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Development in Geared Turbofan Aeroengine

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Abstract. This paper looks into the implementation of epicyclic gear system to the aeroengine in order to increase the efficiency of the engine. The improvement made is in the direction of improving fuel consumption, reduction in pollutant gasses and perceived noise. Introduction of epicyclic gear system is capable to achieve bypass ratio of up to 15:1 with the benefits of weight and noise reduction. Radical new aircraft designs and engine installation are being studied to overcome some of the challenges associated with the future geared turbofan and open-rotor engine.

1. Introduction

Year 2001 marks new direction of aviation industry in Europe where the direction of the industry is shaped based on the target set by the Advisory Council for Aviation Research and Innovation in Europe (ACARE) as stated in the Vision 2020 documents [1]. The pressure to be a socially responsible aviation industry, which maintains the balance between economy and the ecosystems within an ethical framework, has been put forward with the aim to reduce fuel consumption (which contributes to CO_2 emission), nitrogen oxides (NOx) and noise emission.

The target is set to reduce fuels consumption by 50%, NOx reduction by 80% for landing and takeoff and 50% reduction of perceived noise (relative to the year 2000 aircraft). To ensure continuity to the effort, Flightpath 2050 has been published in 2011 [2] to bring the effort beyond the year 2020 and towards year 2050. Further reduction of fuel consumption to 75%, NOx reduction to 65% and perceived noise emission to 90% has been set (**Table 1**). This will allow major aeroengine manufacturer to plan the development in the long run.

Table 1. Fuel-burn and emissions reduction goals set by ACARE, after [3].

Category	**ACARE**	
	Vision 2020	**Flightpath 2050**
Fuel	50%	75%
	Relative to year 2000 aircraft	
NOx	80%	90%
	Relative to year 2000 aircraft	
Noise	50%	65%
	Relative to year 2000 aircraft	

One way of achieving the set target in vision 2020 is by increasing the efficiency of the engine through the increase in its propulsion efficiency. A percentage of 20% of reduction in fuel consumption will be coming from engine improvement, another 20% from aircraft improvement and the remaining 10% from air traffic management (**Figure 1**) [4]. For the NOx reduction, 72% is expected to come from engine improvement and the remaining 8% target is expected to come from aircraft improvement and air traffic management. For the noise emission, the majority improvement is expected to come from the engine itself.

Aeroengine improvement can be achieved via increasing its propulsion efficiency, mechanical transfer efficiency and thermal efficiency. **Figure 2** shows the current engine efficiency and its limit of theoretical efficiency. The direction of future aeroengine is expected to take the route of increasing propulsive efficiency. This work will look into epicyclic gearbox application in aeroengine as a way to improve propulsion efficiency of aeroengine. This is align in the direction of improving fuel consumption, reduction in pollutant gasses and perceived noise

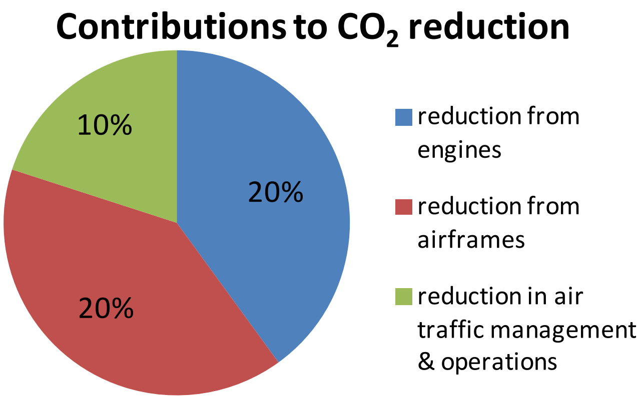


Figure 1. Contribution of engines, airframe, and air traffic management towards the target of 50% reduction in CO2 emission based from year 2000 aircraft, after [4].

