OPTIMIZATION OF A STEAM TURBINE GUIDE VANE BY END WALL CONTOURING USING EVOLUTIONARY ALGORITHMS

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Abstract: The subject of this paper is the optimization of a guide vane of steam turbine control stage by end wall contouring. The investigated control stage is derived from an existing industrial steam turbine design. The end wall contour is varied in rotational direction within specified restrictions by an evolutionary algorithm. The algorithm is directly connected to a mesh generator and a Computational Fluid Dynamics (CFD) solver. The optimization goal is the reduction of the total pressure loss over the guide vane. The geometry of the rotor blade has been retained unchanged. The flow field of the varied stage is compared with the baseline geometry. The optimum candidates are further investigated with CFD simulations for different operating point scenarios. Numerical results show that the axisymetric end wall contouring of the nozzle has a considerable effect on the loss behavior of the nozzle over a wide range of pressure ratios. Due to end wall contouring the boundary layer in the nozzle is significantly affected which results in a significant reduction of the secondary flow effects in the guide vanes.

1 NOMENCLATURE

c_s	nozzle chord
j	number of individual
κ	isentropic coefficient of air
p_1	static pressure at guide vane outlet
$p_{t,0}$	total pressure at guide vane inlet
$p_{t,1}$	total pressure at guide vane outlet
π	pressure ratio
$R_{s,i}$	shroud radius of shroud point i
R^*	transformed coordinates
$R_{s,max}$	max. shroud radius
$R_{s,min}$	min. shroud radius
R_h	hub radius

2 INTRODUCTION

Secondary losses, in addition to profile losses, are one of the most important loss mechanisms in turbo machines. Their influence emerges in particular at blade profiles with high aerodynamic loads, high pressure ratio, high flow velocity and low aspect ratio. Secondary loss can constitute up to 30% of the overall loss. The effect of secondary flows has been intensively investigated by Langston (2001), Sieverding (1985) and Gregory-Smith (1997). Dejc and Zarjankin (1960) have shown that secondary losses and boundary layer effects can be reduced by an axisymetric end wall contour. They used a cubic function to define the end wall contour. Moustapha and Williamson (1985) investigated rotational constrictions in the meridian plane. They asserted that a streamwise downward constriction exhibits a lower loss than a linear constriction. Rose (1994) achieved a significant influence of the static pressure at the profiled wall by a three-dimensional contouring of a high pressure gas turbine. Harvey, Rose, Taylor, Shapar, Hartland and Gregory-Smith (2000) examined a 3D hub contour of a turbine. The contour was described with a divergence from the reference contour at six axial positions in circumferential direction by a Fourier function. The static pressure distribution at the hub surface and the exit flow angle variation were selected as optimization target. Harvey et al. asserted the passage vortex and the overall losses were reduced by the 3D profiled hub. Furthermore, they discovered a new vortex near the hub. Experiments

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by Hartland, Gregory-Smith, Harvey and Rose (2000) validated these results. Eymann, Foersterm Beversdorff, Reinmoeller, Niehuis and Gier (2002) experimentally investigated an axisymmetric end wall contour simultaneous with a blade profile optimization in the first stage of a gas turbine. They asserted that the vortex system behind the first guide vane was dislocated near the end walls. Additionally, Eymann observed a reduction of the passage and the trailing edge vortex as a result of the optimization.

3 GEOMETRY RESTRICTION

The control stage investigated is derived from an existing industrial steam turbine design. Due to the production process of guide vanes for control stages of steam turbines the end wall contour has to be axisymmetric. The shroud contour is defined by an equidistant distribution of seven points which define a b-spline as shown in Fig. 1.

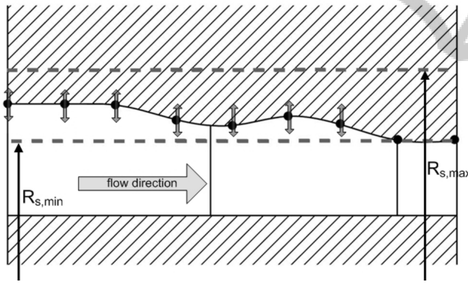

Figure 1: Illustration of geometry restriction.

