Topical Issues in Aircraft Health Management with Applications to Jet Engines

Sorin BERBENTE[1,2], Irina-Carmen ANDREI*[,1], Gabriela STROE[2], Mihaela-Luminita COSTEA[1]

*Corresponding author
[1]INCAS – National Institute for Aerospace Research "Elie Carafoli", B-dul Iuliu Maniu 220, Bucharest 061126, Romania, berbente.sorin@incas.ro, andrei.irina@incas.ro*, icandrei28178@gmail.com, costea.mihaela@incas.ro
[2]University "POLITEHNICA" of Bucharest, Faculty of Aerospace Engineering, Gh. Polizu Street 1-7, Sector 1, Bucharest, 011061, Romania, ing.stroe@yahoo.com

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***Abstract**: Aircraft Health Management Technology for jet engines represents a very important problem, since it develops a large impact on reducing the engine life cycle costs, improving the fuel efficiency, increasing the engines durability and life cycle. This technology is high-end and, in order to enable an improved level of performance that far exceeds the current one, propulsion systems must comply with terms of reducing harmful emissions, maximizing fuel efficiency and minimizing noise, while improving system's affordability and safety. Aircraft Health Management Technology includes multiple goals of aircraft propulsion control, diagnostics problems, prognostics realized, and their proper integration in control systems. Modern control for Aircraft Health Management Technology is based on improved control techniques and therefore provides improved aircraft propulsion system performances. The study presented in this paper approaches a new concept, of attractive interest currently, that is the intelligent control; in this context, the Health Management of jet engines is crucial, being focused on engine controllers which are designed to match certain operability and performance constraints. Automated Engine Health Management has the capacity to significantly reduce the maintenance effort and propulsion systems' logistical footprint. In order to prioritize and resolve problems in the field of support engineering there are required more detailed data on equipment reliability and failures detection and management; the equipment design, operations and maintenance procedures and tooling are also very important.*

***Key Words:** Aircraft Health Management, control systems, jet engines, propulsion control*

1. INTRODUCTION

Aircraft Health Management Technology for jet engines includes a wide range of applications and standardized procedures, customized for each significant part or assembly which has been proven crucial for the safe operation of the aircraft, for all the jet engine running regimes and flight regimes supposed by the flight envelope and the aircraft's flight missions. From the jet engine's stand point, the concept of Aircraft Health Management AHM turns to focus on

Engine Health Management EHM, which further is based on Engine Condition Monitoring ECM. The most significant topical issues of the Aircraft Health Management AHM with application to jet engines, that is Engine Health Management EHM and Engine Condition Monitoring ECM, are pointed out in this paper. By means of AHM and consequently EHM & ECM, a series of long-term significant benefits are obtained by each of the main players in the aviation industry, namely: designers of aircrafts and jet engine, manufacturers, factors involved in operation of civil, commercial and military airplanes. The key benefits with regards to the jet engines are related to reducing the engine life cycle costs, improving the fuel efficiency, increasing the engines durability and life cycle. The importance of AHM & EHM can be highlighted from the economic stand point; thus, the financial impact can be tough, with severe effects acting on both those directly involved and indirectly, on potential beneficiaries of the aviation industry. Just as an example, DHL as a beneficiary of aviation operational services, estimates that the costs of an aircraft on ground AOG can rise up to 925000 euro per day, [1-2]. Another example, which highlights the importance of AHM & EHM from the financial point of view, is the operating cost structure of an airline, as indicated in Table 1:

Table 1 – Operating Costs of a commercial airline

No. #	Type & specifications of operating costs	% of total amount
1	Maintenance (airframe and engine)	11 %
1EM	* Engine Maintenance, Repair and Overhaul MRO accounts for 40 % up to 50 % of an airline's maintenance expenses	------
2	Fuel	30 %
3	Workforce and operation	25 %
4	A/C ownership	15
5	Taxes and fees	9 %
6	Tickets, sales and service	8 %
7	Miscellaneous	2 %
TOTAL amount of operating costs		100 %

The technology involved in AHM & EHM is high-end and in order to enable an improved level of performance that far exceeds the current one, the propulsion systems must comply with terms of reducing harmful emissions, maximizing fuel efficiency and minimizing noise, while improving system's affordability and safety.

Aircraft Health Management Technology includes multiple goals of aircraft propulsion control, diagnostics problems, prognostics realized, and their proper integration in control systems. Modern control for Aircraft Health Management Technology is based on improved control techniques and therefore provides improved aircraft propulsion system performances.

2. ENGINE HEALTH MONITORING EHM CURRENT STATUS AND PROSPECTIVES

The concept of Engine Health Monitoring EHM consists in four pillars, as explained in Fig. 1. The first EHM pillar originates from the jet engine post-design offline evaluation.

Intended as the first stage of EHM, the jet engine offline evaluation consisted in completing the next three steps, but without any engine monitoring at all:

1. As scheduled by the Engine's Maintenance Management EMM, there were mandatory standard visits in the maintenance unit/ shop;
2. Based on the restrictions imposed by the Exhaust Gas Temperature EGT (i.e. the redline EGT which limits the maximum take-off EGT) and Life Limited Parts LLP's,

the concept "fly to failure" supposes that certain parts and/ or assemblies must be removed, at specified time intervals;

3. Unscheduled engine removals can be performed anytime provided that the aircraft and/ or jet engine is under the condition of the force majeure clause FMC.

