Comparative Study of a Powerplant Life Consumption Rate when Installed in Two Different Aircraft Variants

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ABSTRACT

The Hellenic Air Force operates both EMB-145 and EMB-135 LR, Embraer aircraft used in surveillance and civil missions respectively. These aircraft are equipped with the same version of Rolls Royce, AE 3007 turbofan engine. The current study aims to quantify and compare the life consumption rate of this engine when installed in each of the two aircraft variants. Two typical missions, one for each variant, were constructed based on mission profile data dictated by the aircraft commanders. For each mission profile segment, corresponding engine data were matched out of the engine recordings archives held by the Hellenic Air Force. The life consumption rate was based on the Low Cycle Fatigue (LCF) and creep cumulative detrimental effect on the rotor blades of the 1st High-Pressure Turbine stage. For the LCF, the rainflow method was used to determine the respective loading cycles, whereas the Larson - Miller parameter method was used to determine the consumed life fractions due to creep. The main conclusion of the study was that the engine when installed in the EMB – 145 military variant, is much more loaded. Despite the fact absolute life consumption values could hide a great level of uncertainty, the comparative outcomes wherein errors are, to a certain extent, cancelled out, could be used as a rule of thumb when monitoring engine life consumption rates.

1.0 INTRODUCTION

Gas turbine engine diagnostic and prognostic systems aim primarily to increase flight safety and secondarily to minimize operating costs. The aforementioned aims are two sides of the same coin since the basic prerequisite for both of them is the constant monitoring of the engine operating condition in terms of life fraction consumed and life fraction remaining until the component's replacement. In the case of modern engines, such lifing algorithms come embedded into the engine software in order to support, with useful information, the maintenance procedures. However, the user, through the user interface, only has access to high-level information like for instance a *performance margin index* along with a set of relevant thresholds without having any inside knowledge as to how this index is defined and what does it take into account. Given the fact that the rate of engine life consumption depends on many aspects such as the mission profile, environmental conditions (during flight and engine storage) the pilot mentality etc. such pre-programmed metrics may demonstrate a quite sizable uncertainty level. Especially in the case where, the models were developed with reference to a specific user and subsequently applied by other users operating in a completely different environment.

Let us not disregard Volponi's (Volponi 2014) view that an “one-size-fits-all” EHMS will not ever exist. Consequently, the right way to move forward regarding engine diagnostic and prognostic systems is to equip the engine with sensors in order to collect as many data as possible during operations and then use those data to develop tailor-made algorithms for engine fleet management.

Users shall be supported and guided by the OEMs to develop their own tools or alternatively adapt existing tools to their own fleet operating parameters. A less accurate life monitoring method developed based on the user's data may prove more valuable regarding engine fleet management, than a highly sophisticated prognostic algorithm developed with reference to data sets of a different user. Additionally, tailored made engine life consumption studies based on engine recorded data and computationally efficient methodologies, may also be applied for purposes of results validation relevant to engine operating condition produced by the embedded EHMS.

In this direction, the HAF collects from the operations field in a centralized manner data and conducts comparative studies in order to enrich with very precise qualitative and quantitative measures its insight regarding engine fleet life consumption. This could be regarded as a database populated with a simple rule of thumb type of info build on solid, field operating data.

Comparative, rather than absolute value studies, are preferred since the material behaviour cannot be predicted accurately enough, like for instance the operating conditions to which the engine is exposed. Moreover, a user has limited access to the material properties and characteristic curves. Therefore, as mentioned in the abstract, there is always a great level of uncertainty in those calculations not regarding the measurement, (which is also present, but it is only a tiny component) but regarding the discrepancies mentioned above. Over the past years within the frame of the HAF, several studies of this kind were contacted. Each of those studies introduces a methodology in order to extract specific information regarding the engine’s loading and life consumption. For instance the engine loading depending on the mission type was studied for the case of the F-16 (Templalexis et al. 2020) and will be applied for other types of aircraft as well. Once enough data are gathered to train a smart algorithm, then by tracking the aircraft mission history, a parallel database could be building regarding the engine loading, with very low computational effort. A second study followed a different approach regarding engine life consumption tracking which could potentially act complementary to the first one. The engine loading limits of a certain aircraft, along with its powerplant, were defined by examining the lightest and heaviest possible in terms of engine loading, missions (Templalexis et al. 2021). This was demonstrated for the T6 aircraft but it could be applied for any other aircraft operated by the HAF. Having set the possible range of loading, all missions could be placed in between with a certain loading factor. The current study addresses the specific case where an engine is installed in two different versions, or it could also be different aircraft, with more of less repetitive mission pattern, in order to calculate potential differences in engine life consumption.

