ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

INVESTIGATION OF OPTIMUM TURBOFAN ENGINE BYPASS RATIO FOR A LARGE, LONG RANGE BUSINESS JET

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Abstract. *Recent developments in turbofan engine technologies have increased the level of component efficiencies, compressor pressure ratios and turbine inlet temperatures, allowing the design of higher bypass ratio engines in the lower thrust classes, sized to meet the design requirements of large business jets and smaller regional jets. However, the trend of increase in the bypass ratio over the years in the engines developed for those aircraft has not followed the increase found in engines powering larger regional jets, as well as narrow and wide-body jets. The objective of this paper is to investigate the optimum bypass ratio for a turbofan engine sized to meet the design requirements of a large, long range business jet, given a certain engine core technology level. This was accomplished by the proper integration of engine performance (design and off-design point calculations) and engine sizing (weight and dimensions) computational codes with aircraft-related codes (aerodynamics, weight and performance). This combined aircraft/engine analysis was used to carry out trade-off analyses found in the design of higher bypass ratio engines, determining the optimum engine cycle for each mission profile defined for the aircraft.*
Keywords*: Turbofan engine bypass ratio, Aircraft/engine optimum design, Advanced turbofan engines, Turbofan engines core technologies, Business jet turbofan engine design*

1. INTRODUCTION

First patented by Sir Frank Whittle in the late 30´s, it was only in the 50´s that the first turbofan engine became operational, with a very timid bypass ratio (aproximattely 0.25 in the Rolls Royce Conway). The introduction of the turbofan version of JT3 (JT3D) reduced specific fuel consumption (SFC) by nearly 15%, and the latest generation of high bypass tubofan engines presents a cruise SFC almost 45% lower than the early turbojet engines, considering the typical cruise flight conditions (altitude and Mach number) of the current subsonic transport aircraft (Koff, 2004). The historical evolution of turbofan engines SFC used in executive aircraft is presented in Figure 1. Engine data published in recent work (Senna, 2012) and specialized maganize articles (AIN online, October 2012) were the data sources used to assemble the graphics presented hereafter.

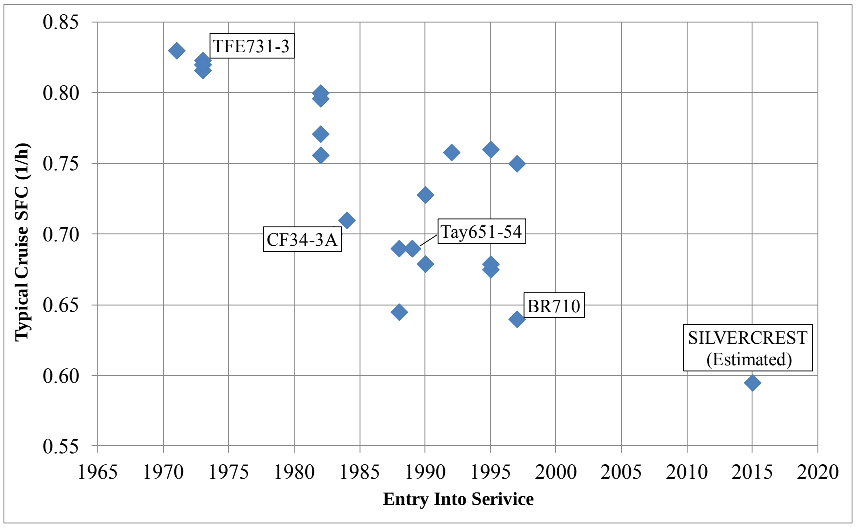

Figure 1. Historical evolution of cruise SFC (Mach 0.85, 10668m) of executive jets turbofan engines.

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Until 1960, errors in estimating the drag of the propulsion system led the engine manufacturers to limit bypass ratio to about 1 (Gunston, 2001). Other studies (Hemsworth & Neitzel, 1966) indicated that initial analyses that considered engine drag proportional to fan frontal area led to significant errors, overestimating the installation drag of higher bypass ratio engines. The better knowledge of the integration of higher bypass ratio engines, together with developments related to the engine core (such as more efficient turbomachinery components, higher cycle overall pressure ratios - OPR and turbine entry temperatures -TET) allowed the development of higher bypass ratio engines. High bypass ratio engines, with bypass from 5 to 6, were the standard in subsonic commercial aviation from the mid 60´s to the mid 90´s. According to Ballal, D.R. and Zelina, J.(2004), higher bypass ratio engines such as the GE90-115B, Trent 892 and PW4084 that were introduced in the late 90´s and the in beggining of the 21st century have design bypass ratio (BPR) values of around 10. Recent information suggests that engines that are entering into service in the next years will have even higher bypass ratios – 11 for the CFM LeapX engine (Flight Global, March 2010) and 12 for the Pratt and Whitney geared turbofan (GTF) family (PW, 2013).