The second EHM pillar refers to the diagnostics and consists in a reactive system based on limited data collection. In principle, there are two steps to be fulfilled:

1. Tailored solutions (i.e. workscoping) based on Engine Trend Monitor ETM results;
2. Unscheduled removals are limited, as number, due to certain prohibitive costs and delays in activities involved and connected to aircraft operation.

The current status of the EHM is represented by the achievement of the second EHM pillar. Up to present, EHM # 1 – Offline and EHM # 2 – Diagnostics are in current use.

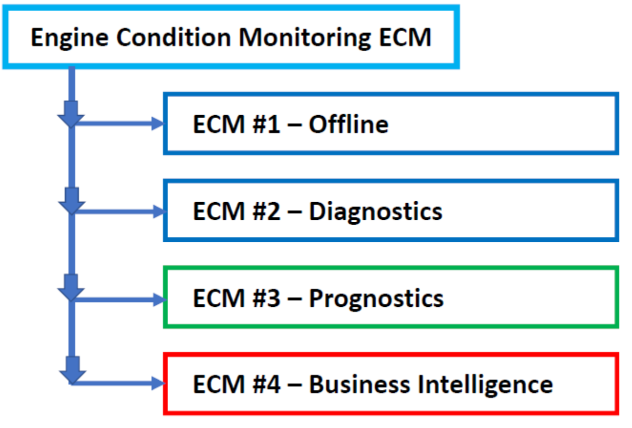


Fig. 1 – The development of the Engine Health Monitoring EHM concept

New prospects and consequent advantages can be foreseen and/ or expected from the future EHM third and fourth pillars: EHM # 3 - Prognostics and EHM # 4 – Business Intelligence. The third EHM pillar EHM # 3 - Prognostics consists on a pro-active system based on predictive algorithms and associated periodically inspections and verifications, i.e. snapshots. The steps of EHM # 3 - Prognostics refer to:

1. Enhanced identification of the upcoming problems, by means of a better monitoring and earlier detection;
2. Continuously improving the maintenance planning and the solution tailoring, by integrating as feedback the solutions to the problems occurred in the past.

The fourth EHM pillar EHM # 4 – Business Intelligence refers to Big Data Analytics based on continuous data stream, that is all-encompassing engine data and beyond. The steps of EHM # 4 – Business Intelligence consist in:

1. Precise forecast for engine Maintenance, Repair and Overhaul MRO cost, scrap rates and removal times;
2. Optimized management of both aircraft and engine fleet and operations;
3. Engine Trend Monitor ETM becomes a major fleet planning tool.

The necessity of EHM & ECM is justified by goals set, operational and financial benefits. The operational goals are of utmost interest. The most significant operational goals refer to:

1. detection of the potential failures in order to avoid or to reduce secondary damages;
2. continuous improvement of the fleet management (focused mainly on the removal and spare engine planning.

The Engine Condition Monitoring ECM provides important operational and financial benefits, with significant impact, as follows:

- Minimizes the unscheduled downtime and optimizes on-wing times,
- Supports early line maintenance decisions in order to avoid secondary damages and aircrafts on ground AOG's situations,
- Supports performance prediction and optimum aircraft operational planning,
- Allows the enhancement of the engine removal planning and the optimization of the spare engine management,
- Allows the optimization of the maintenance planning for off-wing situations,
- Optimizes the core engine cleaning, which generates increased fuel efficiency and consequently the reduction of the overall fuel consumption,
- Contributes to reducing the environmental impact, due to increased fuel efficiency and less overall fuel consumption.

The main goal and benefit of the Engine Condition Monitoring ECM is the cost reduction, from the most important key points: 1/ Operational, 2/ Financial, 3/ Maintenance, Repair and Overhaul MRO; the appropriate actions are summarized in Table 2.

Table 2 – Cost reduction as the main goal of ECM Engine Condition Monitoring

Type	Effect
OPERATIONAL Cost Reduction	OCR # 1 - Early detection of potential failures to reduce or to avoid: • Secondary damage, • Early visits to the maintenance unit/ shop.
	OCR # 2 - Enhanced fleet management
FINANCIAL Cost Reduction	FCR # 1 - Reduced maintenance cost, due to either early detection and/or shop visit avoidance,
	FCR # 2 - Lower unscheduled downtime cost,
	FCR # 3 - Optimized on-wing time,
MRO Cost Reduction	MRO # 1 - Better estimation of the shop visit cost,
	MRO # 2 Improved customized solution tailoring,
	MRO # 3 Continuous increasing and enhancing the knowledge regarding the engine on-wing behavior,
	MRO # 4 Optimizing the capacity planning of the maintenance unit/ shop.

