EXPERIENCES FROM THE JOINT DEVELOPMENT
OF THE GTX100 TURBINE BLADING

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ABSTRACT

The GTX100 is the most recent industrial gas turbine in the ABB fleet. The development of the GTX100 turbine blading was a joint project involving four companies. A thorough evaluation of various design requirements resulted in the selection of a single shaft three-stage turbine configuration.

The cooling techniques employed for the blading are based on the knowledge from the Russian school of design for gas turbines. These techniques have been verified by a considerable amount of experimental data and field experience over a number of years. To incorporate western manufacturing methods, western suppliers were introduced at an early stage in the development. Most of the engineering development of the turbine blading was carried out in Russia. In order to achieve efficient cooperation between Russia and Sweden, specialists from both companies were stationed at alternating companies. The verification of the turbine design is divided into two steps. The first step is cold and hot component testing and the second is the overall engine testing.

INTRODUCTION

Development of a new gas turbine is a major investment for a company and historically it takes several years to finalise a project. Today time-to-market is extremely important and development time needs to be reduced. The main reason for this is the increased speed of change in the market, which makes the project targets more or less continuously moving. From a technological point of view a gas turbine is a challenging product. Gas turbines operate at high pressures and temperatures and rotate at high speeds, as a result of which a variety of advanced technologies are involved when developing a new machine. The combination of rapidly changing market with the need for a variety of advanced interacting technologies presents challenging tasks for the development team.

To reduce the time-to-market it is necessary to start production development of the long lead time components at an early stage of the development program. Investment cast blades and vanes are among the long lead time components in a gas turbine. The reason for the long lead time is that blades and vanes require tooling for wax and core dyes as well as for manufacturing operations like grinding, brazing and coating deposition. Furthermore, extensive and time-consuming process development is required to fulfil technical requirements such as metallurgy, dimensions, air flow, etc.

During the development of gas turbine blading numerous decisions have to be taken, many of which are conflicting with respect to different product targets. The target alone is not sufficient to avoid sub-optimisation. What is ultimately important is the value of each target in respect to the others. For example; the decision must be taken, after balanced consideration, as to the extent to which the product cost should be allowed to exceed the target if, at the same time, the efficiency is improved above the target.

During the development, a ranking list between the most important targets was used. This list, “Buying Criteria” had the following top-five requirements:

- high reliability
- low first cost
- high efficiencies, especially in combined cycle applications
- low environmental impact
- service friendly, low maintenance cost and time

THE GTX100

GTX100 is a modern, high-performance industrial gas turbine (Fig. 1). It is a single shaft design (6600 rpm) and utilises cold-end drive, via a speed reduction gear box. The compressor is built of an electron beam welded rotor and consists of 15 stages with a pressure ratio of 20. The combustor, of annular design, is equipped with 30 newly developed (AEV) Advanced Environmental burners, resulting in very low emission levels of NOx and CO, <15 ppm on natural gas fuel and < 25 ppm on diesel oil fuel in the load range from 50 - 100% (Jansohn et al). The three-stage turbine is built as one module for drive, via a speed reduction gear box. The compressor is built of an
The power output is 43 MW with cycle thermal efficiency of 37%. GTX100 is optimized for combined cycle operation (gas turbine exhaust energy is recovered in a heat recovery steam generator, giving steam for a steam turbine) and has in that application a power output of 62 MW, at an efficiency of 54% down to 70 % load under ISO-conditions. The operating range covered is the most frequent in combined cycle baseload applications.

Figure 1. GTX100 industrial gas turbine

GTX100 TURBINE BLADING

The GTX100 turbine is of 3-stage design (fig 2). The first and second stage vanes and blades are cooled, using the same proven ABB-technology as in the larger models. The first stage blades are made from a single crystal material coated with platinum aluminide to ensure durability. All the other blades and vanes are of equiaxed type using well established, commercially available alloys.

The following text describes the development of the GTX100 blading. Subjects like design principles, partners and suppliers, aerodynamic optimisation, cooling optimisation, and production are discussed.

