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AERODESIGN AND TESTING OF AN AERO-MECHANICALLY HIGHLY LOADED LP TURBINE

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ABSTRACT

Future turbo systems for aircraft engines need very compact geometry, low weight and high efficiency components. The geared turbofan enables the engine designer to decouple the speed of the fan and the LP turbine to combine a low speed fan with a high speed LP turbine.

The low pressure turbine is a key component for this concept. The technological challenge is very much driven by the very high low-spool speed. Resulting from also high inlet temperatures the LP turbine needs cooling of the first stage. A new MTU LPT concept for such a high speed turbine has been developed and tested in a turbine rig. The concept consists of a 2 stage turbine for extremely high speed and high stage pressure ratio (ER 2.3). This leads to extra high mechanical loading and an exotic combination of high Mach Numbers (transonic) and very low Reynolds Numbers.

In this paper some design features are described. Some elements of the airfoil design were also tested in additional cascade tests. The 2 stage turbine was tested at the Altitude Test Facility of the ILA, Stuttgart. The test setup is described including details of the instrumentation. Test data shows a good turbine performance. Measurements are also compared to 3D CFD, which is used to analyse local effects.

NOMENCLATURE

C, C_{ax}	true chord , axial chord
h	blade height
h/b_{ax}	aspect ratio
Ma_{is}	isentropic Mach number
p, p_t	static pressure , total pressure

u	circumferential velocity
$\Delta H/u^2$	aeroloading parameter
$\Delta H/T$	specific work (J/(kg*K))
C_m/u	velocity ratio
Re_2	Reynolds number with chord
s/c	pitch/ chord ratio
te, le	trailing-, leading edge
A	LPT Gaspath Exit Area $A= \pi*(D_{od}^2-D_{id}^2)$
ADP	Aerodynamic Design Point
ATFI	Advanced Technology Fan Integrator
CFTR	Cold Flow Test Rig
ER	Expansion (Pressure) Ratio
HPT	High Pressure Turbine
idFP	ideal Flow Path
ID	Inner Diameter
ITD	Interturbine Duct
LPT	Low Pressure Turbine
N	Turbine Speed (RPM)
OD	Outer Diameter
TEC	Turbine Exit Casing

INTRODUCTION

The main selling argument for future business- and regional-Jets is a significant technical and economical advantage of airframe and propulsion systems compared to the existing technology. The development of today's jet engines is driven by the customer's request for low direct operation costs. This leads to new concepts which deal on one side with higher bypass-ratios, on the other side with the geared configuration, decoupling the fan and LP-shaft speed.

MTU Aero Engines is cooperating with Pratt & Whitney Canada (P&W C), Pratt & Whitney America (P&W A) and Fiat

Avio on the definition, development and testing of geared Turbofan systems. In this cooperation MTU delivers the high speed LPT. The propulsion system considered here is dedicated to empower the lower and medium thrustclass (10-20 klb) for the next generation of business jets and regional aircrafts.

The target of such a new engine is to reduce the direct operating costs by 10% including minimized acoustic emissions and improved environmental friendliness. The name for this system is PW800.

MTU Aero Engines achieved the LPT competence through more than 10 engine programmes since 1980. For geared systems MTU succeeded in the early 1990 with the 3 stage LPT for the Advanced Ducted Propfan (ADP) [1], [2], where very high efficiency levels were realized.

For the verification of the new technologies needed, the work was split into 2 workpackages. The first is the development and manufacturing of the LP turbine technology-rig for a demonstrator engine called Advanced Technology Fan Integrator ATFI [3]. This includes the testing of component characteristics with sea level and flight tests. This package is realized in cooperation with P&W C. The first successful Low Spool Engine Demonstrator was run in March 2001 at a PWC Test Facility after a very short development time of 9 months.

The 2nd workpackage consists of a detailed aero-investigation by establishing an additional highly instrumented coldflow rig. The engine test cannot be instrumented as detailed as it is necessary to get all the relevant information concerning the quality of the aerodynamic design and especially the efficiency split on the component level. Therefore, this coldflow-rig is the 2nd leg for substantiation of the LP-Turbine technology readiness. The Cold Flow Test Rig (CFTR)-tests were performed in April 2002 at the Altitude Test Facility of the University of Stuttgart.

This program also includes the development of new technologies such as advanced rotor concept, assembly-disassembly procedure, extreme minishroud design and light-weight single-crystal for the cooled LP1 blade.

The Concept

High efficiencies need different conditions for each component. High by-pass ratios necessitate larger fan diameters, raising the circumferential velocity at the fan tip. However, this is aerodynamically limited by strong shock systems occurring at high velocities, leading to a limited turning speed of the LP-shaft. The LP turbine on the other hand needs a high speed for optimal blade turning and Mach number levels. The conventional turbofan couples these 2 components on one spool, which leads to a compromised design for both. The geared turbofan concept decouples these two components, hence fan and LPT can work in their individual optimum speed range. In addition this provides the chance to reduce stage count and airfoil count in the LPT without losing too much efficiency. Based on conceptual studies it could be derived that this configuration has the highest potential for the next engine generation.

The Challenge

Several interesting technical solutions have to be found for making this system work. The most challenging are the very high Mach numbers due to the very high stage pressure ratio, the high gasloads on the static structures, the high stress-levels in the rotating parts and on top the high temperature level which implies the necessity of cooling for the 1st stage.

