南京航空航天大学
第六届本科生学术论坛

论文选集

主办单位 教务处 校团委 科技部 学生处 校科协
承办单位 校大学生科协 各学院团委 大学生科协

江苏 南京

二〇一四年十二月

前　言

南京航空航天大学本科生学术论坛，是培养和展示学校本科生学术水平的重要平台，其宗旨是：培养本科生的创新意识，促进学术思想的交流，提升本科生学术研究能力，营造浓厚的校园学术文化氛围。

本届学术论坛启动前，组委会邀请了本科生代表与教师代表共同研究讨论确定了本届本科生学术论坛方案，以“引导本科生普遍参与、力争让学生广泛受益”为工作定位，校院两级层面各有侧重地开展论文的征集评审、学术报告会、学术沙龙等，特别重视专业教师对论文写作过程中的指导。

本届论坛自 2014 年 4 月启动以来，受到了我校同学和老师的广泛关注。院级学术论坛共收到学术论文 734 篇，评审出 181 篇进入到校级论文评审。此外，本届论坛还举办了信息检索、理工类和人文社科类论文写作方法等学术讲座 5 场，邀请校内外学者作学术交流报告 22 场，举办校院两级学生自主沙龙 52 场，举办小型师生互动交流会 23 场。

2014 年 10 月，组委会邀请专家学者对校级 181 篇论文进行了评审，共评选出一等奖论文 10 篇，二等奖论文 20 篇，三等奖论文 30 篇。其中，一、二等奖 30 篇优秀论文收录入《南京航空航天大学第六届本科生学术论坛论文选集》。

“智周万物惟创造，道济天下展经纶”。我们相信，此次本科生学术论文选集的出版定能鼓舞广大本科生严谨学术、勇攀高峰。

南京航空航天大学第六届本科生学术论坛组委会

二〇一四年十二月五日

目　录

Investigation on Geared Turbofans

Xiqiao Yu, Lance Fang, Thomas Lapid, Arthur Wong,

Contents

Abstract

Introducing a new engine, into the aviation industry, is a very difficult process. The company designing the engine must overcome a variety of challenges in order for the engine to be put into mass production. Throughout this report, the challenges these companies face are discussed. Even the first ever geared turbofans faced challenges; these will also be discussed. Some of the challenges faced by companies include noise regulations, carbon emission regulations, limits of the materials used for the engine, etc. By the end of this report, it should be clear how difficult it is to implement a new engine; not just from the perspective of an engineer, but also from the perspective of airline corporations.

Introduction

This comprehensive report will be regarding the geared-turbofan. The purpose of this report it to show the superiority of the geared-turbofan compared to the conventional turbofan. In regards, the performance and also the potential of geared-turbofans in the future. The necessary background information, that is the brief history and the development of the geared-turbofan as well as the challenges the geared-turbofan has faced, will be discussed. The industrial use of both the geared-turbofan will also be included in the background information, so that any reader may be able to understand this report. In order to complete the objective, the various performances of the geared-turbofan shall be compared to the performance of a conventional turbofan. The aerodynamic performance of the geared-turbofan and the conventional turbofan will be presented to make the comparison possible. Performance alone does not decide whether or not an engine is superior to another engine. As the aircraft must fly in the atmosphere, creating noise and polluting emissions are also relevant in deciding whether or not an engine is superior to another engine. The decision of whether an engine should be invested in is also determined by whether or not it is within regulations (for this report we shall be using standard ICAO regulations). Hence this will also be taken into consideration when comparing the geared-turbofan to the conventional turbofan; and determining that the conventional turbofan is obsolete compared to geared-turbofan.

Methodology

Using various sources available to students, information was collected from journals, textbooks, websites, articles, etc. Once all the information was collected, calculations were performed, facts were written down, and images were found. When a source of information was found, the reference was recorded in order to ensure they are properly referenced in our paper.

Background

Before giving the background and review of the geared turbofan engine, we will first explain a regular turbofan engine. The turbofan engine is a derivation of a turbojet engine; the turbofan engine is essentially a turbojet engine with a large fan attached to the front of it, a basic diagram of a turbofan engine is shown below.

