THE GEARED TURBOFAN TECHNOLOGY – OPPORTUNITIES, CHALLENGES AND READINESS STATUS

C. Riegler, C. Bichlmaier
MTU Aero Engines GmbH
Dachauerstraße 665, 80995 München
Germany

ABSTRACT

In striving to improve metrics, especially to lower fuel consumption, weight and cost, and to reduce noise and emissions, the jet engine manufacturers world wide are continuously looking for new concepts to introduce a step change in the turbofan engine development. One promising concept having been investigated for two decades is, to apply a speed reduction gear on the low spool of a two-shaft engine between the Fan on the one (slow spinning) side and the LPC and the LPT on the other (fast spinning) side, making the configuration geared compared to the direct drive turbofan. By means of de-coupling the Fan speed from the rest of the low spool turbo machinery the designer gains an additional degree of freedom which allows him to better optimize the turbo machines independently.

The general principle of geared configuration is to further increase bypass ratio over current designs in order to improve propulsive efficiency and hence thrust specific fuel consumption, and decrease noise and weight at the same time. This is achieved by reducing Fan speed and pressure ratio for high bypass ratio Fans, and increasing LPC and LPT speeds and thus keeping efficiencies high and stage and A/F count low. This requires some fundamentally new design methods and technologies on the component level as well. As an example the opportunities and challenges for the high speed LPT are presented in some detail. The high spool speeds result in high work extraction per stage and therefore low stage and A/F count. In addition due to the rather low stage loading aerodynamic losses can be kept low and efficiencies are high. On the other hand the high speeds generally cause a high Mach Number level, and the structural loading of the rotating hardware is very high as well.

The technology required for a turbofan with a Fan drive gear has been progressing extensively over the last two decades, and significant improvements in terms of technology readiness have been achieved. With the upcoming GTF™ Engine Demonstrator's first test run planned for later this year – a joint activity between P&W, MTU, Avio and VAC – the technology development will peak in a flight demonstrator in 2008.

NOMENCLATURE

ADP	Advanced Ducted Propfan
ATF	Altitude Test Facility
ATFI	Advanced Technology Fan Integrator
Avio	Avio Propulsione Aerospaziale
BPF	Blade Passing Frequency
CLEAN	Component Validator for Environmentally Friendly Aero-Engine
DOC	Direct Operating Cost
EIS	Entry Into Service
FTB	Flying Test Bed
FDGS	Fan Drive Gear System
GTF™ Engine	Pratt & Whitney´s Geared Turbofan™ Engine
HSS	High Speed Seal
ICAO	International Civil Aviation Organization
JB	Journal Bearing
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MTU	MTU Aero Engines GmbH
NGPF	Next Generation Product Family
PNLT	Perceived Noise Level Tone corrected
P&W	Pratt & Whitney
SHP	Shaft Horse Power
TF	Turbofan
TRB	Tapered Roller Bearing
TSFC	Thrust Specific Fuel Consumption
VAC	Volvo Aero
VITAL	Environmentally Friendly Aero Engines
V18	Bypass Nozzle Jet Velocity

1. INTRODUCTION

1.1. Air Traffic Growth

Air traffic has been growing continuously over the last decades – in terms of passenger kilometer per year as well as in terms of the active aircraft fleet (number of aircrafts actively participating in air transport) – and it is predicted to grow further. FIG 1 shows the past and predicted future air traffic development.

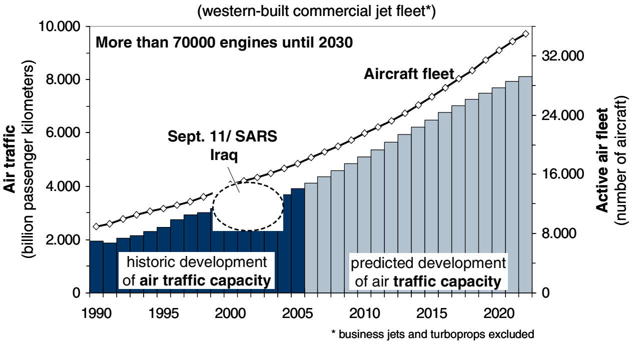

FIG 1. Air Traffic Development.

1.2. Environmental And Economic Challenges

Along with this generally positive development for the aviation industry there obviously come serious challenges for the environment (emissions), the community (noise) and the available fuel resources which will limit the future growth at some point. In an effort to minimize the environmental impact the politics world wide (e.g. the ICAO) as well as local authorities have been defining increasingly stringent regulation for aircraft engine emissions and community noise. As an example FIG 2 shows the development in airport noise restrictions from 1980 to 2000. A clear trend towards tighter restrictions can be observed, which will not only impact landing fees but mid-term limit an airline's ability to use a particular airport. From this perspective flight noise (and hence engine noise contribution) is becoming an important economic factor for the airline as well as the airport region.

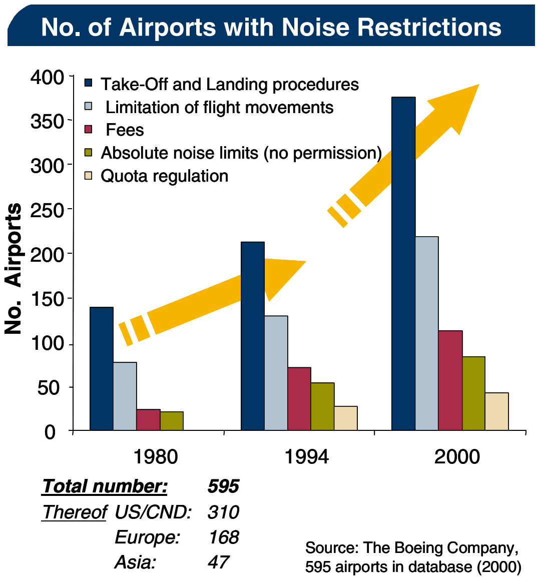

FIG 2. Airport Noise Restriction Development.

