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Turbofan engines efficiency, historical trends, and future prediction – A review

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Abstract

Technological development in the aviation business is usually dictated by diverse safety, economic, environmental, and social goals set by governments, regulatory agencies, and the market. Recently, a rapidly increasing interest in making air transportation climate neutral has been observed. The objective of this study is to analyze the historical trends of aircraft engine fuel efficiency, identify parameters affecting engine efficiency and initiate a discussion about future technology development needed to meet the expectations. The commercial turbofan engines test data comparison is provided in this study, followed by a theoretical assessment. The presented test data trends show a clear correlation between specific fuel consumption decrease and engine parameters like bypass ratio and overall pressure ratio increase, which is confirmed by theoretical assessment. Based on performed analysis results, a bypass ratio increase was indicated as the one potential path to reduce aircraft engine fuel consumption. Bypass ratio improvement could be achieved by fan diameter increase and rotation speed reduction in the case of turbofan engine architecture. A larger fan rotor requires a high torque drive and significantly increases engine weight which could be compensated by the lightweight design of the engine components, e.g., by applying composite materials.

Keywords: turbofan engine, bypass ratio, overall pressure ratio, specific fuel consumption, safety, composite materials

1. Introduction

Aviation is essential for global business as it provides the worldwide transportation network, creates jobs and supports international trade and tourism. Due to its nature and global impact, the aviation industry is monitored and regulated by a number of international bodies and agencies, including the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA), the European Union Aviation Safety Agency (EASA) and the United States Federal Aviation Administration (FAA).

According to ICAO data, "The air transport industry supports a total of 65.5 million jobs globally. It provides 10.2 million direct jobs. Airlines, air navigation service providers and airports directly employ around three and a half million people. The civil aerospace sector (the manufacture of aircraft, systems, and engines) employs 1.2 million people. A further 5.6 million people work in other on-airport positions. Another 55.3 million indirect, induced and tourism-related jobs are supported by aviation" (ICAO, *Economic Impacts of COVID-19 on Civil Aviation*, 2022).

The outbreak of the COVID-19 pandemic in 2020 significantly affected the aviation industry worldwide, and airline activity and profitability plummeted dramatically almost overnight. Until now, the demand recovery has been uneven and driven mainly by COVID-19 case counts, vaccinations, and governmental restrictions. It is projected that U.S. airline system traffic, measured in revenue passenger miles, will return to 2019 levels by 2024 (domestic) and 2025 (international) (Corning, 2021). Despite the impact of COVID-19, the international aviation industry is still expected to grow materially over the next 30 years (COP26, 2021).

The aviation industry is considered strongly susceptible to changes in business cycles; therefore, airlines must lower their operating costs to minimize the volatility in profits. Considering that, in the long run, oil prices are expected to increase due to growing global demand and higher extraction costs (Corning, 2021), airlines will need to use more modern fuel-efficient aircraft to keep their costs under control.

The aviation industry's role in the global economy's growth also makes it a significant contributor to the environmental footprint. While the world as a whole is facing global warming, the aviation industry is required to focus on sustainable development. Governments and global agencies are supporting and/or imposing environmental-friendly initiatives and the development of new aircraft and engine technologies. The recent UN Climate Change Conference UK 2021 (COP26) resulted in the signing of a declaration of the International Aviation Climate Ambition Coalition, in which signatories committed to working on reducing aviation CO2 emissions at a rate consistent with efforts to limit the global average temperature increase to 1.5°C and achieve net zero CO2 emissions by 2050 (COP26, 2021).

The aviation industry is expected to grow significantly over the next decades; however, to meet global demand, increase profits and achieve environmental goals, it needs to focus on fuel-efficiency improvements and new technologies development. Therefore, the objective of this study is to provide an analysis of the historical trends of engine fuel efficiency based on test data as well as theoretical assessment leading to the identification of major parameters affecting engine efficiency. Additionally, a discussion is underway on future technology development needed to meet the expectations.

