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Aero-Engine Fan Gearbox Design

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Introduction 1/2

The most significant difference between a Geared Turbofan (GTF) engine and conventional Direct Drive Turbofan (DDTF) engine is that the GTF adopts a **reduction gearbox** locating in-line between the fan and the low pressure (LP) compressor/turbine shaft.

For a DDTF engine with high bypass ratio (BPR), the rotational speed of the fan should be slower than the engine with a conventional BPR, due to the limitation of the fan blade tip speed, to prevent efficiency loss, and to lower the SFC and noise levels.

However, the slower speed of the LP shaft would result in LP compressor/turbine efficiency loss or stages increasing.

Hence, a geared turbofan engine with a reduction gearbox located between the fan and LP shaft would be able to optimize the rotational speeds of both the fan and LP shaft to reduce stages of the rotating parts, and to reduce SFC and noise levels.

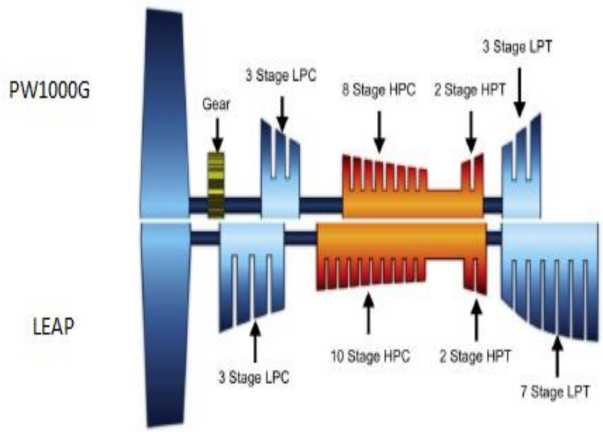
Introduction 2/2

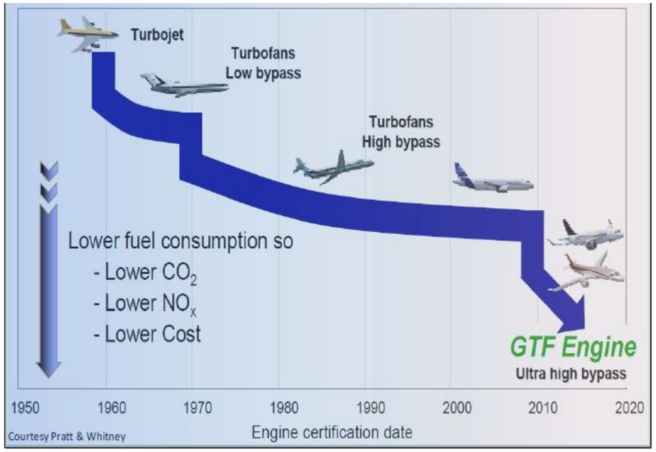
It has been concluded that the GTF engine has no significant SFC reduction compared with conventional DDTF engines at the same BPR <10, but the GTF engine will have a much lower parts count.

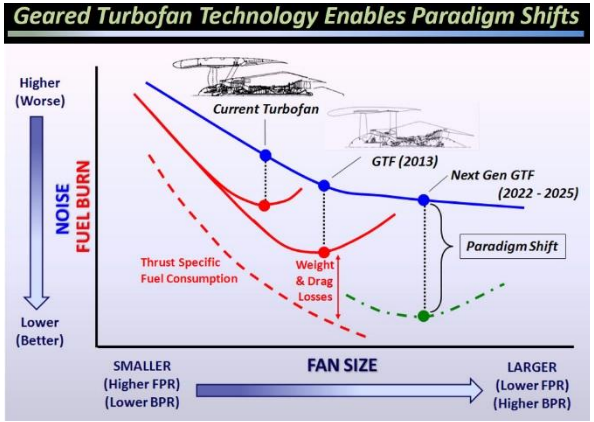
When the engine BPR reaches 10 or above, the conventional DDTF engine is no longer considered as a design candidate since it faces high aerodynamic efficiency losses, unacceptable noise level, and parts count rising - hence weight increasing.

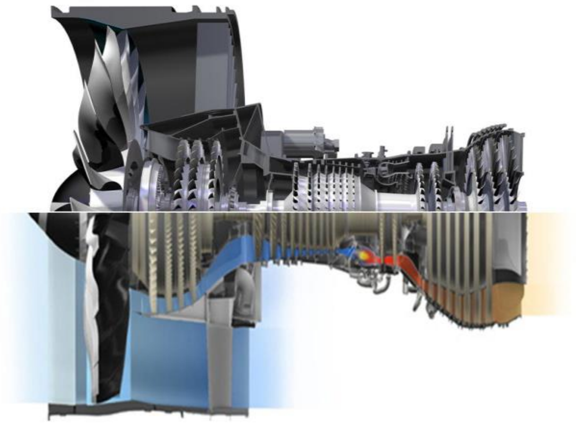
Therefore, the GTF engine is more favored with an ultra-high BPR, and the most significant advantages of a GTF engine is that it has a much smaller parts count, and relative low SFC and noise levels.