Design Principles

A turbine blade or vane has a complex geometry on both its inside and its outside (fig. 3). The geometry on the outside is given by the fluid dynamics in order to minimise the performance losses. The geometry on the inside is given by the cooling requirements, which are set by the maximum material temperatures that can be accepted and by the heat flux from the gas flow. The cooling patterns on the inside of a blade or vane become rather sophisticated and investment casting is the only possible manufacturing method.

At the start of the project the development team analysed the targets and buying criteria and came up with some general design guidelines, which were very important, especially in the conceptual design. A special focus was concentrated on the reliability, since this was the key issue in the buying criteria. The analysis ended up in the following design guidelines for reliability:

- Use well-proven design solutions from the entire ABB gas turbine fleet, wherever this is in line with project targets. This approach gives the benefit of proven designs which experience has shown to be reliable.
- Use a simple design with as few parts as possible in order to keep down the number of parts and improve the reliability.
- Extensive testing for validation of all the new components. This gives experience in machine-like conditions.
- Use state-of-the-art tools (software) for the dimensioning and validation of the gas turbine to ensure a high calculation accuracy. Apply different tools and cross-check the results obtained in order to double check.
- Collaborate with the best expertise/partners in areas where this is needed to include the best competence available.
- Involve suppliers early in the design process in order to facilitate the manufacturing of high quality components. Manufacturing quality is affected in the early design.
ABB UNITURBO has been involved in several stationary gas turbine development programs. The company which was established by ABB and A. Lulka-Saturn OAO in 1993. In spite of its youth ABB UNITURBO consists of engineers with long experience of gas turbine engine development. Since its formation, ABB UNITURBO has been involved in several stationary gas turbine development programs.

Howmet Exeter Casting Ltd, established in 1970, is the prime supplier for GTX100 blading, i.e. responsible for delivery of engine-ready blades and vanes. Exeter Casting specialises in the casting of single crystal, directional solidified and equiaxed airfoils for the industrial gas turbine and aerospace market.

Vickers Precision Machining have been supplying gas turbine components to the world’s leading turbine manufacturers for the past 35 years. They have the expertise to provide manufacturing solutions for complex engine-ready components such as turbine blades, nozzle guides, vanes and heat shields for the industrial, marine and aerospace gas turbine sectors.

The blade design work was carried out in co-operation between ABB STAL and ABB UNITURBO, two companies with different backgrounds. Engineers at ABB STAL have a background from industrial gas turbine design whereas engineers at ABB UNITURBO have an aeroengine background. Furthermore, the engineers are brought up in two different systems, i.e. Western Europe and former Soviet Union.

The Russian aeroengine design approach for cooling, aerodynamics, and mechanical integrity, is to a large extent based on experimental data from full scale component and engine tests. The computer software used in this particular case is PC-based and tailor made for blade design with a quasi-3D approach. The western industrial gas turbine design approach is based on empirical design criteria, in depth 3D computer analysis and simulations on commercial software for work stations. It has been very useful to evaluate and combine the results from the two approaches during the development of the GTX100 blading.

Another difference is the market orientation and awareness. The ABB STAL development team, used to market economy has developed tools to optimise the product to fulfill customer requirements such as reliability, first cost, performance, life cycle cost, etc. The ABB UNITURBO engineers, however, with their aeroengine background, are more focused on the technical attributes of performance and reliability.

The basis for the co-operation between ABB STAL and ABB UNITURBO is an open atmosphere with mutual respect for each other’s opinions and ideas. Product targets and priorities were clear for both teams from an early stage of the program. This ensure that no difficulties was encountered in our co-operation, despite the different backgrounds of design philosophy and culture.

Aerodynamic Optimization

The meridional flow path of the turbine section is shown in Fig 4. The number of stages and load distribution between the stages were chosen during the Concept Phase and optimized during the detailed design by using 3D flow analysis codes.

The shape of the gas path has been optimized with respect to performance, leading to a diverging channel with cylindrical sections over the blades in the 1st and 2nd stage. The 3rd stage blades and all rotor knives under the vanes work against honeycomb sealings. This offers insensitive clearance independent of the axial position of the rotor relative to the stator during operation.