The focus in this paper is the aerodynamic design. The most interesting new aerodynamic feature is the combination of HP turbine like Mach numbers and very low Reynolds numbers under the challenging mechanical boundary conditions.

The main topics to be investigated in this program were:

- the feasibility of the specified efficiency level at the aero-design point
- the turbine map, the component's behavior at partload and offdesign conditions
- the lapse-rate (impact of Reynolds number on efficiency and flow rate)
- the impact of the combined effect of Mach- and Reynolds numbers
- the detailed measurement including the interturbine duct, profile pressure distributions on the vanes, stage worksplit and the stage reactions
- the derivation of potential for further improvements for the real product
- the influence of high airfoil area-taper on the radial work-distribution in the turbine

This includes the validation of aerodesign tools for this application class.

BOUNDARY CONDITIONS AND MAIN DESIGN PARAMETERS

The main design parameters at Rig Aero-Design-Point (ADP) are given in table 1.

No. of stages	2
Pressure Ratio	> 5.7
$\Delta H/u^2$	1.4
c_{ax}/u	0.55
Re-No. Blade 2	60,000
Ma_{exit} Blade 2	1
Speed [RPM]	10000
Inlet Flow Rate [kg/s* $\sqrt{(K / bar)}$]	145
$A*n^2$ [inch ² *rpm ²]	6.9

Table 1: Turbine Characteristics

Aerodynamic Boundary Conditions

The comparison of pressure ratio vs. stage count of this test turbine compared to other LP turbines is given in figure 1. Conventional turbines need up to 7 stages for the pressure ratio of ≈ 5.5 . The first technological step was done by an Engine 3 E turbine for the Advanced Ducted Propfan with P&WA. This MTU LP-turbine had 3 stages for this pressure ratio. The turbine

presented here also is designed for a geared turbofan but handles the same pressure ratio with two stages. In spite of the massive difference in aerodynamic loading (pressure-ratio wise) it is also possible to achieve high efficiency levels as it will be described later.

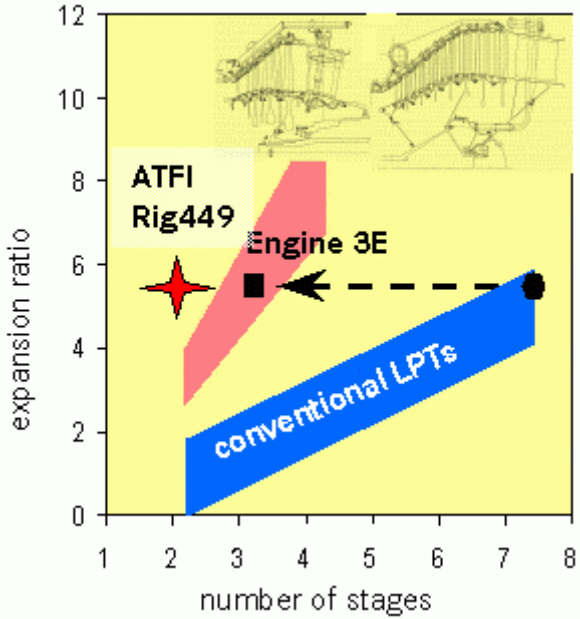


Figure 1: LP Turbine Aero-Loading Pressure Ratio vs. Stage Count

In the beginning of this project it was realized that this turbine features an extreme combination of very high Mach number level for LP turbines and very low Reynolds numbers, especially in the 2nd stage. This is presented in figure 2. The Mach-Number of > 1.0 is HPT-like, the Reynolds number of 50,000 (based on chord length) corresponds to LPT's for small jet engines.

Hence, there was concern with respect to fully separated flow on the airfoil suction sides and prediction quality of aerodynamic design tools.

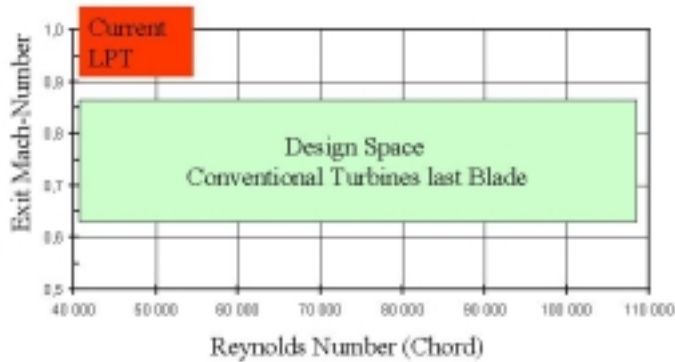


Figure 2: Exotic Combination of Mach and Reynolds Number in the last Blade

Therefore, typical profile shapes were derived from the last blade. This was transformed into 2 cascades to confirm the CFD Results. The cascades have been tested at the *High Speed Cascade Wind Tunnel* of the *Universität der Bundeswehr München* [4] and some results are presented here.

