# Scheduled and SHM Structural Airframe Maintenance Applications Using a New Probabilistic Model

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# SCHEDULED AND SHM STRUCTURAL AIRFRAME MAINTENANCE APPLICATIONS USING A NEW PROBABILISTIC MODEL

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## ABSTRACT

This paper focuses on aircraft structure maintenance. A general mathematical framework based on a probabilistic analytical model was developed to provide the average number of fuselage panels to be replaced after any number of cycles and over the aircraft lifetime under fatigue damage failure [1]. This paper proposes a study to explore structure maintenance strategies using this analytical model. Both scheduled maintenance and condition-based maintenance using SHM are considered for different aircrafts with different lifetimes and timetable inspections. In each case, the aircraft lifecycle cost is evaluated in terms of average number of panels changed. A similar study based on Monte Carlo method is presented in [2]. We studied the results given by this approach considering same maintenance strategies as mentioned above. Because the simulation conditions are not exactly the same, the results obtained using the PAM are a little bit different than the ones obtained by Monte Carlo simulations; indeed, it shows an adequacy. Compared to Monte Carlo method, the analytical model is of a great interest regarding the accuracy because the recurrence formula leads to an exact expression of the average number of fuselage panels to be replaced.

**KEYWORDS :** *probabilistic analytical model, aircraft structure maintenance, condition-based maintenance, structural health monitoring, fatigue damage*

## ACRONYMS

SM: Scheduled maintenance
SHM-CBM: Condition-based maintenance using SHM
PAM: Probabilistic Analytical Model
MC: Monte Carlo method
AMS: Analytical model simulations
MCS: Monte Carlo simulations

## INTRODUCTION

Currently, aircraft maintenance consists in predetermined regular inspections according to manufacturer's instructions. During these scheduled maintenances (SM), engines, non-structural elements and structural airframe are checked and maintained according to a predefined timetable.
Each structural part has predetermined inspection intervals included in the overall inspection schedule of the aircraft and all damages that may possibly threaten the safety of the structure are repaired. In this preventive approach also called damage tolerance approach, structures are designed to withstand small damages and only large damages are repaired. Systematic replacement of predefined equipment is done even if no failure occurs. The maintenance schedule optimization requires a trade-off between reliability and cost. It involves minimizing cost while maintaining the desired level of safety. Frequent inspections may provide structure safety. However, they lead to high cost as it is a conservative approach. Moreover, during the earlier stage of commercial aircraft lifecycle, only a small fraction of aircrafts need to replace fuselage panels.

 

Therefore, frequent scheduled inspections may lead to a wasting of resources by scrapping expensive parts which are still usable. Besides, this time-based inspection approach is only performed on some parts of the structure and not on the whole structure.
More global approach to identify damages in structures has been addressed and the ability to monitor the structure health is become increasingly important. Maintenance philosophies have therefore evolved towards the preventive condition-based maintenance [3,4]. This concept is subordinate to events such as sensor data or parameter indicators giving the real-time status of an equipment. Data and parameters are compared to a predetermined threshold reference value and when an exceeding occurs, it triggers the maintenance before the degradation causes a failure.
Over the last decades, the Structural Health Monitoring (SHM) technique has been widely investigated and the SHM system appeared to be a good tool for condition-based maintenance, especially, to reduce both downtime and maintenance costs. Such a system uses on-board sensors and actuators to detect continuously damages. Airframe structures can also be monitored using this technique and maintenance actions to be followed up are evaluated. Advantage of the SHM system is to provide on-line global damage identification and real-time status at any time.
Our purpose focuses on structure maintenance strategies by considering crack fatigue damage in aircraft fuselage panels. Engine and non-structural maintenance are outside the scope of this paper and only structural maintenance is addressed. Fatigue damage which is one of the most important modes of failure is considered. It occurs during the ground-air-ground cycles leading to repeated pressurization/depressurization cycles and consequently, to repeated loading/unloading cycles. Cracks can therefore appear and propagate in structure panels that may give rise severe failures.
In the context of the SM strategy, safety of structures is ensured by checking for cracks that would cause fatigue failure before the next scheduled maintenance. Inspection intervals are determined such that no crack can grow to critical size before the next inspection. Detected cracks whose sizes reach a predetermined threshold are repaired or replaced. Consequently, safety and lifecycle cost are affected by maintenance intervals and replacement threshold.
In the case of the condition-based maintenance approach, maintenance is requested when a detected crack size exceeds a predefined threshold and grows in the neighbouring of the critical size. The number of maintenance stops is therefore much less than the one of scheduled maintenance and that leads to cost savings. In the SHM-CBM strategy, the SHM system provides data that give real-time informations on the structures status and are used to assess the necessity of maintenance. The basic difference between the SHM-CBM and the SM maintenance strategies is that the first one allows to follow up the structure status at any time as frequently as necessary. According to the monitoring results, maintenance operations are scheduled and corresponding maintenance cost can be evaluated. Savings on lifecycle cost by using such a SHM technique over the SM strategy have been estimated [2].
In [1], a general mathematical framework based on a probabilistic analytical model (PAM abbreviated) was presented in order to simulate the lifecycle of an aircraft and compare different structure maintenance strategies. This PAM model calculates the average number of fuselage panels to be replaced after any cycle and over the aircraft lifetime by using useful analytical recurrent formulas.
This paper proposes a study to explore structure maintenance strategies using PAM. Both scheduled maintenance and condition-based maintenance using SHM are considered for different aircrafts with different lifetimes and timetable inspections. In each case, the aircraft lifecycle cost is evaluated in terms of average number of panels changed or repaired. A similar study based on Monte Carlo (MC) method is presented in [2]. We studied the results given by this approach considering same maintenance strategies as mentioned above. Because the simulation conditions are not exactly the same, the results obtained using the PAM are a little bit different than the ones obtained by Monte Carlo simulations (MCS), indeed, it shows an adequacy. Compared to MC method, the analytical model is of a great interest regarding the accuracy because the recurrence formula leads to an exact expression of the average number of fuselage panels to be replaced.