2. Aircraft engines efficiency and the historical trends of fuel consumption

The overall efficiency of the aircraft engine is driven by propulsor and engine core efficiencies. The overall efficiency is directly connected with engine fuel consumption, which can be measured as a ratio of the amount of thrust generated by the engine in a unit of time to fuel mass consumed in the same period. Such a parameter is called Thrust Specific Fuel Consumption (TSFC) and is expressed in [lb/lbf/h] unit (or [kg/N/h] in SI units), which should be understood as a mass of fuel expressed in pounds [lb] consumed in the time expressed in hours [h] when the engine generates a unit level of thrust expressed in pounds of force [lbf] during this period of time.

Depending on the engine architecture, different air mass flow ratios measured in the bypass duct and consumed in the thermal cycle can be observed. The ratio between these two is called Bypass Ratio (BPR).

In the gas turbine engine, the incoming air is compressed, then mixed with fuel and burned to generate hot gases driving the turbine system. Air compression is commonly performed by two or more axial compressors operating with different rotation speeds. Each one is equipped with multiple stages of rotating blades and stationary vanes. In such an arrangement, the cumulation of air compression achieved at each stage of the compressor is called the Overall Pressure Ratio (OPR) and is expressed as a ratio between stagnation pressure measured on the compressor system inlet and outlet.

Today, the two most common aircraft engine architectures used to power commercial aircraft are the turbofan and turboprop. The early 1940s Daimler-Benz developed the first low bypass turbofan engine, DB007, to improve fuel efficiency over the turbojet architecture, which was known starting in the late 1920s and was usually installed on military aircraft. However, this design never moved to the regular production level. The first production turbofan engine was the Rolls-Royce Conway, developed in the 1950s. It entered into service in the early 1960s and powered the Boeing 707-420. It offers 17500 lbf of rated thrust, and its design includes approx. 40-inch diameter fan. This early design offers poor performance compared to today's units. Its OPR vary around 14:1, BPR is equal to 0.3, and TSFC measured at Take-Off (T/O) condition is 0.725 lb/lbf/h (Taylor, 1970).

The next generation of the engines showed significant improvement in BPR and OPR. For example, we can use the Pratt & Whitney JT8D engine entered into service in the mid-1960s. The engine was equipped with a 49-inch diameter fan, significantly improving BPR (0.96 to 1.8, depending on the engine variant). Also, the OPR was increased to the level of 16:1 – 20:1. Consequently, all improvements allowed the engine to provide 21000 lbf of rated thrust with reduced T/O TSFC down to 0.49 – 0.65 lb/lbf/h (ICAO, *Aircraft Engine Emissions Databank*, 2021).

Aviation business growth pushed engine designers to reduce fuel consumption further. This resulted in a radical change in turbofan engine architecture. Further improvements in BPR parameters opened a new category of high bypass turbofan engines, with CFM56 introduced in 1974 being its early example. A significant increase in fan diameter (up to 72 inches) and BPR (5.0 – 6.8 depending on engine configuration) combined with OPR improvement (in the range of 21:1 – 33:1) provides further T/O TSFC decrease down to 0.32 – 0.39 lb/lbf/h (ICAO, *Aircraft Engine Emissions Databank*, 2021).

Currently, leading aircraft engine designers (Pratt & Whitney, Rolls-Royce, and General Electric/CFM) follow the trends of BPR and OPR improvements to meet fuel efficiency expectations.

Today the two most efficient engines available in the market powering single-aisle aircraft are Pratt & Whitney PW1100G and CFM LEAP-1A (CFM is a 50/50 joint venture of General Electric and Safran Aircraft Engines). Both are used to power Airbus A320neo. To meet the fuel consumption goal set by the aircraft manufacturer, P&W and CFM have implemented different design features.

The LEAP-1A has been designed as a classic 2-spool high bypass engine. The BPR has been significantly improved, achieving a level of 11.3 and with the rated thrust in the range of 24000 – 32000 lbf. This is a result of the implementation of a 78-inch diameter fan. Moreover, the OPR has been improved (up to 30:1 – 39:1) in comparison to older engines in this class (e.g., CFM56). Consequently, LEAP-1A achieved one of the lowest T/O TSFC (0.25 – 0.26 lb/lbf/h) of all engines available in the market (ICAO, *Aircraft Engine Emissions Databank*, 2021; CFM International webpage; Type-certificate data sheet, LEAP-1A & LEAP-1C series engines; LEAP Brochure).