The current manuscript is structured as follows: First a brief literature review is given regarding gas turbine engine lifing studies. Then a case study is presented regarding the life consumption of an engine installed in two different versions of an aircraft. The study abides by the characteristics presented before. It is based on real-time recorded data, has a comparative character and is tailored to the mission profile and circumstances of the Hellenic Air Force. The propulsion system and the two aircraft variants are briefly described. Then an outline of the engine model and the tools used for it to be built is given, followed by a thorough explanation of the engine lifing methodology adopted. Finally engine lifing comparative results are reported and commented upon.

2.0 LITERATURE REVIEW

According to the engine certification rules, engine lifing is conducted based on the engine’s critical parts. Critical parts are defined as those parts whose failure is likely to cause hazardous effects. Such parts are primarily the rotor discs and spacers, the combustor thin shell walls, the shafts and the casings of any rotating component which are meant to contain any raptured bit of material originated from a rotating part. As pointed out in (C.H. Tao et al. 2000) the failure caused by rotating components accounts for more than 80% in the military engines. Among them, the 40% of rotating components failures are brought about by the failure of rotor blades. Even if blade rapture is not considered a failure that can cause hazardous effects since engines are designed to contain the blades and retain enough shaft balance, blades remain the best engine part upon which the lifing could be based because they have the biggest probability to fail first and ground the engine and the aircraft. Moreover, despite that is not considered as a highly critical engine component, there are cases where a broken blade caused severe DoD damage putting in danger the safe completion of the mission.

Blade deterioration is classified as recoverable and non – recoverable. Recoverable in the sense that a maintenance action, can fully alleviate the blade deterioration. Blade lifing methodologies, are obviously only related to non-recoverable deterioration. Engine performance monitoring, is a prerequisite for any diagnostic, prognostic or life consumption study. However there are no clear boundaries between these three highly interrelated notions. Focusing on the etymology of the word diagnosis, it interprets to the notion of reaching the knowledge (gnosis) through the analysis of a certain set of information. In the gas turbine engine practice, the term is used to describe the process of analysing measurable deviations of gas path thermodynamic parameters, in order to acquire knowledge regarding engine faults, like for instance blade fouling, corrosion, tip clearance gap increase etc. This approach was founded by Urban (Urban, L. A., 1972) through the introduction of *linear gas path analysis*. Over the following decades, it was brought to the next level by focusing on aspects like alternative mathematical formulation of the *Influence Coefficient Matrix*, sensor induced faults isolation, smart algorithms to automate the whole process etc. In parallel, other research groups, turned their attention into transient engine performance instead of the steady state flow solution, which has traditionally been the gas path analysis theoretical basis. (Dengji Zhou et al. 2020) intended to diagnose gas path faults by analysing how blade profile parameters are changing through time. Another approach of reaching the goal of diagnosis, which can be interpreted as the current operating state of the engine also called its health condition, is to count using proper metrics, the evolution of deterioration caused by mechanisms such as corrosion, LCF and creep, without relying necessarily on visible imprints. The main underlying assumption is that non recoverable, invisible bits of deterioration are being accumulated to the material. This is usually reported as life assessment, rather than diagnosis. Another branch of diagnostics is based on mechanical loading input, rather than on gas path thermodynamic parameters' values. Among the most common diagnostic techniques that fall in this category, are: Vibration monitoring, oil metal debris concentration, incoming air debris concentration, etc. The current work is based on blade – usage based on lifing. Abdullahi (Abdullahi O. Abu et. al, 2014) gives a thorough insight on such methods. Prognosis on the other hand, is the process of analysing data, in order to acquire knowledge about a certain state that comes in force during the future. The main difference with diagnosis is that the state is not currently valid, as it is in the case of diagnosis, and therefore one does not have the option to valid his result in statu nascendi. For the case of gas turbine engines, all the above-mentioned methodologies to conduct a diagnosis could be projected to the future to prognose the future engine state. The ultimate knowledge is being sought when gas turbine engine prognostics are applied, is to define the point in future that the engine will become non usable, either due to a catastrophic failure or due to unaffordable operating cost.