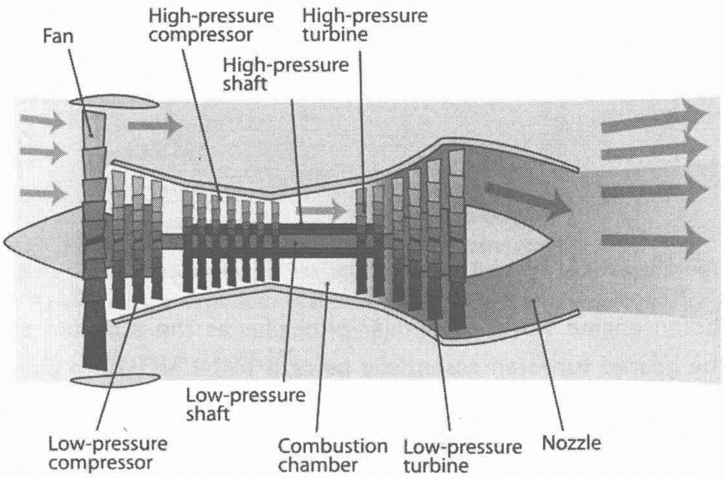


Figure 1 The schematic of a geared turbofan, Source: http://en.wikipedia.org/wiki/Turbofan

Turbofans are widely used today, for example in the A380 uses the Rolls-Royce Trent 900 turbofan engine (Matthew Perra, 2008). Turbofans like other engines had problems initially due to technology and material limitation of the time of its initial usage. Some of these challenges include high fuel inefficiencies, low pressure ratios and turbine inlet temperature as years passed some of these issues were solved however new problems arose. It was not until the 1960's that the turbofan was used in the civilian sector. An example of this is the Pratt & Whitney JT8D. It was first put into service in February 1964 on the Boeing 727 (Riegler and Bichlmaier, 2007). Initially turbofan engines had low bypass ratios; the Pratt & Whitney JT8D from the 1960's has a bypass ratio of about 1 (Kane, 2012) whilst the modern Rolls-Royce Trent 900 has a bypass ratio of about 8.7. A higher bypass ratio results in a lower thrust specific fuel consumption which is ideal for modern day operating principles, thus showing that in the past turbofans were very fuel- inefficient whilst modern turbofans are much more fuel efficient.

Turbofans have various configurations such as; Aft-fan, basic, two spools, boosted two spools, geared, high pressure turbine, low pressure turbine, single shaft and three spools (Kane, 2012). In this paper we will be focusing on the geared turbofan (GTF).

The geared turbofan engine (GTF) is basically a turbojet combined with a turbofan as well as a planetary gear reduction box, an example of this type of engine is the Pratt and Whitney PW1000G. Pratt and Whitney knew of the geared turbofan concept since 1980's. The concept of the geared-turbo is the decoupling of the low pressure turbine and the low pressure compressor from the fan (Larsson et al., 2011). However they did not attempt to design one due to the limitations of technology, materials at the time, and also the safety and reliability requirements (for the new technology at the time); would be too difficult to satisfy during that era (Ragheb and Ragheb, 2010). Note: Pratt and Whitney was not the first to produce a geared turbofan, the first turbofan was the Garrett TFE731 (now Honeywell TFE731) in 1970. Below is a basic diagram of a geared turbofan engine.