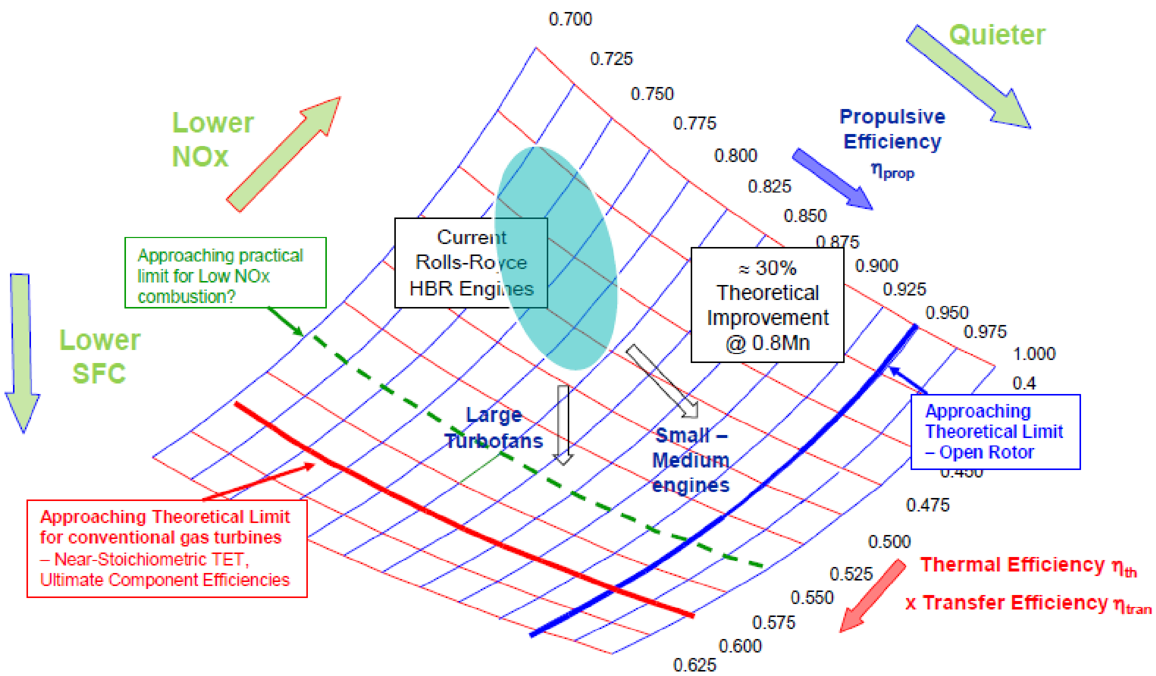


Figure 2. Schematic representation of the efficiency of aeroengine and its limit, after [5].

The report will be laid out as follows. The next section will present the architecture of epicycle gearbox. Current development and implementation of geared aeroengine is presented in Section 3. Geared Turbofan^{TM} (GTF) engine from Pratt & Whitney (PW) and UltraFan^{TM} engine from Rolls-Royce (RR) will also be presented in the section. The report then will be followed by the discussion section on challenges and issues related to geared turbofan aeroengine. The work is then summarised in the conclusions section.

2. Epicylic gearbox

At present, the architecture of turbofan engine fan blade is rotated by the low pressure (LP) spool energy extracted by the LP turbine blade. Bypass ratio is the ratio of air passing over the core of the engine. High bypass ratio will increase the propulsive efficiency. At the moment, typical engine have 80% of bypass ratio. This can be achieved by high volume intake of air larger diameter of fan. As the fan blade size increases, the tip linear velocity will increase, thus causing noise and efficiency reduction, whilst slowing the speed will reduce the optimum speed of the LP compressor.

One way to overcome this problem is by having a gear system which reduces the shaft's speed from the turbine to fan through the implementation of epicycle gear system. Not only that, fewer compressor stages are needed due to increase in efficiency. This equates to weight savings, fewer parts to maintain and quieter engine [6].

Epicyclic gear system consists of 3 gears being assembled as a system. They consist of a central sun gear, one or more planet gear and a ring gear as shown in **Figure 3**. All the planet gears are hold by planet carrier frame and rotate concentrically with the ring and sun gear.