In the case of PW1100G, the manufacturer P&W decided to introduce innovative Geared Turbofan (GTF) architecture. The unique feature of such a design is the speed-reducing power gearbox (planetary gearbox in this case) connecting the engine's Low-Pressure Turbine (LPT) with the Fan rotor. In classic turbofan architecture, Fan and LPT rotors are fixed with rigid shafts and operate with the same rotation speed. Such geared design provides more torque to the fan rotor than the classic configuration and consequently allows an increased fan diameter of up to 81 inches, providing a higher BPR (11.4 – 12.7). At the same time, PW1100G shows a similar level of OPR (29:1 – 39:1) compared to LEAP-1A and also a slightly lower T/O TSFC (0.23 – 0.25 lb/lbf/h) (ICAO, *Aircraft Engine Emissions Databank*, 2021; Epstein, 2015; Type-certificate data sheet, PW1100G-JM Series Engines; Pratt & Whitney webpage).

Table 1. Example turbofan engine parameters comparison

Time	Engine example	Rated Thrust [x1000 lbf]	Fan Diameter [inch]	BPR	OPR	TSFC [lb/lbf/h]
Early 1960s	Rolls-Royce Conway RCo.12	17.5	~ 40	0.3	14:1	0.73
Mid-1960s	Pratt & Whitney JT8D	21	49	1.0 ÷ 1.8	16:1 ÷ 20:1	0.49 ÷ 0.65
1970s	CFM 56	18 ÷ 34	60 ÷ 72	5.0 ÷ 6.8	21:1 ÷ 33:1	0.32 ÷ 0.39
Today	CFM LEAP-1A	24 ÷ 32	78	10.5 ÷ 11.3	30:1 ÷ 39:1	0.25 ÷ 0.26
	Pratt & Whitney PW1100G	24 ÷ 33	81	11.4 ÷ 12.7	29:1 ÷ 39:1	0.23 ÷ 0.25

Taylor, 1970; ICAO, *Aircraft Engine Emissions Databank*, 2021.

Furthermore, based on the data collected by the International Civil Aviation Organization (ICAO), a clear correlation was observed between BPR, OPR and T/O TSFC, as presented in Figures 1, 2, 3, 4 and 5. An increase in both BPR and OPR parameters results in T/O TSFC reduction. The referenced ICAO Aircraft Engine Emissions Databank revision 28c (ICAO, *Aircraft Engine Emissions Databank*, 2021) contains a summary of ground engine tests and includes inter alia BPR, OPR, Rated Thrust and Fuel Flow for over 800 tests performed on various Turbofan and mixed Turbofan engines starting from the early 1970s up to 2021. Figures 1 to 5 show non-averaged date points representing individual engine ground tests.

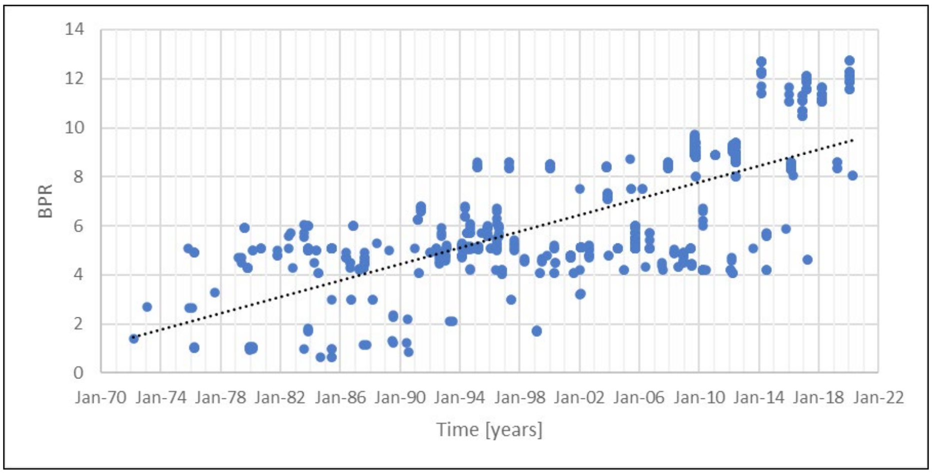

Figure 1. Engines BPR trend over time

Authors' own work.

