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Advanced Technologies for Next Generation Regional Jets - Survey of Research Activities at MTU Aero Engines

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Abstract

This paper will address current demands and developments in advanced compressor and turbine design at MTU. Latest highlights achieved on new HP compressor and LP turbine technologies will be presented. Both components constitute key competences for MTUs civil aero engine business.

The paper will start with an overview on engine key requirements for the next generation of regional aircraft expected for the years 2013-2015. Engine concepts include conventional high bypass turbofans and more advanced new concepts such as geared turbofans. Subsequent compressor and turbine design requirements have been derived from detailed configuration analysis and competitive assessment among the aero engine industry. Strong emphasize will be put on both high performance and economic improvements compared to existing engine families in service. Fuel burn reductions in the range of 15% and maintenance cost reductions of more than 30% are the most prominent challenges.

Subsequent to the requirements the paper will illustrate the MTU technology and conceptual approach to satisfy the demands. Highly innovative world class compressor concept will be presented which are presently under test validation. The main characteristics of the new compressor concepts are full 3D Aero including casing treatment, all blisk light weight tie shaft rotor and advanced thermal management and radial gapping concepts. In addition, dedicated technology activities to further support significant improvements in efficiency, weight and costs will be highlighted, also including potential benefits from advanced control, monitoring and design methodologies.

Similarly for turbines, latest developments and efforts at MTU will be described. Apart from conventional turbines special focus will be attributed to high speed LPTs, typical for geared turbofans. It is well known that MTU together with Partners Pratt & Whitney and Fiat Avio have been intensively working on the geared turbofan concept to provide a step change improvement to the aircraft customer. MTU has been dedicated to take responsibilities in the high speed LPT and the HPC components.

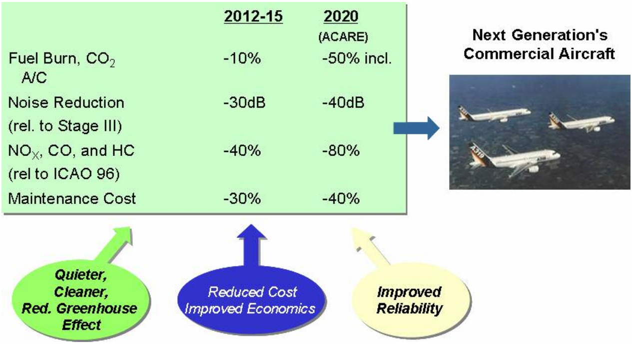
Abbreviations

ACARE	Advisory Council of Aeronautical Research in Europe
ADP	Advanced Ducted Propfan
ATE	Aerospace Technology Enterprise
ATFI	Advanced Technology Fan Integrator
BPR	Bypass Ratio
CLEAN	Component Validator of Environmentally Friendly Aero Engine
ECMS	Engine Control & Monitoring Systems
EEFAE	Efficient Environmental Friendly Aero Engine
6th FRP	EU 6thFramework Program
HPC	High Pressure Compressor
LPC	Low Pressure Compressor
LLP	Life Limited Parts
LPT	Low Pressure Turbine
MEMS	Micro Electronic Mechanical Systems
MTU	MTU Aero Engines GmbH
OPR	Overall Pressure Ratio
PAX	Passengers
PR	Pressure Ratio
TET	Turbine Entry Temperature
TF (GTF)	Turbofan (Geared Turbofan)

Introduction

The application of turbofan propulsion to subsonic transport aircraft has gone through an evolutionary process during the past 40 years, which substantially has contributed to the success of commercial aviation. This process, driven by the market needs, produced numerous technical innovations to the engine yielding significant improvements in engine performance economics, in safety and reliability and also in terms of noise and emissions.

With respect to the future, the replacement of existing 100-200 PAX aircraft will be a next opportunity for introducing a new generation of aircraft and engines. In preparing the transition into a new generation of aircraft the aero industry is facing fierce headwinds in terms increasing fuel prices, noise restrictions, limiting exhaust gas emissions, not only in Europe, but within the entire globe.



	2012-15	**2020** (ACARE)
Fuel Burn, CO_2 A/C	-10%	-50% incl.
Noise Reduction (rel. to Stage III)	-30dB	-40dB
NO_X, CO, and HC (rel to ICAO 96)	-40%	-80%
Maintenance Cost	-30%	-40%

Fig. 1: Commercial requirements for next generation Aircraft impose significant challenges

Fig. 1 illustrates the future demands and indicates the principle approach for the engine manufacturer. Further advanced engine components and new engine concepts are compelled to provide fuel burn reductions up to 50 % combined with extensive noise and emission reductions up to -40dB cum and -80% NOx respectively. Half of the fuel burn reductions are attributed to the engine; the remainder will be supplied from the aircraft manufacturer. Correspondingly cost constraints are expected to drop maintenance and manufacturing costs of the engine by up to 30% and more. The targets shown in Fig. 1 are specified into short to mean term customer needs and longterm visions as projected by European aeronautic agencies ACARE. Similar requirements have also been published by US organizations such as ATE. In consequence of the aggressive demands, the development of future engines will require to comprehensively deploying the potentials from

- further improving existing engine types
- new engine concepts
- and significantly further advanced component technologies for compressors turbines and combustors , including efficiency increase, weight reduction and life extensions.