The aforementioned prognostic and diagnostic methods, consist the theoretical basis of various methods which support the corresponding engine diagnostic and prognostic tools. Such tools, may use more than one method in a complementary manner to produce more reliable output. Then, those computational tools are turned into algorithms which equip internal diagnostic modules accompanying the engine which include all the necessary software and hardware components, taking as input engine operating information and providing the user directly with the knowledge of diagnostic or/and prognostic nature. Those EHM modules used to be operating off – board keeping just the sensors and the data recorders on – board. Module architectures are gradually shifting towards more and more onboard features.

The current study focuses on gas turbine lifing, targeting in specific, among all engine LLP, the first stage of turbine rotor, for the reasons explained in the introductory section. There are three main life consuming mechanisms for blades: Corrosion, LCF and creep and potential interactions between them. Regarding creep failure mechanism, most of the life estimation methods are related to the Larson Miller parameter method. The later requires as an input the blade thermomechanical loading history. Sanaye (Sepehr Sanaye et. al, 2020) give in their introduction a good review of recent relevant research. Researchers, differentiate themselves, in the way blade thermomechanical loading is calculated and also regarding ways engine recorded operating history is taken into account. Regarding LCF there are several lifing approaches which are based on material’s theory. A relevant categorization is given by Christ (Christ HJJA et al. 2003). In the current research, given the fact that the total number of cycles are calculated by the manufacturer, we are only confined in counting the loading cycles. The most commonly used method for cycle counting is the rainflow method, with several variants proposed. Chachurski (R. Chachurski et al., 2011) give a good literature review on LCF cycle counting.

3.0 AIRCRAFT – POWERPLANT DESCRIPTION

The current comparative study will be conducted on the (VIP) Embraer-135LR and Erieye EMB-145 AEW&C versions of the same aircraft, powered by the RR AE 3007A1P turbofan engine. Both aircraft are operated by the HAF, the first as a VIP passenger civil aircraft used mainly to cover government transportation needs and the second for missions as intended by its role.

Figure 1: HAF VIP EMB-135 LR [13]

The Rolls-Royce AE 3007A is a two shaft, turbofan engine. The low-pressure spool connects the single stage fan with the 3-stage LPT and the high-pressure spool links the 14-stage HPC to the 2-stage HPT. It has an annular combustion chamber and also a forced core-to-bypass mixer at the engine exhaust area.

3.0 ENGINE MODEL

Two typical aircraft missions were considered. Missions were designed by pilots and engine ratings were picked out of a few, specific flight record files. Those files belonged to two specific aircraft and recordings spanned over a period of 6 months, in order to minimize uncertainty related to aircraft and engine variability and also uncertainty related to engine aging. Values were picked from the listings based on flight altitude, Power Lever Angle (PLA) angle and flight Mach number. The reason for examining two mock missions is first, to avoid complex procedures regarding permission for publication and secondly, and most importantly the missions needed to be as representative as possible of the aircraft usage profile and the best way to achieve that other than analysing all recorded missions and define a median, is to take advantage of the pilots experience. The engine recorder tracks rotational speeds (needed for the stress calculation) and inter turbine gas temperatures. For the proper blade temperature calculation however, the compressor outlet temperature (acts as a blade coolant) and turbine inlet temperatures are also needed. Instead of a simple 1-D hand calculation, the GasTurb V10 software was incorporated to model the engine and calculate more accurately the required temperatures.