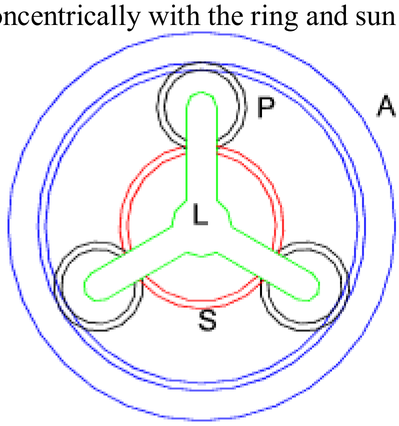


Figure 3. Typical Epicyclic Gear Arrangement, Sun gear (S), planet gear (P), planet carrier (L), and ring gear (A), after [7].

There are 3 different arrangements of epicyclic gear system. They are summarised in **Table 2**. The advantages and disadvantages of the epicyclic gear system are listed below.

Advantages:

- Load sharing between several gears.
- Compact and efficient arrangement for space and weight saving due to inline arrangement.
- Concentric rotation of input and output shaft provides less bending moment reaction from rotation radial forces.

Disadvantages:

- Complex design.
- Assembly of meshing gear is limited to certain location of teeth.
- Requires additional gear for non-inline assembly.

Table 2. 3 types of arrangement for epicyclic gear system, reproduced from [8].

Arrangement	Fixed gear	Input gear	Output gear	Gear ratio	Range of ratio input to output	Advantages/ Challenges
Star	Carrier frame	Sun gear	Ring gear	(N_R/N_S)	2:1 - 11:1 (opposite direction)	Torque balances due to counter rotating
Planetary	Ring gear	Sun gear	Carrier frame	$(N_R/N_S)+1$	3:1 - 12:1 (same direction)	Stress carried by joints from carrier to planet gear
Solar	Sun gear	Ring gear	Carrier frame	$(N_S/N_R)+1$	1.2:1 – 1.7:1 (same direction)	Stress carried by joints from carrier to planet gear
N_S=number of sun teeth, N_R=number of ring teeth (per gear)						

3. Current development

3.1. Geared Turbofan

Epicyclic gear system in star arrangement is used for the speed reduction from the LP turbine blade to the fan blade in Pratt & Whitney Geared Turbofan^{TM} PurePower® engine arrangement. The LP shaft attached to the sun gear acts as driver and the ring gear is attached to the fan blade. The planet carrier holds 5 planet gears and doesn't rotate relative to the engine nacelle (**Figure 4**). Speed reduction of about 3:1 (9000 rpm from turbine to 3200 rpm on the fan) is achieved and resulted optimum working condition on the LP turbine blade and the fan blade [9].

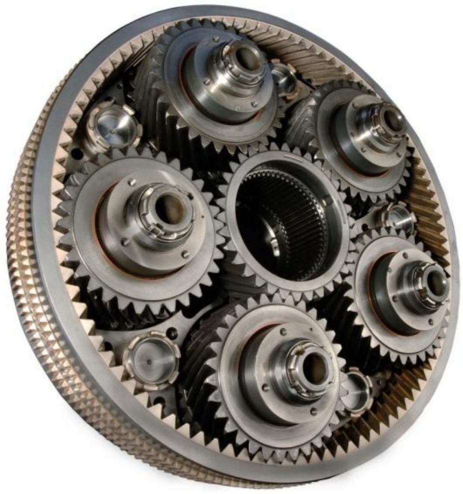


Figure 4. Epicyclic gear box setup with 5 planet gears in Pratt & Whitney Geared Turbofan^{TM} engine, after [10].

Figure 5 shows the difference between the conventional turbofan and the GTF arrangement. The main differences which can be seen are; i) the increase of the fan blade diameter allowing higher bypass ratio, ii) weight reduction due to less stages of LP compressor LP turbine blade, and iii) the existence of gear system in between the LP compressor and the fan [10]. The differences in turns have decreased the system complexity, reduced the overall length of the engine, saved cost, and improved efficiency. The larger fan with slower speed will be less noise pollutant to the airport and surround community [10].