In addition,
- smart control of overall engine and component operation as well as
- power optimized engine accessories and systems

will supplement the improvements from the turbo machinery components.

In preparation of the new engine generation for regional transport, extensive configuration and installation studies are under way. Similar studies should help to align airframe and market needs with the engine manufacturers capabilities. As shown in Fig 1, significant improvements in engine economics, environmental capabilities and reliability are being expected. Translated to a more general set data, the following engine requirements were evaluated relative to existing engines

- 5-10% improved propulsive and thermal efficiency, via increased BPR, OPR and turbine inlet temperature
- 0,5-1% increased efficiencies per component
- 20% reduced cooling air consumptions
- 50-100% increased LLP life
- 20-30% manufacturing cost reductions

across the entire engine.

Similar requirements call for extensive new technologies and new configurational answers. Present Paper will specify such answers from MTU perspective. Prime emphasize will be put on engine architectural options and on dedicated MTU key components such as HPC and LPT.

Advanced Engine Concepts

Future advanced engine concepts will in general continue to aim at further improving thermal and propulsive efficiency (reducing specific thrust) and developing low noise, fuel and cost efficient components. Fig. 2 shows this trend as applied to the further development of existing engine types. Further increasing the bypass ratio (BPR) up to 10-11 will enhance propulsive efficiency and further reduce the engine noise due to reducing jet velocities and reducing fan tip speeds.

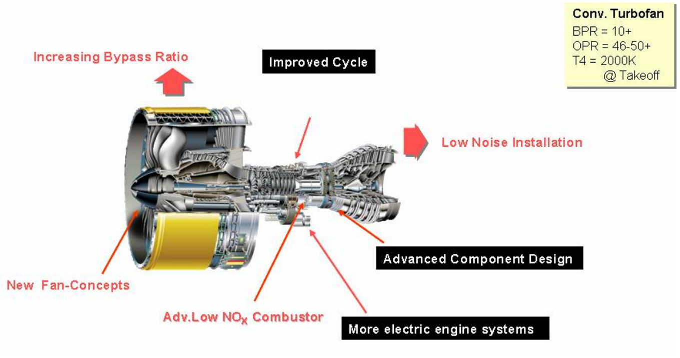


Fig. 2: Future advanced Turbofans will continue the trends of recent designs

Increasing of overall pressure ratio (OPR) and turbine entry temperature (TET) will enhance thermal cycle efficiency and need even more powerful and compact engine cores which should counteract the weight penalties from enlarging BPR and Fan diameters. For regional application OPR and TET are expected climb towards and beyond 40 and 1900 K respectively. On the component level, further increase of efficiency has to come along with enhanced stage loadings. Enhanced stage loading throughout compressors and turbines should allow to reducing stage count for minimizing manufacturing costs. For the HPT cooling air consumption has to be limited by introducing advanced cooling concepts including new aspects such as cooling air cooling.

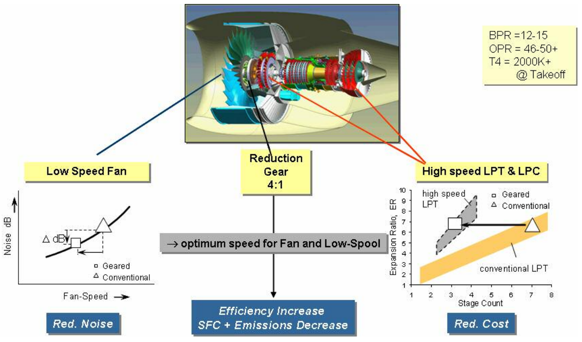


Fig. 3: The Geared Turbofan for maximum propulsive efficiency and minimum noise

The geared turbofan features a new engine concept, aiming at very high Bypass ratios and OPRs (Fig. 3). Since more than 15 years, Pratt and Whitney America (P&WA), Pratt & Whitney Canada (P&WC), Fiat Avio and MTU are jointly working on the development of geared turbofan engine technologies for small and large thrust class applications. In 1992 the partners successfully run the Advanced Ducted Propfan (ADP) demonstrator engine for bypass ratios up to 14 to demonstrate the technology for fuel efficient long range applications. More recently they introduced the Advanced Technology Fan Integrator (ATFI) representative to smaller thrust class engines (Fig. 4). Latest Efforts aim at a new PW6000 based GTF demonstrator to support the development of 20-30 klb new engine generation for regional aircraft. The GTF bears the advantage to separate the low speed Fan component from the LPC and the LPT. Thus both component categories, i.e. Fan on the one side and LPC/LPT on the other side can run at their optimum speeds allowing uncompromised maximum benefit in terms of component efficiencies, stage count (weight, cost) and noise (low fan speed for minimum noise).