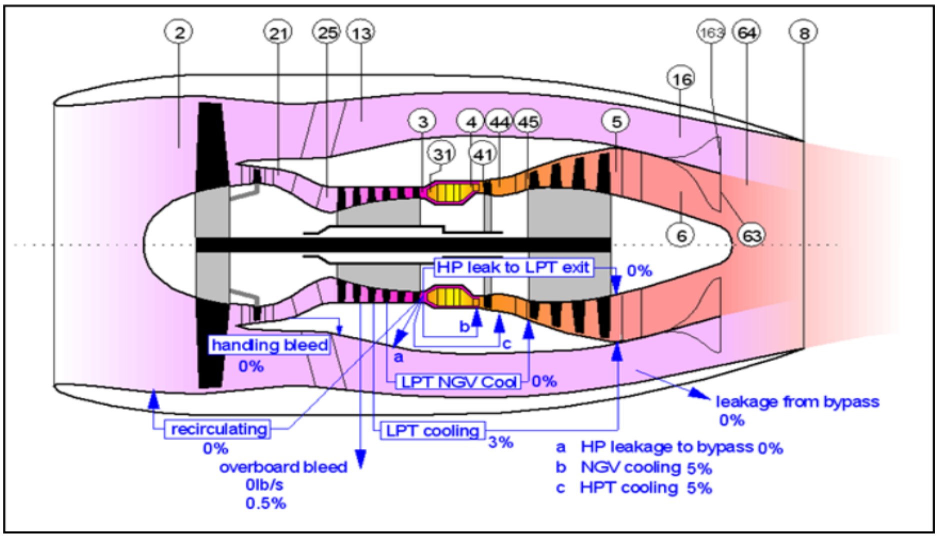

Figure 2: AE 3007 GasTurb Model

All off-design points for both missions were simulated and trimmed accordingly, in terms of assumed values for efficiencies, in order to match the closest possible HP spool rotational speed and interturbine temperature. Table 1 summarizes the efficiency values used for the engine model:

Table 1: Model Isentropic Efficiencies	
LPC isentropic efficiency	0.82
HPC isentropic efficiency	0.79
LPT isentropic efficiency	0.87
HP Spool mechanical efficiency	0.99
LP Spool mechanical efficiency	0.99

4.0 MISSION DEFINITION

Aircraft Erieye EMB-145 AEW&C is an air command platform, able to support air and naval military operations. The basic flight pattern of this aircraft after having climbed to its operating height, is to scan a certain area doing repeating straight cruise legs interrupted by close turns. During climb there is a maximum climb rate limitation due to the antenna structural limit. Other limitations during flight are related to the aircraft AOA and the optimum antenna operation. Table 2 summarizes typical settings for EMB-145 flight legs that can be encountered during a mission.

Table 2: EMB -145 Typical PLA settings

Flight Phase	Maneuver	PLA angle [^{0}]
Take - Off	Taxiing	IDLE 22 – 28
Take - Off	Accelerate – Take off	MAX 90 - 100
Climb	Ascend/Departure IFR	72 - 78
Cruise	Patrol	28 - 72
Cruise	Close turns	60 - 90
Cruise	Descend	IDLE 22 - 28
Cruise	Landing	22 - 28
Landing	Reverse thrust	0- 22
Landing	Taxiing	IDLE 22 – 28

Aircraft EMB-135 LR (VIP) is used as a transporter with maximum passenger capacity of 32 persons. PLA settings for flight legs that can be encountered during a mission, are summarized in Table 3. Main differences with the *Erieye* version are the following:

- It carries no radar which makes it lighter and needing less power for a certain manoeuvre.
- It has no specific (antenna) structural limitations, therefore climb rate does not need to be controlled.
- It executes straight cruise legs from Point A to Point B without being interrupted by repeating turns.

Table 3: EMB -145 Typical PLA settings

Flight Leg	Maneuver	PLA angle [^{0}]
Take - Off	Taxiing	IDLE 22 – 28
Take - Off	Accelerate – Take off	MAX 90 - 100
Climb	Ascend/Departure IFR	72 - 78
Cruise	Patrol	28 - 72
Cruise	Descend	IDLE 22 - 28
Cruise	Landing	22 - 28
Landing	Reverse thrust	0- 22
Landing	Taxiing	IDLE 22 – 28

5.0 LOW CYCLE FATIGUE AND CREEP CALCULATIONS

5.1 LOW CYCLE FATIGUE COUNTING

The engine, as operated by the HAF, does not have an LCF cycle counter installed. An overly broad approach is to count one cycle each time the engine completes a full start – stop cycle. However for this study that would be an oversimplification since it is known that when flying the -145 aircraft version, there are much more throttle adjustments that need to be done. Consequently, the rainflow cycle counting method as applied in (Templalexis at al. 2020) and in (M. Musallam et al. 2012) was applied to the High Pressure (HP) spool, in order to have a more accurate recording of the engine cycles. The stress as a parameter was substituted by the PLA, which is constantly recorded during flight and it is directly proportional to the stress level developed during operation. Half and full cycles are counted. Regarding stress only normal components were taken into account. Under the aforementioned assumptions, the number of cycles counted would be the same regardless of the *load handle* considered (PLA or Stress). PLA was preferred because it is a direct output from the flight recorder. Figures 3 and 4 demonstrate the PLA time history for the two flights addressed.