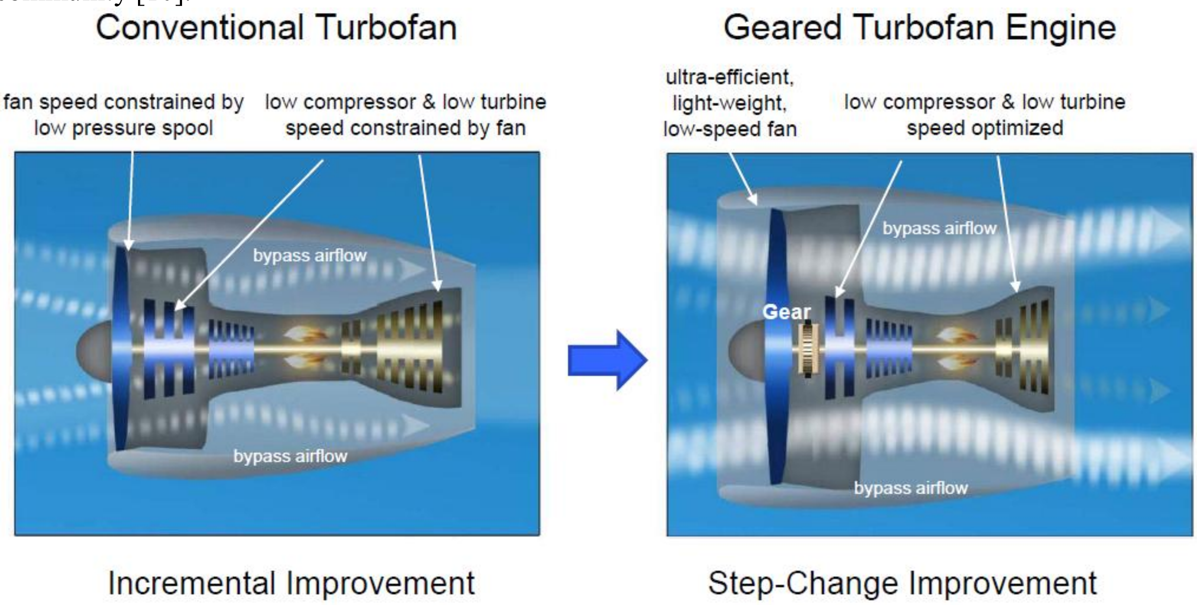


Figure 5. Comparison between conventional turbofan and geared turbofan architecture, after [10].

Table 3 summarises the GTF engine ranges developed by PW showing the bypass ratio which increases up to 12:1. The engine configuration can be set to match the requirement from 70 – 230 seating aircraft for corporate and narrow body aircraft market. It also shows the increase in the fan diameters. The thrust can be scaled in the range from 10,000 to 40,000 lbs. The engine is claimed to improve 16% of fuel consumption, 3,000 tonnes reduction of CO2 per year, halves NOx emission and noise reduction of 77% [11].

3.2. UltraFan™

Rolls-Royce is expected to come out with a geared turbofan engine called UltraFan™ engine in 2025 (**Figure 6**). The technology will be based from their scalable three spools Advance engine which is expected to increase the bypass ratio from 11:1 to 15:1 [13]. The UltraFan™ engine which equipped with variable ditch fan thrust reverse will provide weight save in nacelle to overcome bigger nacelle for longer fan blade. LP turbine will be removed to make it to two and half spool arrangement, thus reducing more weight (**Figure 7**). The aim is to provide better efficiency and lighter engine to compete with the GTF from PW in the narrow body and single aisle market [14]. The UltraFan™ engine will also be used for the development of open-rotor engine by Rolls-Royce to meet the Flightpath 2050 target [15].

Table 3: PW GTF PurePower® Engine Family range, reproduced after [12].