So far, geared systems were confined to demonstrator applications only, but within the scope of new challenges from environmental and commercial constraints, studies have confirmed that the GTF will become a highly attractive alternative for the new generation of aircraft. The emerging demonstrator program will demonstrate this to the public.

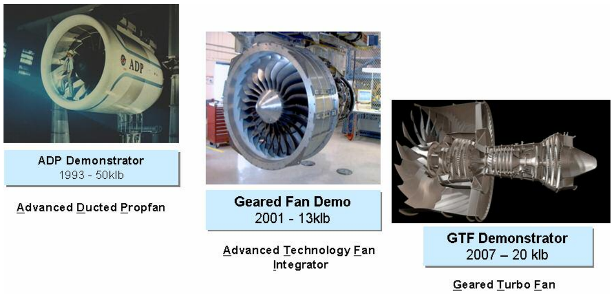


Fig. 4: MTU/PW support the new concept by extensive GTF demonstrator programs

In addition, latest considerations also include counter rotating Fans again, both ducted and unducted (Fig. 5). Similar concepts have already been studied during the eighties and nineties but in those times they were rejected due to strong weight and noise penalties from the big two stage fan propulsion system. Meanwhile new approaches obviously have been generated to overcome such hurdles and to start new technology initiatives to generate technical maturity within acceptable timeframes (e.g. GenY).

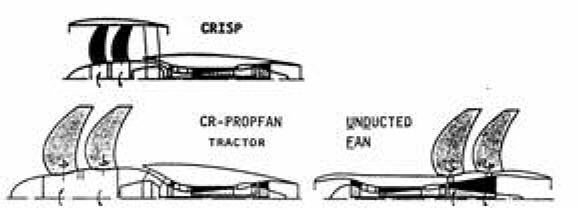


Fig. 5: Counter rotating Fans designed by MTU

Future HPC Compressor and LPT design requirements

The HPC is one of MTU's prime competence components within its civil and military aero engine development activities (Fig. 6).

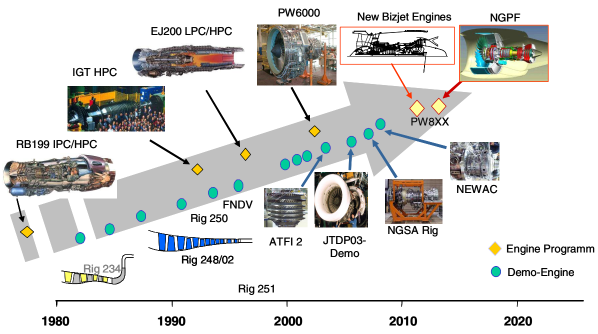


Fig. 6: HPC development at MTU

MTU developed the HPC for the RB199, which is used in the Tornado aircraft and more recently the HPC for the new EJ200 which is the propulsion system for the Eurofighter. By providing the HPC for the PW6000, MTU started to supply the regional civil aircraft market. Presently MTU prepares for developing highly advanced axial compressors for engines for the next generation of midsize regional jets and for future mid and large size business jets. As shown in Fig. 6, extensive technology and demonstrator programs have been accompanying the product developments. For the anticipated future applications, corresponding activities are already underway.

Fig. 7 illustrates the current trends in compressor development towards higher stage loading, both for HPC and LPC. The High-speed low pressure compressors (LPC) – as used for geared turbofans will adopt stage loadings similar to the HPC. The pressure ratios needed, will be accomplished by only half the stage count of conventional LPCs.

For the high pressure system, there are two major HPC categories, addressing the different range application:

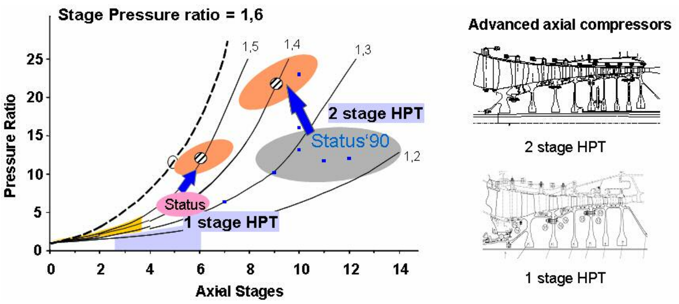


Fig. 7: Pressure Ratios for engine concepts with 1 stage HPT and 2 stage HPT

1. Axial compressors for big core engines with a two stage HPT, dedicated primarily to long range applications. In this class the trend towards highest OPRs leads to HPC pressure ratios around 18-22 whilst the stage count will be not higher than 8-10. Corresponding efficiencies will need to reach the 90% polytropic efficiency goal.

