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Thermodynamic Analysis of an Aircraft Engine to estimate performance and emissions at LTO cycle

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Abstract

Nowadays, pollutant gases emitted from the civil aircraft are doing more and more harm to the environment with the rapid development of the global commercial aviation transport. Emissions of aircraft engines whose rated output is greater than 26.7 kN and whose date of manufacture is after 1 January 1986, are regulated under the provisions established by ICAO to guarantee that engines, at the reference emissions Landing and Take-Off cycle, do not exceed certain regulatory environmental limits. For this purpose, an analysis of the aircraft engine at Landing and Take-Off cycle conditions to determine the emission is important.
The aim of this paper is to study the GE90-94B engine built on the proven success of the early GE90 engine models, that with a nominal thrust of 416.8 kN and a dual dome annular combustor, powers the Boeing 777-200 aircraft. The engine is modelled and simulated with the modular code ESMS, that has the ability to simulate a generic engine at design and off-design conditions without creating a new source program. A thermodynamic design simulation at cruise condition has been realized, using a few known operating characteristics and some general design parameters can be determined. Thereafter an off-design analysis varying the operating mode has been reported; consequently, the thermodynamic parameters as fuel consumption, thrust, bypass ratio, turbine inlet temperature and exhaust temperature change. Moreover, using the results of the ESMS simulations it is possible to estimate, with a correlation, the NOx emissions during the Landing and Take-Off cycle.

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Keywords:Aircraft engine, aircraft performances, aircraft emissions, thermodinamic analysis, off-design analisis, LTO cycle;

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1. Introduction

During last years, the ICAO (International Civil Aviation Organization) agency that draws up standard for civil air traffic has becoming increasingly careful on aircraft pollutant emissions, especially during low altitude operations defined by Landing and Take-Off (LTO) cycle because its impact on human health and environment. In this context, a drastic reduction of NOx emission plays a key role leading CAEP (Committee on Aviation Environmental Protection) to fix long-term goal of 60% reduction in NOx emission for 2026. Moreover, ACARE (Advisory Council for Aviation Research and Innovation in Europe) has reconsidered to extend the existing Vision 2020 to a new horizon towards 2050 with 90% reduction of the same pollutant (ACARE Flightpath 2050). The actual limits of NOx emissions must be met by the aircraft engine to pass the certification procedure, based on engine tests at reference LTO cycle conditions, i.e. taxi / ground idle, approach, climb out and take-off operations. Emission index of NOx in all these operating conditions are summarized in a unique index, the LTO total NOx emission, representing the global NOx emission of the engine at airport. Then, aeroengine manufacturers must continuously develop new high-performance engine, both in terms of specific fuel consumption and pollutant emissions. In order to meet such goals several innovative solutions have been developed during last years, such as intercooler systems, LPP (Lean Premixed Prevaporized) burners, active core concept, Ultra-High Bypass Ratio (UHBR) turbofan, much of these are still at a low TRL (Technology Readiness Level). In this context, a preliminary design of the aircraft emissions is important [1], [2], [3]. Modular codes can be useful to aid simulations, thanks to their versatility and low computational time.

In this work, a modular code has been exploited to evaluate performance of the widely employed GE90 engine, a high-bypass ratio turbofan engine built by GE Aviation and powering Boeing 777 long-range aircraft. In a first step, a design of the engine has been assessed at cruise conditions, followed by an off-design analysis during the LTO cycle operating conditions. Trends of the main thermodynamic quantities of the engine has been reported and exploited to estimate LTO cycle emissions of NOx pollutant.

Nomenclature		**Acronyms**	
A	Area [m^2]	ACARE	Advisory Council for Aviation Research and Innovation in Europe
BPR	Bypass ratio [-]	ESMS	Energy System Modular Solver
D	Diameter [m]	CAEP	Committee on Aviation Environmental Protection
EI	Emission Index [g/kg]	HPC	High Pressure Compressor
F	Thrust [N]	HPT	High Pressure Turbine
h	Altitude [km]	ICAO	International Civil Aviation Organization
M	Mach number [-]	LPC	Low Pressure Compressor
OPR	Overall pressure ratio [-]	LPP	Lean Premixed Prevaporized
p	Pressure [kPa]	LPT	Low Pressure Turbine
S	Severity parameter [g/kg]	LTO	Landing Take Off
SFC	Specific fuel consumption [mg/h N]	TRL	Technology Readiness Level
T	Temperature [K]	UHBR	Ultra-High Bypass Ratio
w	Humidity of oxidizer [-]		
η	Efficiency [-]		
Δp	Pressure Losses [-]		