Althought the design BPR of commercial passenger transport aircraft engines has been considerably increased, no comparable trend is observed in engines designed for executive jets. The historical evolution of the BPR of executive jets turbofan engines is presented in Figure 2. As it can be noted, an upper limit of 6 has not been surpassed, even when most recent designs are considered.

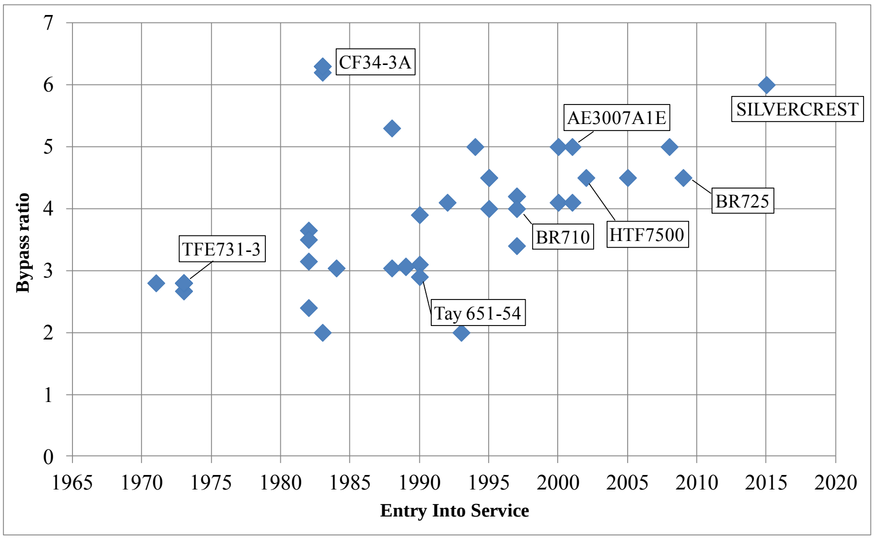

Figure 2. BPR evolution of executive jets turbofan engines.

The turbofan engine is more fuel efficient than the turbojet engine, for the current subsonic commercial aircraft flight envelope, given its higher propulsive efficiency. For a given aircraft flight speed, V_a, and a propelling exhaust gas speed, V_g, the propulsive efficiency η_p can be calculated by Eq. (1) (valid for a single exhaust stream engine and for a fuel to air ratio much smaller than one). Engine net thrust (F_N) can be determined by Eq. (2), when the exhaust gas is completely expanded to the ambient pressure. In this equation, W_2 represents the total flow of air entering the engine.

$$\eta_p = \frac{2V_a}{V_g + V_a} \tag{1}$$

$$F_N = W_2 (V_g - V_a) \tag{2}$$

Combining the two equations presented above, a direct relationship between propulsive efficiency and specific thrust - ST (the ratio between net thrust generated by the engine, F_N, and the air flow used to generate thrust, W_2) can be yielded, as presented in Eq. (3) (Hill & Peterson, 1992).

$$\eta_p = \frac{1}{1 + \dfrac{F_N}{2W_2 V_a}} = \frac{1}{1 + \dfrac{ST}{2V_a}} \tag{3}$$

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The analysis of Eq.(3) leads to the conclusion that the propulsive efficiency can be increased by decreasing specific thrust, for a given aircraft flight speed. Since the engine overall efficiency, η_o, is the product between propulsive efficiency and thermal efficiency, η_{th}, which is basically a function of turbomachinery efficiencies, cycle pressures and temperatures, one can state that maximizing the propulsive efficiency for a given aircraft mission, and thus flight speed V_a, must be the design target of a new turbofan engin. However, the reduction of specific thrust, which in practical terms is achieved by means of increased bypass ratio and decreased fan pressure ratio (FPR) lead to the following consequences, which limit the practical lower limit of specific thrust for a single stage fan turbofan engine (Fletcher & Walsh, 1998):

- Engine frontal area increases, increasing aircraft drag;
- Propulsion system weight increases;
- The number of low pressure turbine stages that drive the fan is rapidly increased;
- Bleed air and power offtakes have a greater impact in engine installed SFC.

The specific thrust, at maximum take-off, sea level static (SLS) standard day conditions of executive jets turbofan engines is shown in Figure 3. It can be noted by the comparison of engines BPR and specific thrust that higher bypass ratio engines in fact present lower specific thrust.