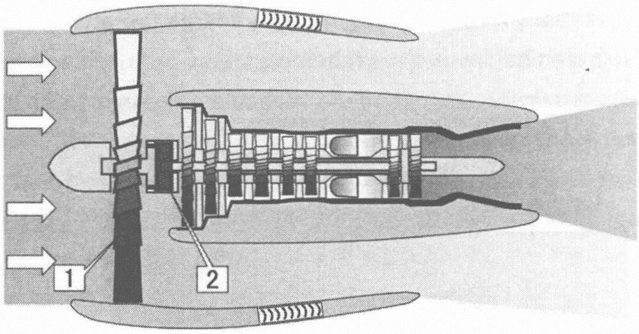


Figure 2 The schematic of a geared turbofan http://en.wikipedia.org/wiki/Geared_turbofan

The geared turbofan engine works on similar principles as the turbofan and the turbojet. This is due to the geared turbofan essentially being a turbofan with a planetary reduction gearbox. The planetary gearbox is simply a gearbox with a central gear or the sun gear that has multiple gears or planet gears orbiting around the central or sun gear. The geared turbo fan engine has a reduction gear between the fan and the core engine's spool, this gear allows the low pressure compressor and low pressure turbine to operate at an optimum speed and lower pressure ratio while the fan operates at a lower speed (Riegler and Bichlmaier, 2007) which in turn reduces the amount of noise produced an example of this is found in the PW8000 where the drop in fan speed led to a noise emission decrease of 30EPNdB (Effective Perceived Noise in decibels)(Kandebo, 1998). This configuration leads to an increase in efficiencies and reduces the amount of stages in the geared turbofan engine (Larsson et al., 2011). The PW8000 in comparison to other turbofan engines in its time had 40% and 50% less stages and airfoils respectively (Kandebo, 1998).

In general a geared turbofan engine would have the following properties: (Ragheb and Ragheb, 2010, Kandebo, 1998, Larsson et al., 2011, Riegler and Bichlmaier, 2007)

- Greater thrust than turbofan or turbojet
- Fewer stages in the engine than other engine types
- Less noise emission than other engines due to a decrease in fan speed
- Geared turbofans are high bypass ratio engines
- Higher propulsive efficiency than other engine types
- Lower thrust specific fuel consumption than other engine types

From the above, it can be said that the general principle of the geared turbofan is to increase the bypass ratio which improves propulsive efficiency and lowers thrust specific fuel consumption, whilst decreasing noise (Riegler and Bichlmaier, 2007).The geared turbofan is a logical solution to our modern challenges which include; gradual increase in air traffic, fuel prices, fuel scarcity, noise pollution and environmental emissions that lead to global warming (Riegler and Bichlmaier, 2007). Below is a graph of the estimated growth of air traffic from 1990~2020 (Riegler and Bichlmaier, 2007).

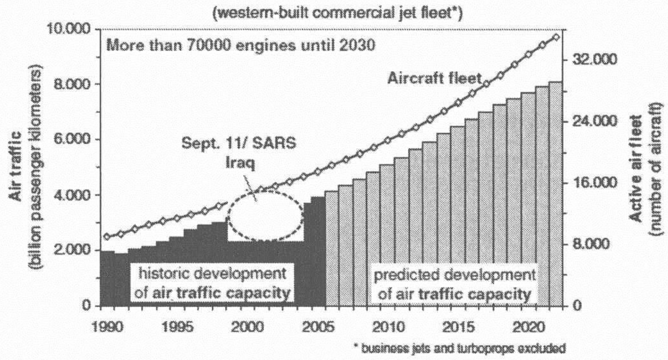


Figure 3 Projected growth of air traffic (Riegler and Bichlmaier, 2007)

Challenges of the Geared Turbofan

The following are some challenges of the geared turbofan that have either been an issue or is currently an issue. (Wiltshire, 2011)

- Complex compared to other engine types
- Heavier than turbofans
- Low spool system
- Gearbox reliability
- Gearbox lubrication

As the rpm of the low pressure system increases, so does the stresses experienced by the low pressure turbine discs. To solve the issue of the turbine discs being unable to withstand the stresses upon it, the mass of the turbine discs were increased (Wiltshire, 2011).