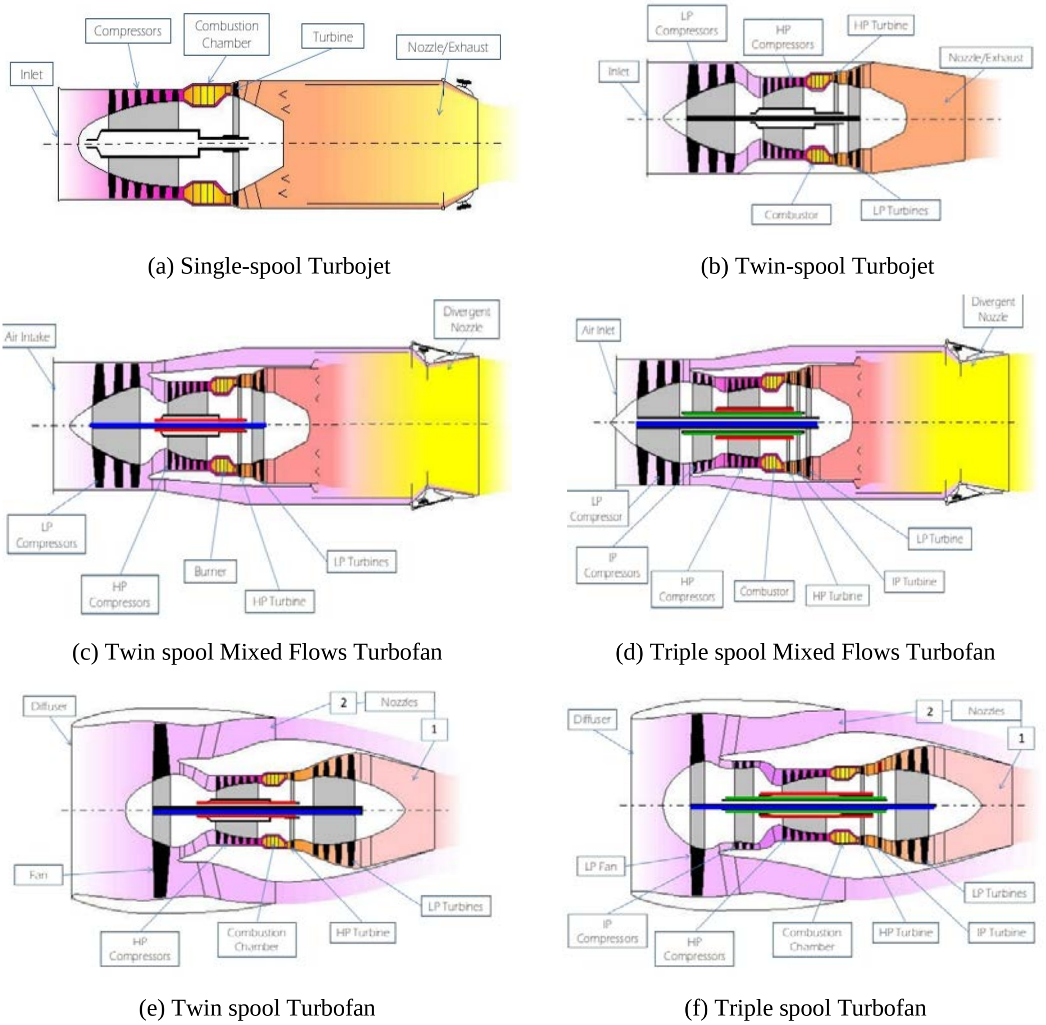
3. REPRESENTATIVE CASES OF JET ENGINES

The types of jet engines are: the turbojet, the turbofan engine, the turboprop and the mixed flows turbofan engine.

This study focuses on the categories of jet engines used as propulsion systems for the purpose of supplying commercial airliners, civil airplanes and military aircraft (combat, fighter or multirole aircraft) which are as presented in Fig. 2 – Fig. 6: turbojet, turbofan (equiv. high-bypass turbofan), mixed flows turbofan (equiv. low-bypass turbofan), twin spool or triple spool constructions for turbojet and turbofan engines.

The commercial airliners can be powered by pairs of 2, 4 or 6 high by pass turbofan engines (which are also referred as un-mixed flows turbofan engines), e.g. the A380 aircraft powered by 4 Rolls Royce Trent 900 turbofan engines.

Other types of turbofan engines, such as CF6-50/80 C2, V2500 IAE, PW 2000, CFM 56-3/58/7, CF 34-8/10, GE 90-110B/115B which can be mentioned [3-8] are also in current use. The turbofan engines are designed to provide lower fuel consumption, while for the military applications, the turbojet and the mixed flows turbofan engines are designed to provide high levels of thrust.



(a) Single-spool Turbojet (b) Twin-spool Turbojet

(c) Twin spool Mixed Flows Turbofan (d) Triple spool Mixed Flows Turbofan

(e) Twin spool Turbofan (f) Triple spool Turbofan

Fig. 2 – Schematic diagrams of turbojet and turbofan engines, [5]