Market laws of supply and demand in turn regulate the fuel price which has been fundamentally increasing over the years as well. Uncertainties in fuel price prediction are rather high, various scenarios range from about $ 1.3 / gallon (low price scenario, abundant oil and kerosene) all the way up to more than $ 5.0 / gallon (high price scenario, permanent oil crisis) with the most realistic scenario averaging at about $ 2.0 / gallon (mid price scenario, no oil shortage but high demand). Increasing fuel prices do not only impact cash operating cost (COC) in general, the share of fuel cost increases as well which makes fuel burn even more one of the key requirements for future products. Aside from the long-term increase in fuel price the rather short-term cyclic fluctuations due to political and economical events endanger the economic strength of airlines with inadequate aircrafts in terms of fuel burn.

1.3. Next Generation Product Requirements

Driven from the continuous growth in air traffic and the resulting challenges for environment, community and the natural oil resources the requirements for the next generation of aircrafts and aircraft engines are very challenging as well. FIG 3 summarizes the major design objectives for the next generation turbofan engine from MTU's perspective relative to the engines in-service today.

Criteria	Existing Engine	Objective
Fuel Burn	Base	> -12%
Noise	-2 to -4 dB rel. ICAO stg. 4	> - 20dB rel ICAO stg. 4
Emissions	-40% rel ICAO96	-60% rel ICAO 96
Maintenance Cost	Base	> - 30%
Reliability	Base	Zero Target (no IFSDs)

Source: P&W

FIG 3. Next Generation Turbofan Objectives.

Aside from fuel burn, noise and emissions obviously the other metrics directly impacting COCs are as important, therefore time-on-wing, reliability and total maintenance cost can not be compromised at all.

1.4. The Geared Configuration As The Answer

Meeting the requirements will be a challenge for any engine supplier, but MTU - together with its partners P&W, Avio and VAC - is convinced that the geared engine configuration is the favorable answer. While the concept provides a step change in performance, emissions (due to low fuel burn) and noise, it is an evolutionary step from the direct drive turbofan, and as a result does not impose unreasonable risk to the customer, as a more revolutionary step like the counter-rotating turbo machinery concept does.

2. THE GEARED TURBOFAN CONCEPT

2.1. High Bypass Ratio Turbofans

As laid out in chapter 1 one fundamental objective for the next generation product is to reduce mission fuel burn, which is largely driven by thrust specific fuel consumption (TSFC). Traditionally the reduction of TSFC has been achieved

- by improved gas turbine cycle thermodynamic efficiency or
- by improved propulsive efficiency.

Improved cycle efficiency can be achieved by the increase of overall pressure ratio and peak cycle temperatures, which is usually limited by available materials and/or cooling techniques. Obviously improved component efficiencies are also a major contributor.

Propulsive efficiency of a turbofan engine in turn is mostly dependent on bypass nozzle jet velocity V18 for a given flight condition. Propulsive efficiency will be high when V18 is low. Low V18 can be achieved by low Fan pressure ratio which requires a large Fan diameter for a given thrust demand. Therefore the Fan speed has to be reduced to keep Fan tip speed in a reasonable order of magnitude in terms of transonic losses and resulting efficiency. The natural outcome of applying this design philosophy is a high bypass ratio turbofan engine with a rather low flow specific thrust. The general trends of Fan pressure ratio and bypass ratio can be seen in FIG 4.

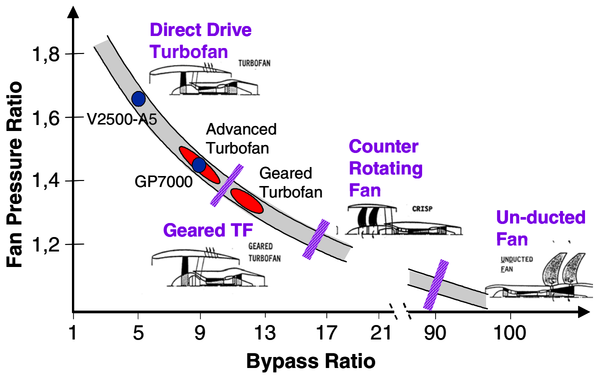

FIG 4. Turbofan Engine Concepts with Varying Bypass and Fan Pressure Ratio.

Along with the low jet velocity V18 comes low jet noise (see [1] for details), and because of the correspondingly slow Fan speed the Fan emitted sound pressure level and hence noise level is low as well, at least for the ducted TF, the geared and counter rotating configurations. For dramatically increased bypass ratios and un-ducted Fan configurations noise becomes a serious issue. FIG 5 shows the general trends of TSFC and noise versus flow specific thrust (Fan diameter, bypass ratio) for ducted turbofan engines.

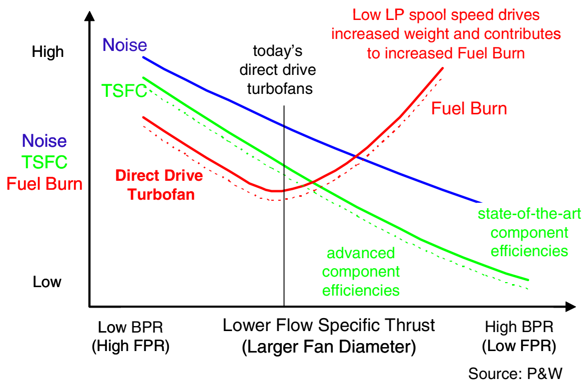

FIG 5. Ducted Direct Drive Turbofan Noise, TSFC and Fuel Burn Trends.

2.2. Geared Turbofan As The Next Step

When applying the above described concept of low flow specific thrust and large Fan diameter, which goes along with slow Fan speed, the direct drive turbofan suffers from increasing length, weight and cost of the other low spool turbo machinery (LPC, LPT). This is due to the fact that the LPC and LPT have to convert shaft horse power into work potential and vice versa at a low spool speed level, which requires a large number of stages and as a result a large A/F count. Additionally the torque transmission requirement for the low pressure shaft increases, while the maximum diameter is limited by a more and more reduced diameter of the core engine. FIG 5 shows the adverse trend of increasing Fan diameter and bypass ratio on fuel burn driven by the weight increase of the other low spool components of a direct drive turbofan.

This problem can be overcome by de-coupling the Fan from the low spool speed by means of a Fan Drive Reduction Gear System. The FDGS allows the LPC and the LPT to run at higher and more appropriate speeds, thus reducing length, weight and cost for the same specific work output. Obviously this advantage comes with the additional weight of the FDGS itself which is more than offset by the reduction in LPT stages relative to a direct drive turbofan.