These seven points are varied in radial direction within the following restriction of R_s:

$$R_{s,min} = R_h + 0.25 * c_s \leq R_{s,i} \quad (1)$$
$$R_{s,max} = R_h + 0.5 * c_s \geq R_{s,i} \quad (2)$$

By virtue of undisturbed flow conditions at the inlet and outlet of the guide vane channel the radial shroud contour gradient equals zero. The cross section of the outlet remains unchanged for all geometry variants.

4 EVOLUTIONARY ALGORITHM

The optimization of the shroud contour is a complex multi dimensional problem. The optimization parameters are the radial positions of the seven points, which describe the contoured shroud. Due to the seven degrees of freedom a simple analytic solution is not suitable. In order to achieve a systematic optimization of the contoured end wall an evolutionary algorithm has been used. The main loss mechanism in guide vanes is the total pressure loss due to secondary flow regimes. Hence the total pressure loss of the guide vane is selected as fitness function for the evolutionary algorithm. It is evaluated as shown in Equation (3). The evaluated pressure is mass flow averaged.

$$\zeta_{Pt} = 1 - \frac{1 - \left(\frac{p_1}{p_{t,1}}\right)^{\frac{\kappa-1}{\kappa}}}{1 - \left(\frac{p_1}{p_{t,0}}\right)^{\frac{\kappa-1}{\kappa}}} \quad (3)$$

An evolutionary optimization algorithm is based on the technique of adaption and evolution as shown by Rechenberg (1994) and Weicker (2002). The workflow of the used evolutionary algorithm is shown in Fig. 2.

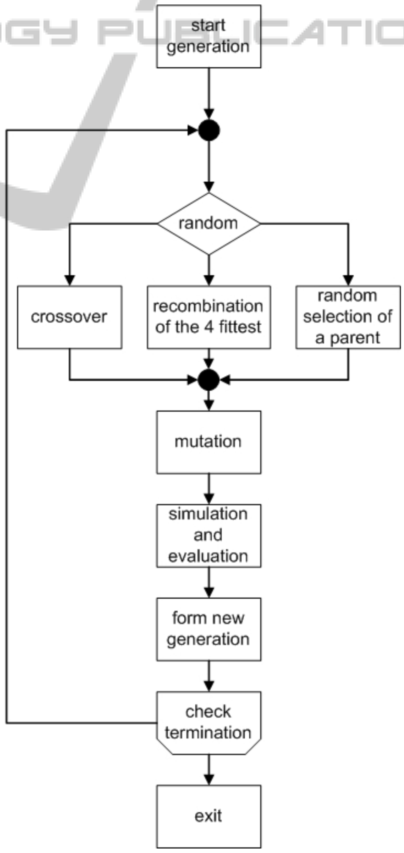

Figure 2: Workflow.

4.1 Evaluation of the Fitness

After gaining the geometry information for the child individual the pressure loss is evaluated. Due to the influence of the end wall contouring on the secondary flow phenomena every single individual must be simulated by means of 3D-CFD. For this reason the evolutionary algorithm is directly connected to a commercial mesh generator and a CFD solver. ANSYS CFX 11.0 is used as CFD solver. The mesh generator creates the three-dimensional numerical model and hands it over to the CFD solver which simulates and evaluates every single child individual. The numerical mesh of the guide vane has a resolution of about 1 mio. control volumes. The "Shear Stress Transport Model" is used as turbulence model. The convergence criterion of the CFD solver is an overall residual below 10^{-5}. Figure 3 shows the scheme of the evaluation process. One single evaluation process needs about 30 minutes.

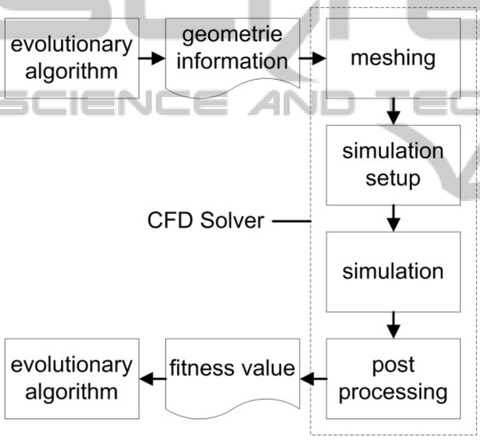

Figure 3: Evaluation process.