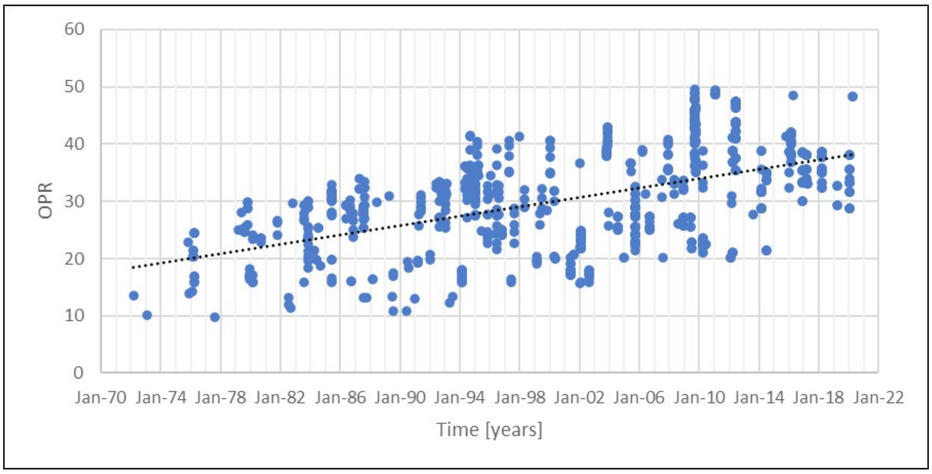

Figure 2. Engines OPR trend over time

Authors' own work.

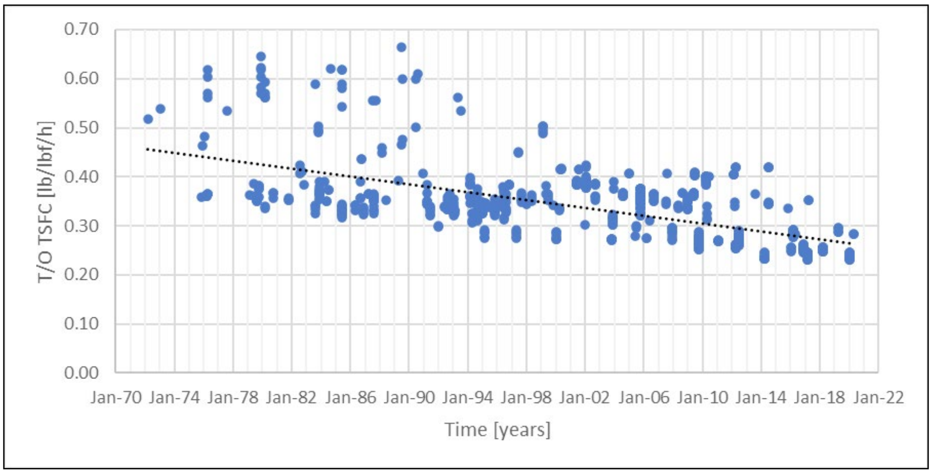

Figure 3. Engines T/O TSFC trend over time

Authors' own work.