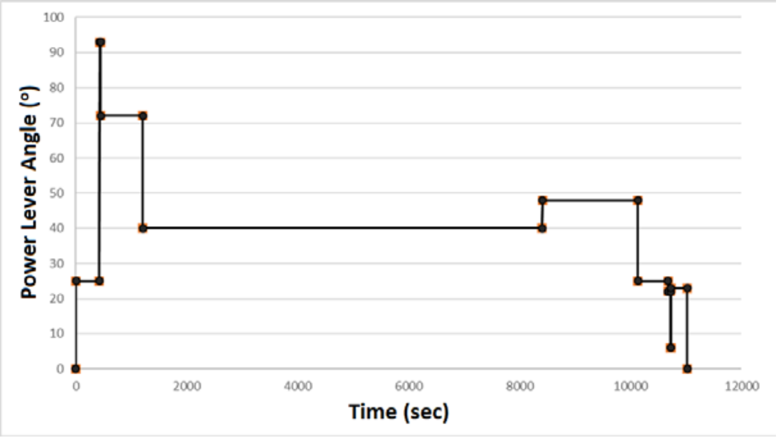

Figure 3: PLA History for EMB-135

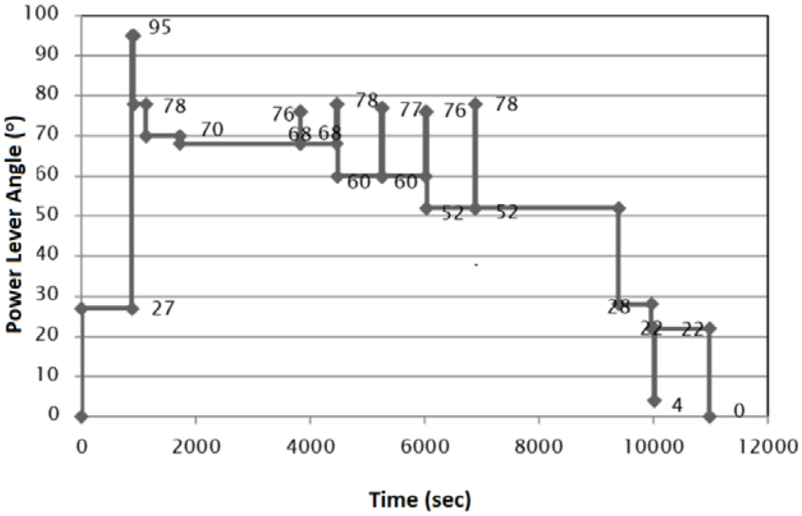

Figure 4: PLA History for EMB-145

5.2 CREEP CALCULATION

Creep damage is related to the level of thermomechanical loading it is subjected. The method that is followed to determine the life consumption due to creep, is the Larson - Miller parameter method (Larson Frank et al. 1952). According to this method the creep life fraction is determined based on the stress and temperature levels the blade operates. Life fraction consumed during the time spent at a certain operating condition is calculated from Equation (1):

$$LFi = \frac{t_i}{t_{f,i}} \tag{1}$$

Where, the time-to-fraction (t_f) given to the denominator is calculated from Equation (2), as follows:

$$t_f = 10^{\left(\frac{10^3 LMP}{T_b} - 20\right)} \tag{2}$$

the numerator expresses the time spent at a certain operating condition.

Equation 2 needs as inputs, the LMP value as well as the blade metal temperature (T_b). The blade material used for the turbine rotor blades of the AE3007A engine, is the CMXS 4. For a certain stress level, the LMP can be read from the material master curve shown on Figure 5.