Mechanical Boundary Conditions

The most relevant parameter for the mechanical boundary conditions is $A \cdot n^2$. This is a characteristic number to assess whether the stress level of the design is within allowable structural limits. A is the gaspath area at turbine exit and n is the turbine speed at blocktest condition, which comes up with the worst combination of high speed and high temperature. Here, the maximum value encountered is $6.9 \text{ (inch} \cdot \text{rpm)}^2$. The normal values for conventional LP-Turbines are typically below $3.0 \text{ (inch} \cdot \text{rpm)}^2$ (figure 3). This leads to typical design features for the blading design, especially a high area taper from hub to tip to reduce the stress levels. Furthermore the stator vanes are subject to increased gasloads by the high pressure ratio. This has to be considered in the design of the airfoil shape.

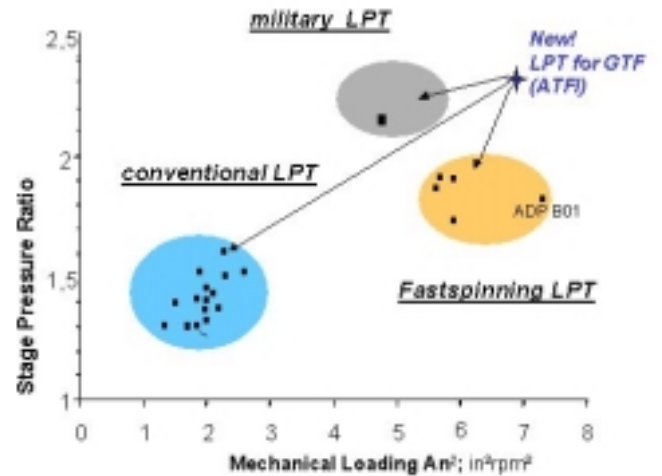


Figure 3: LP Turbine Mechanical Loading

AERODYNAMIC DESIGN

Gaspath

The Smith turbine loading diagram in figure 4 shows that, due to the high circumferential velocity u, the turbine works in an area of higher efficiency levels. What is also seen is that this type of machine works in the design space of HPT's.

This means it has the positive aspect of a high circumferential velocity u but is combined with the efficiency wise detrimental high Mach number level in the gaspath and on the airfoil surfaces. An additional positive characteristic is that the average blading acceleration exceeds values of $c_2/c_1 \approx 2.3$, while conventional modern turbines only have accelerations of around 1.8.

An important aspect for the overall optimisation is the best possible blading efficiency without creating high TEC losses

due to high blade exit Mach numbers and swirl in the absolute frame.

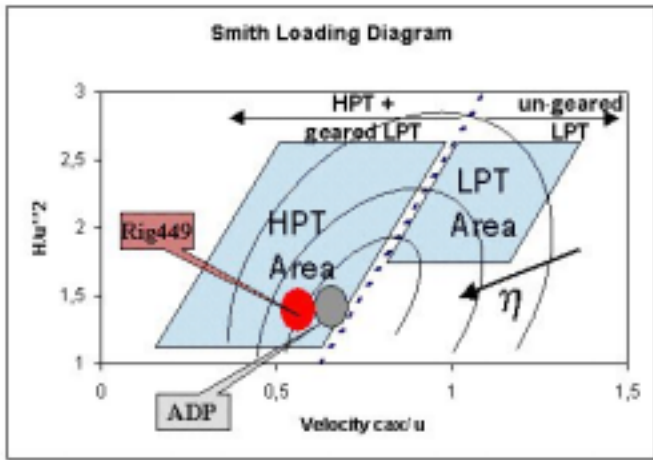


Figure 4: Smith-Loading Diagram

Caused by the very high stress levels in the rotating parts the overall optimization of the HPT/ LPT and the cycle is essential. The best aerodynamic result will occur with a good mixture of low axial Mach numbers, moderate turning and blade count. Very important is also to realize the maximum possible gaspath steepness without getting flow separation in the interturbine duct. This rises the average circumferential velocity u , lowers the loading $\Delta H/u^2$ and the turbine length is minimized.

This is an example for a potential system optimization. If the parameter A^*n^2 has to be lowered for example by 10%, one way could be to decrease the exit area by 10%, another to reduce the speed by 5%. These choices would lead to principally different efficiency drops. Figure 5 shows the effects, which lead to the following conclusion: If it is reasonable from the systems side it is better to change the speed and not the turbine exit-area for getting the lower stress levels. The limiting factor can be the gear-ratio for saving the optimum fan speed.

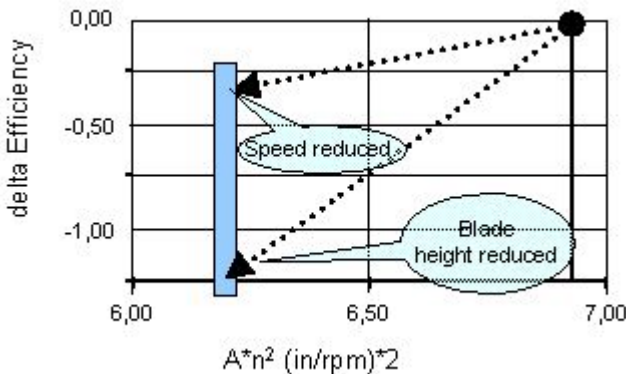


Figure 5: Relation Efficiency = f(speed; blade height)

Airfoil Design

The following figure 6 gives an impression of the 3D-shaped blading for the LPT. High aspect ratios need strongly tapered profile shapes. The tip region needs very thin airfoil sections resulting in very high pitch to chord ratios (>1.2). For this blade the area-ratio hub vs. tip exceeds 3.5, compared to $<<2.0$ for typical conventional turbines. At the hub this results in very thick airfoils sections with very low pitch to chord ratio (smaller than 0.6). Both conditions worsen the aerodynamic situation to perform low loss profiles, because this gives a further rise in the Mach number level. The aerodynamic design-space for geometrical optimization is therefore very limited.