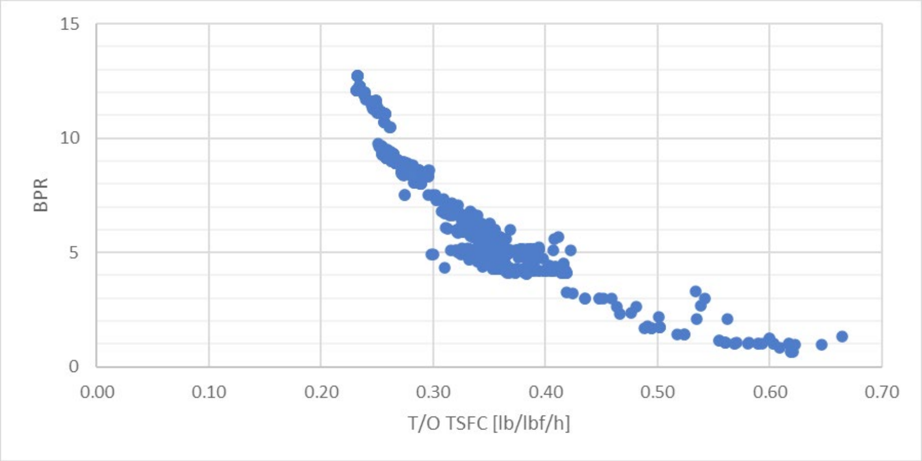

Figure 4. BPR correlation with T/O TSFC
Authors' own work.

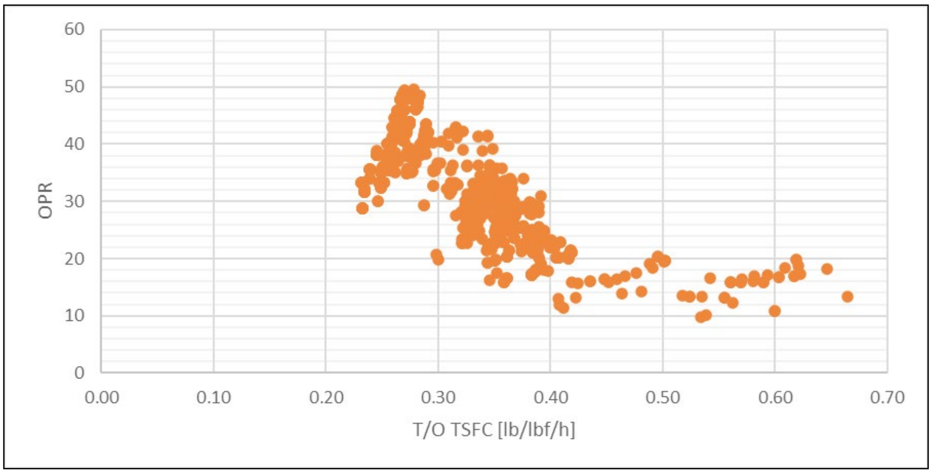

Figure 5. OPR correlation with T/O TSFC
Authors' own work.

In summary, based on the comparison of parameters of presented example engines (Conway RCo.12, JT8D, CFM56, LEAP-1A, PW1100G) and the summary of the ICAO databank, there are clearly visible trends showing BPR and OPR increase over the last 50 years. Moreover, both BPR and OPR increase correlates with T/O TSFC reduction.

3. Fuel consumption theoretical assessment

As extensively explained in "Aircraft Propulsion, Second Edition, Farokhi (2014)" in Chapter 3 entitled "Engine Thrust and Performance Parameters" and in "Theory of Aerospace Propulsion, Sforza (2012)", Chapter 1 entitled "Idealized Flow Machines", turbofan engine overall efficiency is a product of engine thermal and propulsive efficiencies. Thermal efficiency is the ability of the engine core to convert heat added by the fuel burn into kinetic energy. Then, kinetic energy is converted by the propulsor (a fan rotor in the case of a turbofan architecture) to the engine thrust with a certain level of efficiency, called propulsive efficiency. Equation 1 explains the relationship between propulsive efficiency and engine inlet and outlet air velocity:

$$\eta_{propulsive} \approx \frac{2}{1+\frac{V_9}{V_0}} \tag{1}$$

$\eta_{propulsize}$ – propulsive efficiency
V_0 – inlet air velocity
V_9 – outlet air velocity

Equation 1 assumes that the fuel mass flow compared to air mass flow is marginal and can be ignored. Based on the equation, lowering the difference between inlet and outlet air speed improves propulsive efficiency and consequently engine overall efficiency.

From the conservation of momentum, the thrust generated by the propulsor is expressed by:

$$F = m_p(V_9 - V_0) \tag{2}$$

F – engine thrust
m_p – propulsor air mass flow

The consequence of V_9 reduction is a decrease in engine thrust, assuming no change to air mass flow. Therefore, to maintain the desired thrust level and simultaneously improve propulsive efficiency, the outlet air velocity V_9 will be reduced, and at the same time, the air mass flow m_p will increase. Such an effect can be achieved by increasing the diameter of the propulsor (Fan) and driving it with reduced rotation speed.