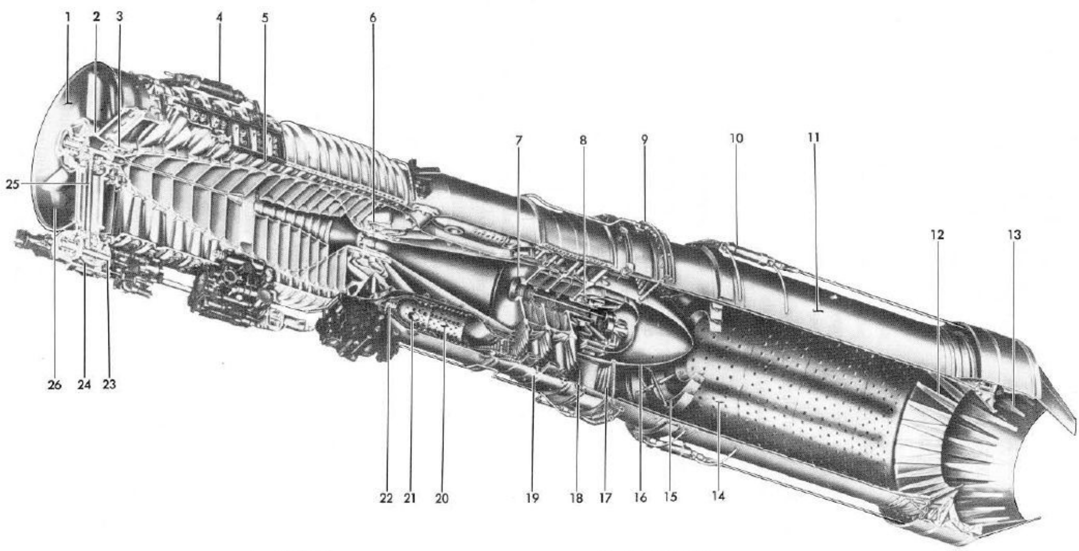
A comparison of the turbojet engine architecture points out the single-spool construction, Fig. 2.a, versus twin-spool construction, Fig. 2.b, which is more advantageous due to the increased adaptability to the aircraft flight regimes and enabling a safer operation, due to removing the engine's operating line from the surge line.

The most efficient configuration is the triple-spool turbofan engine, Fig. 2.d, 2.f, for the same reasons as above: engine featuring adaptability and enhanced safety during all operational sequences. Considering the clarity and accuracy as mandatory for any technical study, the proper use of terms and definitions must be mastered.

For this reason, from the engine's architectural standpoint, the references related to Fig. 2d, 2f are: Turbofan engine = High-bypass Turbofan = Distinct Flows Turbofan = Turbofan with Distinct Core and Bypass Flows = Turbofan, while the references related to Fig. 2c, 2e are: Mixed Flows Turbofan engine = Low-bypass Turbofan = Mixed Flows Turbofan, had to be introduced.

Fig. 3 – J-85 GE-17A Turbojet Engine [1,6], powering the Cessna A-37A/B attack aircraft

Due to the reduced cross section, the turbojet engines and the mixed flows turbofan engines are preferred as propulsion systems for the military aircraft (combat/ fighter/ multirole). The thrust of both turbojet and mixed flows turbofan engines can be significantly increased, for short periods of time, by means of the reheat engine cycle; such engines are equipped with afterburners (i.e. afterburn units). Fig. 3 shows the J-85 GE-17A Turbojet Engine [1, 6].



1	Air Intake	14	Tailpipe Liner
2	Front Gear Case	15	Flame Holder
3	No. 1 Bearing Housing	16	Exhaust Cone
4	Variable Vane Actuator	17	Afterburner Spray Bars
5	17 Stage Compressor Section	18	Tailpipe Temperature Thermocouple
6	No. 2 Bearing Housing	19	3 Stage Turbine Section
7	3 Stage Turbine Wheel	20	Combustion Chamber
8	No. 3 Bearing Housing	21	Cross Fire Duct
9	Afterburner Fuel Manifolds	22	Fuel Nozzle
10	Exhaust Nozzle Flaps Actuator	23	Horizontal Accessory Driveshaft
11	Tailpipe	24	Transfer Gear Case
12	Primary Exhaust Nozzle Flaps	25	Vertical Accessory Driveshaft
13	Secondary Exhaust Nozzle Flaps	26	Variable Inlet Guide Vanes

Fig. 4 – J-79 GE Reheated Turbojet Engine, [7] powering fighter and bomber aircraft

The General Electric J-85 family is based on a small single-shaft turbojet engine, that in military versions is produced with afterburning variants, while civilian models, known as the

CJ610, are supplied without an afterburner; the CF700 adds a rear-mounted fan for improved fuel economy. The J-85 turbojet engine was developed initially for the ADM-20 Quail (i.e. a large decoy missile) and further found applications in other light-jet applications including the supersonic Northrop F-5/T-38 family, as well as in commercial CJ610.

Fig. 4 shows a cutaway view of the afterburning J-79 GE Turbojet Engine [7].

The General Electric J79 basic solution is an axial-flow turbojet engine, which was developed for reliable Mach 2 performance, powering the Convair B-58 bomber.

The J79 was used to power a variety of fighter and bomber aircraft (such as: Convair B-58 Hustler, Lockheed F-104 Starfighter, McDonnell F-4 Phantom II; North American RA-5 Vigilante, IAI Kfir) and a supersonic cruise guided missile (i.e. SSM-N-9 Regulus II).

The commercial version of General Electric J79, designated the CJ805, powered the Convair 880, while an aft-turbofan derivative, the CJ805-23, powered the Convair 990 airliners and a single Sud Aviation Caravelle demonstrated the benefits of a bypass engine over the existing Avon turbojet.

The gas generator of the J79 was developed as a stationary 10MW-class free-turbine turboshaft engine for naval power, power generation, and industrial use, called the LM1500. The J79 was replaced from powering fighter aircraft by afterburning turbofans (such as the Pratt & Whitney TF30 used in the F-111 and F-14) and newer generation turbofans (e.g. the Pratt & Whitney F100 used in the F-15 Eagle), which give better cruise fuel efficiency by-passing air around the core of the engine.