P&W PW1000G vs. CFM International LEAP



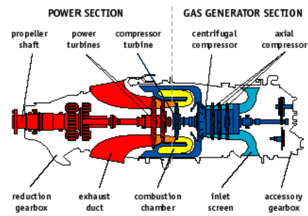
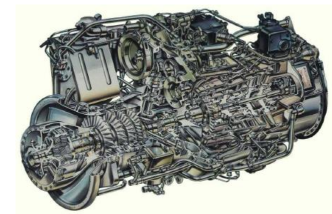
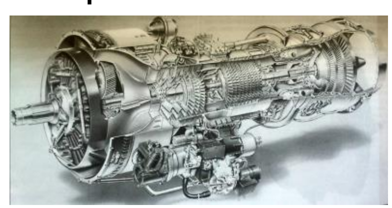




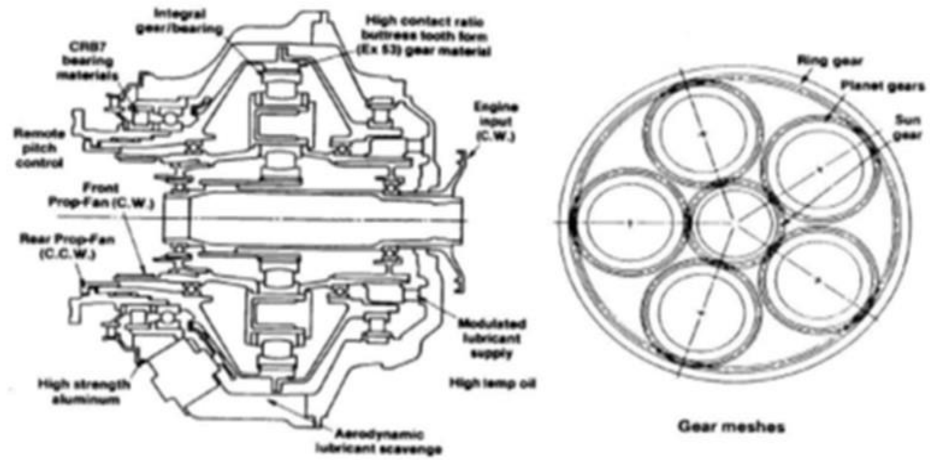


Using in-line gearbox reduces the overall length of the GTF engine as there is less stages for the compressor or the turbine. The P&W PurePower PW1000G geared engine has 3 LP turbine stages whereas the LEAP GEnX engine has up to 7 stages.

Geared Engines

Honeywell Turbofan LF 507	P&W Turboprop PT6A	Rolls Royce Turboshaft GEM
The single stage gearbox is a star arrangement with seven planets and is driven by the LP shaft. The gears are helical. 	The gearbox has two planetary stages, with helical involute gears. The first stage has three planets and the second stage five planets. 	**A planetary gearbox, epicyclic type with sun and planet gears.** 
Honeywell Turbofan TFE 731	**Rolls Royce Turboprop TYNE**	**IAE Turbofan V2500**
A planetary gearbox with involute spur gears. The fan shaft is linked to the ring gear and the input shaft is attached to the sun gear. 	Double reduction gearing by compound planetary train with helical gears. The input is from the LP shaft and the output is the planet carrier linked to the propeller. The annulus is fixed and the speed ratio is 15.9:1 	The gearbox is a planetary type with simple helical gears. The speed ratio is 3:1 

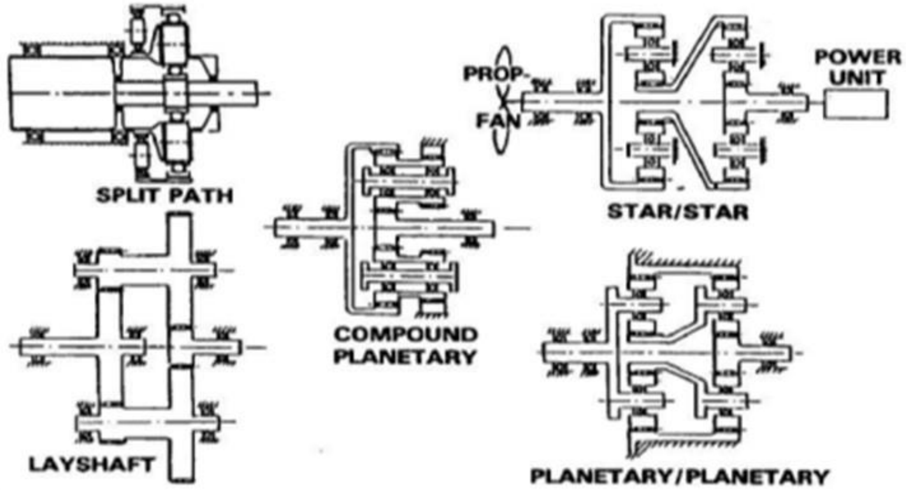
Advanced Prop-fan Engine Technology (APET) Counter-Rotating Differential Planetary Gearbox



The Advanced Prop-Fan ("Open Rotor") Engine Technology (APET) shows that a Prop-Fan powered aircraft can provide a 21% improvement in fuel burn and a I0% advantage in direct operating costs relative to a turbofan powered aircraft with comparable technology. However, key engine-related technologies should be considered:

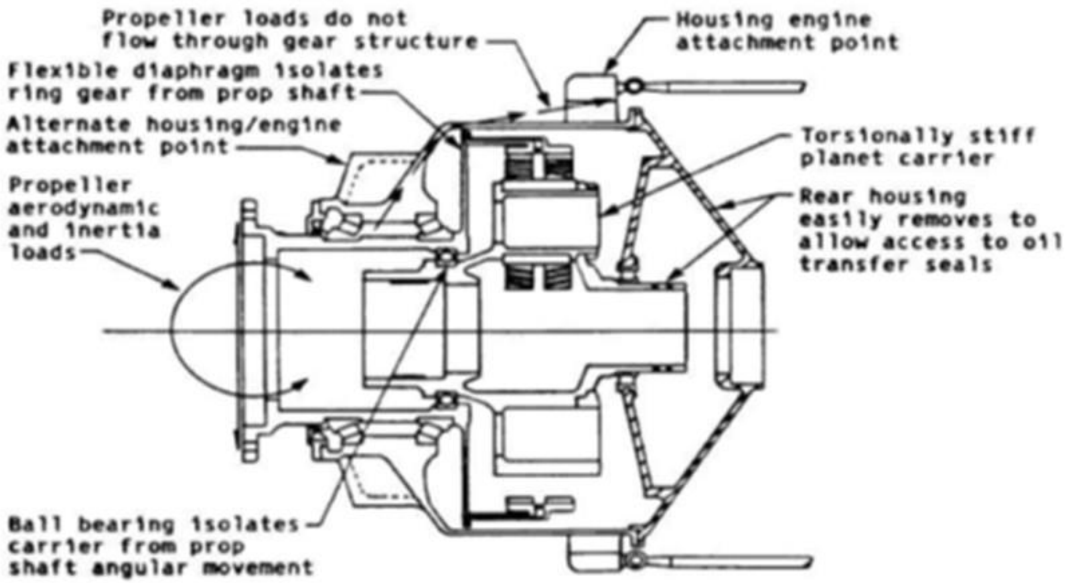
- The large 12,000 horsepower size reduction gearbox,
- Prop-Fan/nacelle/inlet/compressor interactions,
- The small size high-pressure compressor.

