ATFI-HDV: Design of a new 7 stage innovative compressor for 10 – 18 klbf thrust

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1. Abstract

This paper will address current demands and developments in compressor design and will illustrate latest highlights achieved on new HP compressor technology at MTU. The HP-Compressor is a key element to the progress of future aero engines. For MTU the HP compressor is a key component of competence.

The present paper will give an overview on latest ATFI Technology program yielding a highly innovative compressor concept for the 10-18 klb thrust class with significant improvements in efficiency, weight and cost characteristics over existing systems.

The main characteristics of the new compressor are full 3D Aero including casing treatment, all Blisk light weight tie shaft rotor and advanced thermal management and radial gapping concepts.

Besides design features, the presentation will also give an overview on validation testing including a rig and core demo assembly.

Abbreviations

6th FRP	EU 6th Framework Program
ACARE	Advisory Council of Aeronautical Research in Europe
ATE	Aerospace Technology Enterprise
EEFAE	Efficient Environmental Friendly Aero Engine
TF (GTF)	Turbofan (Geared Turbofan)
MEMS	Micro Electronic Mechanical Systems

2. 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 aero industry is facing fierce headwinds in terms increasing fuel prices, noise restrictions, limiting exhaust gas emissions, especially in Europe.

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%. The targets shown in Fig 1 are specified into short to mean term customer needs and long-term visions as projected by European and US aerospace organizations such as ATE and ACARE.

	Today	2007-2010	Vision 2020 (EU: ACARE)
Fuelburn/CO_2	base	-7-10% FB	**- 50%** incl. Aircraft
Noise, rel Stge 3, cum	-(14-18) dB	-30-33 dB	**- 40dB**
IFSD-Rate	0,005/1000EFH	**0**	**0**
(engine)	base	- 8-12%	**-(15-20)%**
t/Weight,PPS	3,6-4,5	>>4	>>4
S rel ICAO'96	-30%	-40+%	**-80%**
	base	+50-100%	+50-100%
sts (Maint.,Manuf.)	base	**- 25-30%**	N/A

Fig 1. Mid- and long-term requirements for aero engines

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.

3. 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 more fuel- noise and cost efficient components (Fig. 2).

Fig. 5 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.

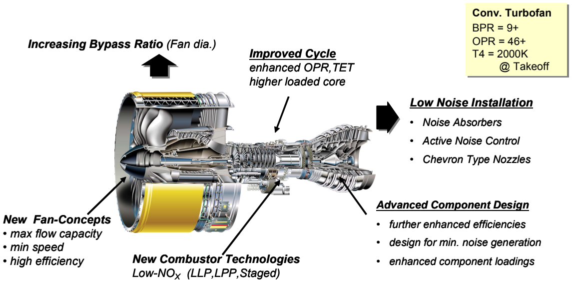

Fig. 2: Future adv. Turbofans will continue the environmental trends from recent designs

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 long range application OPR and TET are expected climb towards and beyond 50 and 2000-2100 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.

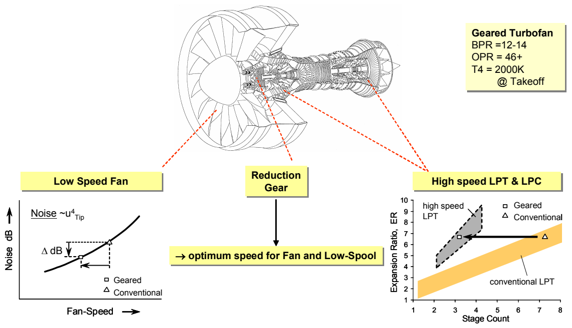

Fig. 3: The Geared Turbofan concept

The geared turbofan features a new engine concept, aiming at very high Bypass ratios and OPRs is the Geared Turbo Fan (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).

Fig. 4: ATFI-1 Demonstrator 2001

4. Future Compressor Design Requirements

To enable the advanced engine concepts, extensive efforts will be necessary to further improve the quality and performance of the engine components. An important role has the HP-compressor, which is one of MTU's prime competence components within its civil and military aero engine development activities.

MTU has 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 presently enters the regional civil aircraft market.