2. Axial compressors (Fig 7) for core engines with one stage HPT for short and medium range applications. The HPC pressure ratio will increase considerably beyond 12 while keeping the stage count lower than 7. A typical example constitutes the MTU HDV12 for the PW6000 engine (18-25 klb thrust range): 6 compressor stages are generating a PR of about 11, offering high efficiency, outstanding performance, operability and durability to competitive costs.

Independent of the application, the new compressor generation will need world class efficiency levels in the range of 90% and despite the requirement for nearly double the life of existing systems, the weight will have to be minimized to levels that are 10-20% lower than known from existing engines for similar thrust classes. Cost wise a challenge, as indicated above, in the order of 20% and more will have to be fulfilled.

On the LPT side, MTU has a strong history on both developing conventional low speed turbines for conventional turbofan engines and also high speed LPTs for Geared turbofans (Fig. 8).

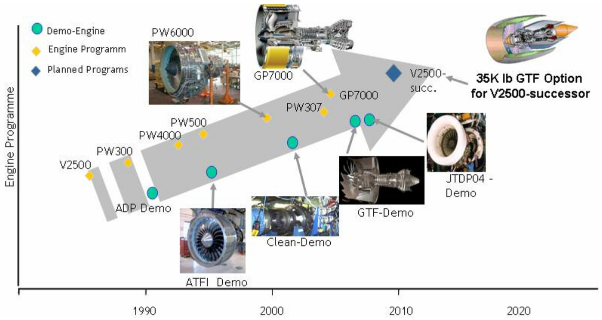


Fig. 8: LPT development at MTU

Similar to the HPC, a perpetual strive for simultaneously increasing stage loadings, reducing stage count and further increasing efficiencies will be mandatory. Efficiency levels will have to increase up to 93% . For GTF typical loadings will be in the range of PR 7 in 3 stages or PR 5 in 2 stages respectively yielding stage pressure ratios up to 2.2. The correspondingly very high wheel speeds needed claim for new design concepts to minimize blade and disc weights such as to maximize the benefit from significantly lower stage counts.

The conventional LPT will have to strive for lower stage count as well without loosing efficiency. This drives high flow path radii and very high specific loadings. The subsequent weight challenge results rather from the big geometric size of the LPT than from the high speed levels for GTFs.

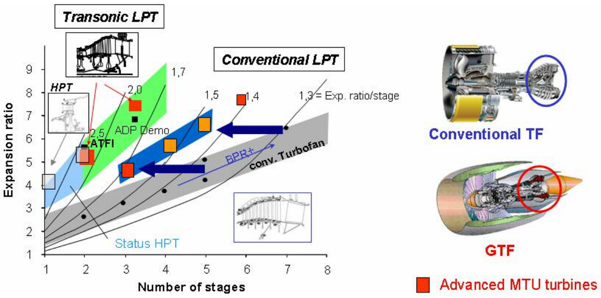


Fig. 9: Advanced LPT design

Advanced Compressor design

Fuel burn and maintenance costs reduction of future advanced engine concepts require a new compressor generation with world class efficiencies. Future HPC designs will feature high efficiency levels in the range of 90% while weight and part count have to decrease further. This results in a higher loading of the compressor blading with very high requirements on the aerodynamics of blade profiles and blade shape in order to avoid flow separation, shock losses and secondary flow losses. Especially the hub and the tip region of the blades have to be designed very carefully. The interaction of near wall leakages, tip clearance flow, secondary flow vortices and profile boundary layers are a big challenge for the design engineer due to different behavior at different engine operating points.

Especially at part speed the airfoils have to work under bad inflow conditions and tend to flow separation. For these flow conditions the flow in the tip region can be stabilized by the use of so called casing treatments (Fig. 10).

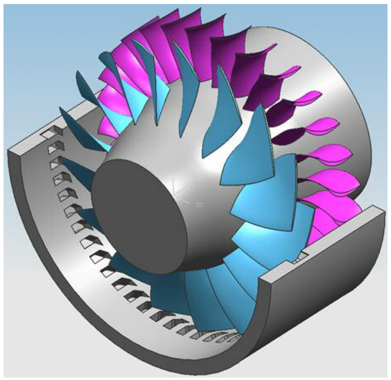


Fig. 10: HPC with Casing Treatment

Casing treatments suck in the low energetic flow directly over the blade tip and inject it in front of the blade leading edge. Through this the weak end wall boundary layer gets energized and stabilized and the tip leakage vortex is reduced. That leads to a much higher compressor stability primarily at low engine speed (Fig. 11).