In-Line Gearbox Concept



- The **star/star** and **lay-shaft** **arrangement is large and heavy**,
- The **compound planetary** **generates centrifugal loads on the bearing**,
- The **planetary/planetary** **arrangement first stage carrier speed is too high**.
- The **split path** **with the lightest weight and smallest diameter arrangement is usually selected**. The first of two stages is a **star arrangement** to reduce the number of planets. Using high strength materials and limiting the number of gears and bearings improve the durability and reduce the maintenance costs with a better efficiency.

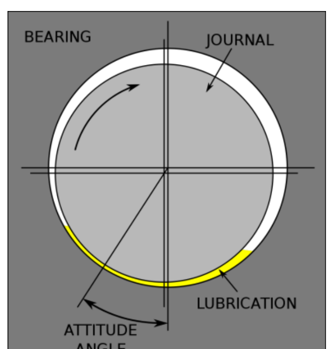
NASA Advanced Gearbox Technology (AGBT)
Gearbox Structural Features

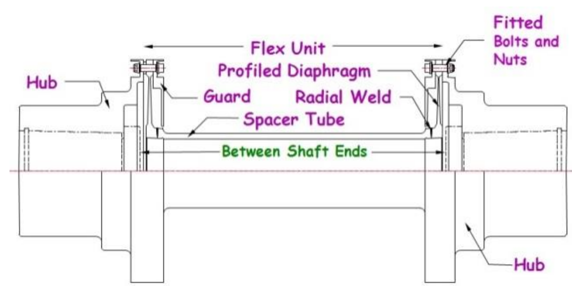


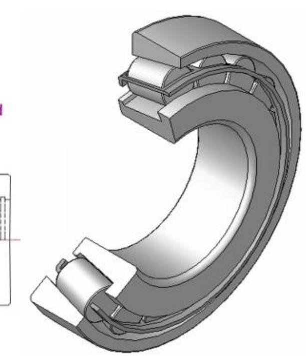
- The AGBT program objective was to design a long-life, low maintenance gearbox for Allison prop-fan engine. The counter-rotating gearbox had a speed ratio of 8.33:1, designed to transmit 13,000 hp. The input speed from the engine was 9,500 RPM and the output speed to the fan was 1,140 RPM.
- The final gearbox is a **differential planetary** with double helical gears and four planets, double row cylindrical roller bearings between the planet carrier and the planets, tapered roller bearing for the prop-fan, and a flexible ring gear and diaphragm to provide flexible mounting.

P&W PurePower PW1000G Gearbox 1/2

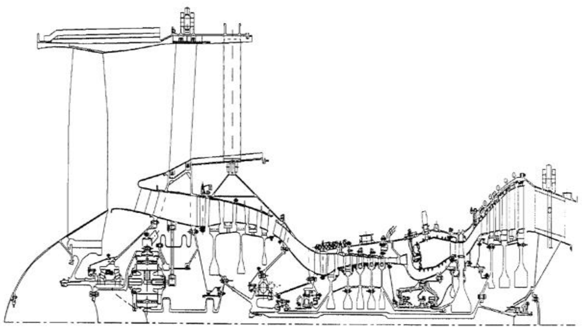
- **Engine**: the engine reduces the fuel consumption by 16% and up to 25% on next generation aircrafts, and reduces the noise by 31 dB compared with a Stage-3 noise level. The reduction in CO_2 emissions is by 15%, and up to 50% for NOx emissions.
- **Gearbox**: the input shaft is coming from the LP compressor/turbine and runs at 9,000 RPM. The output shaft is mounted on the ring and linked to the fan, which has an average speed of 3,000 RPM. The planet carrier is fixed. The gearbox is a five planet star gearbox, with a speed ratio of 3:1. The **double helical** gears are made from high-strength steels.
- **Bearings**: selected between the planet carrier and the planet gears are journal bearings. The sun and the ring are mounted on splines, and a flexible diaphragm coupling combined with tapered rolling bearings, isolate the gearbox from any adverse fan load.