Engine Program	**PW1200G**	**PW1500G**	**PW1100-JM**	**PW1400G**
Engine Type	Geared Turbofan™ (GTF) Engine with scaled engine core; current models from 10,000 to 40,000 pounds of thrust	Geared Turbofan™ (GTF) Engine with scaled engine core; current models from 10,000 to 40,000 pounds of thrust	Geared Turbofan™ (GTF) Engine with scaled engine core; current models from 10,000 to 40,000 pounds of thrust	Geared Turbofan™ (GTF) Engine with scaled engine core; current models from 10,000 to 40,000 pounds of thrust
Aircraft Family	Mitsubishi Regional Jet	Bombardier CSeries	Airbus A320neo	Irkut MC-21
Aircraft Models	MRJ70, MRJ90	CS100, CS300	A319neo, A320neo, A321neo	MC-21-200, MC-21-300, MC-21-400
Passenger capacity	70-96	100-145	124-220	130-230
Engine Models (thrust in pound-force)	PW1215G:15,000lbs PW1215G:17,000lbs	PW1521G:21,000lbs PW1524G:23,300lbs	PW1124G:24,000lbs PW1127G:27,000lbs PW1133G:33,000lbs	24,000-33,000lbs
Architecture	1-G-2-8-2-3	1-G-3-8-2-3	1-G-3-8-2-3	1-G-3-8-2-3
Bypass Ratio (BPR)	9:1	12:1	12:1	12:1
Fan Diameter	56 inches	73 inches	81 inches	81 inches
Entry Into Service (EIS)	2014	2013	October 2015	2016

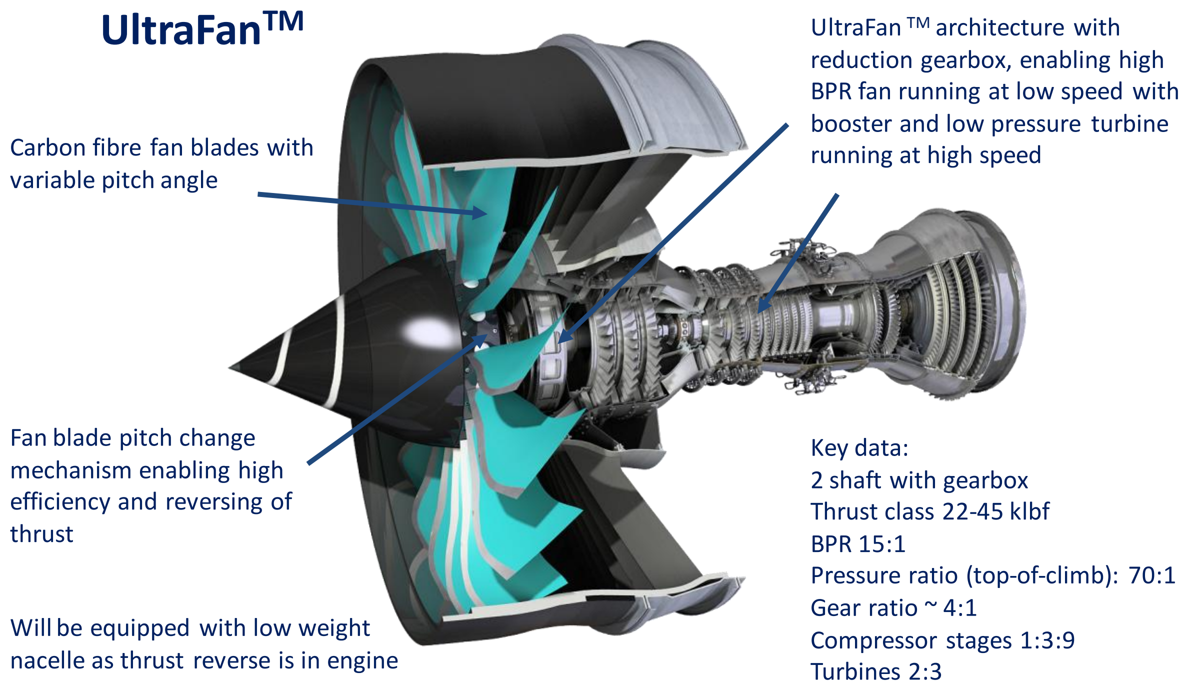


Figure 6. UltraFan™ engine architecture and key data based on Rolls-Royce materials, after [16].