In this paper, the analytical model PAM is first briefly depicted. In the second section, both scheduled maintenance and condition-based maintenance using SHM system are considered and the results obtained by using PAM are discussed and confronted to MC ones.

## 1 THE PROBABILISTIC MODEL IN BRIEF

The probabilistic analytical model detailed in [1] is based on recurrent formulas which provide the probability to change a fuselage panel at any cycle over the aircraft lifetime. Probabilities are expressed as analytical formulas depending only on both the initial crack size, the crack size with no maintenance from the aircraft entry into service to the considered cycle and the replacement threshold according to the maintenance strategy. Fatigue crack damage is considered. As previously said, repeated loading and unloading during the ground-air-ground cycles can lead crack initiation and propagation. The average number of fuselage panels to be replaced after any cycle over the aircraft lifetime is determined.

The principle of the proposed model consists in considering any maintenance stop number $i$, $i \in IN$. At this stop $i$, either there is no panel changed between the entry into service and stop number $i$, either a panel was changed at one of stops number $j$, $j \in IN$, $1 \le j < i-1$, $i \ge 2$. The last panel change has been at stop $i-1$ and there is no stop between $i$ and $i-1$. Ground-air-ground number of cycles is denoted $n$, $n \in IN$ and the number of cycles from the aircraft entry into service up to maintenance stop number $i$, $i \in IN$, is denoted $n_i$ where the stop number $i$ is such as $1 \le i \le t$, $t$ being the last maintenance stop before the aircraft end of life. Only a single fuselage panel is considered assuming that at the aircraft entry into service, this panel starts with only a single crack damage due to manufacturing process. This initial crack length is represented by a random variable $L_0$. The crack length at cycle $n$ is also a random variable $L_n^*$ to denote the associated random variable to the current crack size with no maintenance from the aircraft entry into service during $n$ cycles. A panel replacement threshold $l_{rep}$ is defined as the crack length from which a panel is replaced or repaired once it is reached, i.e. there is no panel change until $l_{rep}$ is not reached. The probability that there is no panel change at stop number $i$ after $n_i$ cycles is

$$P_{n_i} = P(L_{n_i} < l_{rep}). \quad (1)$$

The analytical model PAM is detailed in [1] and the recurrence formula proof leads to the following property. Let $i \in IN$, $i \ge 2$, be any maintenance stop number and $L_{n_i}^*$ be the crack size at cycle $n_i$ such that no panel has been changed since the aircraft entry into service. The probability that there is no panel change at stop $i$ is, $\forall j \in IN$, $1 \le j < i-1$

$$P_{n_i} = P(L_{n_i}^* < l_{rep}) + \sum_{j=1}^{i-1} P(L_{n_i - n_j}^* < l_{rep})(1 - P_{n_j}). \quad (2)$$

The probability that there is a panel changed at stop number $i$ is therefore $1 - P_{n_i}$. Assuming that the fuselage contains $K \in IN$ panels independent and uncorrelated, the total average number of fuselage panels replaced over the aircraft lifetime can therefore be computed by

$$K \sum_{i=1}^{t} (1 - P_{n_i}). \quad (3)$$

## 2 SIMULATIONS AND RESULTS

Two different maintenance strategies such as scheduled maintenance (SM) and condition-based maintenance using SHM technique (SHM-CBM) have been considered to test the model PAM.