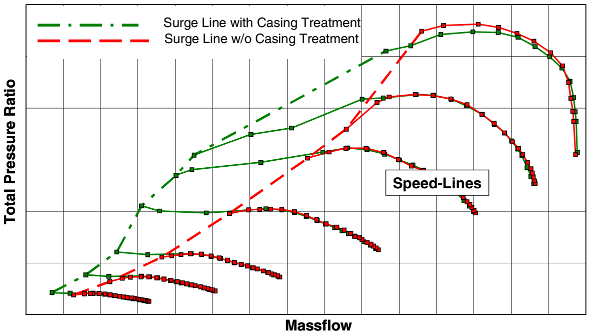


Fig. 11: HPC map with / without CT

Similar geometric modifications can also improve the stability of the hub flow. Well designed fillet radii can avoid flow separation on the airfoil suction side behind the leading edge (Fig. 12 and 13).

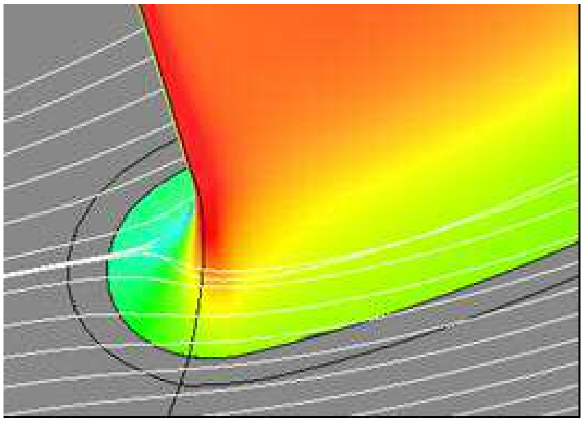


Fig. 12: Streamlines close to end wall for blade with optimized fillet radius

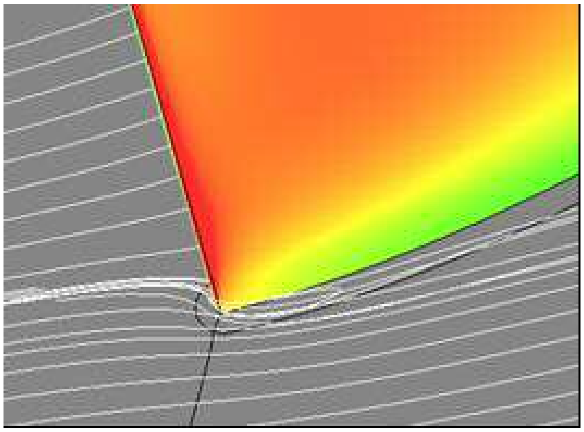


Fig. 13: Streamlines close to end wall for blade without fillet radius

The high incidence swirl of the near wall streamlines reduce the secondary cross flow in the cascade passage. Thus the corner stall can be avoided and the compressor airfoils can operate at high efficiency in a much bigger range. Additional leading edge bulb modification can strengthen this flow effect and reduce the secondary flow losses in the end wall region of compressor blades significantly.

In addition to the reduction in fuel burn the second big challenge for future engines is the reduction in maintenance costs. The required durability of compressors demands to keep the running properties of a compressor on a very high level even after many hours of operation. Deterioration due to particle erosion can cause an extensive decrease in efficiency and stability. The operation of the engine in a sandy environment can decrease the time on wing between overhaul by 70%. Fig. 14 shows a 3D Navier Stokes simulation of particle trajectories in a low pressure compressor. With this method the designer can determine the areas of maximum attack of erosion in the compressor blading which have to be coated for longer maintenance rates.

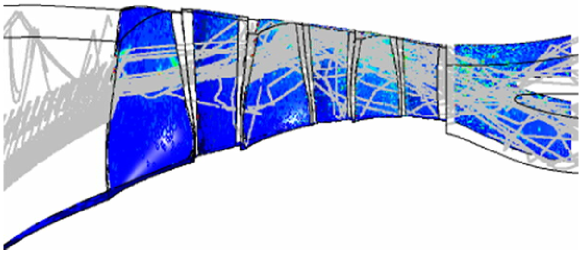


Fig. 14: Particle trajectories in a three stage LPC

MTU Aero Engines has developed a new innovative nanostructured multilayer coating ERCoat^{nt} for a better protection of the compressor blades and vanes. The coating consists of several hard ceramic and soft metallic single layers (Fig. 15) which are evaporated on the blades in a special coating facility. The whole coating is just some twenty to fifty nanometers thick. Therefore the influence on aerodynamics and mechanical behavior of the blades is negligible.

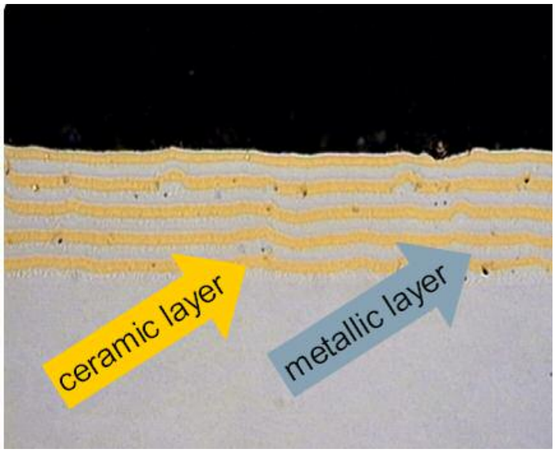


Fig. 15: Nanostructured multi layer coating with hard ceramic and soft metallic single layers

The findings gained from specimen tests with two different coatings showed very good results. Especially in the first test ours in erosive environment the coated specimens had nearly no mass loss (Fig. 16). In order to reach a given maximum mass loss the time of erosion could be doubled for version 1 coating and even tripled for the new improved version 2 coating.

