INCREASED EFFICIENCY BY OPTIMIZING THE LAST STAGE OF A STEAM TURBINE

Introduction

The energy supply now and in the future is one of the most important issues of our time. It is foreseeable that in the future the energy consumption continues to rise and the supply of coal and other fossil fuels becomes more difficult. In order to meet future energy needs, in addition to the development of new renewable energy sources, the existing methods for energy production must be as efficient as possible. Further development and the use of modern technologies in power plants, as well as new computational methods for the optimization of turbo machinery, are options for a more economical use of the existing energy resources. But not only increasing the efficiency is one of the key criteria in today’s turbo machinery development, in the case of electricity generation mainly the reduced emission of pollutants and, thus, the preservation of the environment, represents an increasingly significant role.

This article describes an optimization of the last stage of a low pressure steam turbine followed by a diffuser. Since more than 30% of the power is produced in the last two stages of the turbine, this part provides great potential for improving the efficiency of the cold end of the turbine. The resulting losses may be reduced only to a lesser extent by a heat recovery. Therefore, the optimization of the outflow and the conversion of kinetic energy into potential energy by improving the pressure recovery in the diffuser, can decrease the enthalpy at the outlet of the diffuser and so increase the enthalpy difference and thus also significantly improve the system efficiency.

A decisive factor for optimizing this components is the joint consideration of both the last stage and the diffuser. In most cases, the respective components are designed and optimized separately and therefore the full potential for optimization is left aside. Therefore, it will be presented in this article, first a sequential optimization of the last stage followed by a optimization of the diffuser. In comparison, a coupled optimization of both components will be made to show the differences between these two methods. As a basis for this work, there is a self-made design of a last stage and the diffuser based on information of the industry and literature. In the simulation, next to the flow simulation, a mechanical and dynamical analysis of the stresses and natural frequencies is performed. The calculations are conducted using ANSYS Workbench software. In the first step of optimization, using the optimization software optiSLang, the blades are optimized for fixed diffuser parameters. In the second step, the optimized blades are also fixed and the diffuser is optimized. In the final step, a coupled optimization of diffuser and blades is carried out, starting from the initial design. In the coupled optimization a large number of parameters for both components (51 overall) is involved to also represent the opportunities to solve any large optimization problems efficiently. By the individual optimizations, the sensitive parameters and correlations for the respective outputs and components are also noted.

In the field of optimization of the coupled last turbine stage and the subsequent diffuser, there are already some publications. In most cases, however, the calculations are carried out using 2D codes in order to avoid the high computational cost of 3D simulation. With the constant improvement of computer power and more efficient numerical method, it is worthwhile to work on this topic in the 3D area and more. Overall, all these publications show a clear improvement over the outcome designs that are previously developed sequential.

Application to aerodynamic optimization

In comparative studies on the application of the deterministic optimization for aerodynamic optimization Müller-Flows (2000), Soni et al. (2002), Shapoor (2000) usually stochastic programming algorithms or response surface methods. Pierret and Van den Braembussche (1999) are used in turbo machinery design, for example in the development of engine components, such as at Vogeljanuth et al. (2000). In Sihy et al. (2001) a comprehensive overview is represented.

An example of an applied aerodynamic deterministic optimization using a genetic algorithm is published in Trigg et al. (1997) and the optimized design of transonic profiles also a comparative approach is given in Oyama (2000). Another very comprehensive study of the use of the combination of genetic algorithms and neural networks for two dimensional aerodynamic optimization of profiles is presented in Dennis et al. (1999), who combined a genetic algorithm with an gradient-based optimization method.