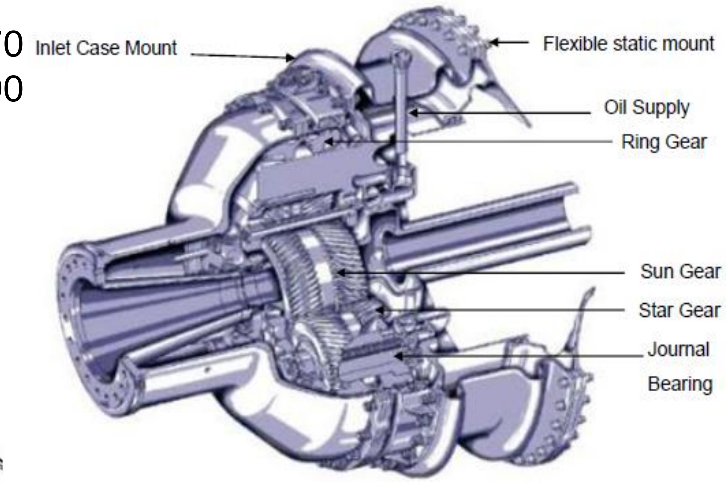


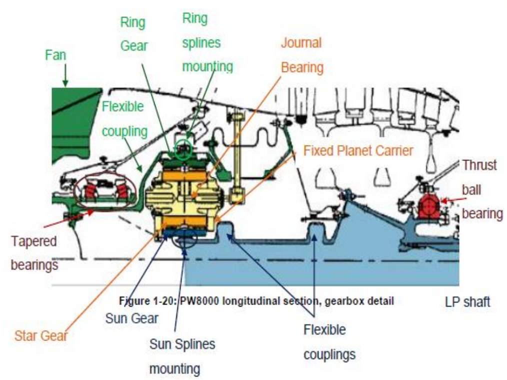
P&W PurePower PW1000G Gearbox 2/2



Airplane Powered

- Mitsubishi Regional Jet MRJ70
- Mitsubishi Regional Jet MRJ90
- Bombardier CSeries CS100
- Bombardier CSeries CS300
- Irkut MC-21
- Airbus A320neo
- Embraer E-Jet E2 Family





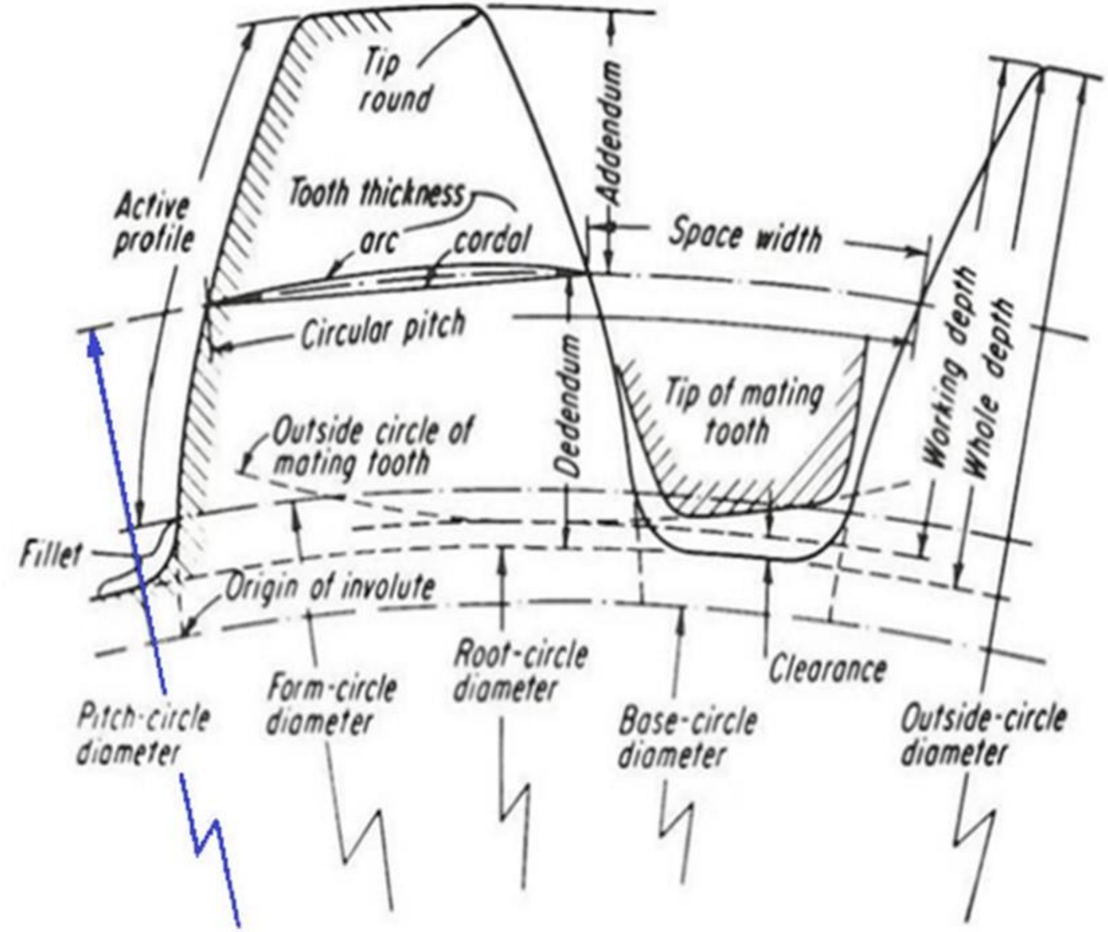
Aerospace Gearing Design Approach 1/2

- The complete range of power and speed or torque should be defined including growth capability. A duty cycle definition is required for calculation of gear and bearing system life, based on varying flight envelope load and duration.
- Gear ratio should be specified with an indication of allowable deviation. Input and output directions of rotation are required in selection of the helix or spiral for thrust direction and lubrication considerations.
- A value for gear system weight should be specified as “dry” gearbox weight and “wet” gearbox with lubrication system weight.
- Gear location and maximum dimensions envelope in details should be defined.
- Reliability requirements specified in terms of mean time between failures (MTBF).