Partners and Suppliers

Collaboration with partners and suppliers is important for gaining competence, sharing experience accessing skilled resources. It is important to achieve win-win situations in all collaborations in order to be efficient and reach the common target. During the development of GTX100 several major collaboration teams were formed. The turbine blading is a joint development between ABB STAL in Sweden, ABB Uniturbo in Russia, Howmet Exeter Casting Ltd and Vickers Precision Machining in England.

ABB STAL is responsible for the overall development of the GTX100 turbine. ABB STAL has experience of gas turbine development since 1944.

ABB UNITURBO carried out most of the engineering development of the gas turbine blading. ABB UNITURBO is a company which was established by ABB and A. Lulka-Saturn OAO in 1993. In spite of its youth ABB UNITURBO consists of engineers with long experience of gas turbine engine development. Since its formation, ABB UNITURBO has been involved in several stationary gas turbine development programs.
After a thorough evaluation of a three-stage versus a four-stage alternative, the three stage solution was chosen, based on the following superiorities:

- Lower first cost
- Lower life cycle cost
- Increased combined cycle efficiency due to decreased cooling requirements
- Slightly better performance in simple cycle

A strictly aerodynamic design for the pressure ratio $\frac{p_{in}}{p_{out}} = 19$ would advocate a four-stage turbine configuration in order to provide minimal losses from the point of view of the airfoils exit velocities, being in the higher subsonic region. At the same time circumstances like high reliability and low production cost favor minimizing the number of turbine components, which brought the three-stage alternative into the discussion.

A three-stage turbine shows higher exit velocities for the blading. By careful profiling using 2D and 3D flow analysis approaches, the potential negative impact on performance can be avoided. Moreover, due to the optimal load distribution between the stages, the three-stage turbine offers higher efficiency for the last stage in part-load modes and gives a lower relative stagnation inlet temperature ($\theta = 30^\circ$) for the 1st blade in comparison with a four-stage turbine. The decrease is due to higher rim speed. Furthermore, a three-stage turbine provides less area to be cooled resulting in higher combined cycle efficiency.

When the loads for each turbine stage were defined the number of blades and vanes was chosen. This choice has to be a compromise between the manufacturing costs, cooling air mass flow consumption and a loss level. The best solution turned out to be relatively sparse cascades with low loss values for the exit velocity in the transonic range. Loss evaluations of the blade and vane rows as well as turbine stages were carried out using several methods of analysis in parallel. Among those, generalized dependencies, regression analysis methods, 2D and 3D Navier-Stokes solvers can be mentioned. A conservative approach was used for evaluating the turbine power, i.e. for each loss component the highest value was taken into account.
Cooling Optimization

At the same time as the drivers for higher cycle efficiencies points towards increased firing temperatures and pressure ratios, more environmentally friendly products put restraints on the temperature level in the combustor. Combining high performance, i.e. increasing turbine inlet temperature and minimizing emissions using the latest technologies, still makes it necessary to preserve as much as possible of the flame temperature until it reaches the 1st stage blade. In order to achieve this a non-dilutive design of the combustor was chosen. This means that the turbine blading has to face a very flat temperature profile at the exit of the combustor, which imposes additional requirements on the cooling.

During the initial phases of the development two options were found feasible for cooling of the 1st blade, namely film cooling and convective cooling. Film cooling was selected because of lower cooling air consumption and lower material temperatures. The main cooling principles for the different stages are, film cooling for the 1st stage, convective cooling for the 2nd stage and an uncooled design for the 3rd stage. In the design of the 1st stage the characteristic matrix is used, located in the aft of the airfoil, offering maximal coolant capacity and structural stiffness. The matrix consists of opposite crosshatched ribs on the adjacent inner walls of the airfoil.

In order to minimize the process losses by extracting cooling air at a high pressure level and then applying it as cooling at a lower pressure, several extractions are necessary. This also enhances the heat pick-up by the coolant as the temperature difference between the fluids is maximized. Air is taken from the compressor at 6 different pressure levels, of which 4 are used for cooling of the turbine blading.

