental database was set up in a preliminary phase of this work and used for calibrating the flow solver and validating the design method. The automatic flow simulation procedure used within the developed design method is set up coupling the flow solver with an *ad hoc* developed automatic mesh generation procedure (GRIDMOD) and evaluation method (AUSWERT). The grid generation method operates maintaining a fixed mesh topology and adapting the mesh mainly in the boundary layer region where mesh lines orthogonal to the wall surface are required in order to ensure an accurate reproduction of the boundary layer development. The evaluation procedure determines the cascade integral aerodynamic coefficients by homogenising the wake flow using the procedure by Amecke (1967). The treatment of the profile velocity distribution with interpolating splines and approximating polynomials ensures the recognition of maxima, minima and inflection points. The main optimisation target of the developed procedure is the reduction of the cascade total pressure losses imposing a fixed operating point. Additional requirements on the profile pressure distribution for cooling demands were introduced in appropriate fashion in the objective function as well. This is a fundamental condition for ensuring the generation of optimised profiles which are relevant for practical applications. A major concern was thereby the development of a method which does not merely optimise the location of the transition zone, sacrificing the quality of the velocity distribution on the blade profile. All the objectives were assembled into a scalar objective function F. The structure of the different terms of this function was tailored *ad hoc* during extensive preliminary investigations in order to ensure a balanced treatment of the various contributions. A combination of polynomial and exponential functions was demonstrated to be suited best for the present problem.

The design method was developed for the application in an industrial framework. Therefore particular attention was given to reduced design time frames. This requirement was met by combining the two-dimensional simulation approach with a global stochastic optimisation technique like Adaptive Simulated Annealing. This algorithm showed best capabilities in coupling with the present highly non linear objective function and ensured a rapid and exhaustive investigation of large design spaces for locating optimal solutions.The developed method was validated at various aerodynamic loadings. A comparison of optimised and reference results underlines the high potential of the present approach for reducing the cascade total pressure losses. The documented results indicate that the method is able to generate geometries fulfilling the specified requirements on flow deflection and profile velocity distribution. A maximal reduction of the total pressure losses coefficient by about 20% is achieved at

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pitch to chord ratio higher than for T151 with respect to the datum profile T150 at reference operating conditions. The slight increase of the total pressure losses coefficient of the optimised blades at the datum pitch to chord ratio is counterbalanced by an evident improvement of the profile velocity shape. The present results indicate the necessity to introduce appropriate terms in the objective function F for the control of the profile Mach number distribution. In fact, even if the presence of these zones does not alter the boundary layer development on the profile surface and therefore the integral performance coefficients, they have to be separately considered in order to produce velocity distributions on the profile which feature optimal aerodynamic characteristics for an efficient cooling of the blade. An optimal acceleration behaviour on suction and pressure surface was achieved using an asymmetrical representation of the blade leading edge. Thus, the suction and pressure side spline segments were decoupled from each other. This led to increased sectional areas of the optimised blades. Therefore, in order to assess the capabilities of the present method at changed boundary conditions, the level of the admissible areas and momentum of inertia was strongly reduced. The results obtained from these additional investigations confirm the validity of the present automatic design approach at changed boundary conditions. The general formulation used for the present method facilitates the extension of its application field to the optimisation of turbine profile blades for gas turbine aero engines. However, some circumstances have to be considered. In fact, while for heavy duty gas turbines the operation point is almost fixed, for gas turbine aero engines different operation conditions have to be taken into account. In this case the efficient operation of the blades at different incidences is of fundamental importance and has to be appropriately considered within the objective function. The present investigations indicate that the optimised turbine blade profiles feature high loading levels in the front part of the suction surface. This has to be accurately limited to ensure an efficient operation at positive incidences. A proposal for the extension of the method in this direction could be to integrate the information deriving from the Euler simulation of the blade at positive incidence within the objective function. In this way the computational time of the method will not be increased significantly. In a second step a selection of the best solutions could be analysed in more detail performing viscous calculations at positive incidences as well.

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