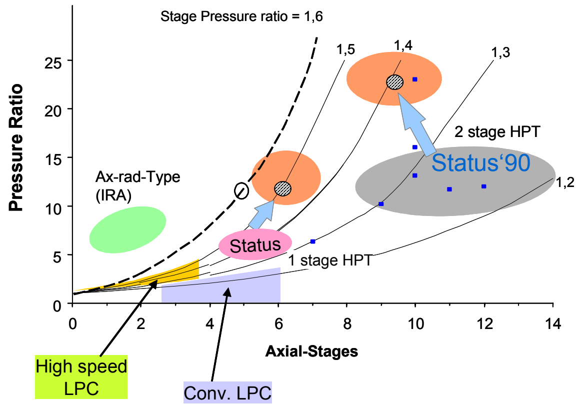

Fig. 5: Compressor design trends

Fig. 5 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:

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 91% polytropic efficiency goal.

2. Axial compressors (Fig 6) 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. Towards smaller engines not only the low Reynolds number effect becomes more demanding, it is also that the challenge to compete with small size, low cost axial-radial compressors increases. To meet these requirements, a next technology step is required for these small size axial compressors.

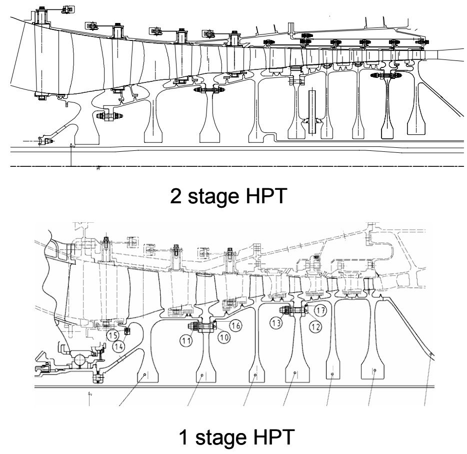

Fig. 6: Advanced axial compressors

For both categories, the need to increase the stage pressure ratio will demand for higher circumferential speeds (Fig.7), which due to mechanical constraints cannot be totally fulfilled. Resulting efficiency penalties will have to be compensated by the introduction of new and powerful aerodynamic technologies and design features.

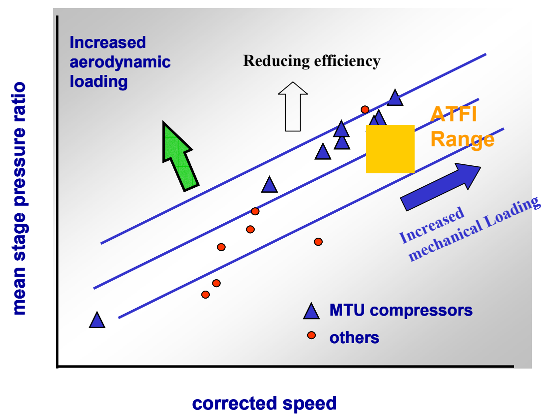

Fig 7: Aero- Mechanic Loading Characteristics of future compressors.

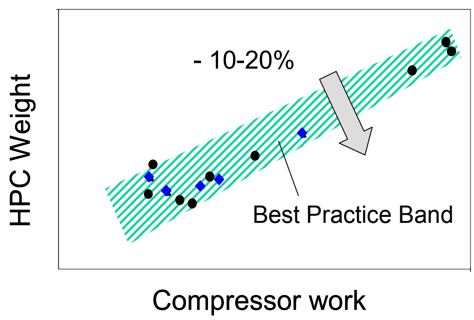

Fig 8: Weight trend for existing and future compressor designs

Despite the higher stage loading created by the allowance of further enhanced mechanical speeds a significant weight reduction is required in order to provide an adequate contribution to compensate the detrimental impact from increasing bypass ratio and fan diameters. Fig. 8 illustrates this trend. The ATFI compressor discussed in this paper addresses these issues.

5. The ATFI Compressor Program

The ATFI – HPC Technology program, which is funded by the German Ministry of Economics and Labor, addresses needs for the future engine Market for regional aircraft application.

The compressor itself is focused at the future PW800 program which closes the PW - MTU product line between 10 and 18 klb thrust. MTU was selected to deliver the HP compressor.