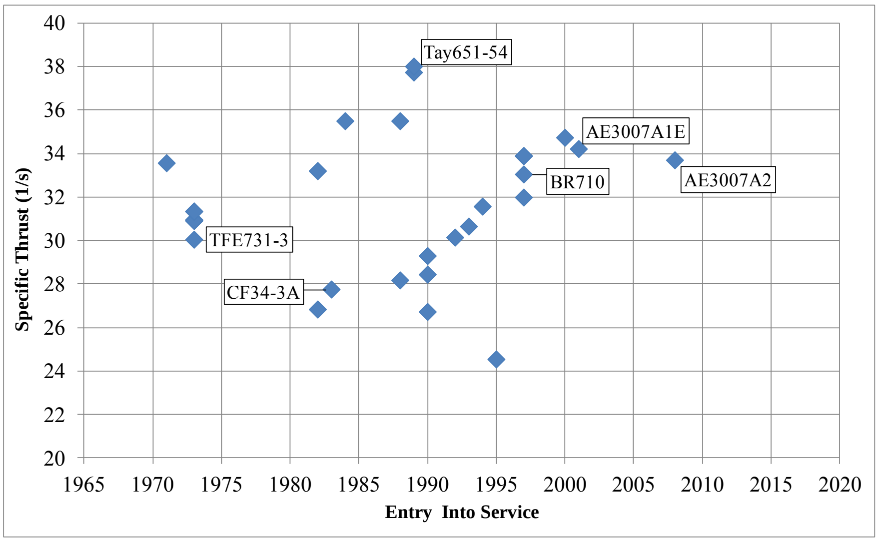

Figure 3. Specific thrust of executive jets turbofan engines (Maximum take-off, SLS, standard day conditions)

The vast majority of turbofan engines designed for executive jets are mixed flow engines. This type of turbofan engine combines the hot (generated by the core) and cold (propelled by the fan) streams in a mixer before propelling a single gas exhaust. When compared to separate flow engines, which have a nozzle for the cold and another nozzle for the hot gases exhaust, the mixed flow engine offers the advantage of a small increase in specific thrust and a decrease in engine SFC. The mixing of the gases also considerably reduces engine noise, since the exhaust gas noise is a function of jet velocity, which is greatly reduced in the mixed turbofan. The optimum FPR for the cycle (the FPR that concurrently minimizes SFC and maximizes ST) is reduced, reducing weight and costs for the fan and the turbine – usually the mixed engine can be designed with one less stage of low pressure turbine than the unmixed engine, helping to minimize the weight penalties associated with this configuration (Kurzke, 2012). Albeit these main advantages, the mixed flow engine architecture presents higher cost and weight. The trade-off between the previous considerations led to the broad use of mixed turbofan engines in executive aviation, while in commercial passenger aircraft, both mixed and unmixed engines are used, although all the higher bypass ratio engines (BPR>10) developed in the recent years are of the unmixed type.

When the considerations above are taken into account, the determination of the design specific thrust of an aero engine is not a trivial task. Since this parameter has a direct effect in several aircraft parameters that are directly related to aircraft performance (available thrust, SFC, weight and drag), the only way to achieve a good conceptual design of an aircraft and an aero engine is by the combined analyses of both entities.

Several studies have been conducted in the past analyzing the application of high and ultra high bypass ratio engines in subsonic commercial aviation. Regarding the general aviation, a study has proposed a very high bypass ratio engine (BPR of 9.2 and FPR of 1.35) that would have a 22% reduction in SFC when compared to the low and medium bypass ratio turbofan engines that were in service at that time (Schrader, 1980). Recent studies, focused in the 150 passenger class commercial aircraft (Oshimizu, et al., 2013), indicated that the optimum bypass ratio for this aircraft

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depends on the technology level available for the engine design. If the current technology is considered, a GTF engine with BPR of 12.5 would decrease aircraft fuel consumption by 11.7% when compared to current in service engines, and if a higher technology level is considered for a 2020 Entry Into Service (such as a 60% increase in OPR, a 210K increase in TET and a reduction in fan and fan case weight of 21%), the BPR that would minimize aircraft fuel consumption would be around 16, decreasing aircraft fuel consumption by 16.3%.

In the present study, several aircraft and engine models are be combined. For a given set of mission requirements and design constraints, engines with different values of BPR are evaluated. The aircraft mission is flown and the impacts of engine design parameters in aircraft range can be observed. This has been done on a technology level approach, where engine design parameters (such as turbomachinery efficiencies, pressure ratios, required cooling flows and TET) are developed through the decades. Specific design requirements for the reference executive aircraft have been implemented, which will be discussed in the next topics.

2. AIRCRAFT MODELS

The adopted aircraft reference model is the Embraer Legacy 650. This aircraft is a large business jet derived from the Embraer ERJ-135, a successful regional aircraft. The aircraft powerplant is composed by two Rolls-Royce AE3007A2 engines, each one producing 4100 kgf of thrust at sea level static (SLS) conditions. General data from the reference aircraft is presented in Table 1 (Data taken from (Aviation Week, 2011) and (Embraer, 2008)). Data related to wing sweep angle and profile thickness ratio were taken from (Ciornei, 2005))