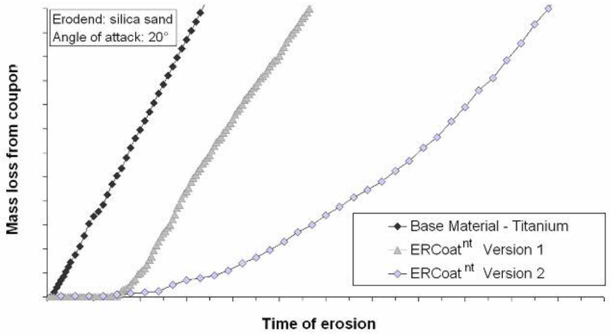


Fig. 16: Erosion test results on specimens

In high erosive environment like in Afghanistan or Middle East Countries ERCoat^{nt} can double the time on wing for compressor blades and increase operational readiness and decrease maintenance costs for the customer.

High Speed LP Turbine Technology Development

Generally the LP turbine faces special challenges in a geared turbofan architecture. Especially the optimization of efficiency and weight becomes important. Due to the high turning speed the number of stages has to drop resulting in a significant stage pressure ratio increase and leading to a high Mach numbers level in the blading. Thus, the aerodynamic challenge is primarily the combination of high Mach numbers in combination with moderate low Reynolds numbers.

The second very important issue is the module weight. Due to the high rotational speeds the mechanical load on the airfoils is very significant. The weight of a high speed LPT is considerably driven by the allowable blade stresses, the disc loads and containment. Due to this intensive interaction is needed between mechanical and aerodynamic optimization.

MTU has gathered a considerable amount of experience with these challenges in the past years through the three technology programs with high speed LP turbines. Already about 15 years ago a three stage high speed turbine has been developed and tested within the ADP Demo program. This turbine featured high efficiency levels of the order of 93% isentropic.

In the ATFI program, which was the second high speed LP turbine program, the concept of high speed turbine was driven to extremely high design parameters like the characteristic mechanical load parameter $A*n^2$, which exceeded a value of 6.5 $(inch*rpm)^2$ in the last stage. This was combined with a stage pressure ratio of more than 2.3. Like in the ADP demo program a turbine was tested within a demonstrator engine and additionally a cold flow rig was tested in the altitude test facility in Stuttgart for detailed aerodynamic evaluation. In Fig. 17 the rig test turbine is shown. One can see the thick discs and the tapered rotor airfoils.

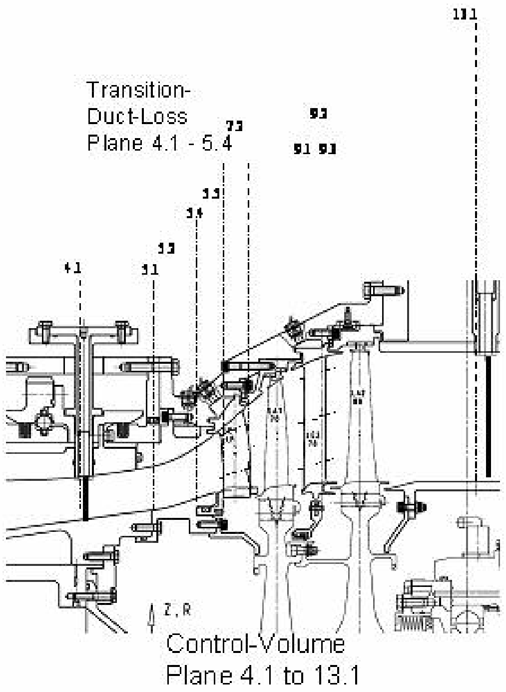


Fig. 17: Test-Rig with Measurement Positions

In Fig. 18 the measured turbine map is displayed in terms of efficiency as a function of the specific work and speed. As can be obtained from this figure, the maximum efficiency is located exactly at the aero design point. The characteristics for higher pressure ratios shows no dramatic drop. Hence, despite the high Mach number levels the turbine is characterized by a well conditioned operating map.

For deeper understanding of the turbine behavior and of course improvement of the CFD validation base local measurements are included inside the rig. This is absolutely necessary for technological advancement.