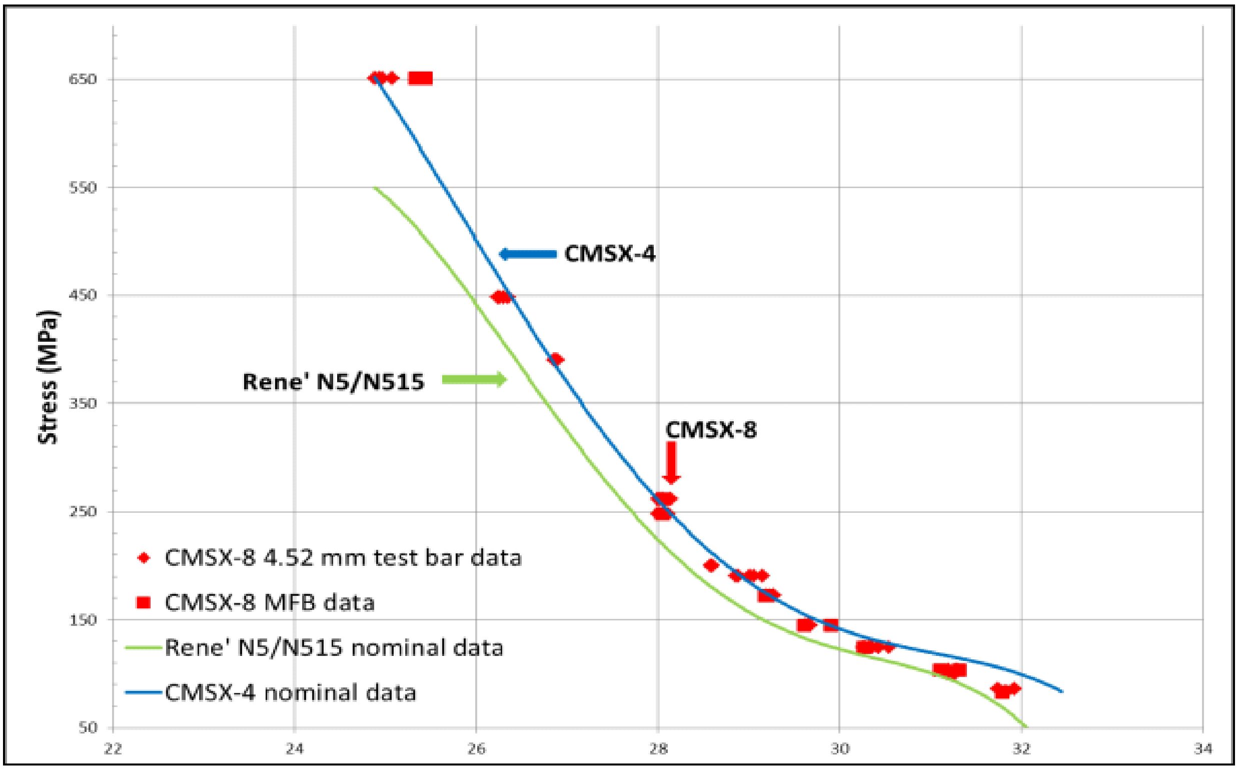

Figure 5: CMSX LMP master curve. (Wahl et al. 2014)

Only the normal stress component is accounted, the one due to the centrifugal force. Additional normal stress components, appearing due to blade bending, are neglected. Stress is calculated at blade roots, the most critical section along the blade span. Equation 3 expresses the normal stress due to the centrifugal force applied to the blade of mass mb rotating at a speed ω (rad/s). The geometrical parameters needed for the calculation were the cross-sectional area at blade root and the distance of the blade root section from the axis of symmetry, values that were directly measured on the engine. The blade was weighted to determine its mass.

$$\sigma_{CF} = \frac{m_b * \omega^2 * h_{CG}}{A} \tag{3}$$

Finally, blade temperature is needed to determine the time-to-fraction based on Equation1is calculated from Equation 4

$$T_b = T_{04} - CEFF * (T_{04} - CT) \tag{4}$$

the gas temperature (T_{04}) at the exit of the combustion chamber, is calculated running the GasTurb engine model. The cooling medium is air bled from compressor exit. Its temperature (CT) is a direct output from the engine model, since it equals to the gas temperature at the exit of the compressor. The cooling efficiency (CEFF) for the engine model was considered equal to 50%, a typical value for such a cooling system.