Table 1. Legacy 650 general data

Main Dimensions		
Length	26.3	[m]
Wingspan	21.2	[m]
Height	6.6	[m]
Weights		
Maximum Take-Off Weight (MTOW)	24351	[kg]
Basic Operating Weight (BOW)	14213	[kg]
Fuel Capacity	9363	[kg]
Propulsion System – 2 x Rolls Royce AE3007A2 Turbofan engines		
SLS Maximum Take-Off Thrust	4100	[kgf]
Fan Diameter	0.978	[m]
Engine Dry Weight	764	[kg]
Aerodynamic parameters		
Wing Reference Area	51.2	[m^2]
Aspect Ratio	7.8	[-]
Wing Quarter Chord Sweep Angle	22.8	[º]
Wing Average Profile Thickness Ratio	0.11	[-]
Performance		
Maximum Operating Mach Number	0.80	[-]
Service Ceiling	12496	[m]
Take-Off Field Length @ MTOW, Sea Level	1750	[m]
Range @ 4 pax, Long Range Cruise (LRC)	7223	[km]

Since one of the objectives of the present study is to analyze the optimum bypass ratio for several cruise Mach numbers, four generic aircraft models were derived from the reference aircraft. The main modification to these derivative models is the increase in wing sweep angle, keeping wave drag to acceptable values in order to cope with the higher cruise speeds. The values of wing sweep angles were estimated based in aircraft with higher cruise Mach numbers, using data from (Aviation Week, 2011) and (Ciornei, 2005). Penalties in aircraft maximum lift coefficient (C_{Lmax}) and BOW were applied, and will be better explained in the following sections. The derived aircraft models and their related quarter chord wing sweep angle are summarized in Table 2.

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Table 2. Generic aircraft models derived from Legacy 650

Aircraft model	Cruise altitude [m] / Mach number	Quarter chord wing sweep angle [°]
L650_M075	11887 / 0.75	22.8
L650_M080	12497 / 0.80	25
L650_M085	13716 / 0.85	30
L650_M090	13716 / 0.90	35

In order to evaluate the aircraft global performance, simple aircraft aerodynamics, weight and performance models were implemented, which will be briefly discussed below.

2.1 Aircraft Aerodynamics Model

The adopted aircraft drag polar is composed by parasite, excrescence, induced, engine and wave drag, respectively shown in Equation (4).

$$C_D = C_{D,par} + C_{D,exc} + C_{D,ind} + C_{D,eng} + C_{D,wave} \tag{4}$$

The aircraft wet area was calculated using the methods presented in (Torenbeek, 1976) and the geometric data available in (Embraer, 2008). The parasite drag was estimated by the "Simplified Method for Predicting Drag Polars of Clean Airplanes" of (Lan & Roskam, 1997), assuming an equivalent skin friction coefficient similar to the Boeing 737. Excrescence drag was calculated using the method presented in (ESDU 94044, 2007). Regarding the induced drag coefficient, the aspect ratio was taken from (Embraer, 2008) and the Oswald efficiency factor was calculated as recommended by (Howe, 2000). Engine drag (encompassing nacelle, spillage and nacelle wave drag) was calculated using the method available in (ESDU 81024, 1994). This method was parameterized and implemented in the main code. Aircraft wave drag was calculated as a function of lift coefficient, wing quarter chord sweep angle, average profile thickness and profile technological factor, using the Korn equation as presented by (Mason, 2006).

Regarding the aircraft C_{Lmax}, it was taken from (Antunes, A.P.; et al., 2007) as 2.05. This value applies to the original aircraft (L650_M075), and penalties in the C_{Lmax} were applied for the derived aircraft with increased wing sweep angles using the curves provided in (Raymer, 1992), which relate the C_{Lmax} of a double slotted flap configuration to the wing quarter chord sweep angle.

2.2 Aircraft Weight Model

The aircraft weight model was created based on the information resumed in Table 1. Since the engine weight was calculated separately, as a function of the selected engine cycle and thrust requirements, a baseline reference aircraft in which the BOW did not account for the powerplant weight was created. Using the recommendation of (Howe, 2000), the powerplant system, including the pylon, was estimated to be 1.56 times the engine dry weight. Therefore, the reference aircraft baseline BOW, without the propulsion system and pylons is 11829 kg. It is worth mentioning that the complete propulsion system, including the pylons, accounts for around 17% of the aircraft BOW.

Since wings with higher sweep angle tend to be heavier than straight wings, the derived aircraft models with increased wing sweep angle had their BOW penalized, according to the subsonic aircraft wing weight model of (Carichner & Nicolai, 2010).

2.3 Aircraft Performance Model

The evaluation of the aircraft range, for a fixed available fuel quantity, was carried out by a simplified performance model, as presented in Figure 4. The mission was divided into four segments. The first one, comprising warm up, taxi, take-off and climb, was simplified using the recommended values of historical mission segment weight fractions from (Raymer, 1992). This approach was also used in mission segment three (descent and landing). An allowance of 6% of total fuel weight was considered for reserves (mission segment number four) and trapped fuel, as recommended by the same Reference. Given the aircraft long range (in the order of 7000 km), the "Accurate Determination of Range and Endurance by Numerical Integration of Specific Range and Endurance" method, presented in (Lan & Roskam, 1997) was selected and implemented for the cruise calculations, with the simplification of constant cruise altitude.