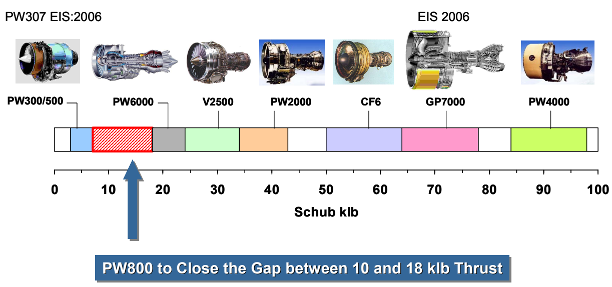

Fig 9: ATFI HPC applications

6. ATFI-HPC Characteristics

The main characteristics of the ATFI are
- Take of thrust: 10 to 18 klbf
- OPR ~ 30
- HPC overall pressure ratio ~ 11
- Number of stages: 7
- Length: -20% to baseline technology
- Weight: - 30 % to baseline technology
- Life > 25000 cycles
- Low manufacturing & maintenance costs

7. The ATFI-HPC Design

7.1 Technology Features

The ATFI-HPC has been developed based upon the design, production and in service experience gained from MTU's compressors from the EJ200 and PW6000 programs as well as on numerous technology programs.

To fulfil the challenging targets as described above new design methods, tools and technologies (Fig. 10) are required. The main technology features incorporated in the ATFI HPC are:

- Advanced 3D aerodynamic profiles.
- Casing Treatment on two stages which may allow to omit two variable vanes actuation systems.
- Light weight material for IBR and casing.
- Friction welded dual material tieshaft which combines the advantages of strength and thermal expansion.
- New axial venting system for improved tip clearance and rotor life.
- New manufacturing methods as cast OGV
- All blisk design.
- Advanced brush seals.
- Protective coating.

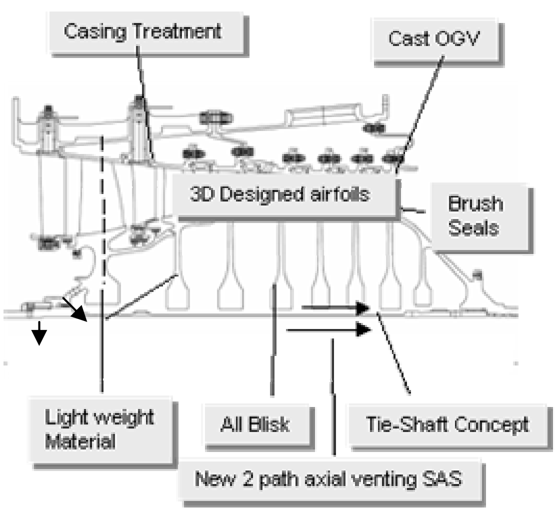

Fig. 10 New concept for small axial compressor

7.2. Aerodynamics

The ATFI-HPC is designed for a class of engines which are considered being close to the lower end for an application of pure axial compressors. The small core size which goes along with short blades, the blades on the rear stages have a height significantly less than 20mm, is a specific challenge to complying with the requirements of efficiency and operability within the constraints of manufacturing tolerances and the sportive cost and weight targets.

In general the number of compressor stages has to be minimized. An intense trade study showed that seven stages is the optimum for that size in respect to efficiency, weight and cost. To avoid highest threats in view of weight, a rather high aerodynamic stage loading had to be accepted, as shown in Fig.7. Since the efficiency usually decreases with increasing stage load, this deficiency had to be compensated by advanced aero design.

The aerodynamic design of the ATFI-HPC was performed using the 3D Navier-Stokes-Code TRACE, which was calibrated with the results from the HDV12 compressor. The full 3D analysis included all compressor stages as well as the cavities. As previously shown in /4/ the interaction between cavity flow and the main flow has a significant influence on the compressor efficiency.

3D features like bow, sweep and end bends have been introduced, since they proved to deliver substantial benefit to highly loaded compressors flows.

The ATFI compressor includes casing treatment on the first two stages for excellent part power stability. In recent years, MTU has successfully introduced and demonstrated casing treatment throughout several technology programs. To evaluate the onset of compressor instability in the ATFI, extensive 3D unsteady Navier-Stoke computations at part power speed have been performed. MTU's casing treatment has proved to yield approximately 15% additional surge margin. In consequence, this has the potential to fix the two variable vane stages in a next design step and also to omit the actuation system, which is a significant reduction to cost and weight.

Conventional compressors typically include bladed rotors, which suffer from a parasitic air leakage between blade and disc. Single stage HPC rig tests and HDV12 compressor tests revealed a significant improvement on compressor efficiency up to several tenths of a percent if bladed rotors are replaced by blisks. Since the ATFI includes an all blisk rotor, full advantage from that effect could have been taken. Figure 11 shows a view on a rear stage blisk.