The weight of geared turbofan is a challenge since geared turbofan engine is heavier than a direct drive turbofan engine for the same fan diameter. This is disadvantageous; however the geared turbofan produces better efficiencies. The geared turbofan still however suffers from the oil overheating. The oil used as lubricants to cool the system faced a high temperature increase due gearbox system, this issue was solved by spraying only the areas with increased temperature this avoided excessive heat in the system (Wiltshire, 2011). Geared turbofans have larger fan diameters than the regular turbofan therefore increasing the weight of the engine, one way to avoid this issue is to use lighter materials or design the engine so that it can have the same performance for a smaller fan size (Riegler and Bichlmaier, 2007). Blade life can also be an issue that needed to be solved, instead of increasing the weight of the blades which would also solve the issue. The high pressure turbine blades were instead casted in yttrium based material. (Kandebo, 1998)

An ongoing challenge of the geared turbofan would be the desire to further increase the high bypass ratio which in turn would increase efficiency of the engine as well as the decrease TSFC and the noise pollution of the engine. As the geared turbofan is still a not a matured concept its reliability is also an issue which can only be solved through extensive research, testing and financing.

The challenges are investigated more in-depth throughout the report.

Regulations

Before any new engine can be entered into service, it must meet certain regulations. For our case, we will be using ICAO (International Civil Aviation Organisation) regulations.

Greenhouse Emissions

For engines to be certified following emissions must be controlled

- Smoke
- Gaseous emissions
- Unburned hydrocarbons
- Carbon monoxide
- Oxides of nitrogen

Pollutants are measure and reported in grams, pollutants being unburned hydrocarbons, carbon monoxide and oxides of nitrogen.(ICAO, 2008)

To determine gaseous and smoke emissions, must use the following:

Table 1 Gaseous and smoke emissions regulation

LTO operating mode	Thrust setting
Take off	100% F_{∞}
Climb	85% F_{∞}
Approach	30% F_{∞}
Taxi/ground idle	7% F_{∞}

Where F_{00} is the rated thrust.

To calculate gaseous and smoke emissions the aircraft will spend a specified amount of time in each phase shown below:

Table 2 Time in operating mode in different phases

Phase	Time in operating mode, minutes
Take off	0.7
Climb	2.2
Approach	4.0
Taxi/ground idle	26.0

The smoke number must not exceed during any of the four phases: Take off, climb, approach, and taxi/ground idle.

$$Regulatory\ smoke\ number = 83.6 * {F_{00}}^{-0.274}$$

Where F_{00} is the rated thrust.

Smoke number found using the equation above, the smoke number must not be higher than the value found by that formula OR a value of 50, preferably the lower one is not exceeded.

The gaseous emission levels shall not exceed the following ratios:

For Hydrocarbons (HC): $\frac{D_p}{F_{00}} = 19.6$

For Carbon monoxide (CO): $\frac{D_p}{F_{00}} = 118$

For Oxides of Nitrogen (NO_x):

a) For engines of a type or model where the date of manufacture of the first individual production model was on or before 31st December 1995 and for which date of manufacture of the individual engine was on or before 31st December 1999.

$$\frac{D_p}{F_{00}} = 40 + 2\pi_{\infty}$$

b) For engines of a type or model where the date of manufacture for the first individual production model was after 31st December 1995 or for which date of manufacture of the individual engine was after 31st December 1999.

$$\frac{D_p}{F_{00}} = 32 + 1.6\pi_{00}$$

c) For engines of a type or model where the date of manufacture of the first individual production model was after 31st December 2003:

1) For engines with a pressure ratio of 30 or less:

i) Engines where $F_{00max} > 89\ kN$:

$$\frac{D_p}{F_{00}} = 19 + 1.6\pi_{00}$$

ii) Engines where $26.7\ kN < F_{00max} < 89\ kN$:

$$\frac{D_p}{F_{00}} = 37.572 + 1.6\pi_{00} - 0.2087F_{00}$$

2) For engines with a pressure ratio of more than 30 but less than 62.5:

i) Engines where $F_{00max} > 89\ kN$:

$$\frac{D_p}{F_{00}} = 7 + 2\pi_{00}$$

ii) Engines where $26.7\ kN < F_{00max} < 89\ kN$:

$$\frac{D_p}{F_{00}} = 42.71 + 1.4826\pi_{00} - 0.4013F_{00} + 0.00642\pi_{00} * F_{00}$$