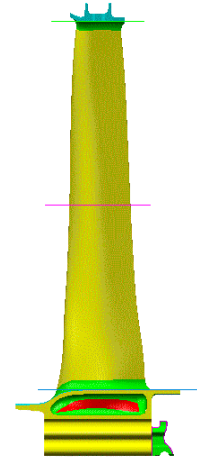


Figure 6: Side View of 2nd Blade with Area Taper

The favorable design characteristic here is the high aspect ratio (h/b_{ax}) of approximately 6, which is twice the value of the other typical small gasturbines. This reduces the extension of radial distortions related to the gaspath height and the secondary losses decrease.

The additional challenge for this turbine is the cooling of the 1st stage (mixing losses, airfoil shape). This means that the turbine has to combine the whole complexity of high-pressure turbines including intensive cooling with the very low Reynolds numbers. The Reynolds number level is driven by the turbine size and especially by the mechanical boundary conditions.

The modern conventional low pressure turbines have relatively high efficiencies. This is mainly possible due to moderate Mach number levels. However, this high speed LP turbine has transonic flow for the whole blading over the complete radial span. This is driven by the very high stage pressure ratio. Figure 7 shows the comparison of typical Mach number distributions for a fast-spinning LPT, a conventional LPT-blading and a highly-loaded transonic high pressure turbine.

The conventional blade shows Exit Mach-Numbers < 1.0 but local Mach numbers on the suction side may well exceed 1.0 locally in modern engines. The fast spinning and the high pressure turbine blade show exit Mach numbers near 1.0 and higher. This leads to typical phenomena for this loading-class. Peak Mach numbers of 1.2 and higher on the suction side result in shocks. Therefore complex shock boundary layer interactions occur, increasing the losses in the flow.

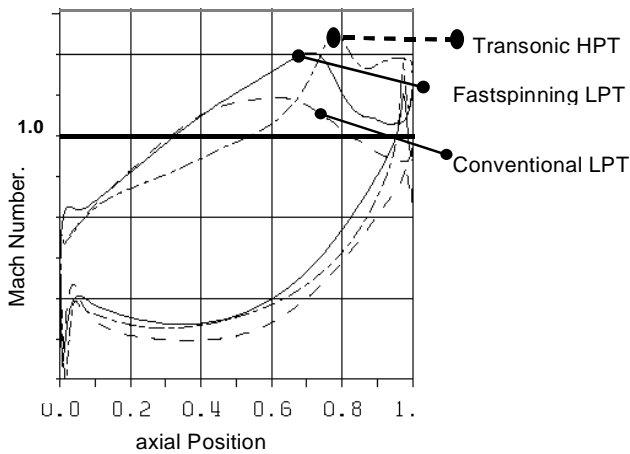


Figure 7: Comparison of typical pressure distributions for conventional LPT, highspeed LPT and HPT

CASCADE INVESTIGATIONS

As stated above the aerodynamic design of high Mach numbers and low Reynolds numbers inside the airfoil passage in combination with the strong mechanical requirements, especially in the rotor blades, proved to be quite challenging. It lead the aerodynamic design into regions with limited experience. Therefore, prior to the final design for the 2-stage turbine two cascade tests were performed in order to improve confidence for the design. Two especially critical sections of the last blade were investigated in a cascade test. For this the hub (T132) and the tip section (T133) of this blade were chosen.

The hub section (T132) features a low pitch to chord ratio with high blockage and very low Reynolds number of about 60,000 based on chord length. The second airfoil (T133) is a typical tip section with high pitch to chord ratio, approximately sonic exit Mach conditions and Reynolds numbers of about

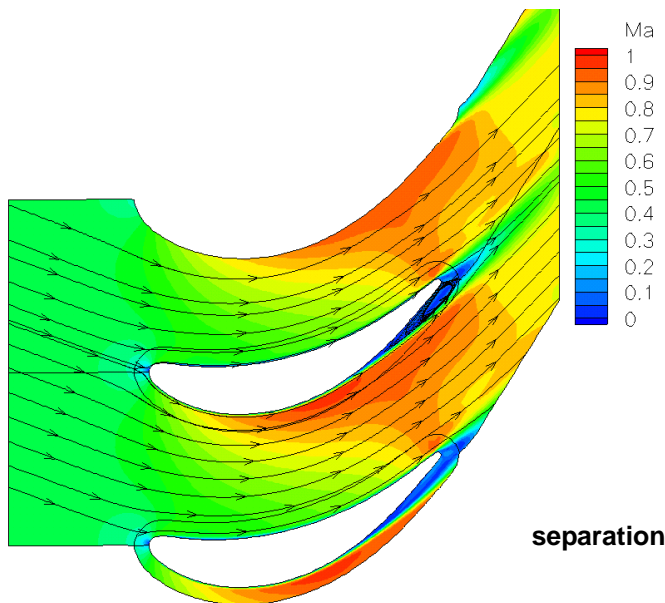


Figure 9: Comparison of Schlieren picture (experiment) and numerical solution of T132, $Re_{2th} \approx 60000$; $Ma_{ex} \approx 0.8$; $Tu_{in} \approx 1.5\%$

77,000.