The impact of increasing Fan diameter and bypass ratio on fuel burn for the geared engine configuration is shown in FIG 6 in addition to the directed drive curve already discussed in FIG 5. Compared to the direct drive the geared turbofan provides minimum fuel burn at higher Fan diameter / bypass ratio. Hence the geared turbofan concept is the enabler for turbofan engines with bypass ratios beyond today's designs with the benefit of low noise, low TSFC and achieving low fuel burn at the same time. Therefore the geared engine configuration contributes significantly to achieving two of the key design objectives discussed in chapter 1 – low mission fuel burn and low noise (see also [3]).

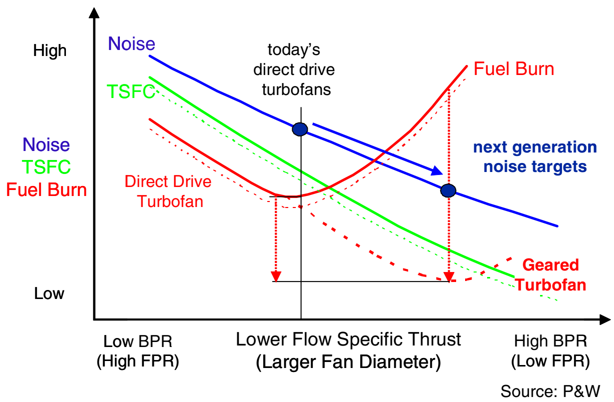

FIG 6. The Geared Turbofan Concept as the Enabler of High Bypass Ratio Turbofan Engines.

2.3. Opportunities

As derived from the fundamental thoughts in chapters 2.1 and 2.2, the geared engine configuration offers the advantages of a high bypass ratio turbofan engine with correspondingly

- slow Fan speed,
- low Fan pressure ratio and bypass nozzle jet velocity,
- high propulsive efficiency and
- low Fan noise and jet noise,

but avoids the drawbacks of a direct drive high bypass ratio concept like

- low LPC and LPT efficiency and
- increased overall engine length and weight stemming especially from the low spool components LPC and LPT on the low speed level.

FIG 7 summarizes the opportunities mentioned above.

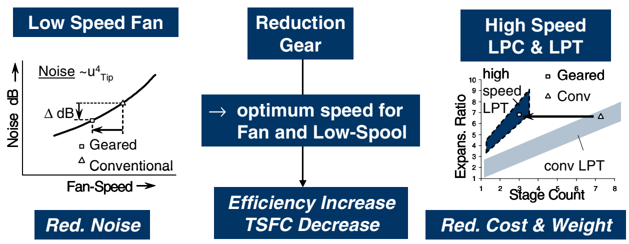

FIG 7. The Geared Engine Configuration – Opportunities.

Thus the geared engine configuration allows for a turbofan engine with

- improved (reduced) TSFC and mission fuel burn,
- reduced engine noise level,
- reduced length, weight and number of parts and
- reduced maintenance cost.

FIG 8 shows the fuel burn and noise potentials for a GTF™ engine versus a direct drive turbofan concept and versus existing engines for the thrust class of a single aisle airplane application.

Single Aisle Comparison	Current engine	Advanced TF	GTF
Fuel Burn	Base	-6%	-12%
Noise, rel. ICAO stage 4	-2 to -4 db	-12 dB	-20 dB

FIG 8. The GTF™ Engine Concept – Metrics Potentials.

2.4. Challenges

A new concept like the GTF™ engine obviously brings some challenges to the table, which have to be addressed carefully in order to get the technology ready for the product application. As a matter of fact the GTF™ engine concept focuses on the low spool components. The high spool components are not different compared to those of the high spool of an advanced twin-spool direct drive turbofan engine.

2.4.1. System Level

When compared to a direct drive turbofan with the same Fan diameter (and hence similar TSFC), the GTF™ engine weight is significantly lower because the FDGS weight is easily outweighed by the long and heavy LPC and LPT components of the direct drive due to the increased stage count and size relative to the GTF™ engine. When comparing the GTF™ engine to a lower bypass ratio direct drive turbofan (more the optimum direct drive configuration) the GTF™ engine might come out a bit heavier, but obviously has a significant TSFC benefit, see FIG 6. Relative to the direct drive the weight contributions from the components are quite different. For the GTF™ engine the Fan and LPC groups including the FDGS add up to a significantly higher portion of the total propulsion system weight, which is compensated for mostly by the LPT and the low shaft, see FIG 9.

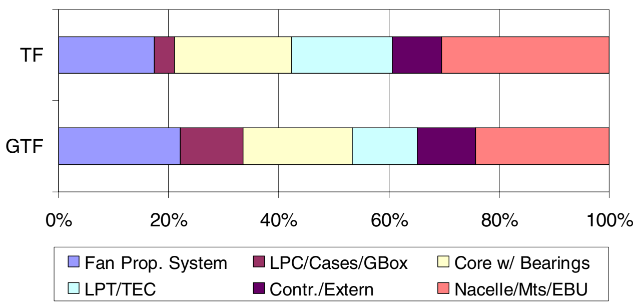

FIG 9. Weight Breakdown GTF™ Engine versus Direct Drive TF.

The FDGS losses fundamentally impact TSFC in a negative manner. This is indeed a minor issue because of the rather high gearbox efficiency and the fundamental conceptual benefit in propulsive efficiency of the GTF™ engine. Nevertheless the FDGS losses have to be kept as low as possible. These losses are an additional heat source for the oil system as well. Therefore the thermal management system has to be designed carefully to avoid oil overheating by providing sufficient cooling capacity of the fuel-cooled and air-cooled oil coolers. Key to success is obviously to reduce heat rejection as far as possible by minimizing FDGS losses.

2.4.2. Low Spool Components

The major low spool components which need attention are

- the Fan,
- the Fan Drive Gear System,
- the high speed LPC and LPT.

Fan

The Fan is not too different from a direct drive design. It features highly 3D swept aerodynamic profiles, and due to the lower spool speed losses are fundamentally reduced. As mentioned already the higher bypass ratio and higher Fan diameter result in a larger contribution of the Fan component to engine weight. Hence design methods and/or alternate materials (light weight aluminum, composites) are key to weight reduction.