Application to coupled optimization of the last stage and successive diffuser

One of the first works in this area was published in Willinger (1987). In 1987 the aim of this work was not to optimize the coupled components, but in general, to determine the interaction of both components. In particular, the radial gap between rotor and casing was varied, while they observed improvements in the pressure recovery in the diffuser. With increasing the radial gap, the pressure recovery was improved, but with greater flow losses. These losses could not be outweighed by the greater pressure recovery. By increasing the marginal gap, the gap current experiences more energy which allows for certain construction of the diffuser to avoid separations. In particular this has the advantage that shorter lengths of the diffuser are possible, as well as greater diffuser opening ratio. Similarly, in this work, the proposal will be given a numerical optimization to determine further interaction phenomena and to integrate them into the optimization. Also Jung (2000) initially dealt only with the phenomenon that occur in a coupled calculation and developed in his work an efficient numerical method for the calculation of the coupled model. An optimization is presented for example in Kretzmer and Geim (2003) using a low pressure turbine stage and a subsequent axial radial diffuser. Here, the diffuser has been optimized under fixed blade geometry. The optimization was carried out using a numerical method and in a second sample using an experimental optimization. Both methods achieved significantly better performance than comparable standard designs. The best result came from a 3 channel diffuser. Further work on this area was performed by Fan et al. (2007) in a coupled optimization. It turned out that the inhomogeneous flow of the output stage are one of the main reasons for separations in the diffuser. By optimizing the coupled system, also a much better overall performance was achieved. In Stier and Musch (2008) a coupled optimization is also carried out with the focus on the influences of the tip jet, the influence of the flow on the diffuser is investigated with the background of the CO2 reduction. One result of this work was the development of an efficient method for determining the release tilt of the diffuser, which makes, coupled with an optimizer, very quickly a streamlined design of a diffuser possible. One of the probably most recent work in this area represents Musch et al. (2013). In this work, both last stage and diffuser, were optimized using a “covenant matrix adaptation”. To reduce the high computational complexity of this optimization a 2D through-flow code called “SLIQ” by Denton (1978) was first used and then were the results validated in a further step using a 3D simulation. Result of this work was that a significantly greater potential exists for a coupled optimization. The physical explanation for this greater potential lays in the fact, that the pressure distribution in the outlet of the last stage is the inlet pressure distribution of the diffuser. Therefore, it was also recognized that diffusers, which are based on standard correlations, always lead to a not fully utilized overall performance. A similar work can be found in Burton et al. (2012).

Numerical Model and Simulation

For this work a geometry of the last stage and the diffuser was made based on information from industry. The first developed model was improved by hands, until it was nearly comprehensive with machines in the industry, so that the optimization is also in an area of practical importance.
Based on a fully parametric geometry model the software ANSYS Turbogrid and ANSYS Meshing is used to realize an automatic mesh generation with in mean 3.5 mio. hexahedral elements for the last stage used and 180k elements for the diffuser. The CFD simulation is realized by the ANSYS CFX solver in combination with mechanical and dynamic analysis for further restrictions in the optimization with 57k tetrahedra elements in the mean.

The boundary conditions for the CFD simulations, are also based on requirements of the industry. It is performed a steady state analysis with a k- turbulence model and a pressure profile combined with a velocity profile from a real existing low pressure turbine. Also the static temperature of 320 K was set. The setting for the turbulences and the rotation speed is equal to 50 s⁻¹. The influences of the pressure and temperature of the CFD analysis were not considered, because they are marginal next to the influence of the centrifugal force. The material used for the blades was X5CrNiCuNb16-4 (Material specs from Edelstahlwerke (2008)).

For the mechanical and dynamical boundary conditions the rotation speed is equal to 50 s⁻¹. The influences of the pressure and temperature of the CFD analysis were not considered, because they are marginal next to the influence of the centrifugal force. The material used for the blades was X5CrNiCuNb16-4 (Material specs from Edelstahlwerke (2008)).

For the optimization process the speed of convergence to the restrictions, defi ned as equality and inequality constraints is given as $\sigma_d \geq \sigma_{d\text{lim}}$. The necessary tools to achieve a good convergence for such applications is the optimization objective or as restrictions, which are shown in the tab. 2, 4, 5. Next to the CFD residuals there were also proved that the output parameters reach a convergent result, for example shown for the total isentropic stage efficiency in Fig. 5.