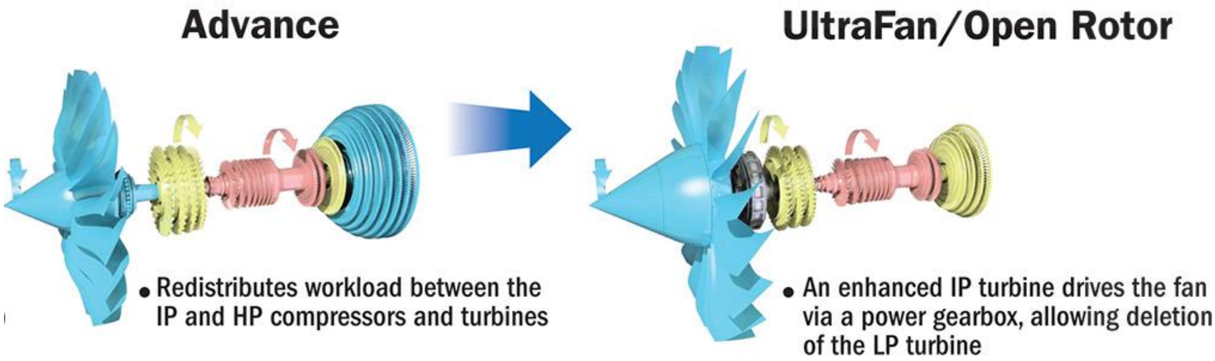


Figure 7. Schematic view of the development of Rolls-Royce's UltraFan™ engine based on the Advance engine, after [17].

4. Discussions

4.1. Engine installation

One of the challenges with the high bypass ratio is the increase in the size of the engine. The conventional under wing engine installation causes ground clearance difficulty (**Figure 8**). An unconventional installation of the engine might be required to overcome this problem. This in turns will require radical new aircraft design. Not only that, the performance of the engine for below or above wing installation is going to be different.

There are few possible designs that have been studied to scale the geared engine from turbofan to open-rotor concept. Lockheed Martin's boxed-wing and MIT double bubble design are among one of the few designs looked at (**Figure 9**) [18, 19]. Recently, PW has proposed a radical engine installation of reverse and tilted engine configuration. The propulsion and the gas generator are separated, tilted and on reverse flow direction to each other (**Figure 10**) [20]. All the new revolutionise designs are due to accommodate the installation of the high bypass ratio engine.

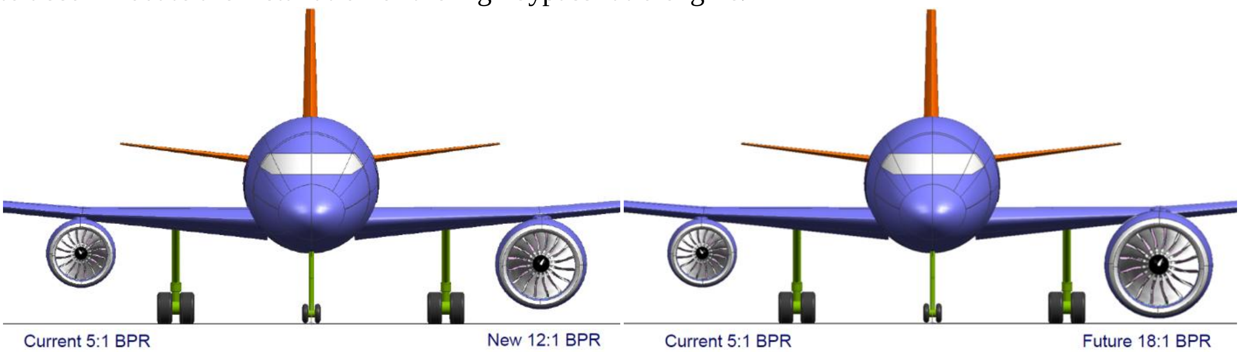
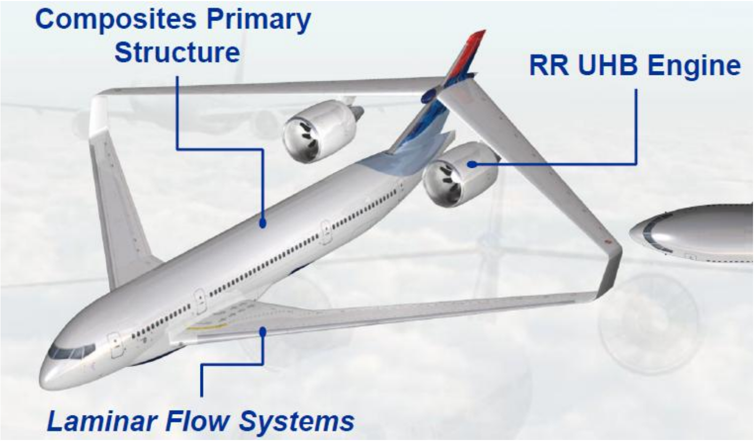