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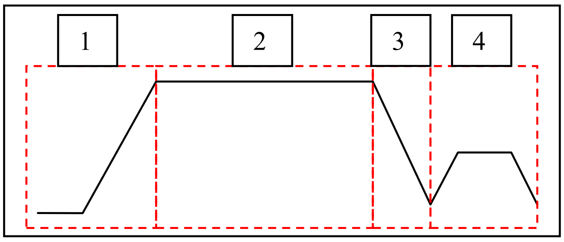

Figure 4. Simplified aircraft mission profile

The balanced take-off field length was calculated using the Take-off balanced field length estimation method presented in (Torenbeek, 1976).

3. ENGINE MODELS

The engine models used in the calculations were employed to estimate engine performance at design point and off design conditions, engine weight and nacelle dimensions. Modeled engines were sized to meet certain aircraft design requirements, which will be better detailed in the 'Design Requirements' section. As previously described, several engine technology levels were considered, related to the decade of the engine design. Components efficiencies, cooling air flow requirements, maximum TET and achievable compressor pressure ratios were altered for each technology level. The process used to create the engine models is presented in Figure 5. This iteration process was used to guarantee convergence on optimum FPR, TET and turbomachinery efficiencies.

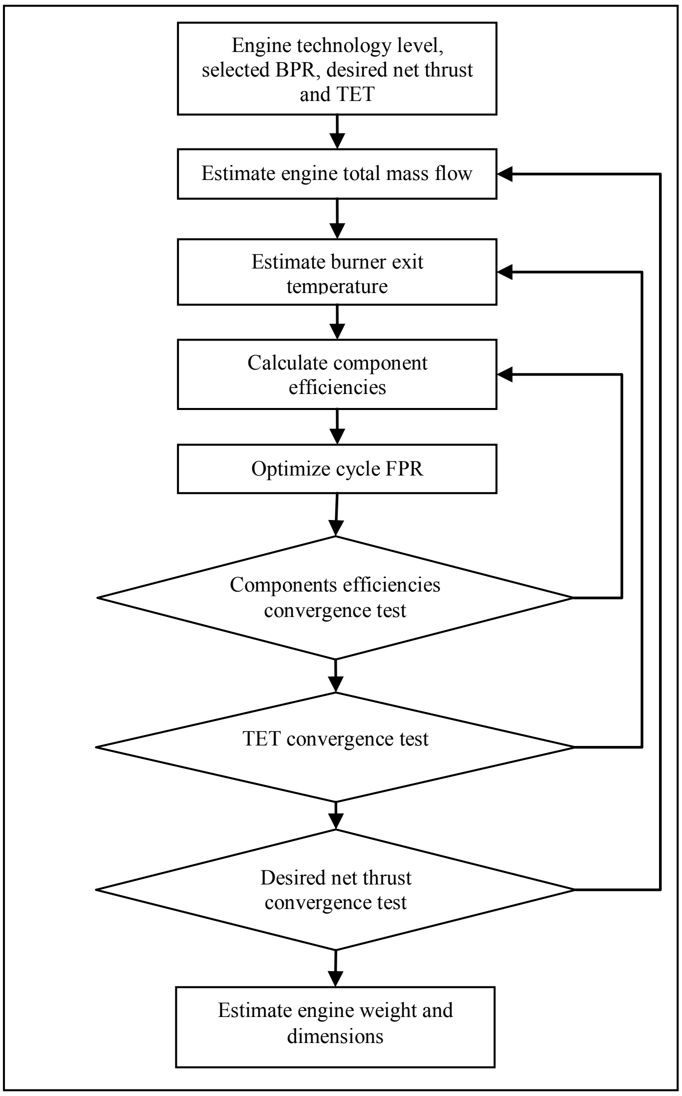

Figure 5. Mixed flow turbofan engine modeling process

ISSN 2176-5480

3.1 Engine Performance Model

Engine design point and off design performance calculations were done using Gasturb 12 (Kurzke, 2012). The selected flight condition for the engine design point was the aircraft top of climb, as presented in Table 2. Since the majority of turbofans used in executive aircraft are mixed flow engines, a boosted core, mixed flow engine architecture was selected. The creation of the engine models was automated inside the main code. After the engine model was created, the calculations were performed by calling the DLL files associated with the engine.

The FPR for each cycle was optimized at the design point for minimum SFC and maximum specific thrust by setting the ratio of total pressures between the bypass and core flows at the mixer entry (P16/P6) slightly below one, in order to also accomplish good part load performance (Kurzke, 2012). The maximum FPR value obtainable for a single stage fan engine design was limited to 1.9, and the fan root pressure ratio was considered to be 80% of the fan tip pressure ratio (Fletcher & Walsh, 1998). Regarding the cycle design point TET, graphics presented in (Kurkze, s.d.) were used to select the most appopriate value for each cycle overall pressure ratio. As stated by this Reference, the burner exit temperature of modern aero engines, during cruise, is in the range of 1500-1700K, and for constant cycle OPR not much can be gained by increasing the cycle TET. The maximum allowable TET for each engine technology level was applied for the take-off performance calculations, and the estimates were based on the data provided on (Heidmann, J., 2011). The obtainable pressure ratios for the booster and high pressure compressor were considered a function of engine technology level, based on information available on (Saravanamuttoo, 2002) and (Klinger, et al., 2011).