The deterministic optimization problem:

$$\begin{align*}
\mathbf{d}_* & = \arg \min_{\mathbf{d}} f(\mathbf{d}) \\
\text{s.t.} & \quad g_i(\mathbf{d}) = 0, \quad i = 1, \ldots, m \\
& \quad h_j(\mathbf{d}) \leq 0, \quad j = 1, \ldots, l
\end{align*}$$

is defined by the objective function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ subject to the restrictions, defined as equality and inequality constraints $g_i$ and $h_j$. The variables $d_1, d_2, \ldots, d_n$ are the optimization or design variables and the vector of the partial safety factors $\gamma$ ensures the system or design safety within the constraint equations $\gamma_m$, for example defining a safety distance $w(\mathbf{d}, \gamma) = \gamma_m \gamma - \gamma_0 \geq 0$ between a defined limit state value $\gamma_0$ and the nominal design value $\gamma_m$ of a physical response parameter $y$. In structural safety assessment, a typical constraint for the stress is given as

$$w(\mathbf{d}, \gamma) = \sigma_d / \sigma_y - \sigma_y \geq 0$$

ensuring the global safety distance

$$\Delta_s = \sigma_d \left(1 - \frac{1}{\gamma} \right)$$

between the defined quantile value $\sigma_d$ of the yield stress and the nominal design stress $\sigma_y$ with the global safety factor $\gamma$. Whereby, in the real approach with given uncertainties $\sigma_d$ corresponds to the mean of Mises equivalent stress $\sigma_m$, at the current design point.

Global variance-based sensitivity analysis

A global variance-based sensitivity analysis, as introduced in Saltelli et al. (2008), can be used for ranking variables $\xi_1, \xi_2, \ldots, \xi_m$ with respect to their importance for a specified model response parameter.
In the following, this procedure will be repeated, for the rotor, diffuser and the coupled system. The constraints for the optimization regarding the geometry of the blade and diffuser are resulted mainly from the industry through guidelines. Additional constraints were safety factors for the stresses and a minimal distance of the eigenfrequencies to the machine frequency. For the objective the were two output used. First for the rotor optimization the total isentropic stage efficiency and second for the diffuser and coupled optimization the specific performance as shown in Tab. 1.

Sequentual optimization work flow

As a result of the sensitivity analysis, the coefficients of prognosis can be used to measure the importance of the input variables. One example is shown in Fig. 8 for the isentropic stage efficiency. The largest variance of the efficiency is described by the profile at 75% of the blade span. Fig. 9 shows the meta-model of the total isentropic stage efficiency in the subspace of the most important parameters. The results after the adaptive response surface method optimization and the preoptimization in comparison to the initial design are shown in Tab. 2 with an increasing of the efficiency of nearly 2% in addition to compliance with the constraints.
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After the blade optimization, the diffuser optimization is performed. Fig. 10 shows the parametrization. Therefore, 11 parameters are used for the diffuser optimization. The objective for this optimization was the specific performance. The resulting increasing of the specific performance is very low, because it is not possible for the optimizer to get a better design out of diffuser optimization. The diffuser is limited to the fixed flow field of the last stage. This means, it is just possible to get a more improved specific performance with changing the flow field in the diffuser. This is reached in this case through increasing the pressure recovery. But as shown there is not a lot of further potential available.

Coupled optimization work flow

The last step is the coupled optimization of the rotor and diffuser. Now, the specific power is used as the optimization target. The optimization results are presented in Tab. 5. As shown in this table the specific performance is much better in comparison with the sequential optimization. The optimizer reaches the same level of stage efficiency like the sequential optimization but with keeping the pressure recovery as it was in the initial design. That means with the possibility of changing all parameters, the optimizer could change them in a way that both components benefit. This clearly shows the advantage of the coupled optimization compared to the sequential optimization.