Figure 8. Schematic view of increase in engine size relative to its under wing installation position of conventional engine, after [10].



(a)

(b)

Figure 9. New concept of aircraft design for open-rotor and turbofan high bypass ratio engine: a) Lockheed Martin's box-wing concept [18], and b) MIT's double bubble concept [19].

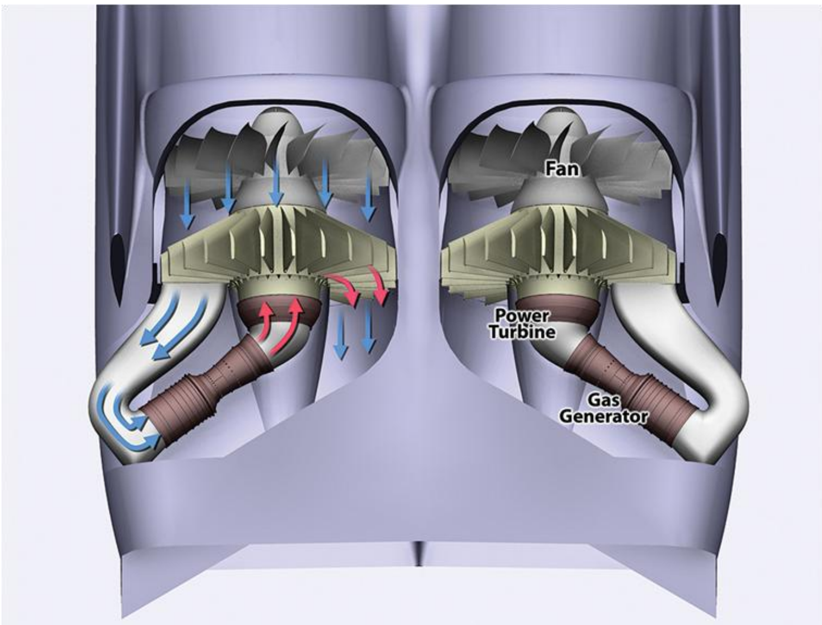


Fig. 10: PW's proposed innovative reversed, separated, and tilted propulsion concept, after [20].

4.2. Mechanical reliability and drag
The introduction of gear system has added additional mechanical components reliability issue. This will add to different dynamic behaviour due to another shaft which turns at different speeds. The interaction is further complicated due to the reduction of compressor and turbine stages. The increase in engine size introduces further drag to the engine. Increase in thrust might be offset by the drag of bigger engine and possibly lower cruising speed (at same thrust) and shallow climbing angle.

5. Conclusions
The following key points are highlighted for the technology advancement and challenges in geared aeroegine:

- Larger fan with smaller core is required to increase the bypass ratio of the engine.
- Geared turbofan could potentially increase bypass ratio to 15:1 in order to increase the propulsive efficiency of aeroengine.
- Unconventional design of aircraft is being designed to overcome the limitation of engine installation.
- Reliability performance of geared turbofan is still unknown.

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