Component efficiencies were modeled as a function of engine technology level, stage loading, entry into service, component sizes and cooling flows, as presented in (Grönstedt, 2011). The required cooling flows for high pressure turbine and high pressure turbine nozzle guide vanes were estimated as a function of TET and technology level, based on the abacus available in (Fletcher & Walsh, 1998). Installation losses related to overboard bleed, as well as duct pressure losses and mixer properties were modelled following the guidelines given in (Fletcher & Walsh, 1998).

3.2 Engine Weight and Dimensions Models

The decreased specific thrust of higher bypass ratio engines tends to result in heavier and physically bigger engines. Simplified engine weight and drag models were implemented in order to account for these effects in the aircraft performance calculations. The engine dry weight was estimated using the methodology available in (MIT, Aurora Flight Sciences and Pratt & Whitney Team, March, 2010), as a function of core massflow, bypass ratio, overall pressure ratio (all evaluated at SLS, ISA maximum take-off conditions, provided by the engine thermodynamic model) and engine materials technology level. Following the recomendations given in the Reference, the "Advanced materials" model was applied for turbofan engines with equivalent technology level of the year of 2005 and onwards. This model was validated by the Reference using the Pratt and Whitney GTF PW1000G model (the engine weight calculated was within ± 1% from the assumed actual engine weight). A quick check of the model was made for the Rolls Royce AE3007A1E engine. Using data published in the Rolls Royce website for this engine (BPR of 4.8, OPR of 23 and inlet massflow of 127.3 kg/s), the calculated engine dry weight was 2.8% superior to the actual engine weight. This result was considered satisfactory for the degree of accuracy required by the present study and the model was considered suited for the high level analyses conducted herein.

The engine fan diameter was calculated based on (Waters, M.H.; Schairer, E.T., 1977) as a function of engine total fan massflow at SLS ISA maximum take-off condition (an input value provided by the engine thermodynamic model), fan hub to tip ratio and fan maximum axial Mach number. These two parameters were estimated as recommended by (Grönstedt, 2011); fan maximum axial Mach number was considered equal to 0.6 and the fan hub to tip ratio as a function of engine EIS. Considering the "short range application" model of hub to tip ratio, the obtained fan diameter for the AE3007A1E engine was 95.2 cm, which is 2.6 cm smaller than the actual engine fan diameter (using the same input data used in the weight estimate). Nacelle dimensions, used as input data for the engine drag model, were estimated by a parametric method created using data available in (Senna, 2012), and are mainly a function of engine fan diameter and bypass ratio.

4. DESIGN REQUIREMENTS

A set of two design requirements were considered for the engine sizing:

- The aircraft must maintain a rate of climb of 1.524 m/s (300 feet/minute) at the initial cruise altitude and at a representative weight of 96% of the aircraft MTOW (Raymer, 1992).
- The aircraft must present a balanced take-off field length below 1889 meters (6200 feet) at MTOW, Sea Level, ISA conditions.

ISSN 2176-5480

The algorithm used to size the engines for the requirements presented above is presented in Figure 6.

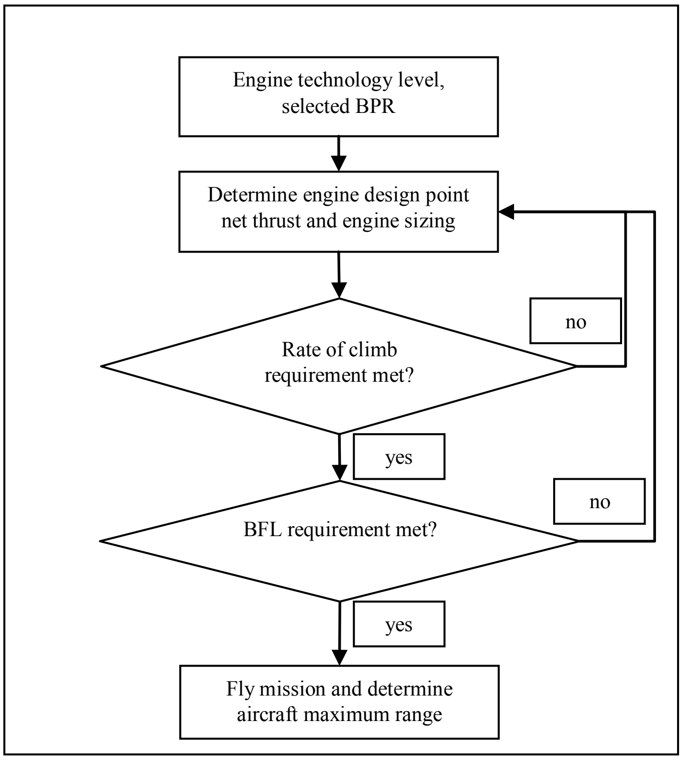

Figure 6. Convergence algorithm employed to size the engines for the aircraft requirements.