As well as the choice of stage loading the continued iterations of the blade and vane profiling have a close connection with cooling optimization of airfoils and flow path boundary surfaces. The Q3D approach was intensively used in all steps of the program. The idea of this method is that the blade and vane temperature state calculation is carried out for individual airfoil cross section (see Fig. 7).

The influence of these profiles on each other as well as the radial flow inside the airfoil, i.e. air heating and "pump-up" effect, are taken into account in the temperature calculation. The blade and vane hydraulic network also reflects the full 3D model of blade or vane. Boundary conditions like heat transfer coefficients from gas and from air to blade and vane wall were obtained from the boundary layer calculation and extensive experimental databases. Figure 8 shows the temperature distribution around the leading edge of the 1st vane. The temperature calculation results were used for the stress-strain calculation in the different cross-sections exposed to bending stresses, stresses caused by the centrifugal forces and temperature stresses. This approach allows rapid calculations with high accuracy in predicting the heat and stress-strain condition of blades and vanes, including the effectiveness and performance of different cooling schemes.

In order to decrease the number of iterations during the initial analysis, a simplified dependence was used on the Concept Phase for the temperature & stress calculation. During the Design Phase the full 3D models temperature & stress calculation of all blading was carried out. This calculation confirmed the reliability of the chosen design.

Mechanical Integrity

The blading design evolved from simple 1D calculations in the feasibility study via quasi-3D calculations in the concept phase to full 3D calculations in the design phase. Figure 9 shows the 3D temperature distribution for the 1st stage blade.

The list of material considered was divided into different levels of preference with regard to cost and delivery time. If the first choice failed to meet the mechanical integrity requirements the second alternative was given highest preference. The approach guided the
development team to find competitive solutions during the development phase.

To ensure the reliability all blades and vanes are designed with design criteria used in other proven designs in the ABB fleet.

Figure 9. 3D Temperature distribution of 1st stage blade

**Production**

One challenging step in blade development is the transformation from calculation results and computer blade models to finished engine-ready components that fulfill the design requirements. To achieve this target a team consisting of representatives from ABB STAL, ABB UNITURBO, Howmet, and Vickers Precision Machining was formed at an early stage of the project.

The only possibility to develop the turbine blading in a short time with an optimised design that is also manufactureable with high quality and low cost is to co-operate from an early stage of development. This type of collaboration means mainly simple communication, e.g. a change in the design needs urgently to be reviewed by manufacturing specialists. If the teams, as in this case, are spread out over different countries, clear routines have to be settled for the communications. Easy communications via fax, phone, e-mail and courier are most frequently used but this does not replace all personal meeting with participants from all parties where in-depth discussions can be held. Another important aspect in collaboration between different companies, as in this case, is to have the commercial relation to each other very clear from the start.

One example of the importance of cross-functional teams from an early stage of the development is the casting of the matrix cooling scheme. Howmet Exeter had no previous experience from production of this design feature. However, by highlighting the problem, and by instigating early production trials an efficient production method could be developed for the internal cooling scheme GTX100 blading.

**Validation of Design**

A continuous validation process has been ongoing during the whole development process from blade design to component and engine testing.

During the design phase, state of the art tools are utilized for dimensioning. The calculations are validated by comparison to well proven blades and vanes in the ABB turbine fleet.

The production phase is validated using ABB specifications as a guide-line. The specification sets the standard concerning, for example, dimensional tolerances, microstructure, X-ray requirements. The final operation in the production of cooled blades and vanes is a flow test to verify that the components fulfill the specified cooling requirements.

The test phase is divided into two steps. The first step is hot component tests with machine like conditions in a test rig at ABB STAL (Fig. 10). The final step is full scale engine tests.

Figure 10. ABB STAL hot component test rig

**SUMMARY**

A team with representatives from the whole production chain from design to final machining was formed at an early stage of the development program. This collaboration has been working very well and even if we cannot prove it we are fairly sure that we have turbine blading today that has been developed both quicker and with a better optimised design than without this collaboration. In this specific case we also believe that we have brought the best technologies from the eastern and western world into one component.

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