Aerospace Gearing Design Approach 2/2

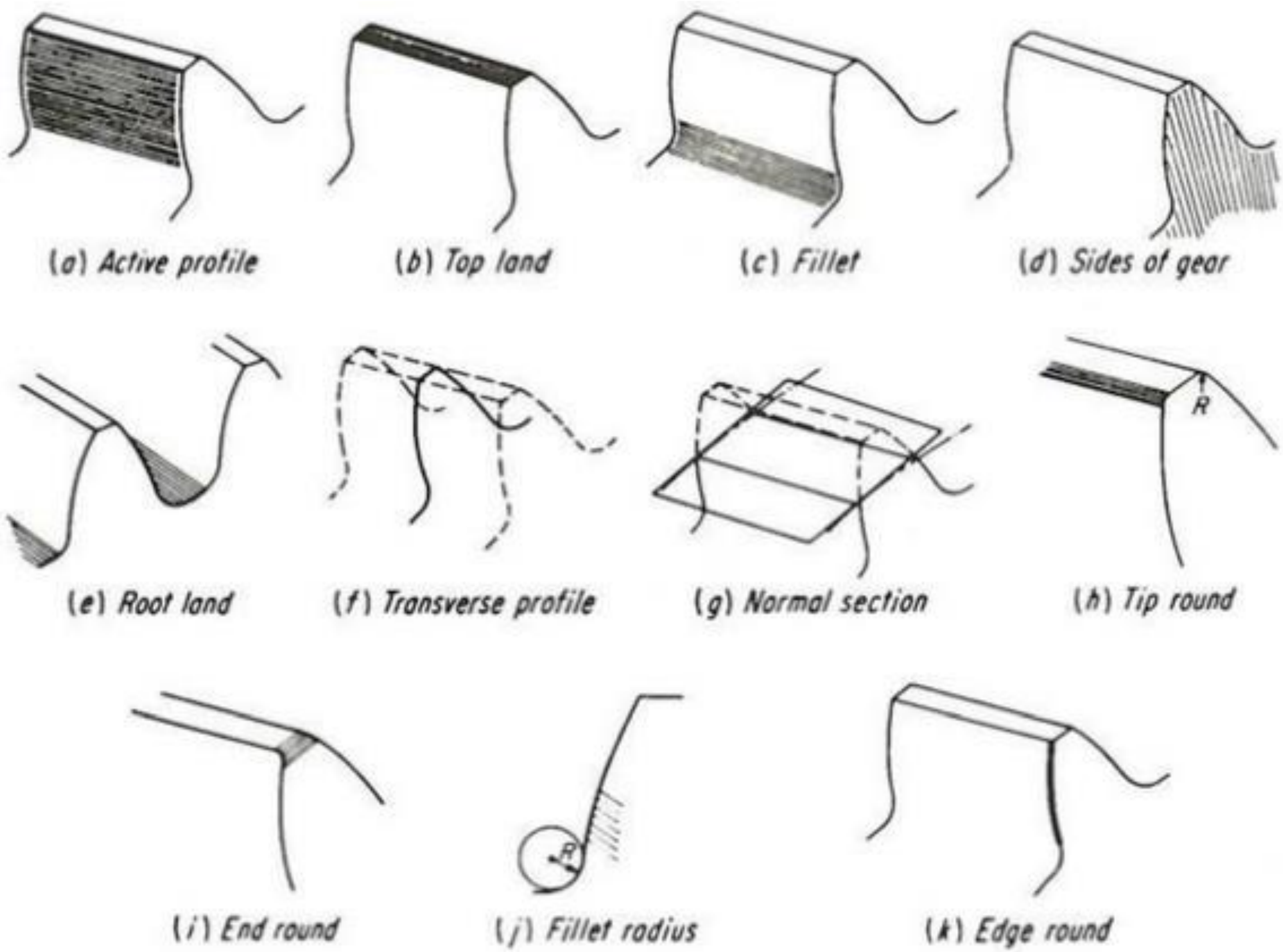
- Guidelines for maintenance procedures and tool limitations should be specified.
- Life cycle cost defined as the total cost maintenance of the system over its operating life, and gearbox efficiently should be established.
- External loads generated by rotor loads, flight or gravity effects, hard or crash landing requirements, or vibrations should be considered.
- Altitude and attitude specifications are required for lubrication system design.
- Requirements for operation with loss of lubricant, typically specifying a time and power level of operation.
- Meeting specified internal noise levels in cabin and flight deck.

Gear Tooth Nomenclature



The **module** is a measure of tooth size in mm. The module is defined as the pitch-circle diameter divided by number of teeth on gear.