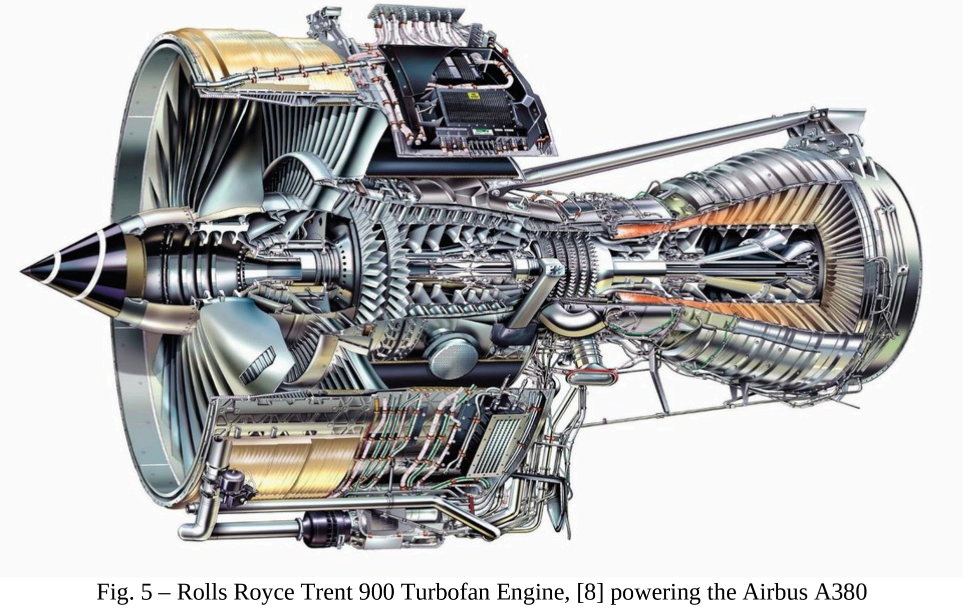


Fig. 5 – Rolls Royce Trent 900 Turbofan Engine, [8] powering the Airbus A380

Fig. 5 shows a cutaway view of the Rolls-Royce Trent 900 high-bypass turbofan engine, which was designed to power the Airbus A380, competing with the Engine Alliance GP7000. Producing up to 374 [kN], the Trent 900 has the three shaft architecture of the Rolls-Royce Trent family with a 2.95 [m] fan, and it has the overall pressure ratio of 37-37 and bypass ratio about 8.5-8.7.

Latest advances in science and technology enabled highly efficient solutions for innovative constructions of turbofan engines. The improvements are targeted for lowering fuel consumption, weight reduction, environment friendly by reducing CO and NO emissions and noise levels.

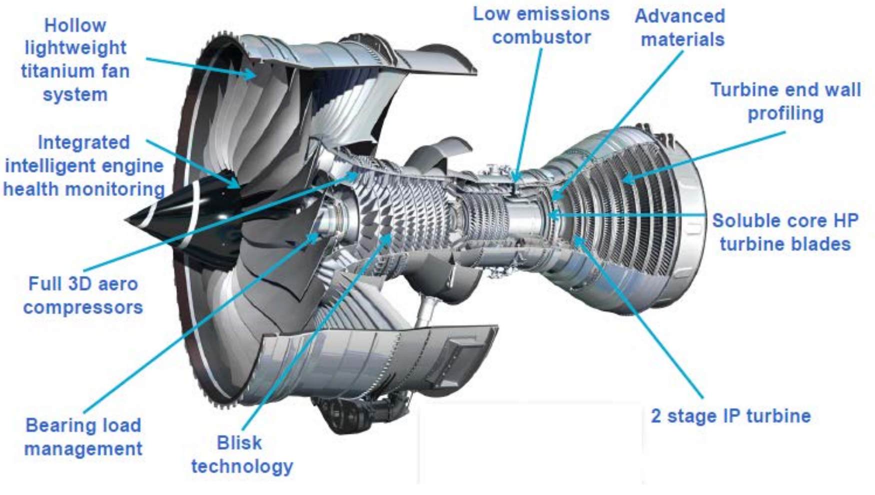


Fig. 6 – Rolls Royce Trent XWB – Advanced Technology for A359, [11]

Fig. 6 highlights advanced technology elements, summarized in case of the Rolls Royce Trent XWB engine [11], as follows: Integrated Intelligent Engine Health Monitoring, Bearing Load Management, Advanced Materials, Full 3D Aerodynamic Compressors, Blisk Technology, Hollow Lightweight Titanium Fan System, Turbine End Wall Profiling, Soluble Core HP Turbine Blades, Low Emissions Combustor.

Fig. 7 exemplifies innovative technology concepts, which in case of the Rolls Royce BR725 Engine are designed to power the G650 Gulfstream, such as: new swept fan blades, Trent technology tailored for increased bypass ratio and increased diameter, improved HPC with 5 stages of Blisk, smoke free combustor, new 3 stage LPT, 16 lobe mixer for minimal jet noise.