Fan Drive Gear System

As with any other new or additional component to a propulsion system one has to be concerned about reliability in terms of flight safety as well as maintenance cost. Gearboxes have been used in engines for flight application for a long time. Examples include

- propeller aircraft (Tyne, TP400, PT6),
- regional aircraft (ALF 507, TFE 731) and
- helicopters (MTR390, PT6).

Some of these engine fleets (and the gearboxes) have accumulated millions of flight hours over the years (e.g. the PT6 engine series). Initial reliability problems with Tyne and ALF507 (RJ85) engines were resolved and are being understood. FIG 10 provides an overview of P&W's in service experience with reduction gearboxes in turboprop and turboshaft engines.

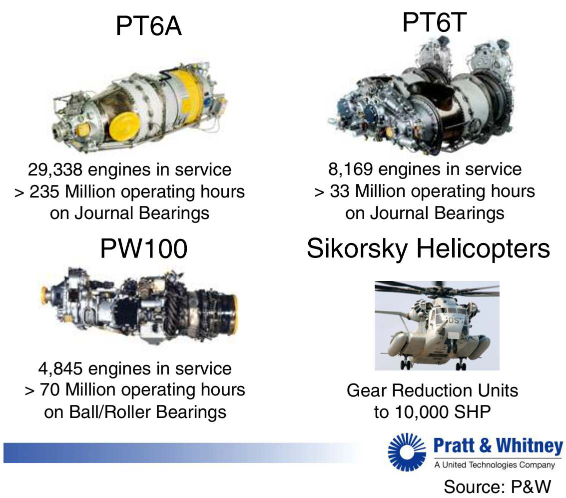

FIG 10. P&W Reduction Gearbox In Service Experience.

The gearbox transmitted power for the next generation product to power the single aisle airplanes will be higher than for the applications in service today. FIG 11 provides a comparison of the gearbox transmitted power during takeoff operation for a variety of engines. It shows that the ADP Demonstrator Gearbox and the NGPF GTF™ Engine Gearbox are at the high end of the applications.

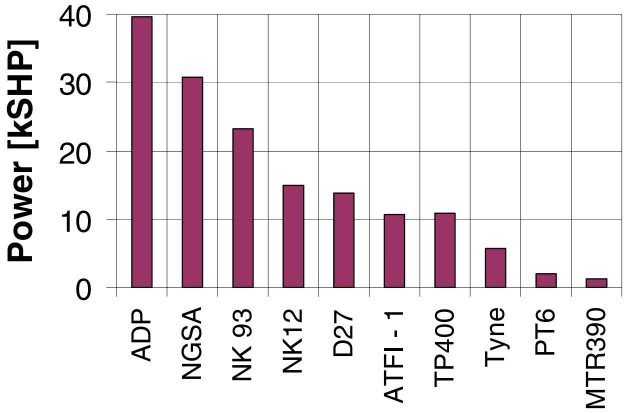

FIG 11. Gearbox Transmitted Power at Takeoff Operation.

The transmission power demand is one major sizing parameter for the FDGS and its components (gears, journal bearings). During the design of the gears and bearings themselves proven standard practice design methods and tools (validated and calibrated to rig and engine experience) as well as standard materials and manufacturing processes are used by our partners P&W and Avio. Furthermore it is made sure that the structural loads are in a well known design range. FIG 12 lists some relevant design parameters for the gears and bearings, and provides numbers for the NGPF application gearbox relative to the proven design space based on P&W's reduction gearbox experience. It can be concluded that the gearbox design is within the limits of the known design space proven by several million flight hours of the PT6 engine family and other commercial and military engines.

Gear Design

Gear tooth bending stress	83% of limit*
Gear contact stress	81% of limit*

Bearing Design

Unit Load	81% of limit*
Peak Oil Pressure	57% of limit*
Bearing Temperature	89% of limit*

* limits as experienced from in service operating reduction gearboxes

Source: P&W

FIG 12. Gearbox Design Space Relative to Experience.

Aside from using standard design practice, the key to a successful development of a FDGS for the next generation product GTF™ engine is a systematic technology development program including rig testing, engine ground and engine flight testing. MTU's partners P&W and Avio have been testing planetary and star system gearboxes in three engine demonstrators and in several rig tests to date. Most of the testing was performed full scale in a design space of up to 40k SHP.

Furthermore in preparation for the GTF™ Engine Demonstrator program P&W and Avio are carrying out a complete rig test program with several gearbox assets to investigate efficiency, fatigue, loads and deformations, lubrication and heat rejection under various operating conditions including full power and even over-speed, over-torque and over-load, various angles of attack, oil flow interruption and windmilling. During the upcoming GTF™ Engine Demonstrator flight tests the journal bearings will be exposed to flight situations without oil supply as could occur in emergency situations as e.g. during zero g flight conditions. FIG 13 provides an overview of 20+ years of FDGS technology maturation, and it also shows the corresponding risk reduction to prepare the FDGS for the product application.

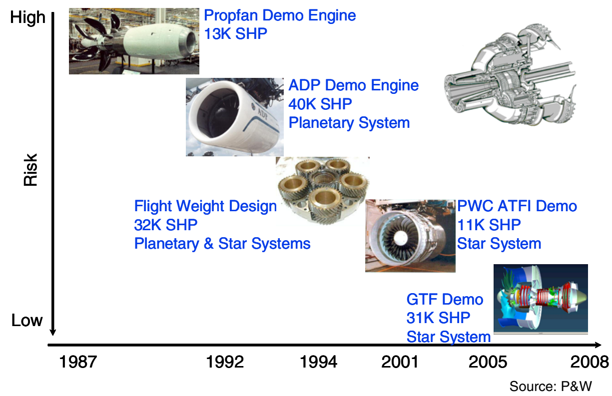

FIG 13. 20+ Years Of FDGS Technology Maturation.

High Speed LPC and LPT

Both the LPC and the LPT are exposed to elevated levels of rotational speed and hence tip speed. This results in high Mach number flow, but less turning is required for the given specific work. Fundamentally aerodynamic efficiency will benefit from those conditions, but high Mach numbers (potentially in combination with low Reynolds numbers for low thrust applications) have to be handled carefully. The high rotational speeds on the other hand cause high structural loading of the rotating airfoils and subsequently the disks. Therefore blade and rotor design has to be done carefully in order to achieve well balanced structural loads avoiding stress peaks, otherwise the low stage count weight benefit will be compensated by heavy rotating hardware.