The results are respectively presented in the next sections. A Matlab program was developed to implement such maintenance strategies and assess their cost-effectiveness using the PAM. The approach based on Monte Carlo method proposed in [2] has also been considered. The methodology proposed in this paper consists in testing the PAM in conditions as close as possible to the MCS ones and the results obtained from AMS referred to the ones proposed in paper [2].

## 2.1 Scheduled maintenance strategy

First, the damage tolerance approach, i.e. the scheduled inspections for various aircraft were considered. For each one, a specific timetable inspection is defined specifying the aircraft lifetime, the number of cycles to be done until the first stop in maintenance and the interval between new inspections until the end of the aircraft life. The number of maintenance stops is predefined. Table 1 shows the four cases chosen to be analyzed with corresponding timetables. For instance, the short-range aircraft number 2 undergoes its first maintenance after 20000 cycles and then, a maintenance is performed every 4000 cycles until the end of its life which is 60000 cycles.

Table 1: Timetable scheduled inspections in number of cycles.

| Aircraft | Lifetime | First stop | Interval |
|---|---|---|---|
| 1 | 55000 | 24000 | 6000 |
| 2 | 60000 | 20000 | 4000 |
| 3 | 80000 | 20000 | 5000 |
| 4 | 80000 | 40000 | 5000 |

Aircrafts with smaller lifetimes are not considered because simulations show that the number of panels changed or repaired at every maintenance stop under every threshold is zero. The panel crack size cannot reach the replacement threshold before the aircraft end of life; this means that there is no panel change during the whole life of the aircraft.

On one hand, all AMS are done by considering a fuselage with 500 independent and uncorrelated panels. All panels are of same dimensions and contain a single crack at their centre assumed to be a through-thickness crack in an infinite plate. As the current crack size, the initial crack size $l_0$ is a random variable assumed to follow a lognormal distribution. The well-known Paris law is used to determine how much the crack grows in a given number of cycles $n$

$$\frac{dl}{dn} = C(\Delta K)^m \quad \text{where} \quad \Delta K = A\frac{pr}{t}\sqrt{\pi l} \tag{4}$$

where $l$ is the crack half size, $p$ the cabin pressure differential, $t$ the thickness of fuselage panel, $r$ the fuselage radius and $C$ and $m$ are the Paris law parameters. $\Delta K$ expresses the range of stress intensity factor and $A$ is a correction factor taking into account the fuselage modelling approximation in particular the fact that the panels are finite in size and stiffened. The atmospheric pressure $p$ is assumed to be constant. Parameters $C$ and $m$ are random variables due to manufacturing process. Aluminium alloy 7075-T6 fuselage panels is considered and the corresponding joint distribution of parameters $C$ and $m$ is estimated. This joint distribution corresponds to a parallelogram which represents the admissible value region of $C$ and $m$ considering experimental data points in the region of stable damage propagation [5]. It is shown that *log(C)* and $m$ are correlated with a correlation coefficient of -0.8065. Probabilities of having a specific damage size after a given number of cycles in Equation (2) are computed using the direct integration method described in [2], i.e. $P(L^*_{n_i-n_j} < l_{rep})$ is borrowed from this paper. This method was chosen in order to better stick to conditions of paper [2].

On the other hand, the results given in [2] are obtained in similar simulation conditions except that a fleet of 2000 aircrafts with 500 panels per aircraft is considered. Each panel is also in this case assumed to contain a single crack.

Moreover, the probability of detecting a crack was simulated using the Palmberg equation. The replacement or repair threshold $l_{rep}$ is set to be 6 mm. In order to fit with our simulation conditions, a probability of detection of 1 was considered in the MCS program. But, only one panel is considered in the recurrence process and a mean is obtained under 500 panels assuming that they are independent and uncorrelated. The method is therefore a little bit different than the MCS's one. Several crack replacement thresholds were used and in each case, the probability to change a panel at each predetermined inspection stop and over the aircraft lifetime is calculated. The average number of panels replaced or repaired is therefore determined. Table 2 shows a part of results obtained for a threshold value of 6mm; they are to be confronted to the mean and the standard deviation given by MCS.