5. RESULTS AND DISCUSSIONS

The obtained aircraft range for each engine design point BPR is presented in Figure 7. The analyses of these graphics lead to the conclusion that the optimum design point BPR, i.e., the BPR that maximizes the aircraft range, is a function of engine technology level and aircraft cruise conditions. Considering the first cruise condition (Mach 0.75 at 11887m of altitude), which is probably the closest to the reference aircraft long range cruise condition, the optimum BPR ranges from 5 to 7 for the 90´s technology level, and from 6 to 8 when the 2030 technology level is considered. When the cruise speed is increased, the value of the optimum BPR is decreased. For the Mach 0.9, 13716 meters cruise condition, the optimum BPR ranges from 4 to 5 for the 90´s technology level and from 4 to 6 for the highest technology level. This is explained by the higher aircraft cruise speed, which is better matched with a lower BPR engine. Since the lower BPR engine will present a higher jet exhaust speed, the propulsion efficiency will be higher, as shown in Eq. (1). In higher cruise speeds, the drag penalties associated with higher BPR engines are also more pronounced. A non-linearity can be noted when one analyzes the difference in aircraft range between the technology levels of 2000 and 2010. This is explained by the assumption of the “advanced engine materials” in the adopted engine dry weight model, for the technology levels from 2005, and clearly shows the sensibility of aircraft range to engine weight.

The isolated effects of design BPR on engine SFC, dry weight, fan diameter and nacelle drag are presented in Figure 8, for an engine technology level equivalent to the year of 2020 and aircraft cruise condition of Mach 0.75 and 11887 meters of altitude. Although the trends are easily observable (the decrease in engine SFC and increase in engine weight and drag), the optimum value that maximizes aircraft range could only be obtained by simulating the installed engine on the aircraft, taking into account all the combined effects.

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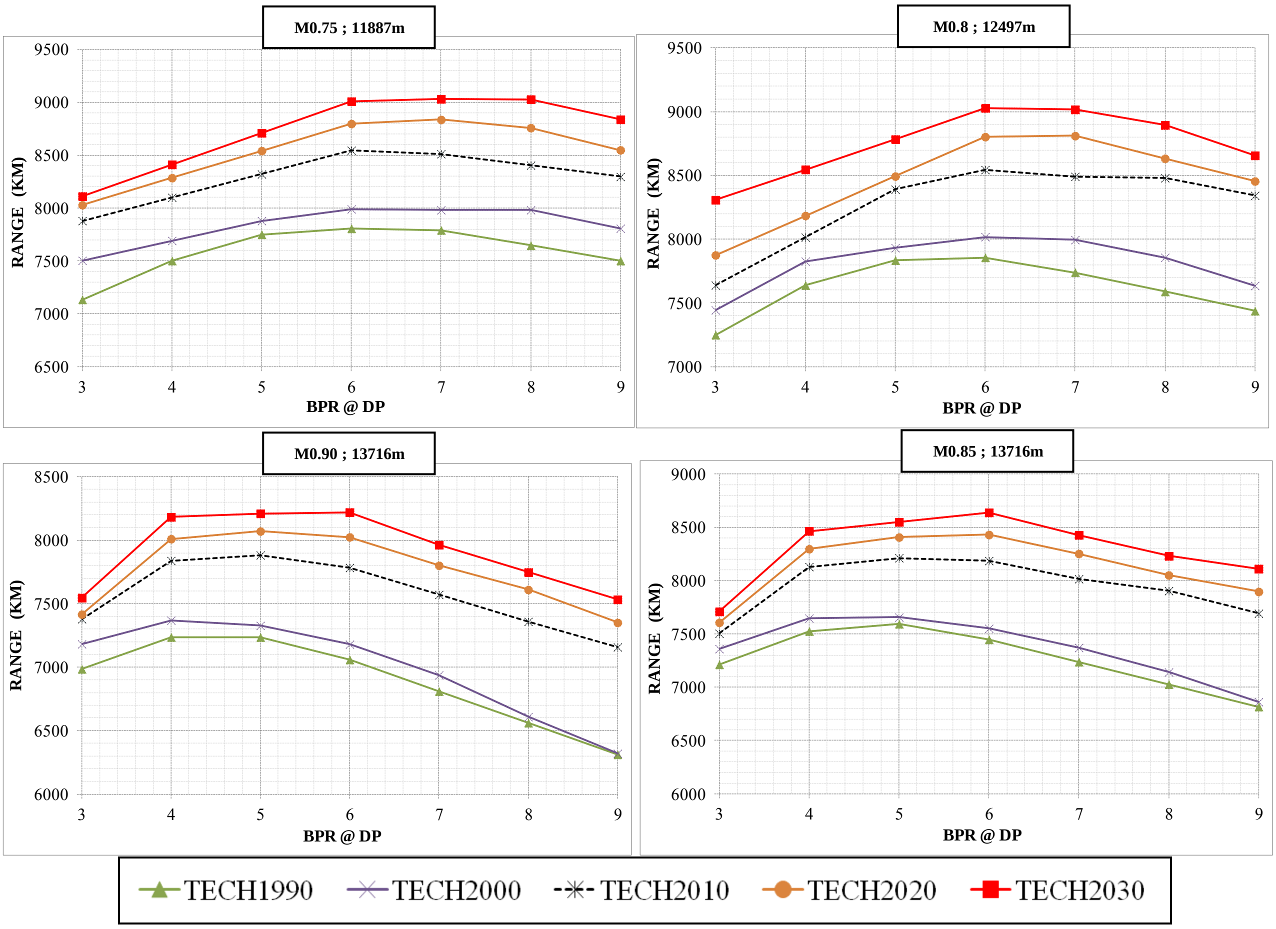