The High-Speed Cascade Wind-Tunnel is an open-loop test facility with an open test section. The whole wind tunnel is installed in a cylindrical pressure tank. The Mach number and Reynolds number can be varied independently from each other.

Profile pressure distributions at midspan as well as inlet and exit flow-conditions (five-hole probe, wake traverses and turbulence intensities) have been measured for the cascade. Also Schlieren pictures were taken. Further details on the secondary flow structures have been obtained, performing oil flow visualizations of the blades at the endwalls. The measurements included various operating points.

For the nominal conditions the obtained pressure distribution is shown in figure 8. It is apparent that the flow on the suction side is fully separated for this operating point (see also fig. 9). This behavior is well captured by the numerical simulation. Detail about the numerical procedure can be obtained from [5] and [6].

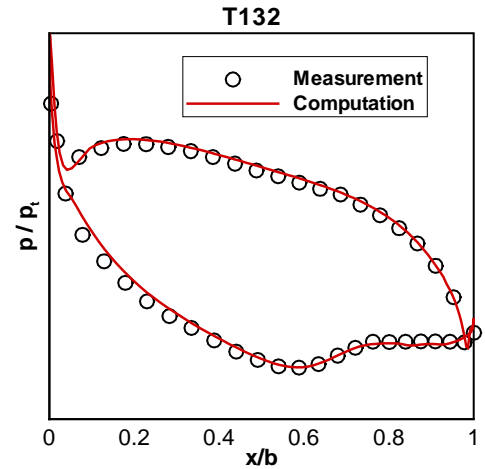
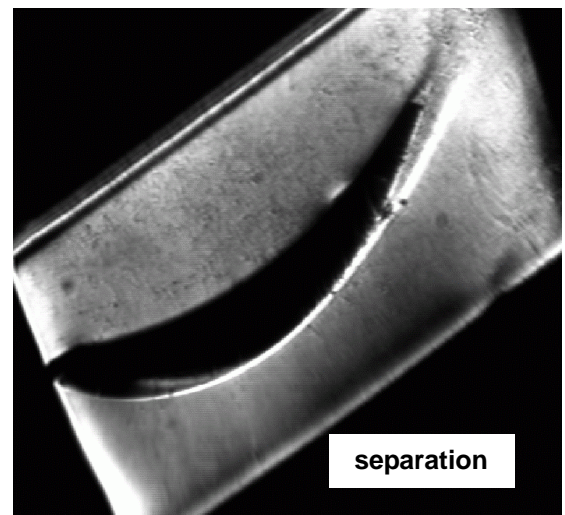


Figure 8: Measured and computed airfoil pressure distribution in the T132 cascade at nominal conditions



In figure 9, where the two-dimensional flow field is shown, this separation can be also seen. The considerable size of the separation is displayed by both the numerical solution and the Schlieren picture. However, the turbulence level in the wind channel was limited to 1.6% for this operating point, which is significantly below the level to be expected for the last blade of the 2-stage turbine. Although the danger of suction side flow separation for this blade is smaller in the turbine than in the cascade test, the blade built into the turbine was modified in order to reduce the separation tendency.

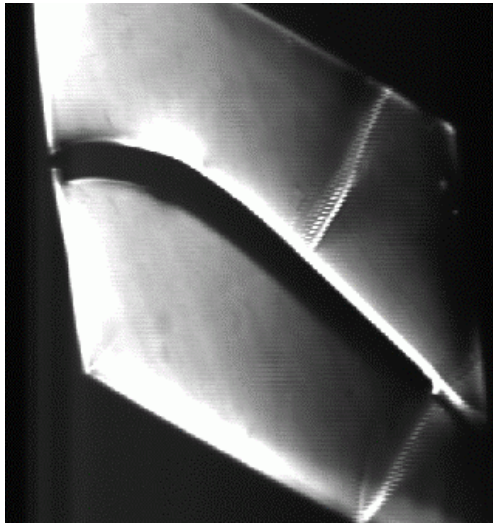


Figure 10: Cascade T133 Schlieren Picture (density), $Re_{2th} \approx 65000$; $Ma_{ex} > 1.0$; $Tu_{in} \approx 1.5\%$

In figure 10 the Schlieren picture of the T133 profile, which models the last blade tip section, is shown. In the design point this airfoil has an exit Mach number above one at a Reynolds number of approximately 77,000. The shock in the vicinity of the throat can be clearly seen. The pressure distribution proved to be very insensitive with respect to variations to higher as well as the lower Reynolds number in figure 10. No separation could be detected. Thus, this type of airfoil shape and pressure distribution was employed in the 2-stage turbine.

COLDFLOW RIG TESTS

Test facility

The two-stage test turbine was installed at the High Altitude Test Facility at the University of Stuttgart, Germany. The test rig is operated in a mode with a closed gas circuit in order to run the rig at Reynolds-numbers typical for jet engines. The inlet and exit conditions can be separately adjusted to simulate different altitude-levels and to cover the whole LPT-map. Before the air enters the rig the flow is homogenized in a large plenum chamber with an integrated flow rate nozzle. Figure 11 presents the installation in the test facility. The turbine power is transformed by a water brake.