Table 2: Scheduled maintenance: Average number of panels replaced.

| Aircraft | Stops | AMS | MCS Mean | MCS Std Dev. |
|---|---|---|---|---|
| 1 | 6 | 5.211 | 4.802 | 2.196 |
| 2 | 10 | 6.598 | 6.112 | 2 .467 |
| 3 | 12 | 31.690 | 30.630 | 5.327 |
| 4 | 8 | 31.690 | 30.500 | 5.320 |

The MCS mean of 6.112 and MCS standard deviation of 2.467 for aircraft number 2 are comparable to the value of the mean 6.6 and the standard deviation of 2.5 in the case of preventive maintenance given in Table 2 in [2]. Our results are a little bit different probably because the probability of detection is not taken into account in the modified MCS program.

Figures 1 to 4 illustrate the average number of panels replaced over the entire life of aircrafts 1, 2, 3 and 4 under different values of the replacement threshold $l_{rep}$ obtained with both the PAM and the MC method. These figures show that results provided by AMS are close enough to MCS ones. The relative error on the results between AMS and MCS for aircrafts 1 and 2 varies from 5.6% to 8.3%. For aircrafts 3 and 4, the relative error is smaller and is around 4%. In all simulation cases, the results provided by AMS are slightly greater than MCS ones. Such results could be expected due to the method which is different as it is explains above. In all cases, the number of panels to be replaced decreases as the predefined threshold increases with both AMS and MCS. Regarding expected the results, this is right. The larger the threshold is, the lesser panels change is. It can be observed that for threshold values smaller than 10mm, the decreasing of the number of panels changed is strong enough when $l_{rep}$ increases. In most cases, there are also larger discrepancies between AMS and MCS. On the contrary, for values greater than 10mm, the number of panels changed slightly decreases as $l_{rep}$ increases and AMS and MCS results are closer. This means that from a threshold of 10mm and for any aircraft, there is a weak effect on the number of panels replaced by increasing the value of $l_{rep}$.

Figures 3 and 4 show close enough results. Maintenance timetables of the two aircrafts only differ by the number of cycles at the first maintenance stop of 20000 (see table 1). One knows that during the early life of commercial aircrafts, the probability that the crack size reaches the predetermined threshold is rather small and panel change is not necessary. For instance, for the short-range aircraft number 2, the first time that a panel crack size exceeds the threshold value occurs after about 40000 cycles. Therefore, there is no effect on the calculation of the probability to change a panel after 20000 cycles or after 40000 cycles and consequently, on the average number of panels to be changed. Therefore, there is no effect on the calculation of the probability to change a panel after 20000 cycles or after 40000 cycles and consequently, on the average number of panels to be changed.