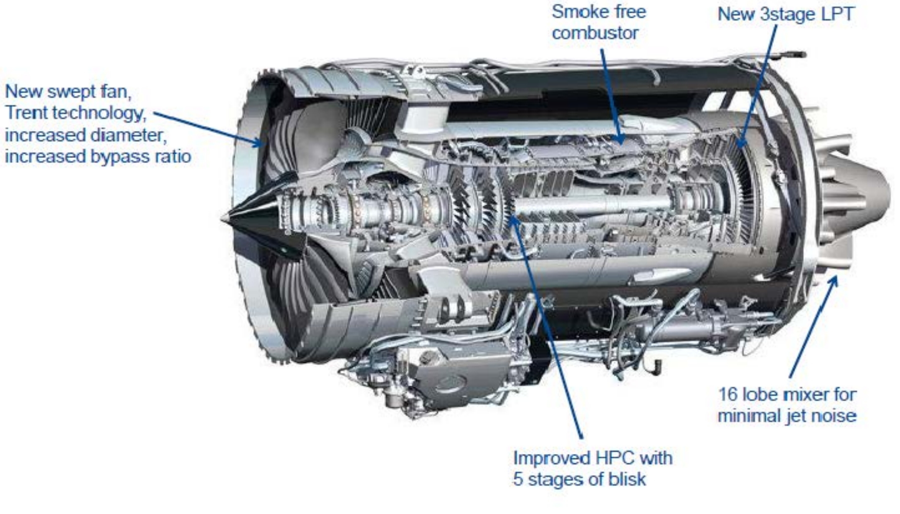


Fig. 7 – Rolls Royce BR725 Engine for Gulfstream G650, [11]

Fig. 8 presents the F100 PW 220E Reheated Mixed Flows Turbofan Engine, powering the F16 Fighting Falcon [9-11]. The Pratt & Whitney F100 Mixed Flows Turbofan Engine (company designation JTF22) is an afterburning turbofan engine manufactured by Pratt & Whitney purposed to power the F-15 Eagle and F-16 Fighting Falcon. Other applications are as follows:

1. F401 engine for Rockwell XFV-12 prototype supersonic VTOL fighter;
2. F100 for powering: General Dynamics F-16 Fighting Falcon, McDonnell Douglas F-15 Eagle, McDonnell Douglas F-15E Strike Eagle, Northrop Grumman X-47B, Vought YA-7F;
3. F401 for powering: Grumman F-14B Tomcat (planned; test aircraft only), Rockwell XFV-12, Vought Model 1600 (proposed).

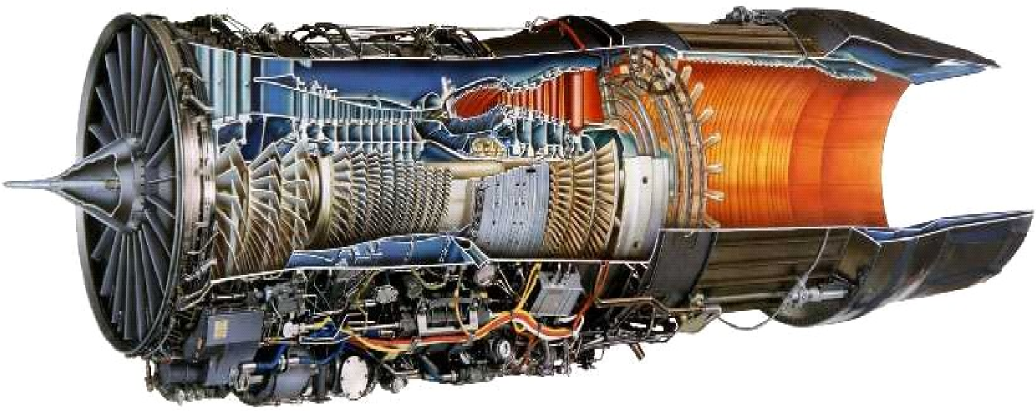


Fig. 8 – F100 PW 220E Reheated Mixed Flows Turbofan Engine, powering the F16 Fighting Falcon [9]

4. PROBLEM STATEMENT: TURBOFAN ENGINES CONTROL FOR CIVIL AND MILITARY APPLICATIONS

The jet engine control problem for military and civil applications is customized in accordance with the type and construction of the selected engine [12-14]. Turbojet and turbofan engines for military applications are intended to power combat aircrafts (fighter and/ or multirole aircraft); the construction of such engines is explained in Fig. 2, while cutaway views are detailed in Fig. 3 – Fig. 8. Since the exhaust nozzle area features variable geometry, the control is performed by the means of two variables, that is the fuel flow rate $\dot{M}_c$ and the nozzle exhaust area A_e; consequently, the control vector consists of two elements [19]. In case of military afterburning turbojets and turbofans, the state vector contains the information on combustor pressure and afterburner pressure, otherwise, only the combustor pressure is referred [21].

Turbofan engines for civil applications are dedicated to power commercial airliners; since the exhaust nozzle area is fixed, the control is performed by means of a single variable, that is the fuel flow rate $\dot{M}_c$; consequently, the control vector consists of one element.

In case of single-spool versus twin-spool and triple-spool constructions, the state vector contains information on the speed for each spool: low-pressure compressor to turbine spool, high-pressure compressor to turbine spool and fan to turbine spool [23].

Since the profile mission of a combat aircraft often requires a sudden increase of available thrust, the MFTE is equipped with an afterburner, which provides a significant augmentation of the engine thrust, by means of a reheat cycle [15-18]. In case of the MFTE and the reheated MFTE respectively, for a better adaptability of the engine regimes to the aircraft flight regimes, and a safer engine operation (due to the fact that the work regimes line is shifted farther from the surge line), the geometry of the exhaust nozzle is variable [23-25].