Subscripts

cold	Cold Flow	comb	Combustor
comp	Compressor	cruise	Cruise
f	Fuel	fan	Fan
hot	Hot Flow	in	Inlet
intake	Intake	is	Isentropic
max	Maximum	mec	Mechanical
noz	Nozzle	t3	Total Inlet Combustor
p	Polytrophic		

2. ESMS modular Code

Gas turbine engines, especially for aerospace propulsion, need a flexible and detailed tool in order to simulate the main gas flow parameters in each relevant stage. ESMS (Energy System Modular Solver) is a modular code developed by Carcasci et al. [4], [5]. The program is capable of undertaking both design [6] and off-design [7] analyses using thermodynamic equations. The engine is divided into multiple components (such as compressor, combustion chamber, turbine etc.) each one connected to another. Connection occurs with mechanic and thermodynamic equations solved using a matrix method. The design procedure necessitates of both component parameters (such as component efficiency, number of stages etc.) and thermodynamic ones (mass flow rate, bypass ratio, rotational speed), in a way that the system can be resolved. Therefore, the output of the design will be thermodynamic properties in each state together with the geometric data of each component. Off-design analyses investigate on thermodynamic and boundary conditions variations only; the geometry is now fixed and it corresponds to the one found in the design procedure.

3. Numerical Setup and Design Analysis

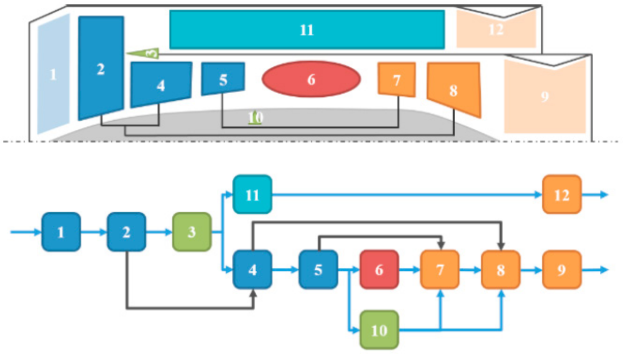
GE90 is a high bypass civil turbofan engine produced recently by General Electric for aircraft propulsion. It is one of the most powerful engine for aircraft application and its major application is for the Boeing 777, a long-range twin-engine aircraft.

The air is compressed by a large-diameter fan and then split into the cold and hot path with a high bypass ratio. The fan, low-pressure compressor, and low-pressure turbine are mounted on the same shaft. Low-pressure compressor, therefore, may not operate at its optimum rotational speed. Big effort to the compression comes from the high-pressure compressor, which features of 10 axial stages. Combustion chamber consists of a dual annular configuration. The gasses then expand into the high-pressure turbine and then into the low-pressure turbine. GE 90 datasheet [8] is reported in Table 1.

Table 1. GE90-94B datasheet [8].

Fan/LPC/HPC Stages [-]	1/3/10
LPT /HPT Stages [-]	6/2
D_{max} [m]	3.125
OPR [-]	40
F_{max} [kN]	416.8
BPR [-]	8.4

Figure 1 provides a general scheme of the engine modelled with ESMS. Blue lines represent fluid-dynamic connections, while the black ones represent power connections. In front of the fan, there is the intake, which contributes to the compression at high velocities.



N°	Compon.	N°	Compon.
1	Intake	7	HP Turb.
2	Fan	8	LP Turb.
3	Bypass	9	Hot noz.
4	LP Comp	10	Bleed
5	HP Comp.	11	Fan duct
6	Combustor	12	Cold noz.

Fig. 1. Scheme of the simulated G90-94B aircraft engine.

Table 2 and 3 summarize the relevant input and output parameters. More in detail, mass flow has been chosen taking into consideration the design process of the intake: neither spillage mode nor suction mode have been considered. Instead, is has been assumed that the air entering the intake is exactly the product of the aircraft velocity times the area featured at the inlet of the intake times the local density. It is known that a proper intake should be designed in this way. Altitude (h) and flight Mach number (M_{in}) are assumed the common ones for a long-range civil aircraft. An iterative procedure changing the TIT in order to match the cruise thrust [9] has been done. Relative errors of the engine performance parameters are around 5% and are surely acceptable considering all the assumption made.

Table 2. Input parameters of components.

$\eta_{is,intake}$ [-]	0.99
$\eta_{p,fan}$ [-]	0.93
$\eta_{p,comp}$ [-]	0.91
$\eta_{p,turb}$ [-]	0.93
$\eta_{is,noz}$ [-]	0.95
η_{comb} [-]	0.99
Δp_{comb} [-]	0.05
η_{mec} [-]	0.99

Table 3. Input and Output of the ESMS model.