A more detailed review of opportunities and challenges on the component level is provided in chapter 3 for the LPT.

2.5. Application Potential

In general the Geared Turbofan concept is applicable to various aircraft sizes (business, single aisle, wide body) and missions (regional, mid range, long range). The physics based benefits over the direct drive turbofan in terms of noise, TSFC and fuel burn as well as engine length, weight and cost are valid for all applications. Obviously the GTF™ engine is the prime concept for applications focusing on low TSFC and noise and thus demanding for high bypass ratio engines. This is especially true for long range missions and wide body airplanes, but also for mid range single aisle airplanes and regional jets. Business jet applications often focus more on weight as an absolute metrics and compromise on TSFC, hence staying with lower bypass ratios where the direct drive turbofan is more attractive in terms of fuel burn and DOC.

The maintenance cost benefits due to reduced stage and airfoil count of the GTF™ engine are obviously valuable for all applications as well.

A potential physical limitation for all high bypass turbofan applications is the required ground clearance for under wing installation, which is more challenging because the GTF™ engine typically features a larger fan diameter for the given thrust class than the direct drive turbofan. For most applications including existing wide body and single aisle airplanes this is not a limitation though.

3. OPPORTUNITIES AND CHALLENGES ON THE COMPONENT LEVEL – LPT

Opportunities and challenges of the high speed LPT result from the elevated rotational speed level due to decoupling from the Fan speed by means of the FDGS.

3.1. High Speed LPT Opportunities

3.1.1. Large Work Extraction Per Stage

The high rotor speed allows for a significantly reduced stage count of the turbine for a given work extraction. Compared to a conventional turbine the stage count can roughly be cut in half at rather low aerodynamic loading per stage. This leads to significantly reduced airfoil count and part numbers over all, and therefore lowers manufacturing costs and reduces maintenance costs as well.

FIG 14 shows the V2500 LPT and the high speed LPT of the technology demonstrator CLEAN which provide similar shaft horse power. The speed level was increased for CLEAN by 60% over the V2500, consequently the stage count was reduced from 5 to 3 stages and the blade count went down to 40%.

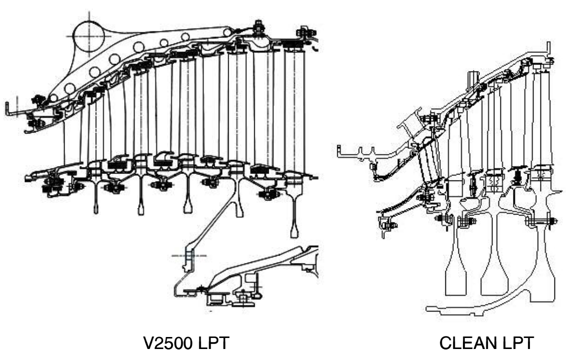

FIG 14. Reduction of Part Numbers with High Speed LPT.

Even though the disks of the high speed LPT are much heavier due to elevated centrifugal loads, the overall design is much more compact, which leads to lower LPT weight in the end.

Assuming an optimum bypass ratio for both the direct drive TF and the GTF™ engine, the weight of the high speed LPT can be reduced to about 70% of the conventional LPT weight. As described above the GTF™ engine has an additional TSFC benefit. To evaluate the weight opportunity of the LPT due to the GTF™ engine concept only, a direct drive TF and a GTF™ engine with the same (high) bypass ratio have to be compared. In this case the weight of the high speed LPT can be reduced even further down to 60% relative to the conventional LPT. This potential counteracts the weight increase of the GTF™ engine due to other new or heavier components as shown in FIG 9.

3.1.2. High Efficiency Level

The high speed LPT achieves high specific work output by means of high rotational speed per stage. This allows to keep the aerodynamic loading $\Delta H/u^2$ in a reasonable range, which is typically on a lower level than in conventional turbines. Therefore efficiency levels can be kept high.

Additionally the average row velocity ratio can exceed values of $c_2/c_1 \approx 2.3$, while conventional modern turbines are more in the range of around 1.8. This enlarges the area of laminar flow at the airfoil and reduces friction losses.

The aerodynamic design of high speed LPTs was subject of a number of technology programs in the past. Detailed results can be found e.g. in [2] and are therefore not discussed in this paper any further.

3.1.3. High Blade Passing Frequency

The fundamental tone frequencies (BPF) of the high speed LPT at landing condition (approach) are in the order of 7 kHz and higher. However, sound of high frequencies propagating through the atmosphere is highly attenuated. Furthermore the frequency related noisiness of the high speed turbine tones perceived by the human ear (PNLT weighing) is significantly lower. Advantageous for the frequency characteristic is the absence of turbine tones at the higher harmonics (2BPF, 3BPF etc.) even at approach condition enabled by a favorable choice of blade numbers. In consequence, the tonal turbine sound at higher rotational speed in terms of take-off condition is even more dampened or not hearable beyond the frequency of 10 kHz.

3.2. High Speed LPT Challenges

3.2.1. High AN^2

The intentionally high rotor speed is very challenging for the mechanical turbine design and the corresponding turbine weight.

FIG 15 shows the design strategy and dependencies for a lightweight design of a turbine stage.

First of all a sophisticated outer shroud design is needed to reduce centrifugal forces for the airfoil (1). The airfoil itself has to carry the loads caused by the outer shroud and of its own tip section (2). The mass of the airfoil including the outer shroud defines the airfoil root (3). The blade (airfoil including shroud and root) defines the radial load of the disk on the one side (4a), and the thickness of the casing to contain a blade in case of a blade loss event on the other side (4b).

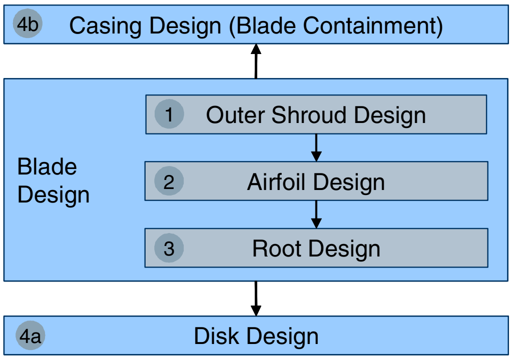

FIG 15. Dependencies for Lightweight LPT Design.