In figure 12 a cross section of the test turbine is shown. To assess the inflow conditions, total pressure and temperature are measured in several radial and circumferential positions in the rig inlet duct. In the exit plane pressure and temperature probes with seven radial measurement positions are installed. Additionally, traversable 5-hole-probes were used to measure data for static pressure, total pressure, Mach number and flow angles. The entire instrumentation in the rig exit plane is installed in a traverse gear and thus can be traversed circumferentially by 2 pitches of vane 2. Furthermore, vanes 1 and 2 are instrumented with pressure taps for wall pressure on the airfoil surfaces in 3 radial positions. Tests were conducted at different Reynolds numbers and LPT expansion-ratios. Each condition includes a circumferential traverse over 1.2 pitches of vane 2.

As completion of the experiments the boundary layer flow was visualised with a colour injection into the airflow. Therefore, injection pressure and viscosity had to be adjusted to the specific thermodynamic conditions of the gas flow. The injection was done for the reference Reynolds number.

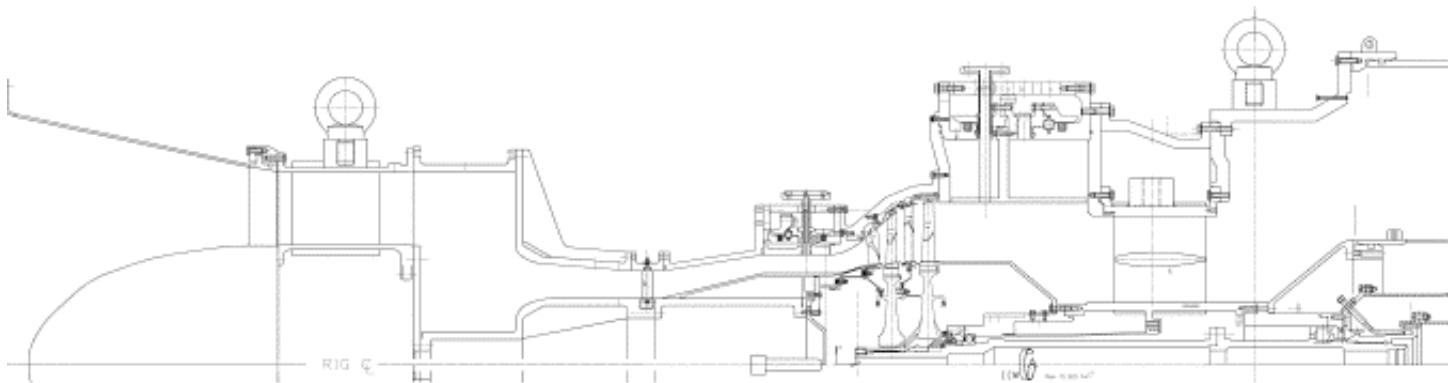


Figure 11: Test-Facility with installed Cold Flow Rig

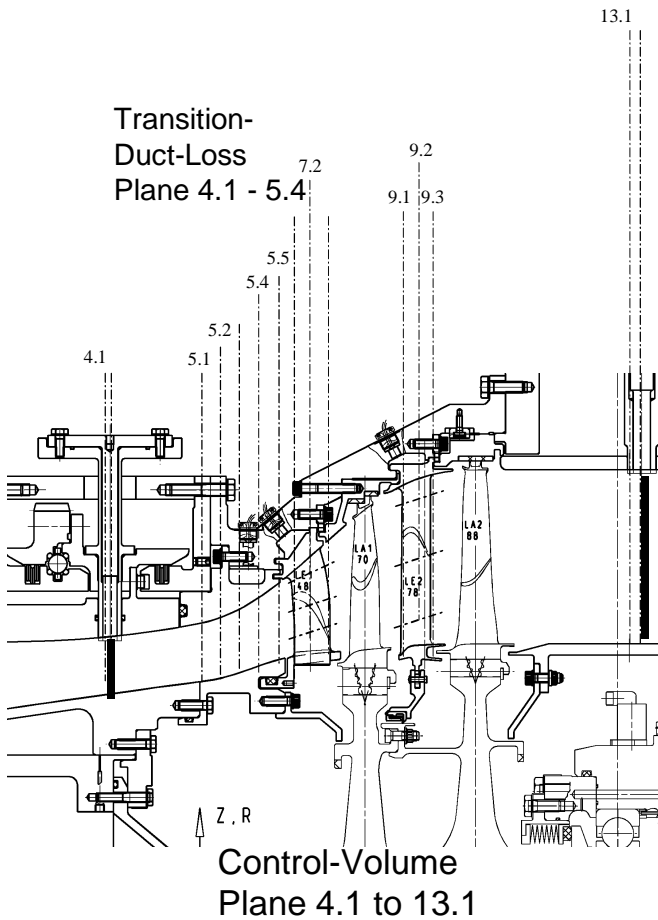


Figure 12: Test-Rig with Measurement Positions

Test Results

The Coldflow Rig has the geometry of the hot demonstrator component. The tests were carried out with an uncooled 1st stage (similarity of work-split; reaction; Mach-Number; Re-Number etc. is realized by restaggering for the missing cooling flows).