Fig. 8 shows a cut view of the F100 PW 220E Reheated Mixed Flows Turbofan Engine, [9], which is powering the F16 Fighting Falcon, aircraft, in current use within the Romanian

Air Force. In case of the mixed flows turbofan engine MFTE for civil applications, the control is performed by means of one variable: the fuel flow rate $\dot{M}_c$; consequently, the control vector consists of one element [28]. The jet engine control can be described by either non-linear, linearized or linear models; in this study, a linearized mathematical model was used, expressed by the state (1) and output (2) equations, where the matrices A, B, C and D (of appropriate order) are computed for each representative operating point (of the jet engine), in accordance with the flight path and flight map [19-22].

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \tag{1}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \tag{2}$$

The most complex model of the jet engine control is that used for the reheated mixed flows turbofan engine, Table 3 detailing the parameters which define the state vector $\boldsymbol{x}$:

$$\boldsymbol{x} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} \tag{3}$$

output vector $\boldsymbol{y}$:

$$\boldsymbol{y} = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} \tag{4}$$

and control vector $\boldsymbol{u}$:

$$\boldsymbol{u} = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \tag{5}$$

Table 3 – Parameters defining the state vector *x*, output vector *y* and control vector *u* in case of the reheated mixed flows (twin spool) turbofan engine

Vector	Parameters	
STATE VECTOR ***x***	x_1	HPC speed, N2 [rpm]
	x_2	LPC speed, N1 [rpm]
	x_3	Combustor internal pressure, [bar]
	x_4	Afterburner pressure, [bar]
	x_5	Combustion chamber internal energy, [kJ]
OUTPUT VECTOR ***y***	y_1	Engine thrust, [kN]
	y_2	Turbine inlet temperature T3T, [K]
	y_3	HPC surge margin
	y_4	LPC surge margin
CONTROL VECTOR ***u***	u_1	Combustor fuel flow rate, [kg/s]
	u_2	Exhaust nozzle area, [m^2]

Table 4 – Parameters defining the state vector *x*, output vector *y* and control vector *u* in case of a twin spool turbofan engine

Vector	Parameters	
STATE VECTOR ***x***	x_1	HPC speed, N2 [rpm]
	x_2	LPC speed, N1 [rpm]
	x_3	Combustor internal pressure, [bar]
	x_4	Combustion chamber internal energy, [kJ]
OUTPUT VECTOR ***y***	y_1	Engine thrust, [kN]
	y_2	Turbine inlet temperature T3T, [K]

	y_3	HPC surge margin
	y_4	LPC surge margin
CONTROL VECTOR ***u***	u_1	Combustor fuel flow rate, [kg/s]

In case of military turbojet and military turbofan, the control of the jet engine is enabled by two parameters:

1. combustor fuel flow rate $\dot{M}_c$ [kg/s],
2. exhaust nozzle area A_e [m^2], (due to the variable geometry feature of the exhaust nozzle).

Therefore, the dimension of the control vector is 2. Many types of turbojet and turbofan engines purposed as propulsion systems for military aircraft are provided with afterburners, and then for this reason, the state vector contains information regarding the pressure inside the combustor and afterburner, as indicated in Table 3. In case of turbojet and turbofan engines as prospective propulsion systems for civil use aircrafts, the exhaust nozzle is characterized by fixed geometry, and therefore, the jet engine is controlled by the means of a single parameter: combustor fuel flow rate $\dot{M}_c$ [kg/s]. The output vector is defined in accordance with the architecture of the jet engine, namely: single-spool versus twin-spool construction, resulting the compressor surge margin (as in Table 5) or the High Pressure Compressor HPC and Low Pressure Compressor LPC surge margins (as in Table 4). For a typical single spool turbojet engine, the linearized model contains the state equation (1) and the output equation (2), with the state vector, output vector and control vector defined as shown in Table 5.

Table 5 – Parameters defining the state vector *x*, output vector *y* and control vector *u* in case of a single spool turbojet engine

Vector	Parameters	
STATE VECTOR ***x***	x_1	Compressor speed, N [rpm]
	x_2	Combustor internal pressure, [bar]
	x_3	Combustion chamber internal energy, [kJ]
OUTPUT VECTOR ***y***	y_1	Engine thrust, [kN]
	y_2	Turbine inlet temperature T3T, [K]
	y_3	Compressor surge margin
CONTROL VECTOR ***u***	u_1	Combustor fuel flow rate, [kg/s]

The problem of jet engine control can be solved if a mathematical model is previously established that accurately describes the behaviour of the jet engine for all the operating regimes and all the flight regimes required by the flight mission profile.

The numerical simulations carried on based on the jet engine mathematical model can provide accurate results on the performances of the studied jet engine (i.e. the thrust, specific thrust and specific fuel consumption) for the design and all the off-design regimes, for the steady state analysis [26-27]. The dynamic analysis of the jet engine highlights the jet engine's behaviour to transient regimes and/ or non-stationary. Adequate mathematical modelling can provide proper results for the dynamic analysis and jet engine control. Further, in conjunction with the Engine Condition Monitoring ECM and Engine Health Monitoring, the jet engine control problem (which includes algorithms, procedures and techniques) can be a solid foundation for Advanced Health Monitoring AHM. In this context, researches regarding the mathematical modelling of turbojet, turbofan engine and mixed flows turbofan engines, targeted and customized for performance prediction at design and off-design regimes, steady state analysis and dynamic analysis, jet engines and aircraft control, optimizations, with the purpose of creating and develop in-house software, are of utmost interest.