Gear Area of Contact & Boundary Zones



Cranfield UNIVERSITY

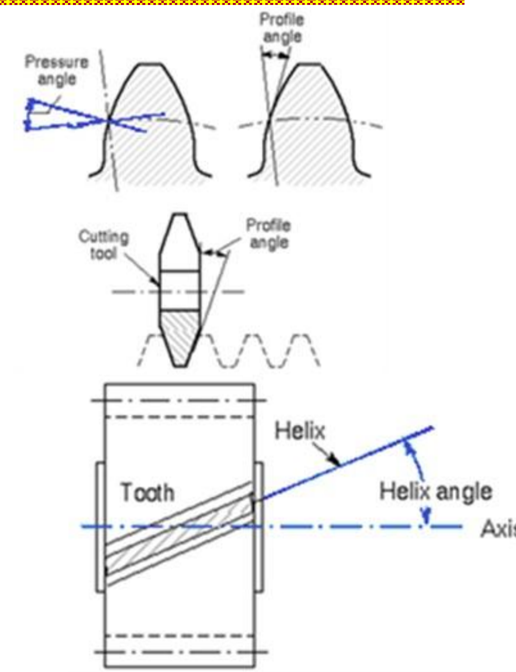
Spur, Helical & Double Helical Gears

Cranfield College of Aeronautics

Spur

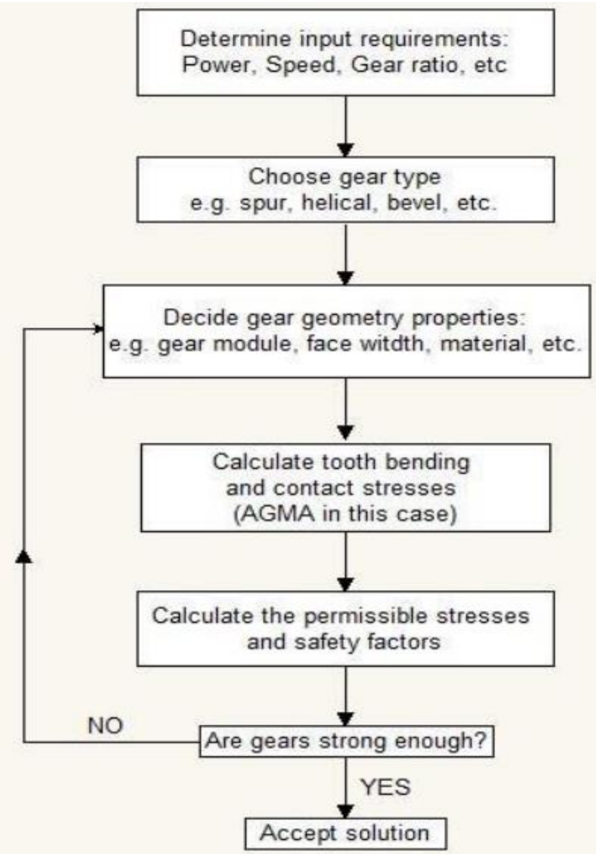
Helical

Double Helical

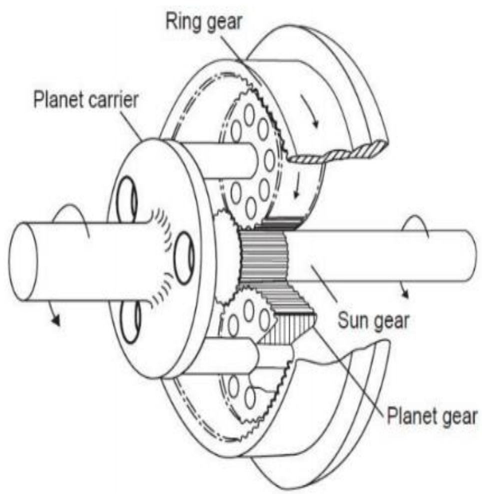


- **Spur gears** teeth are parallel to the axis of rotation and have a pressure angle of 20 to 25 degree. Higher pressure angle results in lower contact ratio hence higher bending stress.
- **Helical gears** transmission are smoother and quieter than that of a comparable spur gear. The helix angle value can be up to 45 degrees.
- **Double helical** gears are used in the applications with high transmission loads and rotational speeds.

Flow Chart of Gear Design



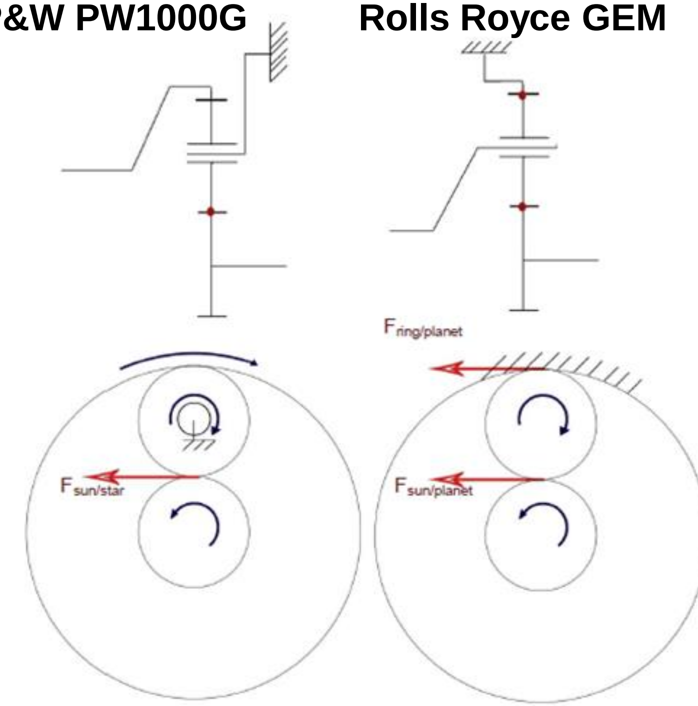
The gearbox design, and particularly the gear design, is based on British Standard ISO 6336 [*Calculation of load capacity of spur and helical gears*]



Planetary (Epicyclic) Gearbox

Star Arrangement P&W PW1000G

Epicyclic Arrangement Rolls Royce GEM



Gear Free Body Diagram

American Gear Manufacturers Association
AGMA 911-A94 [*Design Guidelines for Aerospace Gearing*]

Gearbox Design

This presentation aims at designing an aero engine gearbox. It focuses on stresses and tries to have a gearbox as compact as possible. Stresses are determined with the BS ISO 6336 method and compared with KISSsoft calculation programs for machine design.