3) For engines with a pressure of 62.5 or more:

$$\frac{D_p}{F_{00}} = 32 + 1.6\pi_{00}$$

d) For engines of a type or model where the date of manufacture of the first individual production model was after 31st December 2007:

1) For engines with a pressure ratio of 30 or less:

i) Engines where $F_{00max} > 89\ kN$:

$$\frac{D_p}{F_{00}} = 16.72 + 1.4080\pi_{00}$$

ii) Engines where $26.7\ kN < F_{00max} < 89\ kN$:

$$\frac{D_p}{F_{00}} = 38.5486 + 1.6823\pi_{00} - 0.2453F_{00} - 0.00308\pi_{00} * F_{00}$$

2) For engines with a pressure ratio of more than 30 but less than 62.5:

i) Engines where $F_{00max} > 89\ kN$:

$$\frac{D_p}{F_{00}} = -1.04 + 2\pi_{00}$$

ii) Engines where $26.7\ kN < F_{00max} < 89\ kN$:

$$\frac{D_p}{F_{00}} = 46.16 + 1.4826\pi_{00} - 0.5303F_{00} + 0.00642\pi_{00} * F_{00}$$

3) For engines with a pressure of 82.6 or more:

$$\frac{D_p}{F_{00}} = 32 + 1.6\pi_{00}$$

Where D_p is any mass of any gaseous pollutant emitted during reference emissions landing and take-off cycle, and π_{00} is the reference pressure ratio. (ICAO, 2008)

During the testing of engines for emissions produced, A fuel with the following specifications below must be used.

Table 3 Regulations about fuel use

Property	Allowable range of values
Density (kg/m^3) at 15°C	780-820

Distillation temperature (°C)	
10% boiling point	155-201
Final boiling point	235-285
Net heat of combustion (MJ/kg)	42.86-43.50
Aromatics (volume %)	15-23
Naphthalenes (volume %)	1.0-3.5
Smoke point (mm)	20-28
Hydrogen (mass %)	13.4-14.3
Sulphur (mass %)	Less than 0.3%
Kinematic viscosity at -20°C (mm^2/s)	2.5-6.5

(ICAO, 2008)

Noise Emissions

ICAO uses balanced approach that is reducing noise pollution by the four key factors

- Reduction of noise at source
- Planning and management of land
- Noise abatement operations
- Operating restrictions

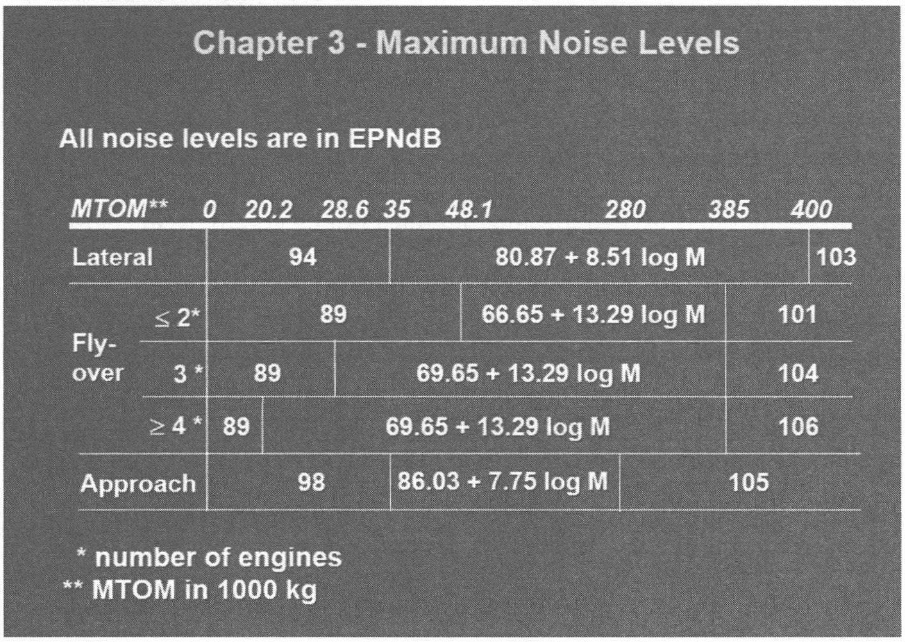


Figure 4 Max noise levels

Source: http://www.icao.int/Meetings/EnvironmentalWorkshops/Documents/NoiseCertificationWorkshop-2004/BIP_2_2_jb.pdf