In figure 13 the measured turbine map is displayed in terms of efficiency as a function of $\Delta H/T$ and speed. As can be obtained from this figure, the maximum efficiency is located exactly at the aero design point. For this point the measured efficiency value is actually slightly above the prediction. The characteristics for higher pressure ratios shows no dramatic drop, so that mismatched engine conditions could be handled without operability-problems. Also the off-design behaviour looks quite reasonable.

Since turbines not operating inside the normal design space pose high demands on the design system, the rig was also used to verify the prediction quality of the aero design tools. Some examples are discussed in the following section.

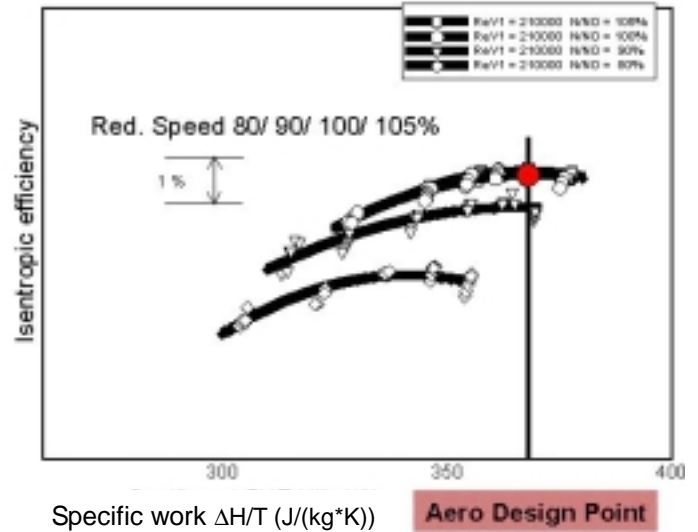


Figure 13: Turbine Characteristic for Several Speeds

In figure 14 the computed and measured pressure distributions are compared for the mid-section of the second vane. The simulation agrees very well with the experimental data. Obviously the inflow conditions are captured as well as the boundary layer flow of the vane itself.

The flow at mid-span is obviously fully attached (see also figure 15). The simulation slightly overpredicts the radial slope of the streamtraces between 25 % and 60 % span. This is an indication that the computation predicts a thicker boundary layer than present in the experimental set-up. The radial pressure gradient forces the slow boundary layer flow towards the hub, if the drag of the main flow is not strong enough to keep it on the ideal streamline. This indication of a slight boundary layer thickness overprediction is not critical, since it leads the aerodynamicist to a safe design.

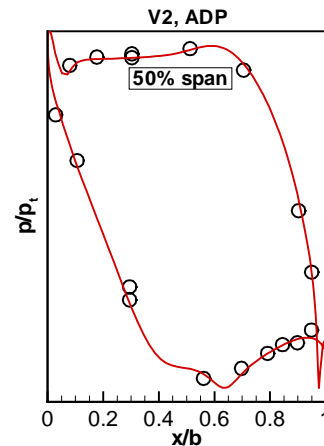


Figure 14: Pressure Distribution on Vane 2 Midspan

Close to the hub the passage vortex system drives secondary flow up to about 20 % span into the flow duct, which is quite well captured by the simulation. In the tip region both Navier-Stokes computation and experiment exhibit a local separation zone in a region with interaction between the tip

passage vortex and the main flow. Obviously the separation in the test turbine is weak, since it differs between different airfoils.

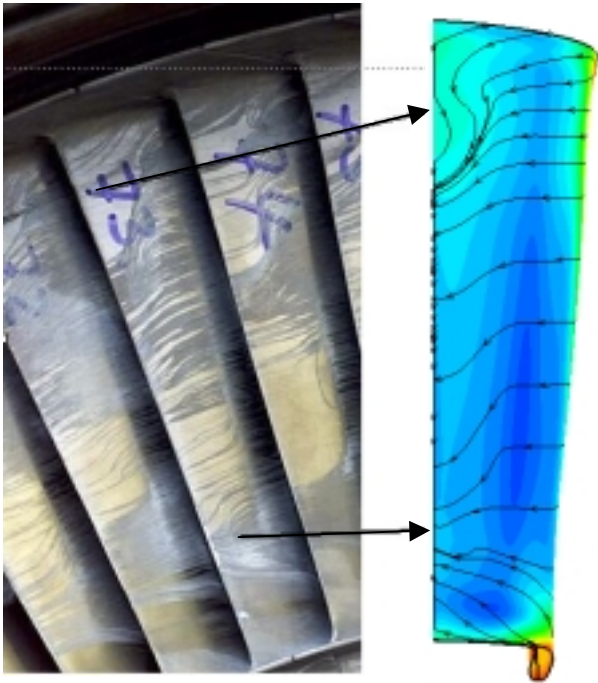


Figure 15: Flow Visualisation for Second Vane, Comparison of Colour Injection and Numerical Simulation

In figure 16 the static duct pressures are displayed in order to check the work split and reaction of the test turbine. The solid symbols characterize the measurement and the hollow symbols the simulation. Both agree well with each other. This gives confidence that no severe separations occur in the turbine and is verifying work split and reaction.