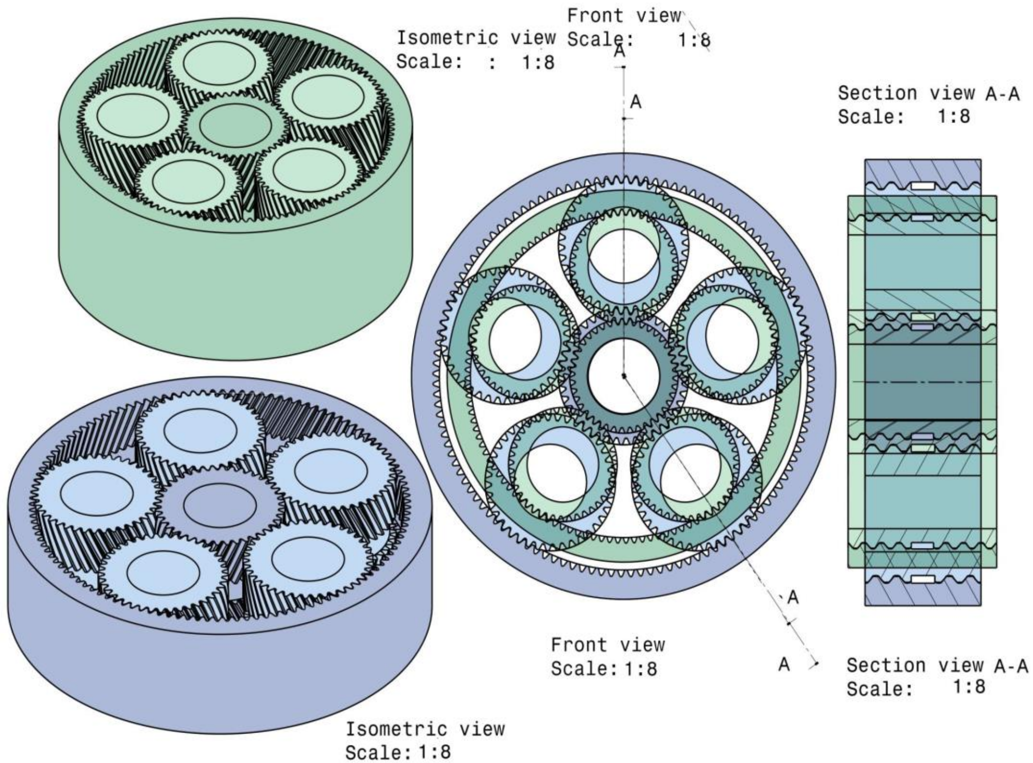
The P&W PurePower PW1000G data is:

- The transmitted power 30,000 hp (22,371 kW)
- Input and output speeds 9,000 RPM and 3,000 RPM respectively
- Speed ratio 3:1
- The gearbox arrangement is star gearbox, with 5 planets. Gears are double helical as the transmitted torque is huge and the speed is high.
- Planet bearings are journal bearings - no axial load.

Selected materials are case-hardened steel formed by diffusing carbon (carburization) for the sun and planet (or star) gear. This material has an **allowable bending stress** equals to σ_{Flim} = 430 Megapascal (Mpa) and its **allowable contact stress** is σ_{Hlim} = 1,500 MPa.

The ring gear is made from nitriding steel (diffuses nitrogen), which has an allowable bending stress equals to σ_{Flim} = 425 MPa and the allowable contact stress of σ_{Hlim} = 1,250 MPa.

Calculated Gearbox Design



Module 6 mm, Z_{sun} = 40, Z_{ring} = 120 **Module 5 mm, Z_{sun} = 40, Z_{ring} = 120**

The root diameter of the ring gear is **833.4 mm** and **694.5 mm**
→ too large and not compact

"Torque Density"

There is a linear relationship between the torque and the weight and size.

"Torque density" is the torque per unit volume. For a given set of criteria, the torque density is similar from one gearbox to another.

By comparing with a **double helical gearbox**, knowing the transmitted torque and the dimensions, the "torque density" can be determined, and so a rough sizing of the gearbox can be calculated.

Gearbox Size Comparison with Rolls Royce GEM 1/3

- Assuming Beam's theory on a gear tooth, the stress is: $\sigma = (M \cdot y)/I$, where: σ - bending stress (MPa), M - moment, or torque (N-m), y - the distance from the neutral axis, I - the second moment of area (m^4)
- Considering that gear tooth having the same amount of stress is equivalent as having a constant torque density.
- It is known that the GEM engine has the following characteristics:
  - Maximum power P = 1,100 hp (= 820,270 W)
  - Gearbox input and output speeds: 27,000 RPM and 6,000 RPM
  - Planetary gearbox with a speed ratio of 4.5
- The torque on the sun gear is determined by:

$$T_{GEM,\ SUN} = P/\omega \approx 820{,}270/(\pi \cdot 27{,}000/30) \approx 290 \text{ N-m}$$

- Knowing the sun diameter (d) and the face width (b):
  - $d_{GEM,\ SUN} = 45$ mm
  - $b_{GEM,\ SUN} = 2 \cdot 22$ mm = 44 mm
- The "torque density" can be estimated as:

$$\text{Torque/Volume} = T/[\pi \cdot (d/2)^2 \cdot b]$$

$$\text{Thus, } (\text{Torque/Volume})_{GEM} \approx 4{,}146{,}960 \text{ N-m/m}^3$$

Gearbox Size Comparison with Rolls Royce GEM 2/3

The P&W PurePower PW1000G gearbox can be sized:

- Maximum power at takeoff 30,000 hp (= 22,370,996 W)
- Gearbox input and output speeds: 9,000 RPM and 3,000 RPM respectively
- Star gearbox speed ratio of 3:1
- $\text{Torque}_{P\&W\ SUN} = P/\omega \approx 22{,}370{,}996/[\pi \cdot (9{,}000/30)] \approx$ 23,746 N-m
- Face width (b) to diameter (d) ratio b/d = 0.8 from P&W video https://www.youtube.com/watch?v=vgQgEftEd8c
- Volume of the gear approximated $V = 0.8 \cdot (\pi/4) \cdot d^3$
- Helix angle $\beta = 30°$

Gearbox Size Comparison with Rolls Royce GEM 3/3

If the same “**torque density**” is applied, the sun diameter is determined as:

$$d_{P\&W\ SUN} = \left\{ \left[\frac{4}{0.8\pi}\right] \left[\frac{T_{P\&W\ SUN}}{\frac{T_{GEM\ SUN}}{V_{GEM\ SUN}}}\right] \right\}^{\frac{1}{3}}$$