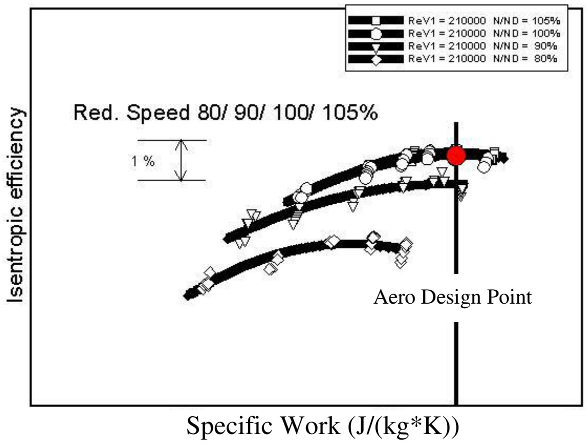


Fig. 18: Turbine Characteristic for Several Speeds

As an example a detailed comparison between experiment and CFD is done using flow visualization. This reveals interesting details on the flow structure in terms of separation size as well as 3D structures (figure 19). This provides also a good basis for comparison with CFD. The flow in the second vane is fully attached at this operating point with moderate three-dimensional flow structure extend. The CFD prediction was able to compute all main structures with a small tendency for a conservative separation bubble prediction.

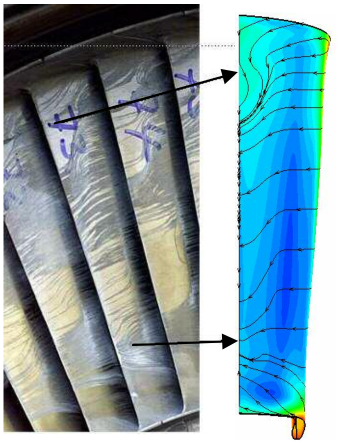


Fig. 19: Flow Visualization for Second Vane, Comparison of Color Injection and Numerical Simulation

In order to further push limits in the design of high speed LPT's the numerical representation of the real geometry has to be improved. One step ahead was the inclusion of the cavity geometry into the CFD model with full representation of the rim at tip cavities (Fig. 20). By this the leakage flow and the mixing effect of the leakage are captured. This provides a significant improvement especially in the prediction of the end wall regions (Fig. 21).

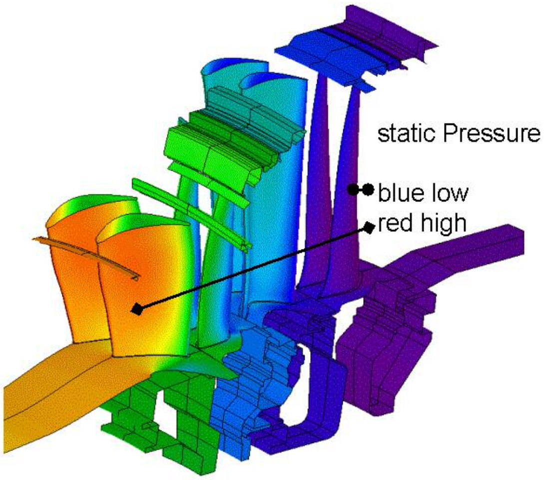


Fig. 20: LP Turbine 3D-CFD Model including Cavities

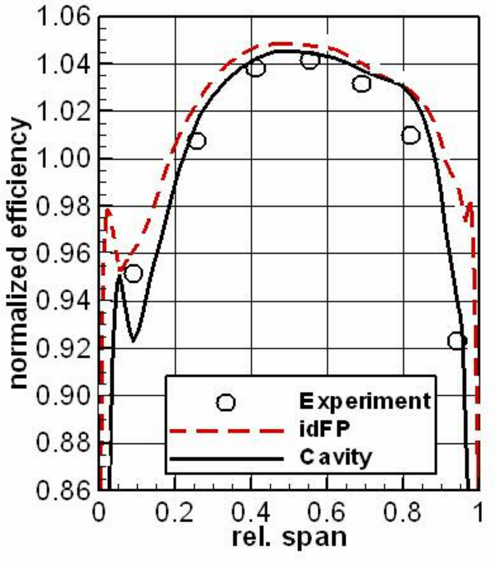


Fig. 21: LP Turbine Component Radial Efficiency Distribution with and without Cavities

The third high speed turbine was developed and tested in the frame of the European CLEAN project. This turbine was designed for the CLEAN engine demonstrator. It is a three stage turbine with a cooled first stage.

The high speed, transonic, highly loaded 3-stage low pressure turbine uses novel technologies and features developed at MTU Aero Engines (Fig. 22 and 23).

The LPT applies attributes like blade attachment for high An² and over speed protection without intermesh. A new low weight rotor with slotted flanges and a new sealing concept has been designed for the turbine.

Fig. 22: High speed LPT vanes and blades

The LPT has been laid out for a high inlet temperature with cooled first stage vane and blade. High lift blading and optimized gas path geometry have been realized using a 3D-CFD. Thus, the demonstrator engine test provides valuable validation for the hardware as well as for the underlying design methods.