Input		
m_{fan} [kg/s]	576.00	
TIT [K]	1365	
M_{in} [-]	0.85	
h [km]	10.690	
Output		Error [%]
F_{cruise} [kN]	65.485	- 5.37
m_f[kg/s]	0.9658	-
SFC [mg/h N]	14.75	- 5.41
D_{max} [m]	3.294	+5.44
$A_{hot,noz}$ [m^2]	0.921	-
$A_{cold,noz}$ [m^2]	3.867	-

4. Off-Design Analysis

The off-design analysis has been realized at sea level conditions (p_{in}= 101325.0 Pa, T_{in}= 288.150 K, M_{in}= 0.0) for LTO cycle operating mode (Figure 2) with the geometry of components obtained from the design simulation.

The LTO cycle is composed of 4 phases:

- Take-off: is the phase in which the aircraft required the maximum thrust and goes from the strip to flying in the air;
- Climb out: the phase after take-off during the aircraft increases the altitude until 3000 feet;
- Approach: is the operating mode from 3000 feet over the touch down point to the end of the rollout on the runway;
- Taxi / Ground Idle: is divide in taxi-out and taxi-in. The first is from engine start to the take-off point and the second is from the end of rollout after landing to parking and main engine turn-off.

These four phases are characterised by different thrusts and times shows in Table 4. The take-off requires the maximum thrust of the engine but has a duration of 0.7 minutes, while the taxi / ground idle phase with a long duration of 26 minutes needs a limited thrust. For this reason, to estimate the total fuel consumption and NOx emissions in LTO cycle is indispensable to analyse all phases.

Table 4. ICAO LTO cycle standard values [10].

Operating Mode	Thrust setting [-]	Time in Operating Mode [*min*]
Take-off	100 % F_{max}	0.7
Climb out	85 % F_{max}	2.2
Approach	30 % F_{max}	4.0
Taxi/Ground idle	7% F_{max}	26.0

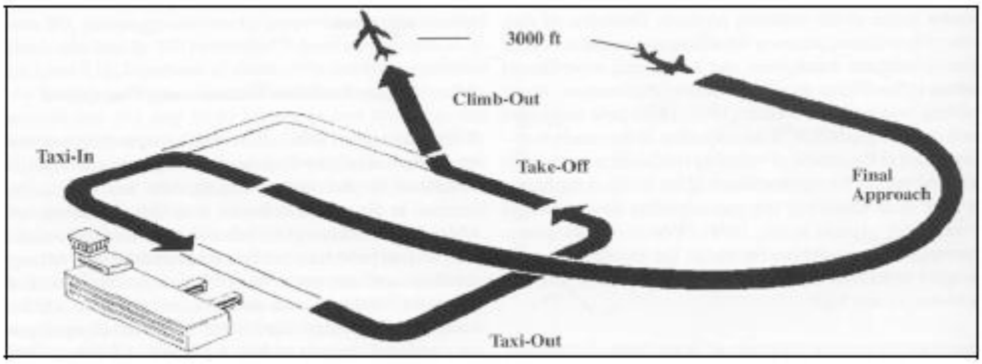


Fig. 2. ICAO reference LTO Cycle [10].

For each phase a simulation has been done changing the Turbine Inlet Temperature (TIT) to match the thrust of the corresponding operating mode condition (taxi / ground idle, approach, climb out and take-off,).
Figure 3a shows the results of thrust obtained in the different phases. For approach and taxi / ground idle operating modes where the thrust is less than the 50% of the maximum thrust (F_{max}) the aircraft thrust is almost completely supplied by the cold nozzle. The hot nozzle produces about 15 – 20% of the total thrust at take-off and climb out conditions. The comparison with the ICAO thrust value [10] shows a good agreement of the obtained results because relative errors are lower than 5%. The trend of the fuel consumption (Figure 3b) is congruent with the thrust trend. The fuel consumption is maximum during take-off in which is required the highest thrust setting. At climb out operating mode the fuel consumption drop given that the aircraft needs a lower load. Taxi / ground idle and approach have the lowest levels of fuel flow rates, about 5 and 25% respect to the maximum fuel consumption. This follows from the fact that taxi / ground idle and approach occur at lowest thrust. The fuel consumption values obtained are compared with the GE90-94b standard fuel consumption ICAO data bank [10]. The value obtained in the taxi / ground idle phase is lower about 25% respect of the ICAO values. Due to the limited thrust required, the engine adopts control systems such as fuel staging and bypass that do not including in the ESMS model and impact to the off-design analysis. For the other operating modes, the differences are negligible because relative errors are lower than 6%. The total fuel consumption during LTO cycle, about of 1124 kg, shows a good agreement (error of 6%) with the measured value [10].