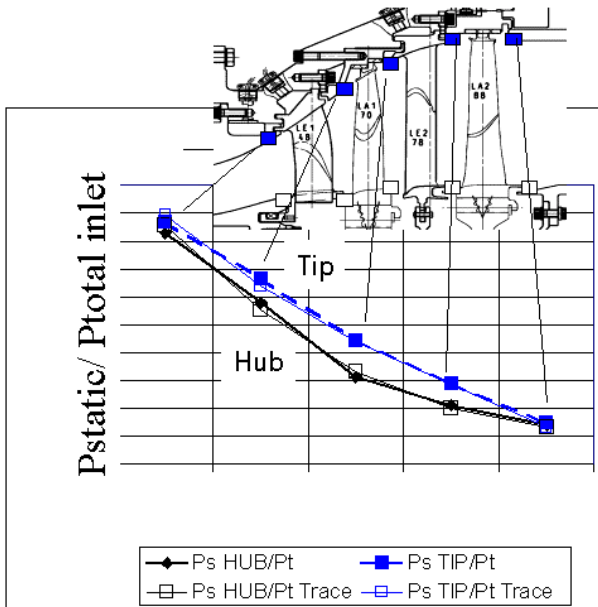


Figure 16: Normalized Cavity Pressures Measurement vs. 3D CFD.

Computations were performed for the ideal flow path (standard aero design procedure) and for the turbine geometry including the inner and outer air seals. A view of this numerical model can be seen in figure 17. It is set-up using additional blocks for the cavities, which are connected to a main flow grid, which uses the same parametrization as the standard computation (ideal flow path).

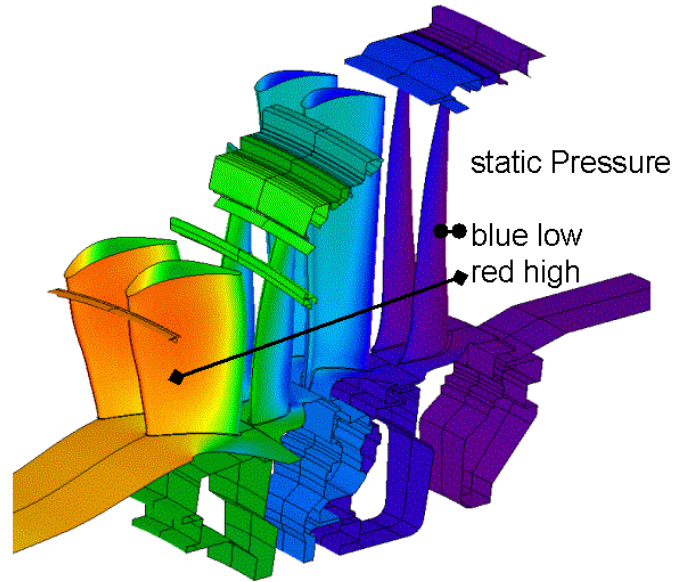


Figure 17: LP Turbine 3D-CFD Model including Cavities

In figure 18 finally the radial distributions of the isentropic efficiency are shown. At mid-span both computations exhibit a very similar efficiency level, which also quite well corresponds to the experimental data. In the endwall regions the ideal flow path computation overpredicts the efficiency. The cavity computation is closer to the measurement, because it captures additional loss mechanisms due to the presence of the cavities and the related leakage flows.

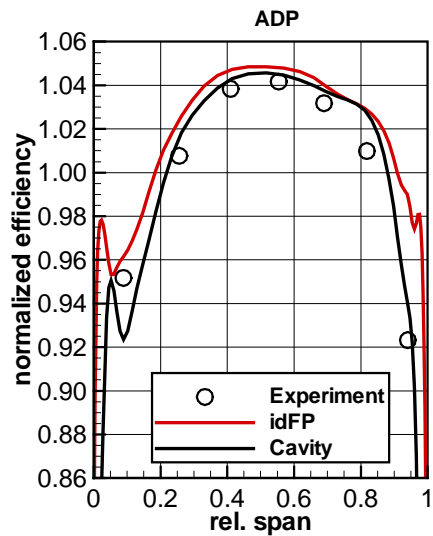


Figure 18: LP Turbine Component Radial Efficiency Distribution with and without Cavities (1 mm Radial Clearance)

The data gathered for this test turbine shows a good agreement between experiment and numerical simulation in terms of quantitative data as well as flow structure. This is of great importance for such designs, which reach beyond current experience.

CONCLUSION

The high speed LPT is an key component for the geared turbofan concept. The LPT discussed in this paper is an exceptionally challenging turbine. Therefore several investigation steps were taken in the aero design of this turbine. These steps are discussed in this paper.

In addition to the final, detailed investigations in a coldflow-rig with engine-like dimensions, cascade tests were performed for two especially critical airfoil sections in order to check losses and boundary layer stability as well as the computation quality. Based on these results the final airfoil design for the 2-stage turbine was carried out.

The measurements inside the test turbine included efficiency level, the turbine characteristic and profile pressure distributions. The results are very promising. Especially the difficult combination of high Mach numbers and very low Reynolds numbers was shown as controllable. Very good turbine characteristics were measured in terms of the efficiency level, which turned out well above 90 %, as well as the behavior in the turbine map. It was also shown that the MTU prediction tools are able to handle this turbine class. Taking the cavities into account showed a further improved prediction quality. These results represent an excellent base for the final definition for the PW800 engine and other similar products.

ACKNOWLEDGEMENT

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