Fig. 23: High speed LPT module

Control System – progressing towards a distributed architecture

Current Engine Control and Monitoring Systems (ECMS) for aero engines possess a centralized architecture: One single unit contains the central processor(s)- every sensor and actuator is linked directly to the central unit by dedicated electrical and power connections (Fig. 24). This is due to the fact that up to now many electronic components could not stand the hot and harsh environment conditions with high temperature and vibration levels typical to aero engines. Electronics had therefore to be placed at a location with moderate environmental conditions – centralized in the ECMS unit.

Driven by the demand from a wide range of applications high temperature electronics are now becoming available on the market. This allows the design of new control architectures which are characterized by having a partitioned software (e.g. logic) running on distributed hardware elements (e.g. processors). The compartmentalization will be adapted to the required functionality meaning for example that the interpretation of a sensor signal will be carried out in an electronic unit located directly next to the sensor.

In addition future aero engines will have to handle an increasing number of electronic accessories. These are bound to stepwise replace the classic hydromechanical systems as the power density and reliability of electromechanical devices and the respective power electronics are now reaching aerospace standards.

Consequently centralized ECMS will be gradually replaced by distributed architecture control systems (Fig. 25), which are already quite common in Automotive control and on their way for other Aerospace applications (e.g. automatic pilot systems).

The advantages of a distributed control system are:

- Development cost reduction by:
  modular standardized software
  modular standardized hardware
  standardized interlinks
  simplified validation
- Maintenance cost reduction by:
  eased fault localization
  eased replacement of modules
- Increased safety by:
  complexity reduction of wiring
  increased redundancy

With regard to engine control and monitoring MTU Aero Engines holds a key position with European military aircraft engines contributing to the Eurofighter (Typhoon), Tornado, Tiger and A400 M. This high degree of experience is the stock from which MTU Aero Engines is currently supporting technological activities for the new central control unit and feasible components of a first generation distributed control system. In addition MTU Aero Engines supports the joint activities of the European aero engine industry to set up a research project on distributed architectures within the 7th framework of the European Community.

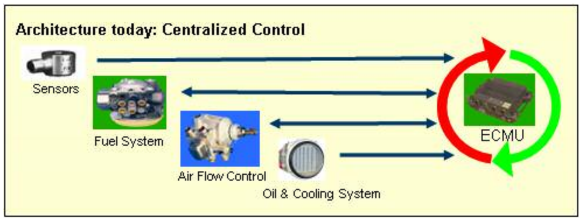


Fig. 24: Centralized control architecture

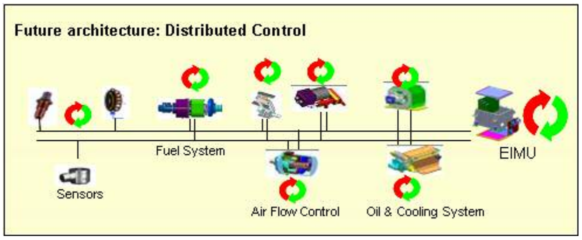


Fig. 25: Distributed control architecture

Summary

Significant fuel burn, noise, emission and maintenance cost reduction will be required for engines for the next generation of regional aircraft. In order to achieve this targets a further improvement of existing engine types will not be satisfactory. A big technology step has to be done with new engine concepts and considerable advanced component technologies for compressors turbines and combustors.

The geared turbofan features a new engine concept, aiming at very high bypass ratios and overall pressure ratios. By separating the low speed fan from the LPC and LPT each component can run in their optimum speed. That results in best component efficiencies (fuel burn), low stage count (weight, cost) and low noise (low fan speed for minimum noise). Since many years MTU participates in geared turbofan demonstrator programs like Advanced Ducted Propfan (ADP), Advanced Technology Fan Integrator (ATFI) and the EVNERT program. Additional studies confirm, that the geared turbofan concept represents a very attractive alternative with a lot of evident advantages versus the conventional turbofan design.

Besides the overall engine concept also the components have to be improved by new technologies. Main focus for the compressor are efficiency and maintenance costs. New design modifications at the hub and the tip of the blades were presented, which allow a high performance level over the whole range of operation. For keeping the running properties of a compressor on a very high level even after many hours of operation MTU has developed a new innovative nanostructured multi-layer coating ERCoat^{nt}. This coating protects the blades and vanes from erosion and doubles the time between overhaul for these parts in erosive environment.

In order to support the geared turbofan engine very efficient high speed LPT's were developed and tested. The design tools were optimized and calibrated and new aerodynamic features have been included in the CFD tools. For achieving the weight targets increased stage loadings and reduced stage counts were realized.

The increased number of electronic accessories for future engines can be handled by a distributed control system. The modular configuration of software and hardware leads to reduced manufacturing and maintenance costs while increasing the safety of each component.

The already performed demonstrator tests of the new geared turbofan design showed very good results and obvious advantages versus the conventional turbofan engine. This technology will help to make a big step forward for the next generation aircraft engines.

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