In FIG 16 a comparison is shown between the outer shroud of a conventional and a high speed LPT blade. To reduce mass a careful cut back is necessary without significant spoiling of the axial and circumferential sealing properties (see dotted contour on the right side). Additionally the knife edges should be used to increase the stiffness of the overhanging parts of the shroud in order to reduce shroud curling. The axial length of the airfoil and the radius of the center of gravity of the outer shroud are two additional major parameters which impact centrifugal loads caused by the outer shroud. Both parameters affect aerodynamics though, and therefore can not be reduced below a certain limit without major efficiency loss.

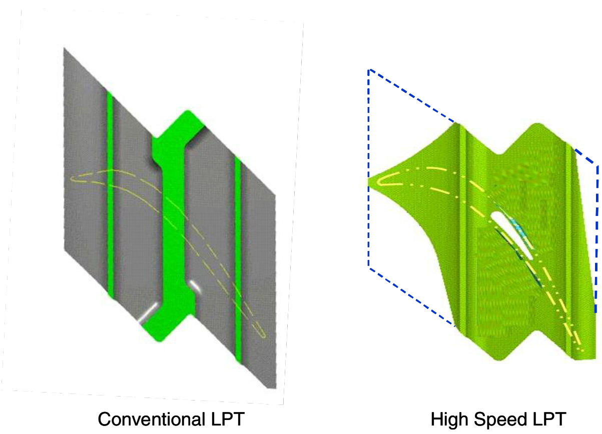

FIG 16. Conventional versus High Speed Blade Outer Shroud Design.

The relevant parameter for the mechanical loads caused by the airfoil due to centrifugal forces is AN^2 with A as annulus area at the turbine stage considered, and the rotor speed N. These loads have to be supported by the airfoil itself as well as by the disk.

The tip section of an airfoil is usually designed for minimum acceptable thickness with respect to castability. Hence a dedicated increase of cross sectional area of the airfoil from the tip to the root (airfoil taper) is required to limit the stress level in the airfoil. A high allowable mean stress level is highly important for controlling the blade weight. The acceptable mean stress level depends on the material properties (HCF, Creep) and on the required margins for local peak stresses (caused by blade shape, vibratory stress, local defects and tolerances). The airfoil root area must be optimized as well to reduce the loads at the outer disk rim to transfer the loads from the airfoil smoothly into the disk rim. Therefore root area, root angle and fir tree shape must be optimized. FIG 17 shows the typical differences between conventional and high speed blade design, as the cut back of the outer shroud, the airfoil taper and the axial length of the blades root area.

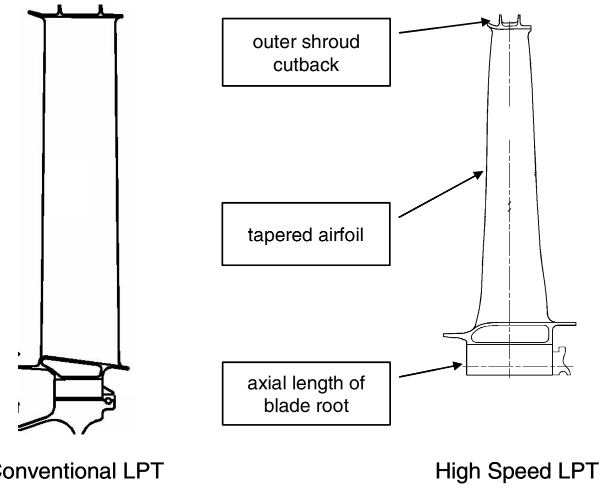

FIG 17. Conventional versus High Speed Blade Design.

In FIG 18 the effect of the high centrifugal loads for the disk design is shown. In conventional designs flanges used to mount the disks are usually between the disks to have access to the nuts and screws. In high speed LPTs flanges and spacers must be kept close by the disks to limit the hoop stress in the parts as known from HPT or HPC design. Therefore the flanges are located close to the disks which adds mass to the disk web itself. To carry these large radial loads a broad hub on the lowest possible radius is needed. A smooth transition into the web limits the radial and the hoop stress.

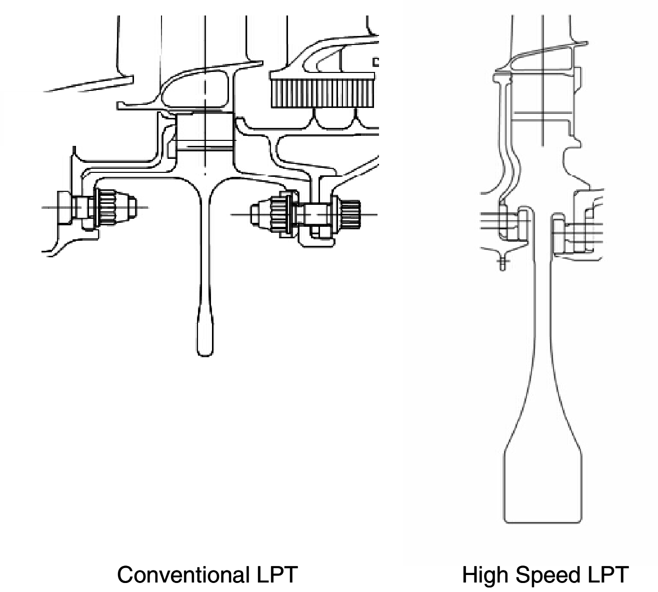

FIG 18. Conventional versus High Speed Disk Design.

3.2.2. High Mach Number Level

Caused by high rotor speed and reduced stage count and therefore high pressure ratios, high flow Mach numbers throughout the turbine will tend to increase losses and decrease efficiency.

Therefore it is beneficial to increase the flow path area especially in the front stages by a rather steep interturbine duct and a large outer annulus radius. In the rear part of the turbine the maximum radius of the annulus is limited by the nacelle line. In this area thin airfoils on a high stress level with low blockage are important to reduce the exit Mach number.

In addition, for low thrust and high flight altitude engine applications the Re number is low which increases the tendency to flow separation. Therefore the aspect ratio of the airfoils should be reduced to minimize losses.