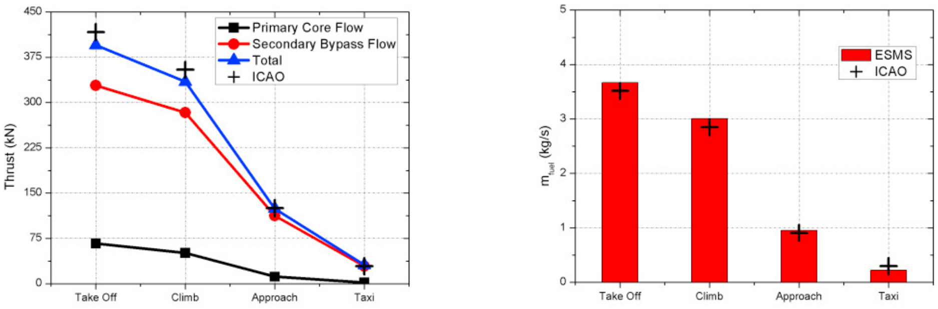


Fig. 3a. Obtained values versus ICAO data bank [10] (a) thrust; (b) fuel consumption.

Figure 4 shows the other main thermodynamic parameters obtained from the simulations. Decreasing the thrust, the turbine inlet temperature (TIT), exhaust temperature (T_{exh}) and overall pressure ratio (OPR) value drop. The exhaust temperature decreases in a little range (700-400 K) while the TIT drop is more relevant, producing a minimum difference temperature in taxi / ground idle phase. The OPR assumes a maximum value of 47 in the take-off phase and decrease such as the thrust for the other operating modes. Inlet air mass flow rate (m_{fan}), the mass flow rate entering the core (m_{hot}) and the corresponding bypass ratio (BPR) in the 4 phases are shown in Figure 4b.The air mass flow rate increase from 400 kg/s in taxi / ground idle to 1375 kg/s in the take-off phase because a higher thrust is required. The bypass ration decrease in take-off conditions given that the hot thrust component increases until about 20% of the total thrust.

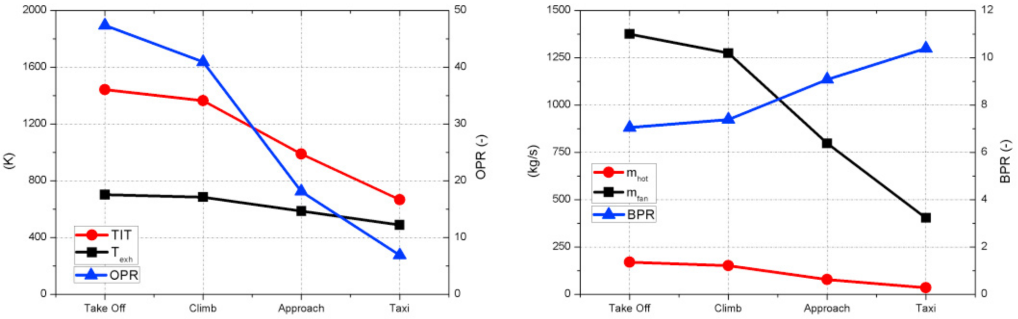


Fig. 4. Main thermodynamic parameters obtained (a) temperatures and OPR; (b) mass flow and BPR.

5. Emissions Analysis

Performance analysis in modern aeroengine design cannot disregard a preliminary prediction of pollutants emission. In order to predict NOx emission during LTO cycle, i.e. the standard procedure for engine certification, a correlative approach has been employed. The lack of data on combustor geometry leads to difficulties in the application of standard correlations because the need of parameters as combustion volume, residence time and primary zone temperature. In order to overcome this issue the Committee on Aeronautical Technologies model [11] has been exploited. This prediction model introduces the severity parameter S_{NOx} defined as (1):

$$S_{NOx} = \left(\frac{p_{t3}}{2956}\right)^{0.4} \exp\left(\frac{T_{t3}-826}{194} + \frac{6.29-100w}{53.2}\right) \quad (1)$$

where p_{t3} and , T_{t3} are respectively the combustor inlet total pressure and temperature, while w is the water/air ratio of the oxidizer. Starting from S_{NOx} value, emission index of NOx (EI_{NO_x}) can be easily provided for a dual-annular combustor, according to [11], by means the following linear function (2):

$$EI_{NO_x} = 23\, S_{NOx} \tag{2}$$

Using combustor inlet pressure and temperature derived by off-design analysis of the engine (Section 4), NOx emission index for the 4 operating conditions of the LTO cycle has been computed and the obtained results have been compared with ICAO exhaust emissions data [10] for GE90 engine, as shown in Figure 5. Results shows a good agreement with the measured data, especially in take-off and climb out conditions. The disagreement during approach and taxi / ground idle can be justified with the combustor part-load operations, such as fuel staging, that are weakly predicted by the employed model [11]. Finally, the estimated EI_{NO_x} values have been exploited to compute LTO emissions required for engine certification standards, which results in a global emission of 30831 g of NOx during LTO cycle. Comparing this value with the measured one [10] results in an error of 0.7%.