6.0 LIFE CONSUMPTION

The methodology for the (HPT) blade lifing is presented in (Templalexis et al., 2020). A brief outline is also given here. The total life consumption (TLF) is computed by summing the life fraction components attributed to LCF (LCFLF) and to creep (ΣCLF) according to the Equation 5.

$$TLF = \Sigma CLF + LCFLF \tag{5}$$

It should be mentioned that Equation 5 is applied in the frame of the current study, in order to compare the engine loading for the two missions examined. Regarding engine maintenance, a flag shall rise when any of these life fractions exceeds 100% due to creep or LCF. Moreover, the interaction between the two failure mechanisms is also neglected.

The first term on the Right Hand Side (RHS), expresses the total life consumed during a mission, attributed to creep. During the flight, Equation 6

$$\Sigma CLF = \sum_{i=1}^{n} LF_i \tag{6}$$

sums up the i^{th} fractions of creep Life Fraction (LF_i) consumed during the n – flight legs.

The second term on the RHS of Equation 5 expresses the life fraction consumed due to LCF (LCFLF) defined in Equation 7 where the number of Total Accumulated Cycles (TAC) during a flight is divided by the number of Total Accumulated Cycles would occur in the Time period Between two Overhauls, (TAC_{TBO}) which for this case equals to 2400 cycles.

$$LCFLF = \frac{TAC}{TAC_{TBO}} \tag{7}$$

7.0 RESULTS

7.1 Low Cycle Fatigue

The following number of cycles were counted. For a typical EMR135 mission 10 half cycles, equal to 5 full cycles were accumulated. For a typical EMR145 mission 12 half cycles and 4 full cycles were recorded, which sum up to a total of 10 full cycles.

The corresponding life fractions consumed are:

$$LCFLF = \frac{TAC_{135}}{TAC_{TBO}} = \frac{5}{2400} = 0{,}00208 \tag{8}$$

$$LCFLF = \frac{TAC_{145}}{TAC_{TBO}} = \frac{10}{2400} = 0{,}004166 \tag{9}$$

Regarding creep life consumption, tables 6 and 7 summarise the corresponding life fractions, whereas tables 4 and 5 the values of the main parameters which led to those results.

Table 4: EMB -135 mission creep main results

Flight Phase	Climb	Cruise	Descend
Mach Number	0,47	0,59	0,64
N2 [rpm]	11.836,8	9.370,8	3.616,8
Strain σ [MPa]	180,7	87,1	7,5
LMP Parameter	29,27	30,3	33,9
T_{π} [K]	1.075,49	960,48	811,61

Table 5: EMB -145 mission creep main results

Flight Phase	Climb	Decreased Climb	Cruise	Close Turn	Descent
Mach Number	0,42	0,38	0,5	0,44	0,57
N2 [rpm]	12.823,2	11.836,8	9.864	12.494,4	4.603,2
Strain σ [MPa]	212	181	125	202	27
LMP Parameter	29	29,3	30,4	28,7	33,1
T_{π} [K]	1.177,31	1.069,21	957,86	1.141,09	827,20

The corresponding life fractions were:

Table 6: EMB – 135/145 corresponding life fractions

$\Sigma CLF_{145} = \sum_{i=1}^{n} LF_i$	$0.59\ x\ 10^{-4}$
$\Sigma CLF_{145} = \sum_{i=1}^{n} LF_i$	$0.519\ x\ 10^{-2}$

Consequently, total life fractions for missions of the EMR135 and EMR145 were:

Table 7: EMB – 135/145 total life fractions for missions

TLF_{135}	$\Sigma CLF_{135} + LCFLF_{135}$	$2.1\ x\ 10^{-3}$
TLF_{145}	$\Sigma CLF_{145} + LCFLF_{145}$	$9.3\ x\ 10^{-3}$

8.0 CONCLUSIONS

The engine life consumption of two Embraer aircraft variants was studied. Two typical missions were constructed based on engine recorded data and pilot experience on the aircraft type. According to the results, loading due to LCF is double for the case of the EMB-145 variant. Life consumption due to creep is much higher, which is expected due to the higher on average, Power Lever Angle (PLA) angles applied. One could practically assume that life consumption due to creep for the EMB-135 usage profile is almost negligible compared to the rest of the life fractions. The study also shows that the engine, as an EMB-145 aircraft propulsion system, has to be closely monitored because of the increased life consumption rate it experiences on that frame. In case the engine has the same maintenance schedule for both aircraft, then a more detailed life consumption study would be useful in order to find out how much margin is left to the EMB 135 critical components before they are replaced.

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