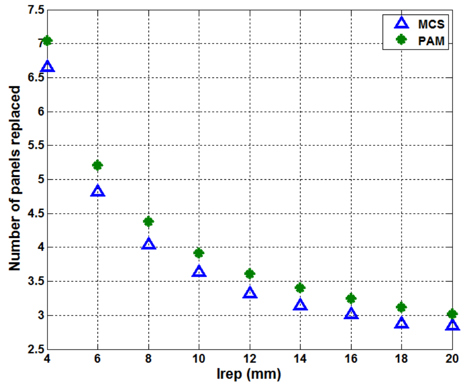

Figure 1: Aircraft 1

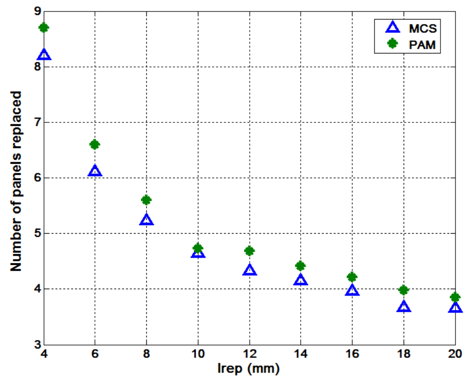

Figure 2: Aircraft 2

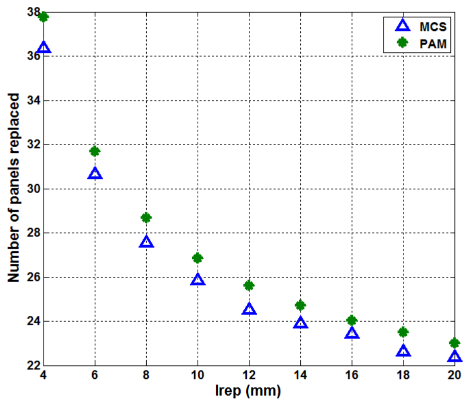

Figure 3: Aircraft 3

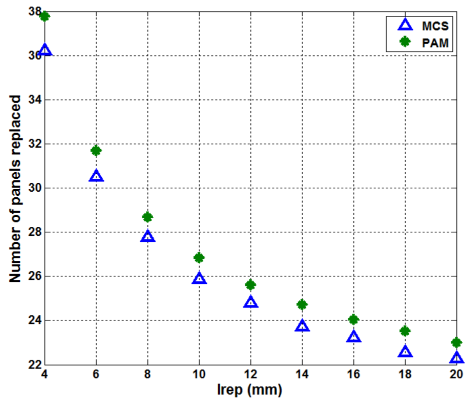

Figure 4: Aircraft 4

Other tracks are currently investigated and other approaches are considered in order to check in a closer way the AMS's conditions. The first one consists in using a Monte Carlo program processing only one aircraft. Another way is to compute probabilities in Equation (2) resting on Monte Carlo simulations; this computation does not use the direct integration method. The analysis of these results are currently under way.

### 2.2 Condition-based maintenance strategy using SHM

Condition-based maintenance strategy using the SHM technique is based on real-time data provided by the SHM system. The damage status of an aircraft structure is evaluated from these data and maintenance can be requested at any time once damage size exceeds a predefined threshold. For instance, a SHM system can provide impedance measurements and a zero imaginary part means that a damage has been detected. The SHM-CBM strategy investigated is similar to the scheduled one except that the damage assessment of the structure is performed by the on-board SHM system.
An aircraft maintenance timetable planes different checks at different times of lifecycles: daily, weekly or monthly until many years. Various operations are performed during these inspections. They may involve quick checks called A-check made overnight in the airline hangar until the complete disassembly of the aircraft during checks that takes place every 5 or 6 years. The aircraft is therefore immobilized during few months. Structure assessment may easily be done during the A-check, basically every 100 cycles until the end of life. This means there are 599 damage assessments. When the SHM-CBM strategy was implemented using the PAM method, the Matlab function which computes the probability that a panel is changed at a given cycle was recalled 599 times. Studies show that during the early life of commercial airplanes, the probability that the damage size propagates greater than the threshold value is rather small. Consequently, there is no need to replace a panel in the early stage of their lifecycle.

In addition, according to simulation results, the first time that there would have panels whose crack length grows greater than the threshold occurs at about 50000$^{th}$ cycles. The reasonable assumption has been deduced that during first 40000 cycles, there is no panel being changed. Therefore, in the AMS process, the first 40000 cycles have been skipped in order to save simulation time. From the 40000$^{th}$ cycle, the structure damage assessment is done every 100 cycles until the aircraft end of life.

Except this point, same methodology is used for AMS as the one described in the previous section. Compared to Table 1, aircrafts number 1, 2 and 3 are considered. We don't mention aircraft 4 because for SHM-CBM strategy, the only relevant information is lifetime and this value is the same for aircrafts 3 and 4.

In this maintenance strategy case, the MCS program used in [2] simulates again a fleet of 2000 aircrafts with 500 panels per aircraft. Two thresholds are considered in order to avoid too frequent immobilization of the aircraft in a near future. But to be able to examine our results with respect to the MCS ones, we set the same value of 6mm to the two thresholds in the MCS program. Again a probability of detection of 1 was set. The first 40000 cycles have not been skipped as for AMS case. The assessment of the structures is done every 100 cycles.

As in the context of the scheduled maintenance, many crack replacement thresholds were used and in each case, the average number of panels to be replaced or repaired have been determined. In Table 3, the results obtained among all simulations for a threshold value of 6mm are shown. They are to be confronted to the mean and the standard deviation given by MCS.

Table 3: SHM-CBM maintenance: Average number of panels to be replaced.

| Aircraft | AMS | MCS Mean | MCS Std Dev. |
|---|---|---|---|
| 1 | 6.16 | 5.78 | 2.2904 |
| 2 | 9.96 | 9.76 | 3.0359 |
| 3 | 41.53 | 40.31 | 6.6466 |

For aircraft number 2, the MCS mean is 9.76 and the MCS standard deviation is 3.0359 while the values of the mean 6.6 and the standard deviation of 2.5 are obtained in the case of Sched-SHM maintenance given in Table 2 in [2]. These differences probably come from the use of the same value of the two thresholds in our modified MCS program while there are two different threshold values in [2]. Moreover, the probability of detection is not taken into account in the modified MCS program.

