FATIGUE LIFE TIME PREDICTION OF POAF EPSILON TB-30 AIRCRAFT - PART I: IMPLEMENTATION OF DIFERENT CYCLE COUNTING METHODS TO PREDICT THE ACCUMULATED DAMAGE

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ABSTRACT

The prediction of fatigue lifetime can be calculated by analyzing the accumulated damage of the aircraft structure through Miner's rule and vertical acceleration spectra.
Two different cycle counting methods were used to analyze the vertical acceleration signal which was recorded during 72 flight hours. The first method was the rainflow counting method and the second one the level cross counting method, which is the method similar to the one used by the Portuguese Air Force (PoAF).
The results of these two counting methods were compared with the spectrum used by Epsilon manufacturer. Once the spectra were obtained, the damage was also calculated using two methods: the method that considers the influence of the mean stress and the method in which the damage is calculated according to the trapezoid rule. At the end all the spectra were used to calculate the damage through these two methods.
The main conclusion was that the operation of the PoAF Epsilon aircraft is more severe than the reference used by the manufacturer, and consequently the lifetime predicted for the aircraft should be 12 % lower than the life defined by the manufacturer.

KEY WORDS: fatigue, spectrum, damage, vertical acceleration, cycle counting methods

1. INTRODUCTION

In order to predict the fatigue lifetime of the aircraft, the manufacturer of Epsilon carried out a real scale fatigue test at the Centre d'Essais Aeronautique de Toulouse (CEAT). During these tests the manufacturer realized that the aircraft lifetime is determined by the fracture of the second bulkhead beam, which occurred after 89458 simulated flight hours (FH) [1]. In this test the manufacturer used a spectrum that was considered characteristic of the typical aircraft operation.
In order to define the secured fatigue lifetime of operation for the PoAF, one of the squadron's aircraft was previously instrumented to measure and record vertical acceleration and local stress in critical areas. The objective of this study was analyse the collected data through two different counting methods and two different ways of assessing the damage.
Finally, the objective is to compare the PoAF damage with the manufacturer's damage in order to predict the lifetime of PoAF aircraft, because the spectrum of vertical acceleration of the manufacturer is different from the PoAF one.

2. FATIGUE CONCEPTS

According to ASTM [2] the fatigue phenomenon is related to dynamics solicitations, which structurally and permanently changes the material in a specific location where cracks will appear. The process involves 4 phases: the nucleation of the crack, the microscopic growing of the crack, the propagation phase, and finally the rupture (fracture) of the material.

2.1 Parameters that influence fatigue

There are several parameters that influence the fatigue behaviour of the material:

- The surface finishing of an aircraft component influences the fatigue behavior. Better surface finishing increases fatigue resistance of materials and the crack initiation is more difficult.
- The dimensions of the component are important because bigger components mean bigger volume and area, so more surface imperfections could occur, thus originating cracks.
- The mean stress increases the ultimate fatigue strength in S-N curve. The Soderberg and Goodman expression are used to count the influence of the mean stress. In this paper it was used the Goodman law according to expression (1), [3].

$$\frac{\sigma_a}{\sigma_{f0}} + \frac{\sigma_m}{\sigma_r} = 1 \qquad (1)$$

- Usually, fatigue crack begins in areas with a high stress concentration factor, because the fatigue strength in these areas is lower.
- The environment of operations influences the fatigue behaviour in a significant way. If the component operates in a wetland area containing salt water, besides the dynamics loadings the component will be attacked by a chemical process which degrades the material (stress corrosion) causing superficial cracks. Another important environment factor is the temperature, which can cause thermal stress in the material.

2.2 Aircraft dynamics solicitation

The structure of an aircraft in his typical operation has to resist to different dynamics loadings that change during the flight. There are 4 phases in an aircraft flight with different loadings: the taxiing, in which the aircraft is on the ground, the take-off, the mission and finally the landing. In this paper the information available is related to 50 flights, which means approximately 72 flight hours. Those numbers were chosen because they can illustrate the basic training of a student pilot.