Interpretation of results

Tab. 3 shows the differences between meta-model and recalculation of the diffuser preoptimization. The overall pressure and velocity distribution in the inlet and outlet of each optimization step is given for comparison. The pressure and velocity profile in the inlet and outlet of each optimization step is shown there is almost the same stage efficiency for both optimizations sequentially and coupled. It should also be noted that only a single parameter (lout) was active in the ARSM of the coupled optimization. One parameter from the diffuser may be enough, to change along with the blade parameters in order to achieve a better overall result.

As a further result, as shown in Fig.s 11-12 and 13-14, the total pressure and velocity profiles in the diffuser inlet and outlet of each optimization step is given for comparison. The overall pressure and velocity distribution in the inlet is nearly equal for all three versions of the diffuser. In the outlet, the distribution of the pressure and velocity of the initial design was much more uniform as it was for the coupled and sequential version. Even so the results for the pressure recovery showed that the initial design and the output parameters and the constraints is also shown. The result is a specific performance advantage for coupled optimization of 1.8% compared to the sequential optimization. Furthermore, the pressure recovery with +12.4% and the stage efficiency with +0.2% are better than the sequential optimization results. Only the safety factor of the coupled optimization regarding the von Mises stress is worse at -5.94% as in the sequential optimization, but meet the constraints of ≥ 1.5. Clearly visible is the large influence of a better pressure recovery on the specific power, although there is almost the same stage efficiency for both optimizations sequentially and coupled.
The pressure recovery of the sequential optimized design was more worst. This can also be seen in this diagrams. The reduced velocity, which is the result of a diffuser to transfer the kinetic energy into potential energy, is much better for the initial and coupled optimized design. There is a high peak of velocity in the sequential version. So the integral of these curves is much higher for the sequential version as it is for the others, which leads to a overall lower pressure recovery regarding that all three got nearly the same inlet conditions.

Fig. 15 shows the scaled form of the different diffuser geometries. In total 313 designs are calculated with a duration of 33 days and for the coupled optimization and 263 designs with a duration of 28 days for the sequential optimization. As hardware two computers with following specifications are used:

- CPU: 2 x AMD Opteron 6376 with 16 cores, 2.3 GHz
- 64 GB of memory

This computational effort shows whether it makes sense to perform an optimizations using 3D calculations or whether it would be better to use 2D calculations or similar replacement model. The computation efforts for both paths are very long and would probably be too time consuming for use in practice. However, the presented method with a less computationally intensive model or equivalent model and subsequent recalculation in 3D could also be a time efficient way to improve the development of such machines.

**Conclusion**

The specific performance benefit of the coupled optimization over the sequential optimization is 1.8% in compliance with all constraints. This is mainly explained through a much better interaction between stage and diffuser. In both optimization methods, a similar high stage efficiency is achieved. However, in the sequential optimization in a way that it prevented the diffuser, to reach a much better overall performance, which is below the overall performance of the coupled optimization. In the coupled variant the same efficiency is achieved, but in such a way that the diffuser could also achieve a very high pressure recovery. During the optimizations the whole parameter space, which is used for both, is equal. Therefore, it can be seen as the final result that the coupled optimization in this work has significant advantages over the sequential. The fact that there is a coupling of the two components since the outlet of the stage and thus the flow field corresponds to the field entry of the diffuser. Both have influence on the performance values of the overall system. Although the flow can be designed that it produces a good stage efficiency for the output stage, but a poor flow field for the diffuser and vice versa.

To give this work a conclusion, there is a recommendation to develop and optimize the last stage and the diffuser in a coupled way to use the full potential of both because:

1. There is a better understanding possible of the relationship of individual performance output parameters and the parameters affecting them across the component boundaries.
2. It can be exhausted additional potential, by simultaneous modification of parameters of both components to a better overall performance.
3. The flow field is adjusted, therewith both components can benefit and not a component is better or worse.
4. It may be more time efficient to develop both components simultaneously.

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Authors // K. Cremanns / D. Roos, A. Graßmann (Niederrhein University of Applied Sciences)

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