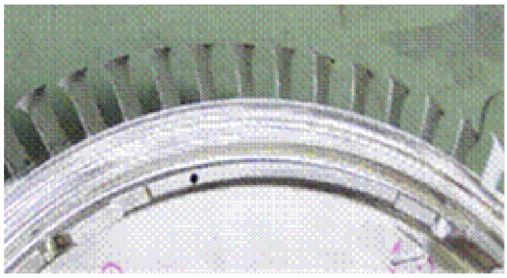

Fig.11: View on a rear stage blisk.

7.3 Mechanical design

The mechanical design of the ATFI high pressure compressor (HPC) is defined by the challenging targets of low weight and short length. In general the length is influenced by

- the aspect ratio of the airfoils,
- the airfoil to airfoil distance and
- the number of stages.

These parameters have also a strong influence on the aerodynamic performance, the structural integrity of the airfoils as well as on the rotor dynamic behaviour. So, a careful balance between aero efficiency and mechanical benefits had to be pursued.

Aspect ratio
To comply with the stringent design specification of short length and low weight a relatively high aspect ratio has been selected for the airfoils. Since high aspect ratio airfoils usually are much more critical in respect to blade vibrations, their design has been tuned on the basis of stage wise forced response analysis.

Blisks
Blisks are attractive not only because of their small weight; but also in achieving small tip clearances, which in turn contribute to fulfil the aerodynamically targets, i.e. efficiency and surge margin. The extensive experience from the EJ200 and HDV12 programs allowed to introducing blisks for all seven stages into the

ATFI compressor, as shown in Fig.12. This decision was supported by our customer's feedback to MTU's excellent blisk manufacturing and repair capability.

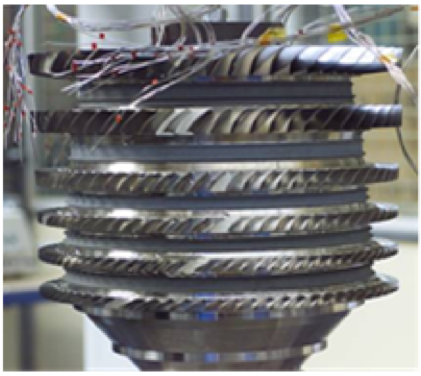

Fig. 12: ATFI All Blisk HPC prepared for Testing

The front stages have Titanium blisks for weight reasons, whilst the rear blisk stages are made out of Nickel. MTU's manufacturing technology did not require compromise the 3D aero design and simultaneously allowed for minimum manufacturing time.

Tieshaft

Driven by the desire to build a very short axial compressor the tieshaft concept has been adopted. This concept is principally shown in Figure 13. Major benefits of the tieshaft design are:

- Length: Since no bolts are required, the distance between the discs and such the compressor length and weight can be minimized and thus supports the all blisk design.
- Life /weight: Without life limiting bolt holes in the discs, the discs can be made significantly thinner if the same lifing criteria are applied. This gives an enormous weight benefit.

Compared to existing tieshaft rotors in service, the ATFI compressor features relative big blisk sizes with higher rotational speed and higher compressor exit temperatures beyond 850K. Since the tieshaft preload is influenced by the centrifugal forces and thermal expansion of the rotor, the preload could significantly change during a flight mission (Fig14.) Extensive skills and experience in design are required, otherwise the preload might become too high during start or the tightness of the rotor might be lost during deceleration. To counteract, a new air system has been designed and a new dual material for the tieshaft has been introduced, which ensure sufficient tightness of the rotor at any time during the flight mission. Figure 14 shows the resulting preload change during a flight mission.