Figure 7. Aircraft range as a function of Design Point BPR, for several engine technology levels and aircraft cruise conditions

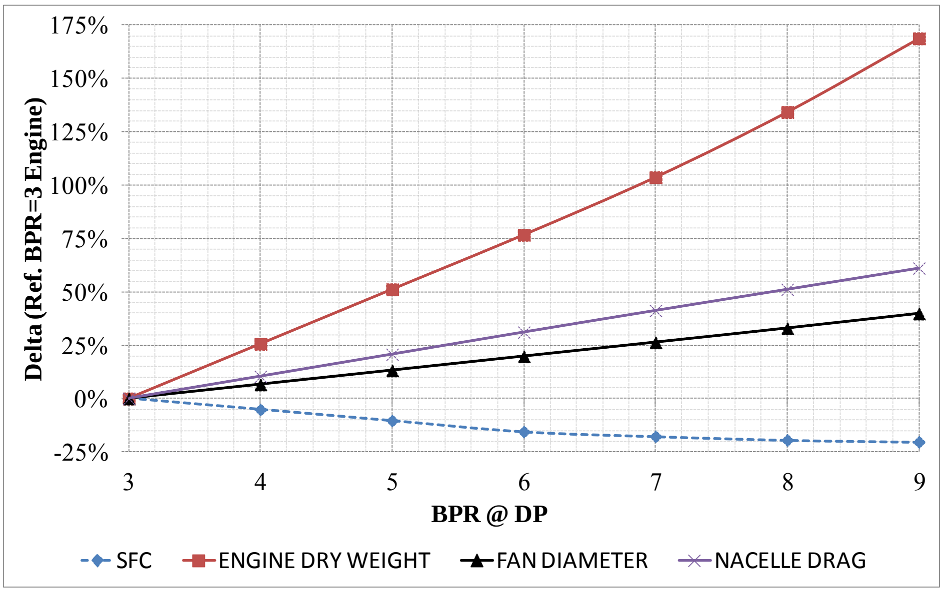

Figure 8. Effect of BPR at engine Design Point in engine SFC, engine dry weight, fan diameter, and nacelle drag.

The obtained results are consistent with the engine data presented in the introduction section of the study. Engines currently under development, specifically designed for business jets also present a BPR value similar to the ones obtained in this study. As previously discussed, the Silvercrest engine, under development by Snecma, presents a BPR value around 6 (AIN online, October 2012). The Passport engine, which is beign developed by GE, is a 7500kgf thrust class engine, with a 132 cm fan diameter (Flight Global, 2013). Since these parameters are close to the ones found in the Rolls Royce BR725 engine (which is a 7680 kgf thrust class engine with a 127cm fan diameter), the BPR of Passport engine should be slightly higher (perhaps around 5) than the one of BR725 (around 4.5), in the author´s opinion (assuming that the core specific power is similar between the two engines).

It is important to highlight that the aircraft performance requirements imposed for the engine sizing have played a significant role in the obtained results. In order to maintain the specified rate of climb at the initial cruise altitude, considering 96% of the aircraft MTOW, the engine must present a large amount of available net thrust, while keeping the installation effects of weight and drag to a minimum. The balanced take-off field length requirement was also demanding, since the highly swept wings designed for low transonic drag present smaller values of C_{Lmax}, requiring more thrust from the engines. If those requirements were alleviated, the value of BPR that maximizes aircraft range would be higher. Since commercial passenger transport aircraft do not present such demanding performance requirements (mainly the climb requirement), higher values of BPR tend to be a more fuel efficient solution. Different engine architectures, such as the GTF and the three shaft engines, and materials technologies, like composite fan blades and Ceramic Matrix Composites (CMCs) turbine blades, will help to alleviate the penalties in weight and dimensions of higher bypass ratio engines. By minimizing these installation penalties, the optimum engine BPR tends to be higher.

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