Also, as clarified in “Elements of Propulsion: Gas Turbines and Rockets, Mattingly (2006)”, Chapter 4 entitled “Aircraft Gas Turbine Engine”, the thermal efficiency is a parameter defined by the ratio of engine kinetic energy output (or shaft power output) to the energy released by the fuel burn. For the Brayton power cycle, the thermal efficiency can be given by equation (3):

$$\eta_{th} = 1 - \left(\frac{1}{OPR}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} \tag{3}$$

η_{th} – thermal efficiency
OPR – overall pressure ratio
γ – heat capacity ratio

Based on Equation 3, the improvement of thermal efficiency is observed with engine OPR increase.

Finally, in the “Theory of Aerospace Propulsion (2012)”, Chapter 1, Sforza provides an equation for specific fuel consumption in the function of BPR and thermal efficiency (4):

$$TSFC = \left[\frac{\eta_{th}\eta_b HV}{V_{avg,h}} + \frac{BPR}{g\left(\frac{f}{a}\right)}\left(\frac{1}{V_{avg,c}} - \frac{\eta_{th}}{V_{avg,h}}\right)\right]^{-1} \tag{4}$$

η_{th} – thermal efficiency
η_b – burner efficiency
HV – heating value of the fuel
BPR – bypass ratio
$V_{avg,c}$ – average air speed of inlet and bypass cold flow
$V_{avg,h}$ – average air speed of inlet and core hot flow
g – acceleration of gravity
f/a – fuel–air ratio

In summary, Equation 4 confirms the correlation found by test data analysis performed in Chapter 2 of this study. Based on Equations 3 and 4, the reduction of TSFC can be achieved by an engine BPR increase or an improvement in thermal efficiency obtained by an OPR increase.

4. Future engines development trends predictions

All equations referenced in the previous paragraph can be summarized to the conclusion that an increased engine BPR and OPR reduce TSFC by improving thermal and propulsive efficiency. As presented in Figures 1. and 2. such increasing trends of BPR and OPR are clearly visible over the last 50 years of aircraft engine development. However, the test results of some past experimental engines (e.g., GE36) outline space for further development in the case of propulsion design.

In 1982, General Electric started developing the GE36 engine known as the unducted fan (UDF) in cooperation with Safran Aircraft Engines. The unique feature of this design was a two-stage contra-rotating un-ducted fan. Both fan rotors were equipped with composite carbon fan blades with up to 140 inches of diameter, providing 25000 lbf of rated thrust. Such an arrangement allowed to achieve a BPR of 32 (compared to the current best in the class engine BPR = 12.7) and proven with engine ground and flight tests (Hager et al., 1988; El-Sayed et al., 2017).

More recently, in 2021, CFM International announced the beginning of a new engine program, RISE (Revolutionary Innovation for Sustainable Engines). The initial concept includes the installation of a one-stage unducted fan with variable pitch composite fan blades and a set of downstream variable pitch Outlet Guide Vanes (OGV). As Travis Harper, RISE program manager, concluded, the use of a large diameter fan operating with low rotation speed expects to improve BPR up to 75 (GE Aviation webpage; Kjelgaard, 2021).

Using a large diameter fan architecture and the efficiency benefit brings some downsides. First of all, a fan rotor diameter increase drives an engine weight increase due to the need for larger fan blades and retention parts use. Also, the low rotation speed of the fan requires LPT to provide high torque to maintain the required level of power generated by the turbine. Such a goal can be achieved by designing a classic multistage (usually 7 or more stages) axial turbine with a relatively high diameter, as observed in the case of the LEAP-1A engine design. Consequently, to compensate for the engine weight increase, the fan diameter growth will be combined with the weight optimization of other components. In unducted fan architecture, significant weight saving is achieved by eliminating the fan case and external part of the nacelle. Moreover, applying composite materials on fan blades and OGVs could bring further weight reduction.