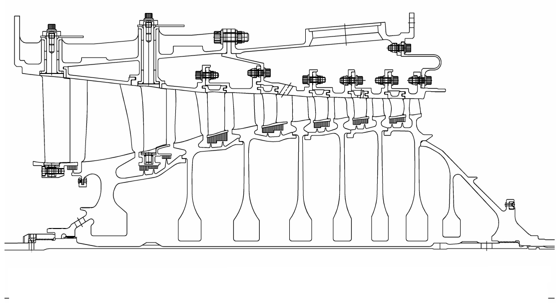

Fig. 13: ATFI-HPC All-Blisk Tieshaft Design

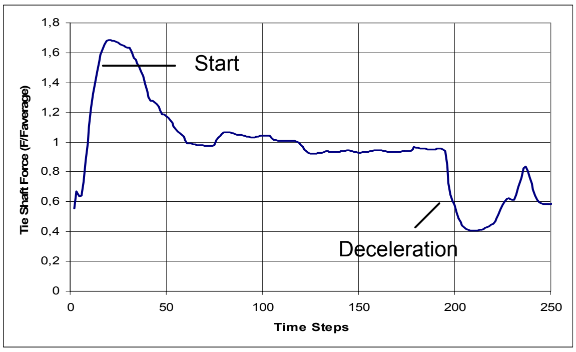

Fig.14: Change of tieshaft load during mission

Tieshaft material

To meet the life target for the tieshaft a dual shaft material has been selected, which combines the requirements for strength and thermal expansion. For this set of material the applied friction welding process has been optimized during the German "Engine-3E Technology Programme".

SAS and brush seals

For the ATFI-HPC a new axial venting secondary air system (SAS) has been defined. The different requirements for a good thermally matched rotor tieshaft system, a thermally fast rotor which allows the rotor to follow the casing during thermal transients without unacceptable increase in radial gaps and minimum air consumption for good compressor efficiency had to be resolved. With the use of MTU's low leakage brush seals and the new axial venting system as shown if Figure 10 both requirements could have been fulfilled.

MTU's brush seals (see Fig. 15) have already been introduced in many military and civil engines, e.g. EJ200 and PW545. The brush seal in the ATFI located at the exit of the compressor has been designed to operate under even more extreme condition of 30% higher rotor speed, 10% higher gas temperature and pressure.

Fig. 15: MTU brush seal

FMEA

To demonstrate the integrity of the novel tieshaft-all-blisk-rotor concept a detailed failure mode analysis (FMEA) has been performed. The analytical results confirmed sustained attachment of the discs even if exposed to the extreme deformation which would occur if multiple HPT blades are released simultaneously. The deformations shown in Fig.15 are exaggerated for presentation purposes.

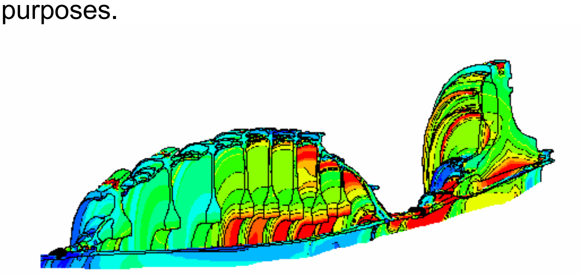

Fig 15: Deformations due to HPT Blade off

8. Compressor test and test facility

8.1 Tests program

The ATFI concept and its new technology features have already been validated in
- numerous component tests, e.g. airfoil structural tests, tieshaft Low Cycle Fatique (LCF) tests
- rotor spin test
- aero rig tests in October 2004.

Currently the compressor is being tested together with the combustor and HP turbine from our partner PWC, within a joint Core Demonstrator program.

8.2 Aero Rig Tests Facility

The ATFI compressor was tested at MTU's test facility in October 2004. The compressor test bed as shown in Figure 16, has also been used for the EJ200 and HDV12. The basic version of the test facility allows speeds up to 19.000 rpm with a max drive power of 16 MW. For high speed compressor, an additional gearbox has been installed that enables speeds up to 26.000 rpm (see Fig 15).

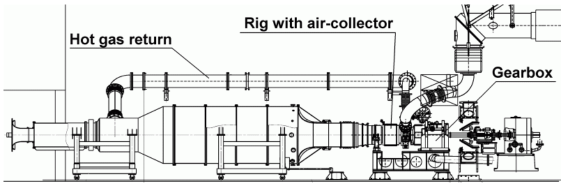

Fig. 15: Cross section of the test facility.

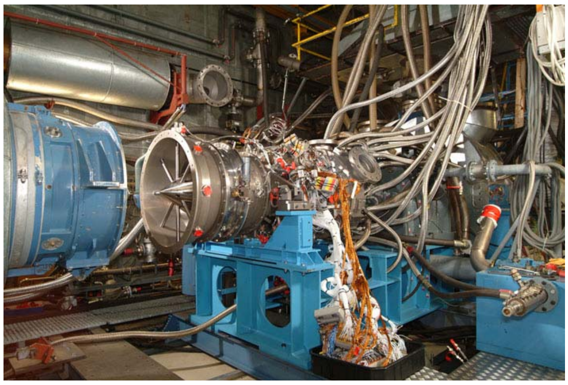

Fig. 16: ATFI in the test facility

For mechanical investigations it is important to provide engine like inlet gas temperatures. MTU's test facility allows inlet temperatures of up to 480K by mixing exhaust air with ambient air as shown in Fig. 15.