For aircraft 1, the relative error on the results between AMS and MCS varies from 5.8% to 8.%; for aircraft 2, it varies from 2% to 7.4%; for aircraft 3, the relative error is lower and varies from 2.4% to 3.%. All simulation results provided by the AMS are greater than the MCS ones. The difference between these results is caused by skipping the 40000 cycles for AMS in contrast for MCS. Moreover, the methodology between the two approaches is different.

Let us now discuss the AMS's results in Table 3 and the AMS's values obtained in the case of scheduled maintenance in Table 2. The AMS's results in Table 3 are greater than the AMS's results in Table 2.

Figures 5 and 6 illustrate the average number of panels replaced over the entire life of aircrafts 1, 2, 3 and 5 under different values of the replacement threshold $l_{rep}$ provided by AMS and MCS. Here again, these figures show that the larger the threshold is, the lesser panels change is. The trends of the results are similar to the figures obtained in the SM case. The first results obtained for the SHM-CBM strategy using the PAM show that the number of panels to be replaced over the aircraft lifetime is greater than for the SM strategy, especially for aircraft 2 and 3. We recall that structure assessments are done every 100 cycles but the maintenance stops in order to change panels are not controlled.

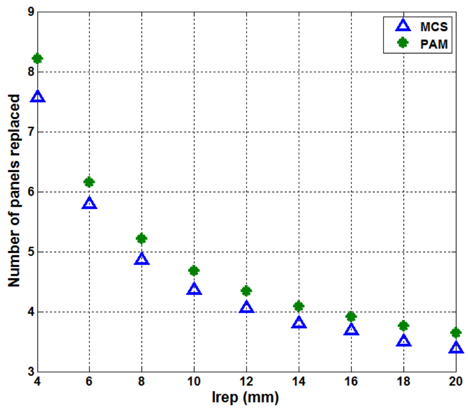


Figure 5: Aircraft 1

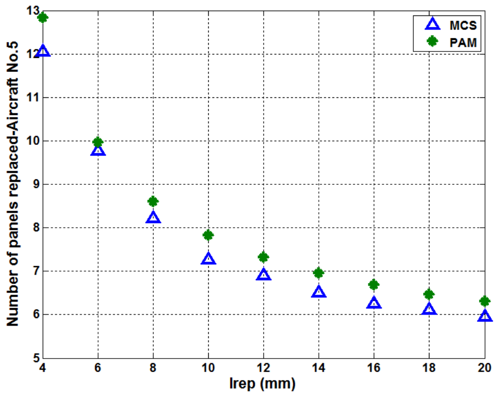


Figure 6: Aircraft 2

We are currently improving our methodology in order to define new strategies to compute dynamically the panels to be changed and decrease the number of maintenance stops to replace panels in contrast to the SM strategy where panel changing is statically defined. Regarding the SHM-CBM strategy, our objective is to define appropriate maintenance strategies to decrease the number of maintenance stops compared to the SM one using SHM technique.

## CONCLUSION

This paper focuses on aircraft structure maintenance strategies by considering the probabilistic analytical model proposed in [1]. Both scheduled maintenance and condition-based maintenance using SHM are simulated for different aircrafts. In each case, the aircraft lifecycle cost is evaluated in terms of average number of panels changed. The results provided by AMS are confronted to those presented in [2] obtained from Monte Carlo method. For scheduled maintenance strategy, they are close enough to MCS ones and an adequacy is shown. Slightly differences occur due to the simulation conditions that are not exactly the same. For condition-based maintenance using the SHM assessment, the results provided by AMS are greater than MCS ones. The difference between the results is caused by two different methodologies. The results obtained for the SHM-CBM strategy using the PAM show that the number of panels to be replaced over the aircraft lifetime is greater than for the SM strategy. Nevertheless, regarding the accuracy, the probabilistic analytical model is a useful method that provides an exact result of the average number of panels to be replaced. Investigations are currently carried out in order to check in a closer way the AMS's conditions in the context of both SM and SHM-CBM maintenances. To achieve this goal, we will take benefit of the SHM system which provides the real-time data on the health status of the structure.

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