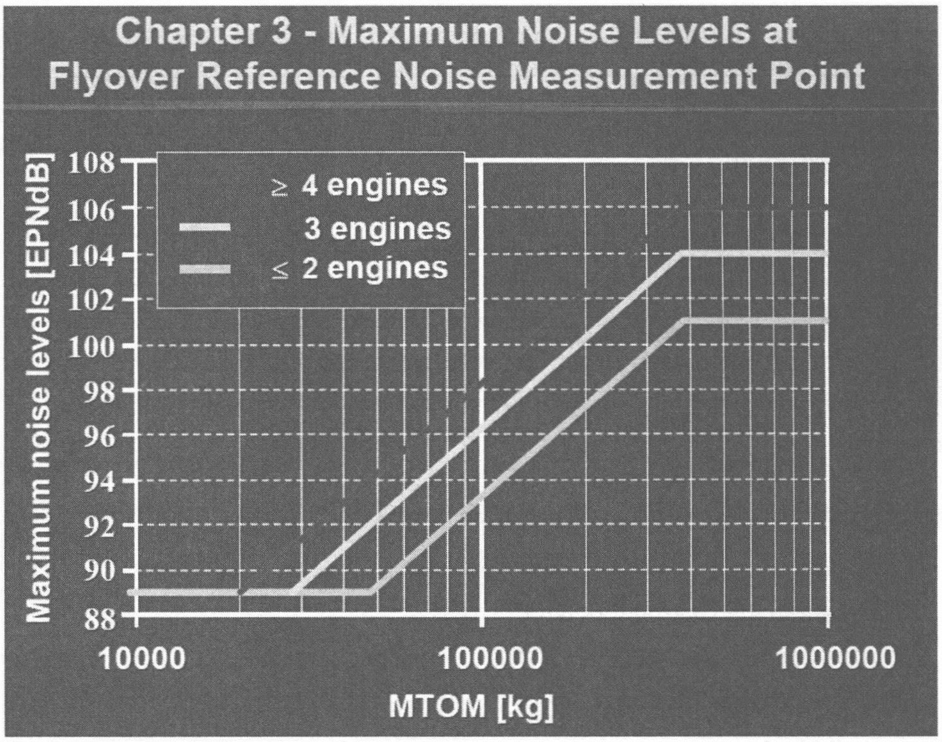


Figure 5 Max noise level at flyover reference noise measurement point
Source: http://www.icao.int/Meetings/EnvironmentalWorkshops/Documents/NoiseCertificationWorkshop-2004/BIP_2_2_jb.pdf

If max noise level is exceeded at 1 or two measurement points (Bottcher, 2004):

However a single point may exceed the limit but must not be greater than 2EPNdb

- Sum of excesses must not be greater than 3EPNdb

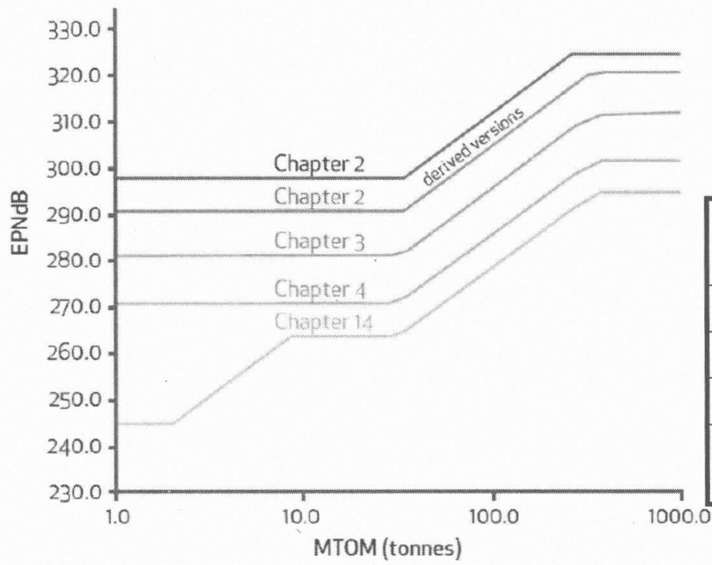
One may use noise reduction systems in order to decrease the amount of noise produced:

- by changing its configuration or operations which reduces noise
- implement a system that reduces noise or counteracts acts the noise produced

Two systems that do these are Variable noise reduction systems (VNRS) and selectable noise reduction systems. (ICAO, 2012)

Airports may fees on noise pollution and emissions due to fuel burn. The noise fees may use the effective perceived noise level (EPNL) as a charge parameter. (ICAO, 2013)

For future development; predicted noise regulations are as follows



Chapter	Applicable Year	Cum Margin (EPNdB)
2	1972	Ch. 3 ~-16
3	1978	0 (Ref)
4	2006	Ch. 3 +10
14	2017 & 2020	Ch. 3 +17 (Ch. 4 +7)

Figure 6 Prediction of future noise pollution
Source: (Dickson, 2013)

Working Principle of a Geared Turbofan

In a typical turbofan engine, the power plant's high-pressure turbine drives the high-pressure compressor, while the low-pressure turbine (LPT) drives both the low-pressure compressor (LPC) and the fan. However, the most efficient fan speeds are slower than those of the low-pressure turbine, resulting in a compromise speed that is not fully efficient for either. In a geared fan system, a reduction gearbox is placed between the fan and the low-pressure compressor, so that the turbine and low-pressure compressor are allowed to turn at high speeds and the fan at lower speeds (Kandebo, 1998). The geared turbofan is to add a gearbox between the compressor and the fan, which makes them work effectively at their own speed. The gearbox can help the fan work independently to the low-pressure compressor and the turbine.

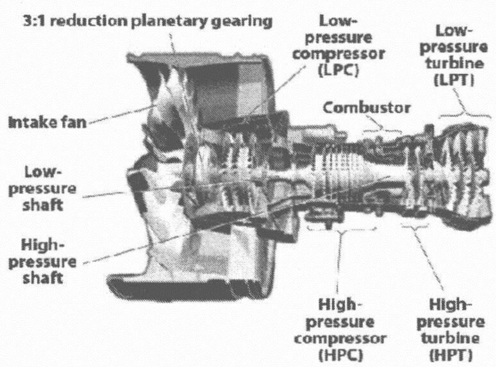


Figure 7 Pratt & Whitney's Geared Turbofan engine schematic
Source: http://images.machinedesign.com/images/archive/72724gtfschemat_0000050947.gif

In a geared turbofan engine (see Figure 4), the incoming air is captured by the engine inlet. Some of the incoming air passes through the fan. It then goes through the gearing system, which makes the fan and the compressor work effectively in their own speed. After that, the air will be compressed in the compressor. Then it goes into the burner, where it is mixed with fuel and combustion occurs. The hot exhaust passes through the core and fan turbines and then out the nozzle, as in a basic turbojet. The rest of the incoming air passes through the fan and bypasses, or goes around the engine, just like the air through a propeller. The air that goes through the fan has a velocity that is slightly increased from free stream. So a turbofan gets some of its thrust from the core and some of its thrust from the fan. The ratio of the air that goes around the engine to the air that goes through the core is called the bypass ratio. The geared turbofan engine is proposed to have a high bypass ratio, since the fan can spin at a relatively low speed.

The Gearbox

By introducing a gearbox into the turbofan, a variety of issues can be encountered. The following indicates some of the issues. E.g. choosing the correct gearbox design and the quality of the gearbox production.