5. ENGINE CONDITION MONITORING

The purpose of Engine Condition Monitoring ECM is to assess engine performances and to detect impending failures, by continuously surveying and monitoring certain key engine parameters. It uses standard aircraft and engine instrumentation for monitoring, and does not need any additional measurement equipment. The engine control key parameters to be measured and monitored are those defining the state vector, output vector and control vector, as described in Tables 3, 4 and 5. In addition to the engine control key parameters, the Engine Condition Monitoring ECM requires other parameters, such as additional engine parameters (e.g. oil temperature, oil pressure, N1/N2 vibrations, valve solenoid positions), aircraft parameters (e.g. altitude, flight Mach number, total air temperature) as well as for the accessories to be monitored and controlled. Engine Condition Monitoring ECM can be successfully used as a complex tool, in association with a software based on full aero-thermo-dynamic jet engine models. Based on aircraft data acquisition systems, real-time in-flight analysis and monitoring techniques, engine stall detection, real-time thrust, the Engine Condition Monitoring ECM can provide information of the current engine operation, can prevent the occurrence of failures, can perform proper control and adjustments such that the engine runs within the safe domain. Featuring the adaptability, the Engine Condition Monitoring ECM provides accurate results for advanced diagnosis, prognosis and analysis, based on continuous system enhancements. It can further be extended to Advanced Health Monitoring AHM.

6. CONCLUDING REMARKS

Proper data acquisition, monitoring, understanding and managing engine data, allow to perform the following tasks:

1/ accurate automatic diagnosis,
2/ prognosis,
3/ modular deterioration diagnosis.

The automatic diagnosis is based on pattern matching, which consists in the comparison of current trend pattern to historic failures stored in database; then, the numerical simulation based on a thermodynamic model, provides information and simulates failure, in order to determine root cause on module base. The prognosis allows to improve the fleet management performance, based on Engine Trend Monitoring ETM; therefore, from each flight report a forecast is expressed, which specifies the remaining cycles or time intervals / days on-wing until a specific EGTM threshold is reached. Then, based on EGTM history, a smoothed deterioration gradient can be calculated, outliers being excluded from statistical smoothing. Eventually, the results for each engine will be included in a fleet ranking report, periodically updated. The next step is represented by Modular Deterioration Diagnosis MDD. Based on the correlation between the engine flight hours and the influence of the Exhaust Gas Temperature EGT on the engine's main modules (i.e. fan, LPC, HPC, HPT, LPT) diagnostics of module contribution to performance loss can be expressed, as well as prognostics of future modular behavior. The main goal of Modular Deterioration Diagnosis MDD is to optimize workscope planning for the whole engine life. An important contribution to Business Intelligence is the Fleet Analysis FA based on Engine Trend Monitoring ETM. Basically, it pin-points the link between cycles since on-wing installation and EGT margin loss since installation. For such an approach, a deterioration matrix is constructed, which allows historical data analysis, investigation and efficient management of the following issues:

- Fleet average and single engine deterioration rates,
- Shop / maintenance unit visit effects (surveillance of the regained performance),
- Performance information of mature engines.

Table 6 summarizes the integration of all available data sources.

Table 6 – A summary of the integration of all available data sources

Source type	Data
Jet engine	• Engine Gas Temperature EGT T_3^* [K], • Fuel flow $\dot{M}_c$ [kg/s], • LPC and HPC speed, N1 [rpm], N2 [rpm] • Deterioration analysis & prognosis • Bleed settings, valve positions, • EGT margin, N2 margin, • Thrust de-rate, • Vibration, oil data
MRO (Maintenance, Repair and Operating Supplies)	• Workscope, • Hardware damage pattern, • Engine MRO history, • Testcell.
Environment	• Current weather conditions, • Airport altitudes and runway length, • Chemical pollution, • Particle concentration (e.g. sand, salt, water, volcanic ash)
Customer	• Line Maintenance Info • Mission Profile, • Utilization Rate, • Operation Region.

The integration of all available data sources has a direct effect on the management effectiveness, especially the Fleet Management FM and Maintenance, Repair and Overhaul MRO and Operating Supplies OS Management, as detailed in Table 7.

Table 7 – Management improvements on fleet and MRO due to advanced data sources integration

Type	Operations	Actions performed
Fleet Management	Engine Fleet decision/ growth	Simulation of performance in current mission
	Mission change	Simulation of fleet performance under changed operations
	Aircraft allocation	Matching of performance and mission
MRO Management (MRO = Maintenance, Repair and Overhaul)	MRO	Additional data further improves prognosis of MRO requirements
	On-wing services	Visualization of services to extend on-wing times, even if unexpected changes may occur, e.g. out-phasing is changed.

Engine Trend Overhaul ETO is a continually evolving and updating process, since it must monitor, analyze and manage high amount of future incoming data. Engine Trend Monitoring ETM represents a key instrument goaled to improve engine operation and MRO – Maintenance, Repair and Overhaul; it may also provide great opportunities for fleet management improvements.

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