3. CYCLE COUNTING METHODS

The counting methods are used to count the number of cycles of vertical acceleration signals during flights in order to predict the accumulated damage of the structure. Two different kinds of cycle counting methods exists [4,5,6]: methods that use one single parameter and methods that use two parameters. In this paper the methods used were the level cross counting method and the rainflow method. The first one is a single parameter method that counts the number of times the signal crosses specific levels (see figure 1), the method is similar to the one used by the PoAF to count cycles in this aircraft so it is referred as FAP Counting (CFAP).

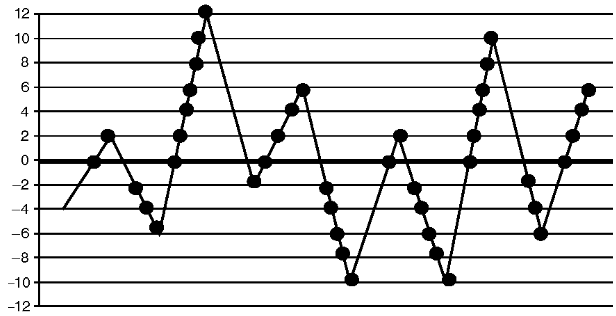

Figure 1 -Level cross counting method

The second one is also quite commonly used in fatigue studies. The computational implementation of this method begins with the analyses of the signal, and then the highest or the lowest peak is chosen.
The new signal will start at this peak and then the distances between the 3 sequential points are analyzed according to figure 2. In this paper this method is refereed as Rainflow Counting (CRAINFLOW).

- If $\Delta S_1 > \Delta S_2$ the cycle is not count;
- If $\Delta S_1 \leq \Delta S_2$ it is count one cycle. The maximum, minimum and mean values of the cycle are calculated;

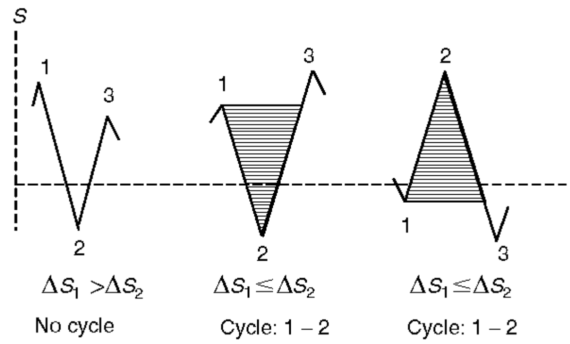

Figure 2 - Computational implementation of the rainflow method

The results of these two different methods that were implemented computationally were compared to the spectrum that the manufacturer used to predict the lifetime of the Epsilon aircraft.
However, to make the comparison with the manufacturer spectrum possible, the spectra that were obtained with each method had to be reorganized.
After that it was used a transfer function determined experimentally by [7] to know the stress magnitude for each cycle based. Before the implementation of both counting methods the signal of the vertical acceleration was analyzed by a range factor to avoid noise or undesirable variations, [8]. The influence of the range factor means a different number of cycles that could be counted. So it was necessary to study the influence of the range factor in the determination of the spectra.

4. DAMAGE CALCULATION

The lifetime of a component is defined taking into account its cycles of operation and the S-N curve that characterizes the material's resistance to fatigue, however in cases of variable amplitude loading the S-N curves can not be used directly.

Therefore, there are several methods to associate the variable amplitude loadings to the component lifetime by calculating the accumulated damage. The main methods are: the linear law of cumulative damage, the hypothesis of non-linear damage and the continuous mechanics damage [9]. The simplest and most used is the first method, the law of Palmgren and Miner.