After evaluating each individual, the next generation is formed. It is based on Darwin‘s principal "survival of the fittest". This means only the fittest individual of the parent generation and the child individuals are transferred to the next generation. The optimization is looped until a certain number of simulations is reached or a stagnation over 50 loops in the optimization process is noticed.

4.2 Evolution Strategy

(μ+λ)-strategy is selected as evolutionary strategy. This means that from μ parental individuals λ child individuals are generated and the μ fittest of the (μ+λ) individuals are passed onto the next generation. Parental individuals can be transferred to the next generation, too. One problem of this strategy is that the algorithm tends to hang up on a local optimum but on the other side the algorithm is quite fast and robust. This is the reason why the (μ+λ)-strategy is selected. Due to the fact that the evaluation of the fitness by CFD consumes about 30 min. per individual, the number of the parental individuals (μ) is set to 20 and the number of the child individuals (λ) is set from 1 to 5. For the creation of the child individuals 3 different mechanisms are required:

- simple mutation
- recombination of the four fittest
- crossover.

The simple mutation slightly varies the shroud geometry of a randomly selected parental individual. The recombination mechanism averages the shroud geometry of the four fittest parental individuals and mutates this average value. The crossover mechanism crosses two randomly selected parental individuals at a random position as shown in Fig. 4. Afterwards this new geometry is also mutated.

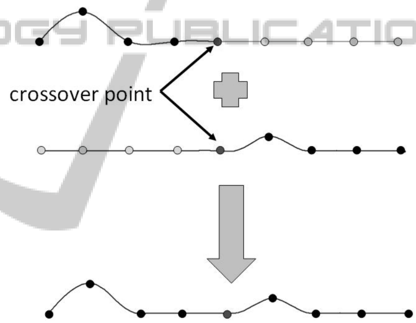

Figure 4: Scheme of crossover.

4.3 Results

In the first step the operating point of the guide vane is kept constant during optimization. The optimum candidate is further investigated with CFD simulations for different operating point. The design pressure ratio over the nozzle is $\pi = 0.5$. Air is the chosen fluid because in a further step the result will be compared with measurements of an air turbine test rig. The original shroud contour with a constant shroud radius $R_{s,i} = R_{h,min}$ is used as the reference geometry.

In order to properly visualize the target function of the shroud variation a multidimensional scaling is used to project the eight-dimensional space on a three-dimensional space. The Euclidean distances between the individuals in the three dimensional space are approximately calculated as a monotonically transformation of the corresponding dissimilarities in the eight-dimensional space. The transformation scheme is given in Equation (4).

$$\begin{pmatrix} R_{s,1} \\ \vdots \\ R_{s,7} \\ \zeta_{Pt} \end{pmatrix} \overset{f_T}{\rightarrow} \begin{pmatrix} R_1^* \\ R_2^* \\ \zeta_{Pt} \end{pmatrix} \quad (4)$$

Elements which are close to each other in the eight-dimensional space are also close in the three-dimensional space. As goodness-of-fit criterion for the approximately calculated transformation the minimum of the squared standardized residual sum of squares (stress), normalized with the sum of fourth powers of the dissimilarities, is used. Further information can be found at Seber (1984), Borg and Groenen (1997) and Backhaus, Erichson, Plinke and Weiber (2006). Figure 5 shows the total pressure loss ζ_{Pt} over the transformed coordinates R_1^* and R_2^*. The map was generated using the information of over 2500 individuals.