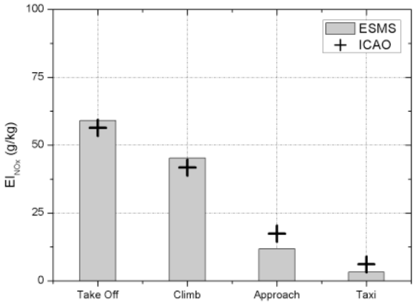


Fig. 5. NOx emission index vs ICAO data bank [10].

6. Conclusions

The International Civil Aviation Organization (ICAO) regulates the emission of an aircraft engine at the LTO cycle with a nominal thrust at sea level greater than 26.7kN, manufactured after 1 January of 1986.

In this paper, the performance and emissions of the GE-90-94B aeroengine with a maximum thrust of 416.8kN placed on the Boeing 777-200 have been estimated.

A thermodynamic design analysis has been realized with the ESMS modular code to model the aeroengine at the cruise conditions. The design shows that the engine performance parameter are in agreement with the datasheet value; the relative error of the parameters are around 5%. The full geometry of each element has been determined in this simulation.

Then an off-design analysis during the LTO cycle operating conditions, has been performed. For each phase, a simulation has been done changing the TIT to match the thrust at related operating mode. The trend of the main thermodynamic parameters such as thrust, hot thrust, cold thrust, BPR, OPR, m_{fan} and m_{core} has been reported.

Finally, the main thermodynamic parameters of the engine in off-design conditions have been exploited to estimate fuel consumption and NOx emissions. The emissions has been evaluated using a correlation that has in input the combustor inlet total pressure and temperature and the water/air ratio of the oxidizer. The results show a global NOx emission of 30831 g and a total fuel consumption of 1124 kg. Comparing these value with the ICAO measured value the error are respectively 0.7% and 6%.

In the future, it could be studied a real flight cycle that include the cruise phase and the LTO cycle phases with the real inlet conditions (pressure, temperature and Mach). This would allow to estimate the global fuel consumption and NOx emission of the aircraft during a flight.

References

[1] S. P. Lukachko and I. A. Waitz; "Effects of Engine Aging on Aircraft NOx Emissions", The American Society of Mechanical Engineers 345 E. 47th St., New York, N.Y. 10017.

[2] Y. S. Chati, H. Balakrishnan; "Analysis of Aircraft Fuel Burn and Emissions in the Landing and Take Off Cycle using Operational Data", 6th International Conference on Research in Air Transportation, 2014.

[3] Y. S. Chati, and H. Balakrishnan; "Aircraft engine performance study using flight data recorder archives", AIAA Aviation Conference, Los Angeles, California, 2013.

[4] C. Carcasci, B. Facchini; "A Numerical Method for Power Plant Simulation", ASME Journal of Energy Resources Technology, March 1996, vol.118, pp.36-43, 1996.

[5] C. Carcasci, L. Marini, B. Morini, M. Porcelli, “A New Modular Procedure for Industrial Plant Simulations and its Reliable Implementation”, Energy 94, 380-390, 2016.

[6] C. Carcasci, L. Winchler, "Thermodynamic Analysis of an Organic Rankine Cycle for Waste Heat Recovery from an Aeroderivative Intercooled Gas Turbine", Energy Procedia 101, 862 – 869, 2016.

[7] C. Carcasci, F. Costanzi, B. Facchini, B. Pacifici; "Performance Analysis in Off-Design Condition of Gas Turbine Air-Bottoming Combined System", Elsevier Energy Procedia, vol.45, pp. 1037-1046, 2014.

[8] GE90-94B datasheet; https://www.geaviation.com.

[9] Cantwell, J. Brian; "The GE90-An Introduction." ed: Stanford course material, 2011.

[10] ICAO, International Civil Aviation Organization; "ICAO Engine Exhaust Emissions Data Bank", ICAO Doc 9646-AN/943, 1995.

[11] National Research Council; "Aeronautical technologies for the twenty-first century", National Academies Press, 1992.