Once the number of cycles was calculated it was possible to determine the damage that these cycles induced in the structure. In this paper the Miner's rule was used according to expression (2). Where n is the number of cycles that were counted at a specific stress and N_r is the number of cycles which could be sustained by the material for previous stress until the material failed through fatigue. Consequently, in order to know N_r it was necessary to determine de S-N curve of the material Alloy 2024-T351, and so axial tension tests and axial fatigue tests were performed. The first one was done to determine the material properties and to guess the first stress to use in the fatigue tests.

$$D = \sum \frac{n}{N_r} \leq 1 \qquad (2)$$

4.1 FAP DAMAGE (DFAP)

This methods was implemented according to [10] to the spectrum that comes from CRAINFLOW, CFAP and the manufacturer. To implement this method the following steps were followed:

- Determination by the S-N curve the number of cycles that the material can withstand before a fracture at maximum stress occurs;
- With the expression (2) by making a variable change and using the trapezium rule the total damage can be calculated by the expression (3).

$$\begin{aligned} D &= \int \frac{dN}{N_r} = 2.3\int_0^5 \frac{N}{N_r} dy \\ &= \frac{2.3 \times 0.25}{2} \sum_{i=o}^{19} \left(\frac{10^{0.25i}}{N_r} + \frac{10^{0.25(i+1)}}{N_r} \right) \end{aligned} \qquad (3)$$

4.2 MEAN STRESS DAMAGE (DTM)

This method was called Mean Stress Damage (DTM) and uses the spectra provided by the manufacturer, CRAINFLOW and CFAP in order to make possible the comparison.

The determination of the accumulate damage it was done by using expression (4) which comes from the Goodman expression but only depends on σ_{max} (maximum stress), σ_{f0} (limit fatigue stress), R (stress ratio) and σ_r (fracture stress):

$$\frac{\sigma_a}{\sigma_{f0}} + \frac{\sigma_m}{\sigma_r} = 1 \Rightarrow \sigma_{\max} \left[\frac{1-R}{2\sigma_{f0}} + \frac{1+R}{2\sigma_r} \right] = 1 \qquad (4)$$

This new expression is very useful because the counted cycles didn't have the same value of R that was used in the experimental test so that it's necessary consider this difference.

The value of R is calculated using σ_{max} and σ_m (mean stress) values. After the application of expressions (3) and using the S-N curve a new value of N_r is calculated. Now the damage can be obtained using the Miner rule, where the n takes the value of the number of cycles with the same magnitude.

5. EXPERIMENTAL TESTS TO DETERMINE THE PROPERTIES OF ALLOY 2024 T-351

To determine the properties of Alloy 2024-T351 specific specimens were created to use in the test machines according to ASTM 466-96 [11].

5.1 Tension test

The tension test was done in 2 specimens with the INSTRON machine model 3369 at Instituto Superior Técnico (IST), whose maximum load capacity is 50 KN. The results obtained are shown in table 1.

Table 1- Tension tests data

	Specimen		
	1	2	Average
E [GPa]	75.15	80.56	77.85
σ_{yield} [MPa]	381.11	395.63	388.37
σ_{UTS} [MPa]	462.24	476.38	469.31

According to FAA [12] the properties obtained in this paper are slightly bigger (for the Young module there is a discrepancy of 7.5 % and for the Yielding stress of 16 %). This test was important because, besides the determination of the properties of the materials in the direction of lamination, it tells the average stress that should be used in fatigue tests.

5.2 Fatigue test

To characterize the material behaviour due to fatigue loading 8 specimens were used, 2 for each stress magnitude. The tests were performed in INSTRON machine model 1342 of the Instituto Politécnico de Setúbal whose capacity of load is 250 KN. The results are shown in figure 3. These tests were performed with stress ration of R=0 and K_t=0 (stress concentration factor).