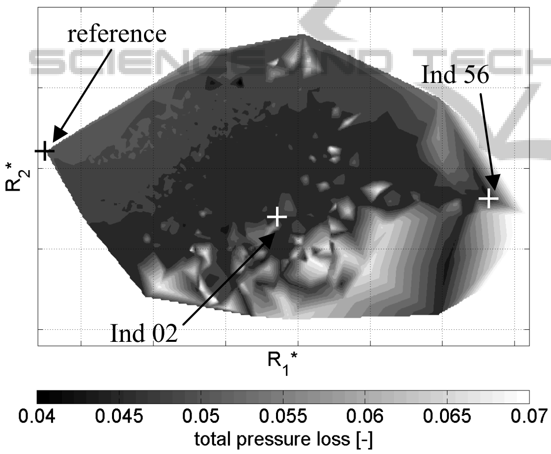

Figure 5: Multidimensional scaling.

4.4 Guide Vane Simulation Results

For comparison a shroud contour according to Dejc and Trojanovskij (1973) was also simulated and evaluated (Ind 02). The optimum contour of the evolutionary algorithm is named Ind 56. The investigated contours are shown in Figure 6.

Table 1 shows the difference of the pressure loss of the both end wall contours in relation to the reference contour. It is calculated as shown in Equation (5).

$$\Delta\zeta_{Pt,rel} = \frac{\zeta_{Pt,ind\ j} - \zeta_{Pt,ref}}{\zeta_{Pt,ref}} \quad (5)$$

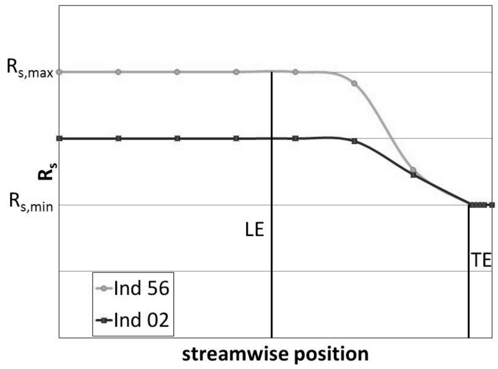

Figure 6: Illustration of the investigated contours.

Table 1: Total pressure loss relative to reference.

	Ind 02	Ind 56
$\Delta\zeta_{Pt,rel}$	-0.1106	-0.1196

In a further step the three geometries are investigated at different pressure ratios over the nozzle. Figure 7 shows the characteristic of $\Delta\zeta_{Pt}$ relative to the reference contour. The dashed line marks the critical pressure ratio of air. It is noteworthy that the advantage of contouring over the straight contour increases as pressure ratio increases. Especially at subcritical pressure ratios the total pressure loss is reduced by end wall contouring. It can be observed that the optimized contour has an significant advantage over the straight and the Ind 02 contour.

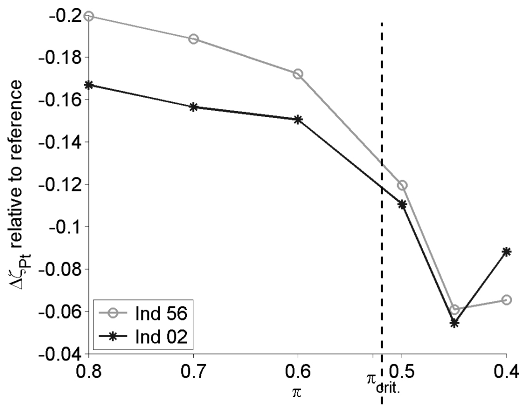

Figure 7: Total pressure loss relative to reference over pressure ratio.

5 CONCLUSIONS

A new axisymmetric end wall design has been designed for a guide vane of a control stage. This end wall design has been gained by an evolutionary optimization algorithm. This algorithm has been successfully connected to a commercial CFD solver. The aim of the end wall contouring was to reduce the total pressure loss and the secondary flow regimes in the guide vane. A significant reduction of the total pressure loss was achieved. This investigation shows that the optimization of the shroud contour is not a simple problem. It shows that an evolutionary algorithm is a suitable optimization method for this problem. However it also shows that the evaluation of the fitness function has to be speed up. One method would be an approximated one dimensional calculation of the flow field in the guide vane. In order to include the influence of the guide vane contour on the efficiency of the control stage, the whole stage will be simulated during the further optimization. In a further step the results of this investigation will be compared with measurements of an air turbine test rig with different end wall configurations.

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