Similarity between Wind and Turbofan Gearboxes

Planetary spur gearing (Ragheb, 2011) comprises of multiple outer gears and an internal gear. The multiple outer gears regarded as the 'planets' revolve around the internal gear view as the 'sun'. In order to achieve a reduction or increase in rpm, an outer ring gear or annulus is required. Figure 4 shows a planetary spur-style gearing system. In a wind turbine, the green annulus is connected to the rotor hub, while the yellow sun gear is connected to the generator. Similarly, to apply this gearing system in a geared turbofan, the fan leads the green annulus, while the yellow sun gear is connected to the low-pressure turbine.

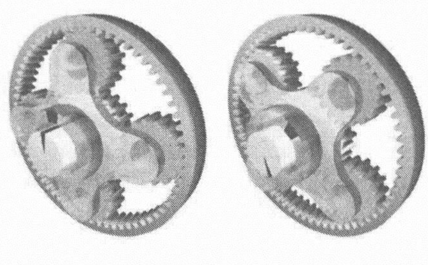


Figure 8 Planetary spur or epicycle gearing system
Source: http://en.wikipedia.org/wiki/File:Epicyclic_gear_ratios.png

As depicted in Figure 4, a planetary gear system contains three component gears: the sun gear, the planet gears, and the annulus. N_{sun} is referred to the number of teeth on the sun gear; $N_{annulus}$ is referred to the number of teeth on the annulus , and N_{planet} the number of teeth on the planet gear. Using the relationship, that the number of teeth is directly proportional to the diameter of a gear, the three values should satisfy the equality of Eqn. 1 which shows that the gears will fit within the annulus.

$$N_{sun} + 2 * N_{planet} = N_{annulus}$$

(1)

With Eqn.1 satisfied, the equation of motion for the three gears is:

$$\left(2 + \frac{N_{sun}}{N_{planet}}\right)\omega_{annulus} + \frac{N_{sun}}{N_{planet}}\omega_{sun} - 2 \times \left(1 + \frac{N_{sun}}{N_{planet}}\right)\omega_{planet} = 0$$

(2)

Where ω_{sun}, $\omega_{annulus}$, and ω_{planet} are the angular velocities of the respective gears. Since angular velocity is directly proportional to the rpm, Eqn. 2 simplifies Eqn. 3 below:

$$\left(2 + \frac{N_{sun}}{N_{planet}}\right)rpm_{annulus} + \frac{N_{sun}}{N_{planet}}rpm_{sun} = 2\left(1\frac{N_{sun}}{N_{planet}}\right)rpm_{planet}$$

(3)

Known values may be substituted into Eqn. 3 in order to determine the relative rpm of the sun and annulus gears, noting the following two equalities of Eqns. 4 and 5:

$$rpm_{sun} = (\frac{-N_{sun}}{N_{planet}})rpm_{planet}$$

(4)

$$rpm_{planet} = (\frac{-N_{planet}}{N_{annulus}})rpm_{annulus}$$

(5)

Quality of Production of Gearbox

Minor misalignments due to wind gust loads or manufacturing inconsistencies rapidly wear down the gears, which in turn creates a vicious and ultimately destructive feedback cycle between misaligned components and gear wear. However, the industry of aerospace has conquered these problems, as helicopters and geared turbofans reveal the stainless reliability required for aircrafts. Pratt and Whitney's PW1000 geared turbofan engine utilizes an epicyclic gearing system, which helps the fan working independently with the low-pressure compressor and the turbine; this epicyclic gearing system is shown below in Figure 5.The decoupling of the LPF from the LP system is achieved via the FDGS (Fan Drive Gear System). The FDGS is comprised of a sun gear, five star gears and a ring gear. The FDGS allows the LPT to operate 2.5 times faster than a conventional engine, while the LPF runs one third slower. The increased weight saving, by reducing the number of aerofoils in the LPC and LPT, from 600 and 900 respectively is better compared to the International Aero Engines V2500 turbofan.