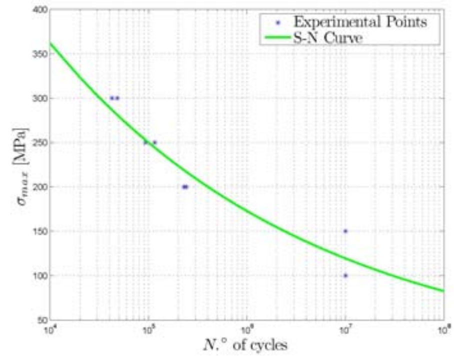

Figure 3- S-N curve of the Alloy 2024-T351 (laminated direction)

6. COMPUTATIONAL RESULTS

6.1 Results of the counting methods

The counting methods were implemented computationally using the MATLAB® programme. As stated at the beginning, different ranges were used to prepare the signal for each counting method. The results obtained with the CRAINFLOW and CFAP for the range values of 0, 0.3, 0.5, 0.7 and 1.2 are shown in figure 4,5,6,7 and 8.

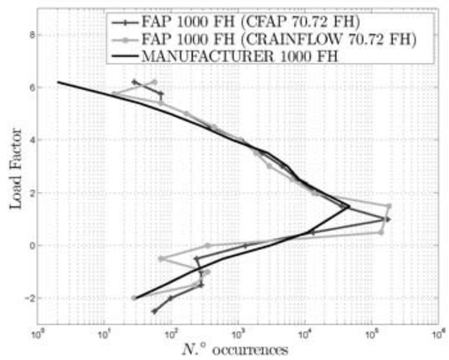

Figure 4 - CFAP and CRAINFLOW spectra (range=0)

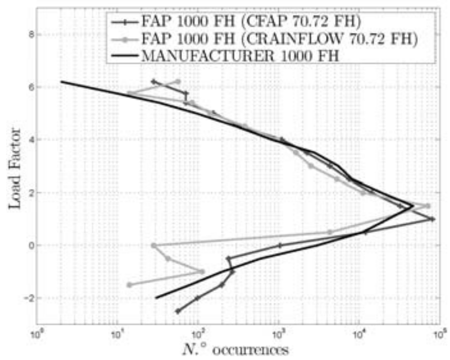

Figure 5- CFAP and CRAINFLOW spectra (range=0.3)

6.2 Results of the damage calculation

Once the spectra of the PoAF squadron were obtained, the damage was calculated by 2 different methods: the DFAP and DTM. Results are shown in figures 9 and 10.

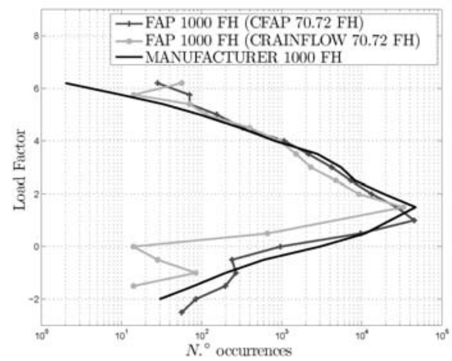

Figure 6 -CFAP and CRAINFLOW spectra (range=0.5)

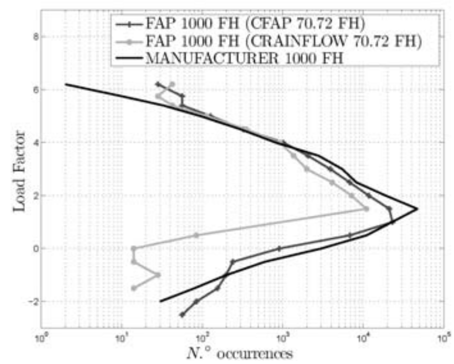

Figure 7 -CFAP and CRAINFLOW spectra (range=0.7)

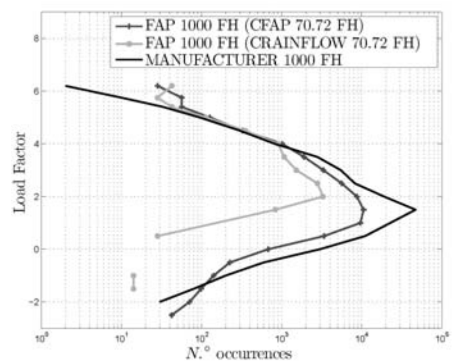

Figure 8 -CFAP and CRAINFLOW spectra (range=1.2)

7. ANALYSES AND DISCUSSION OF THE RESULTS

7.1 Counting methods

By the analysis of figures 4 to 8 the values of range used to obtain a reasonable PoAF spectrum are: 0 and 0.3.