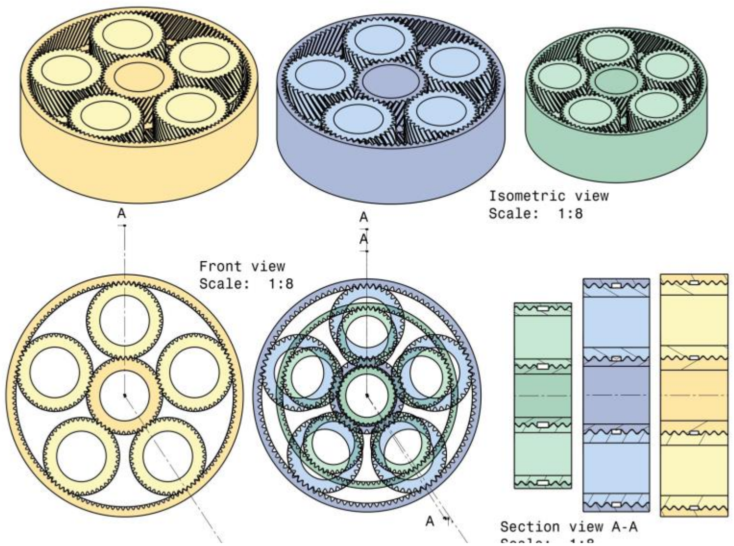
$$d_{P\&W\ SUN} = \left[23{,}746 \cdot \frac{4}{4{,}146{,}960 \cdot 0.8\pi}\right]^{\frac{1}{3}} \approx 209\ mm$$

Assuming the number of teeth of the sun is equal to Z = 35 from P&W video, the module can be determined by the reference diameter formula, see BS ISO 21771 [*Gears - Cylindrical involute gears and gear pairs*]:

- d = Z · m/cos(β)

Thus, m = [cos(β) · d]/Z ≈ [cos(30) · 209]/35 ≈ 5 mm

Gearboxes Size Comparison



	m5, Z_{sun} 35, Z_{ring} 105	m4, Z_{sun} 45, Z_{ring} 135	m4, Z_{sun} 35, Z_{ring} 105
External diameter	641 mm	**651 mm**	513 mm
SH Safety Factor for Contact Stress (min/max)	1.37/2.33	1.50/2.36	**1.02**/1.50
SF Safety Factor for Bending Stress (min/max)	3.95/5.60	3.65/5.27	1.63/3.03
$\sigma_{HP\ KISSsoft}$ (sun/ring) MPa	1,315/1,059	1,228/977	1,213/965
$\sigma_{FP\ KISSsoft}$ (sun/ring) MPa	729/724	701/747	700/740
Weight (kg)	238.5	**274.3**	122.4
Efficiency	0.995	0.996	0.993
Power loss (kW)	120.5	92.1	**145.7**

BS ISO vs. KISSsoft

Module 5 mm, Z_{sun} 35, Z_{ring} 105	ISO Calculations	KISSsoft
SH Safety Factor for Contact Stress Sun/Ring	1.65/1.37	1.63/2.33
SF Safety Factor for Bending Stress Sun/Ring	5.60/4.54	4.05/3.39
σ_H Contact Stress Sun/Ring MPa	586/588	807/454
σ_{HP} **Permissible** Contact Stress Sun/Ring MPa	969/807	**1,316/1,059**
σ_F Bending Stress Sun/Ring MPa	128/133	180/214
σ_{FP} **Permissible** Bending Stress sun/ring MPa	717/602	730/724

Notes:

- KISSsoft is an industrial tool, therefore, permissible stresses are much higher.
- Stresses calculated with the ISO standard are close to the required value.
- Differences concerning bending can be explained by the fact that the ISO 6336 is not initially made to design planetary gearboxes.

Summary & Conclusions

- Two aero planetary gearboxes have been examined in details, the P&W PurePower PW1000G which is a very large civil gearbox and the Rolls Royce GEM which is a very small military gearbox.
- KISSsoft has been used to model these gearboxes in accordance with the BS ISO 6336.
- Based on the model of the military gearbox and the civil gearbox data, a gearbox have been designed for a BPR 15:1 turbofan.
- All BS ISO 6336 and KISSsoft results have been realized to converge toward a safe design for the gears, bearings, splines, and shaft, in agreement with the aero criteria.
- The designed gearbox is close to the P&W PurePower PW1000G when comparing the CAD model and the real gearbox.
- It has been demonstrated that the process of calibrating KISSsoft with a known gearbox provides a useful tool for the definition of the gearbox for a new application.

KISSsoft (example)

KISSSOFT
Calculation programs for machine design

Appendix C Design 1: KISSsoft report

KISSsoft Release 03/2014 B
KISSsoft Hochschullizenz Universität Cranfield

Project

Name : AeroEngineGBdesign

File

Name : PW_m5-close

Important hint: At least one warning has occurred during the calculation:

1-> The circumferential speed is very high (95.2245 m/s)!
This causes the following:
The lubrication is no longer guaranteed.

The calculation is not anticipated for this case!

2-> Calculation of scuffing:
The entered gear pair data is outside the boundary of the calculation method!

The application of ISO/TR 13989-2 has following limitations:

1.0 m/s <= v(=95.2 m/s) <= 50.0 m/s

CALCULATION OF A HELICAL PLANETARY GEAR

Drawing or article number:
Gear 1: 0.000.0
Gear 2: 0.000.0
Gear 3: 0.000.0

Calculation method ISO 6336:2006 Method B

		------- Gear 1	--------- Gear 2	--------- Gear 3 ---
Number of planets	[p]	(1)	5	(1)
Power (kW)	[P]		22370.00	
Speed (1/min)	[n]	9000.0		-3000.0
Speed difference for planet bearing calculation (1/min)	[n2]			9000.0
Speed planet carrier (1/min)	[nSteg]		0.0	
Torque (Nm)	[T]	23735.3	0.0	71205.9
Torque Pl.-Carrier (Nm)	[TSteg]		94941.229	
Application factor	[KA]		1.10	
Power distribution factor	[Kgam]		1.19	