The frequencies of the blades and vanes were measured with strain gauges. To get the data out of the rotational system, MTU's digital telemetry system was used, which has the capacity for about 50 strain gauges and 40 temperatures channels. In addition to the strain gauges, a non contact tip timing system has been used, which measures the vibration of each blade without any impact on the gas path.

Fast pressure transducers flush mounted were installed to measure flow instabilities like rotating stall and to detect the stage which induces the surging of the compressors.

The performance of the compressor was measured using total pressure rakes and temperature rakes in the inlet and in the exit of the compressor. In the inlet a turnable (360°) spoiler carrier was installed on which screens and gauzes can be fixed. These screens are needed to simulate the typical hpc engine inlet profile distortions. This profile has been measured behind the swan neck duct with a radial traversed wake rake. Fig. 18 shows the traverse and the comparison of the measured and requested distribution

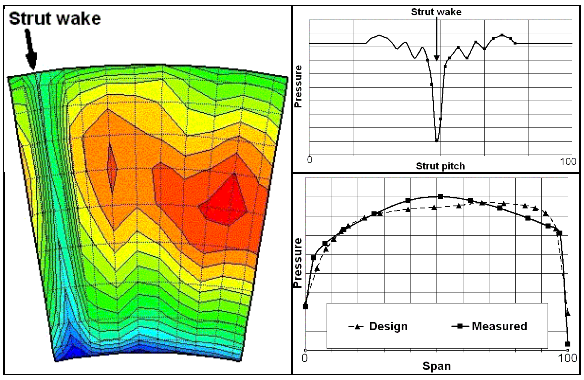

Fig. 18: Measured inlet profile after one strut of the swan neck duct

To get the information of the stages, all leading edges (LE) have been instrumented with pressure and temperature taps (radial and circumferentially distributed). Between all blades and vanes static pressure taps have been fitted.

In total, the compressor was equipped with approximately 800 measurement taps.

During the test all stage characteristics have been calculated online and the results visualized at the test bed, allowing for a very effective testing.

8.3. Test Results

In extensive tests, covering a wide range of test parameter, the outstanding performance of the ATFI compressor could be demonstrated. The main test parameter variation included for the aero rig tests were:

- Compressor inlet pressure (Reynolds Number)
- Inter stage compressor
- VGV schedule settings
- Mechanical rotor speed
- SAS Tests: Rotor cooling mass flow variation
- Variation of rotor tip clearance

Main results are:
- Efficiency target by more than 1% exceeded
- Outstanding stability margins at full power and part power.
- Benefit from casing treatment demonstrated
- Life and burst margin targets fully achieved.
- Full compliance with weight and length targets.

After the completion of the aero rig tests, MTU and PWC were continuing the validation program by testing the compressor in the joint Core Demonstrator. On the first attempt, the core could have been started perfectly. The outstanding performance observed on the aero rig has also been confirmed in the Core test so far.

9. Summary

The ATFI-HPC design was defined by an integrated team of structural mechanics, manufacturing, design, aerodynamics and test engineers from the very beginning of the project. This approach let to a first time right design of the compressor. Due to the intensive use of 3D-Navier-Stokes computation (cavities, part speed, full speed) based on the HDV12 program the stage matching was excellent. HPC tests in October 2004, not only confirmed the achievement of the challenging aerodynamic goals, the HPC convinced also by its superb operability. Furthermore, the stringent length and weight targets could be fulfilled due to major technology improvements:

- An all blisk rotor to avoid secondary losses,
- incorporation of the real 3D geometry of the stator and the stator wells,
- the optimization of the profiles and of the leading and trailing edge thicknesses,
- the avoidance of corner stall,
- the reduction of secondary leakages around blades and vanes and
- the introduction of casing treatment.
- friction welded dual material tieshaft

The combination of all blisk tieshaft design together with the axial vent system and the low leakage brush seals were the basis for the successful design. With this highly innovative design MTU has got a world class compressor which is technology ready for engines in the thrust range of 10-18 klbf.

10. Acknowledgement

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