For these values the results obtained with the rainflow counting method (CRAINFLOW) are very similar to the results that are obtained with the level cross counting method (CFAP). When the range value increases, the CRAINFLOW method is more affected than the CFAP. According to figure 8 the cycles of lowest magnitude are not accounted, so the occurrences are lowest for vertical acceleration events smaller than 2, because when the highest values of range are being used the smallest values of vertical acceleration are not taken in consideration.

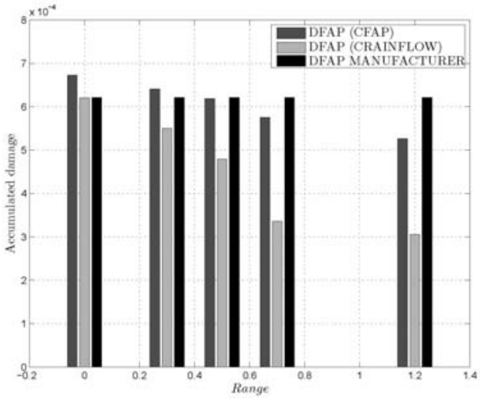

Figure 9- Damage calculated with the DFAP

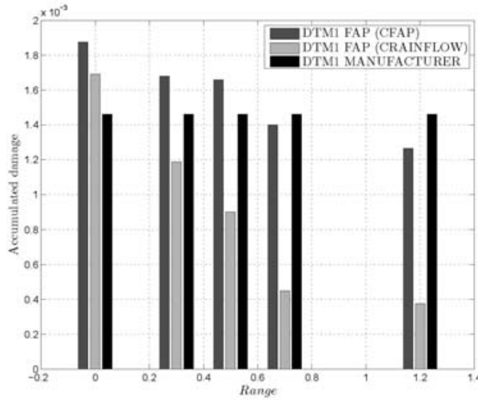

Figure 10 - Damage calculated with the DTM

Table 2-Final results for the TVF obtained from the accumulated damage

Method	range	Spectra	TVF $_{PoAF}$ [FH]	TVF $_{PoAF}$ Final [FH][1]	Difference [%][2]
DFAP	0	CFAP	82666	27553	7.60
DFAP	0.3	CFAP	86786	28928	2.99
DTM	0	CFAP	69628	23208	22.17
DTM	0.3	CFAP	77773	25923	13.06
DTM	0.5	CFAP	78706	26236	12.02
DTM	0	CRAINFLOW	77240	25745	13.7
Average			78799	**26266**	**11.92**

In fact, if at the beginning a level of omission for vertical acceleration values was defined, the small values of vertical acceleration could be rejected without any problem. But in this paper an omission level was not used.

On the analysis of severity it was assumed the hypothesis that higher occurrences of higher load factors can cause more damage than a smaller number of occurrences of lower load factors. According to this hypothesis the PoAF spectra are more severe than the manufacturer, since the number of occurrences for higher values of load factors is slightly higher than the manufacturer; this is clearly visible in figure 4 and 5.

7.2 Damage calculation

From the results obtained in the counting methods is expected that the damage of the PoAF spectrum will be slightly higher than the manufacturer. In order to compare the damage value that was obtained with the different methods, the results were represented in figures 9 and 10.
From the analysis of figure 9 it is for the CFAP with range values of 0 and 0.3 that the PoAF damage is higher than the manufacturer damage. As was stated at the beginning of this chapter the PoAF damage will be slightly bigger that the manufacturer's, so that the CRAINFLOW spectrum cannot be used to calculate the fatigue lifetime of the aircraft because in all cases the value of the damage is not higher than the manufacturer.