An alternative way of powering large-diameter fan rotors has been proposed by Pratt & Whitney. In their PW1100G, the fan has been connected with LPT through speed-reducing planetary gearbox. In this case, the LPT can operate with lower torque but higher rotation speed when the fan rotates slower. Since a high torque generation is needed, LPT design has been significantly simplified down to three stages compared to the seven stages used on LEAP-1A (CFM International webpage; Epstein, 2015). However, the power gearbox installation consumes some weight savings related to smaller LPT. Also, the gearbox generates heat losses related to its efficiency and constitutes an additional component prone to damage and wear, affecting engine durability. Moreover, the LPT's high-speed design causes a need for high-speed Low-Pressure Compressor (LPC) introduction, as a single shaft connects both components.

Today, the most fuel-efficient turbofan engines (e.g., LEAP-1A or PW1100G) include multiple design features and the use of advanced materials to compensate for engine weight increases. New CFM products include carbon composite fan blades, fan cases and fan platforms. This material helps reduce the weight by 500 lbs per engine. Moreover, additive manufacturing has been utilized to combine multiple parts into one for further weight reduction. In addition, applying additive manufacturing resulted in a 25% weight decrease in LEAP fuel nozzles. Another way to reduce engine weight is the application of lightweight Ceramic Matrix Composite (CMC) materials in the High-Pressure Turbine (HPT) and LPT modules. Additionally, CMC materials provide better resistance to high temperatures, which opens a path to increase engine core thermal efficiency (LEAP Brochure).

Similarly, P&W, in the design of PW1100G, P&W used a wide range of weight reduction features, including a composite fan case, composite structural OGVs and lightweight hollow aluminum fan blades. However, the primary weight reduction has been achieved by implementing GTF architecture, allowing the use of thee-stage high-speed LPT powering the fan through a planetary gearbox. In summary, the PW1100G engine weight is lower (6300 lbs) compared to LEAP-1A (6631 lbs), which suggests that the GTF design allows for a better engine weight optimization (Type-certificate data sheet, LEAP-1A & LEAP-1C series engines; Epstein, 2015; Type-certificate data sheet, PW1100G-JM series engines).

Also, it shall be highlighted that all engine designers use lightweight materials mainly to achieve weight optimization of structural stationary components (fan case, structural OGV). Consequently, the usage of composite materials on the rotating parts is relatively low. The only known examples of composite rotating parts are fan blades, fan platforms with their retention ring and, in the case of CMC materials, the turbine blades. This situation leaves a large opportunity for new applications of composite materials on, e.g., rotating disks, spools, shafts and seals.

Finally, the engine's overall efficiency can be increased by optimization of engine core thermal efficiency, which is directly correlated with compressor system OPR. Also, the environmental impact of the aircraft operation can be reduced or even fully eliminated by using Sustainable Aviation Fuel (SAF) or hydrogen to power the engine or by applying a hybrid or fully electric drive system. The discussion about engine drive system efficiency is not the intent of this publication.

In summary, all examples of the most recently developed engines or those being developed (e.g., GTF or UDF) confirm the trend presented in Fig. 1. of BPR increase. The ways of overcoming a design problem with the high torque required to drive a large fan could be different. However, the common area of interest for all presented designs is a need to reduce engine weight to compensate for the use of large-size fans or the installation of a power gearbox or large and complex LPT.

5. Conclusion

From the beginning, aircraft engine designers have constantly been looking for better solutions to improve engine efficiency, reduce fuel consumption, decrease operational costs, and make engines more environmentally friendly. Such efforts are confirmed in the test data showing a constant reduction in fuel consumption over the last 50 years.

Today the most efficient turbofan engines consume over 60% of fuel less in comparison with the first design (Conway RCo.12, 1940s) using this architecture. Such improvement has been achieved by a significant increase in BPR and OPR parameters. Additionally, as has been proven in the experimental engine program (GE36), it is possible further to improve BPR over today's most efficient turbofan engines.

Finally, it is emphasized that engine efficiency improvements usually result in engine weight increases, which can be compensated with design optimization by applying lightweight composite materials.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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