3.2.3. High stage pressure ratio

Due to high stage pressure ratios the leakage over outer and inner air seals will increase. This illustrates the need for a careful seal design. Brush seals and floating static inner air seal rings help to reduce leakage significantly. Special endwall design helps to minimize the impact of the leakage to the main flow in the gas path.

3.2.4. Overspeed Protection And Disk Burst Margin

For low shaft shear events an overspeed protection system is required to limit the burst margin for LPT disks required beyond maximum normal operating speeds. If the shaft shear occurs upstream of the low spool thrust bearing, no axial shift of the low shaft and as a result of the LPT rotor occurs. In this case an overspeed protection on the system level, like a fast fuel shut-off mechanism (electronically or mechanically) is required. Alternatively this event can be excluded by definition when using prime reliable parts in the relevant areas.

If the shaft shears downstream of the thrust bearing, an immediate axial shift of the LPT occurs. In this case a mechanical intermeshing system can avoid a critical overspeed of the rotor. Because rotor speed is much higher than in conventional turbines, the driving torque of the shaft is much lower for a given power demand. This torque has to be counter balanced by blade to vane interactions at the intermeshing location to avoid a rapid acceleration of the turbine. On the other hand the high speed LPT rotor moment of inertia and speed are significantly higher than in conventional turbines and hence the total energy of rotation is very high. This energy has to be dissipated during the intermeshing event into heat.

4. TECHNOLOGY DEVELOPMENT AND DEMONSTRATION

As laid out in chapter 2 the GTF™ engine is the best suited concept to fulfill the stringent fuel burn and noise requirements of the next generation turbofan engine products at the same time. In order to prepare its application to a product MTU together with its partner companies P&W, Avio and VAC follows through a continuous program of technology development and demonstration for the last two decades. The whole scope of technologies from parts to module to engine level is addressed analytically as well as via rig test programs and engine demonstrators. The objective is to get the GTF™ engine concept including all parts and module level technologies ready for application to a product at the latest by mid to end of 2008 in order to protect a potential next generation product Entry-Into-Service of 2012.

4.1. Parts And Module Level Technology

For the front end of the engine P&W and Avio work towards maturation of various areas of technology. FIG 19 shows an overview of the major rig test activities and how they feed into the GTF™ Engine Demonstrator program. Focus is on

- Fan and LPC aero and structures testing with appropriate rotational speed level and therefore aero and structural design space,
- mechanical systems like bearings (tapered roller bearings, journal bearings) and high speed seals for performance, endurance, oil distribution and interruption and misalignment, and
- the FDGS in terms of performance, durability and reliability.

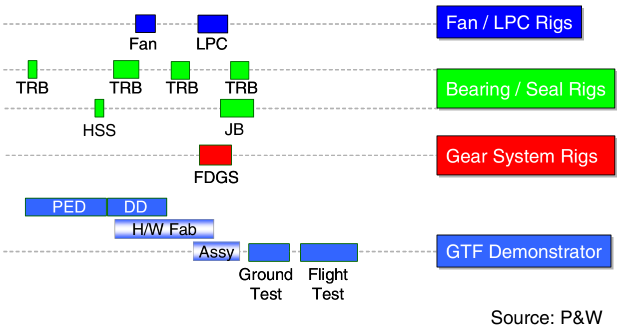

FIG 19. Front End Technology Maturation Plan.

MTU has been continuously working on its LPT technology maturation programs as well. As an example of the previous work ref [1] summarizes the development and testing of the high speed LPT for ATFI. FIG 20 provides an overview of the technology development activities for the high speed LPT.

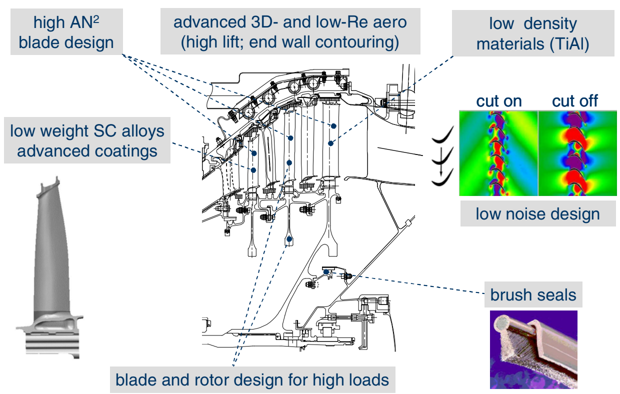

FIG 20. LPT Technology Activities.

Main focus is on:

- advanced 3D aerodynamics (high lift airfoils, end wall contouring) especially for high Mach number and low Reynolds number applications,
- low noise designs taking into account the elevated blade passing frequencies due to the high speed design,
- light weight low density materials especially for rotating airfoils (TiAl),
- high AN^2 blade design (high mean stress levels), and brush seals for reduced leakage, low deterioration and low maintenance cost in a high speed environment.

As for the front end technologies the objective is to reach technology readiness for all high speed LPT required technologies in time to protect an EIS date of 2012. FIG 21 shows MTU's LPT technology maturation plan on a timeline. The rig test programs and the engine demonstrator programs complement one another in order mature the technologies with all aspects being considered.

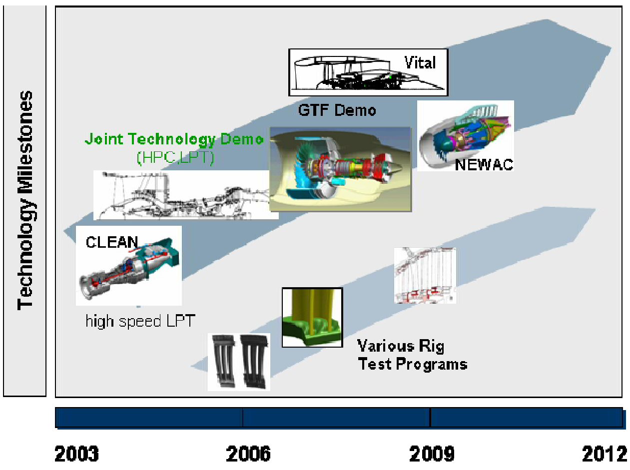

FIG 21. LPT Technology Maturation Plan.