When the damage is calculated with the DTM (figure 10) the spectrum obtained with the CRAINFLOW method for a range of 0 can be used to analyse the fatigue lifetime of the aircraft. Because the damage in that case is slightly higher than the damage calculated with the spectrum of the manufacturer. The spectrum obtained with the CFAP for a range of 0 to 0.5 can also be used to predict the fatigue lifetime. For a range values higher than 0.5 the CFAP and the CRAINFLOW cannot be used because the damage is smaller than the manufacturer's.

7.3 Prediction of Epsilon aircraft lifetime

The manufacturer of the Epsilon aircraft due to a real test done at the CEAT realized that the fatigue life of the aircraft (TVF) was 89458 FH. However it was use a safety factor (CS) of 3 that establish the 29819 FH for the TVF [1].
In this paper the TVF of the Epsilon aircraft was calculated based on the damage values of the methods that provided values of damage slightly bigger than the manufacturer (figures 9 and 10). For example, in the CFAP spectrum for range 0.3 was obtained a $D_{PoAF} = 6.405 \times 10^{-4}$ and a $D_{Manufacturer} = 6.2136 \times 10^{-4}$. The calculation method used was the following:

$$\begin{cases} D_{\text{Manufacturer 1000 FH}} = 6.2136 \times 10^{-4} \\ TVF = 89458 \text{ FH} \end{cases}$$

$$D_{\text{Manufacturer 89458 FH}} = D_{\text{Manufacturer 1000 FH}} \times 89{,}458 = 0.055586$$

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[1] It was used a safety factor (CS) of 3 defined by the manufacturer [1]

2 Relative difference compared to the damage given by the manufacturer spectrum

For the manufacture the ruin of the structure does not happen when the damage is 1, as the Miner's law says, but when the accumulated damage is 0.055586. So it's assumed that the structure of the Portuguese aircraft will fail when the accumulated damage $D_{\mathrm{PoAF} \setminus \mathrm{TVF} \setminus \mathrm{FH}}$ reaches the value of 0.055586. So assuming that the total accumulated damage for the failure of the manufacture it's the same for the Portuguese aircraft it's possible to predict the fatigue life for the Portuguese aircraft:

$$\begin{cases} D_{\mathrm{PoAF\ 1000\,FH}} = 6.405\times 10^{-4} \\ TVF_{PoAF} = ?\,\mathrm{FH} \end{cases}$$

$$D_{\mathrm{PoAF\,TVF\,FH}} = D_{\mathrm{PoAF\,1000\,FH}} \times \frac{TVF_{PoAF}}{1000}$$

$$TVF_{PoAF} = 86786$$

The manufacturer to determine the TVF, which should be taken as a reference by the operators of Epsilon, was used a safety factor of 3. The final TVF considered more reasonable, obtained with the method illustrated above, are shown in table 2. The TVF determined by the manufacturer was 29800 FH.
According to table 2 the fatigue life time of PoAF aircraft should be 11.92 % less than the life time predicted by the manufacturer. For instance this fact it's in conformity with figure 4 where the PoAF spectrum are severe than the spectra type used by the manufacturer.

8. SUMMARY

After this work the main conclusions are:

- According to the counting methods the results obtained with the rainflow counting method (CRAINFLOW) and the crossing level counting method (CFAP) are very similar;
- The best spectrum to predict the fatigue life of a structure are the spectrum obtained by CRAINFLOW and the CFAP methods for smaller values of range (0 or 0.3);
- The damage values obtained with the DTM method are higher than the results of the DFAP, consequence of the nature of the process;
- The load spectrum of Portuguese Epsilon aircraft is more severe that the spectrum adopted as a reference by the manufacturer. Therefore the fatigue life time of the Portuguese Epsilon TB-30 should be 26000 FH, 12% less than the fatigue life time that was determinate by the manufacturer.

9. RECOMMENDATIONS

In this work the prediction of the fatigue life time was based on the damage accumulation and the Miner's rule. In the future this study should be done assuming the propagation of the crack. This new study will give the adequate inspection periodicity of the critical zone and it will also predict the fatigue life using a different method.

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