4.2. 15+ Years Of Engine Demonstrators

Complementing the rig tests programs and taking the learning one step further on the systems level, MTU,P&W, Avio and VAC have been running engine demonstrator programs all along. For more than 15 years these companies have been partnering to demonstrate the benefits of the geared engine configuration with demonstrator engines, the most important and successful ones being

- the Advanced Ducted Propfan (ADP) in 1993,
- the Advanced Technology Fan Integrator (ATFI) in 2001, and
- the European Technology Program CLEAN in 2004, see [4].

FIG 22 shows the ADP and the ATFI engines which have covered the takeoff thrust range of 13 klb up to 50 klb.

The ADP has featured an MTU high speed LPC and LPT and completed sea-level tests at P&W's Florida facility as well as altitude tests at NASA Ames' ATF in 1993. The ATFI build 1 has featured an MTU high speed LPT which was successfully tested in a low spool dedicated engine test at P&W Canada's sea-level test bed in 2001.

The next step in this continuous line of geared engine technology demonstrator engines is the GTF™ Engine Demonstrator program which is going to test towards the end of 2007, see FIG 22. This engine will be designed for the thrust class of engines for the NGPF airplanes. Compared to the demonstrator programs so far the upcoming GTF™ Engine Demonstrator program will be the first one to include flight tests, hence taking all the aircraft/engine installation and integration aspects into account.

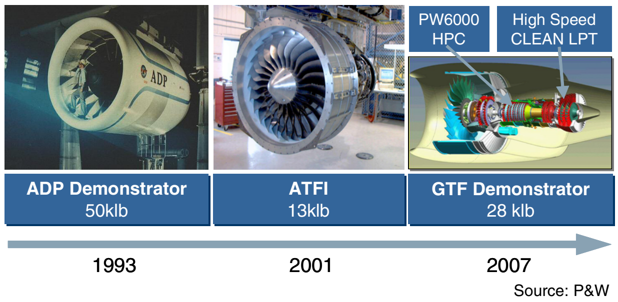

FIG 22. Geared Engine Configuration Demonstrators

4.3. GTF™ Engine Demonstrator Program

As mentioned above the GTF™ Engine Demonstrator will be the first flight test demonstrator program of the GTF™ engine concept by the involved partner companies P&W, MTU, Avio and VAC. This will take the technology maturation from the engine level to the propulsion system level, which we consider to be a very significant milestone on our journey to technology readiness of the GTF™ engine concept.

The program is lead by P&W as the partner being responsible for the low spool compressors, Fan Diffuser, HPT, system design and component integration as well as for all interfaces to the test beds including the flying test bed aircraft. In addition significant partner participation is ensured by MTU (HPC and LPT), Avio (FDGS), VAC (TEC) and Goodrich (Nacelle). FIG 23 shows the partner participation for the major components.

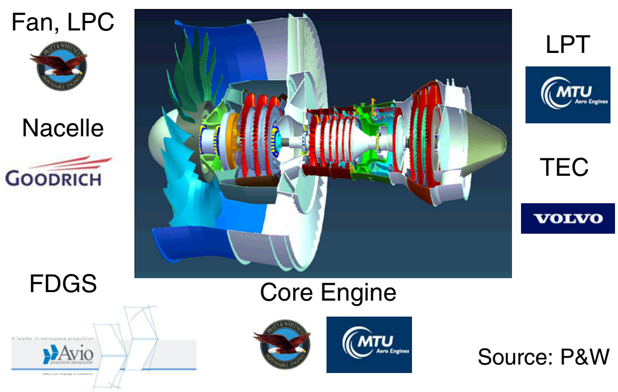

FIG 23. GTF™ Engine Demonstrator – Partnership.

The engine is comprised from the PW6000 core, the CLEAN LPT and TEC adapted to the PW6000 inter turbine duct, and an all new front end including a high bypass ratio low pressure ratio Fan, a high speed LPC and a Fan Drive Reduction Gear System.

The program timeline foresees target-to-fire in November 2007 at the P&W ground test facility in Florida, USA. Subsequently the engine will be installed on a P&W owned FTB (Boeing 747) in New York State, USA, flight tests are scheduled for 2008. The program is intended to demonstrate technology readiness for the GTF™ engine concept by end of 2008, see FIG 19.

The engine's test program will focus on key learning which has not yet been achieved in the previous demonstrator programs. The FTB will especially provide learning for

- the in-flight performance and operability including extreme operating conditions as e.g. windmilling and windmill relights, and
- the functionality and performance of the FDGS and the thermal management system under real flight conditions including zero-g, windmilling, windmill relight, maneuver loads and deflections.

Furthermore the tests will provide significant insight into the aircraft/engine installation and integration aspects which can only be learned once the real aircraft/engine integration is executed. The upfront ground tests allow for detailed acoustics tests as well as for system functionality checks and check-out of the engine for flight.

5. CONCLUSIONS

In a world of continuously growing air traffic the demand for environmentally friendly aircraft engines is strong. Market requirements focus on emission and noise reduction, but also on purely economically driven objectives like fuel burn and TSFC caused by the increasingly high fuel prices, and production and maintenance cost.

The geared turbofan is the only turbofan engine concept which allows significant reduction in fuel burn, maintenance cost and noise at the same time, and which will be technology ready near-term to support EIS dates the aircraft manufacturers and airline customers are envisioning. While the ducted counter-rotating Fan engine architectures are promising in terms of TSFC and fuel burn, their technology readiness is more than one decade away. Open rotor concepts (un-ducted Fans) are likely to provide even higher TSFC and fuel burn benefits, but are struggling with achieving noise requirements as we understand them today, and are likely to require dramatic changes in terms of engine/airframe integration. Hence the GTF™ engine is THE best concept for the demands of the market.

In order to mature the geared engine configuration technology MTU and its partners P&W, Avio and VAC have been following through a series of technology development programs on the parts, module and system level for the last two decades. The efforts include rig testing as well as engine system ground testing, as e.g. during ADP, ATFI and CLEAN programs. The current GTF™ engine demonstrator program is the next logical step taking technology maturation to the propulsion system level by a flight test demonstrator. Based on these activities the GTF™ engine concept is going to achieve technology readiness in 2008 to support a next generation product EIS date as early as 2012.

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