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Skipping unnecessary structural airframe maintenance using an on-board structural health monitoring system

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Abstract
Structural airframe maintenance is a subset of scheduled maintenance, and is performed at regular intervals to detect and repair cracks that would otherwise affect the safety of the airplane. It has been observed that only a fraction of airplanes undergo structural airframe maintenance at earlier scheduled maintenance times. But, intrusive inspection of all panels on the airplanes needs to be performed at the time of scheduled maintenance to ascertain the presence/absence of large cracks critical to the safety of the airplane. Recently, structural health monitoring techniques have been developed. They use on-board sensors and actuators to assess the current damage status of the airplane, and can be used as a tool to skip the structural airframe maintenance whenever deemed unnecessary. Two maintenance philosophies, scheduled structural health monitoring and condition-based maintenance skip, have been developed in this article to skip unnecessary structural airframe maintenances using the on-board structural health monitoring system. A cost model is developed to quantify the savings of these maintenance philosophies over scheduled maintenance.

Keywords
Condition-based maintenance, structural health monitoring, reliability, synchronization, structural airframe maintenance

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Introduction

Maintenance is usually scheduled to prevent failure of a structure, and the maintenance interval is determined based on reliability (Torres-Echeverria and Thompson,[1] and Baek et al.[2]) or cost (Abjallah and Adzakpa[3]). There is ongoing research on alternative condition-based maintenance (CBM) that continuously tracks a deteriorating system and requests maintenance when the deterioration level crosses a pre-determined threshold. The condition of the structure is monitored using structural health monitoring (SHM) techniques. In literature, a structure's health has been monitored using the electrical or magnetic impedance method (Giurgiutiu et al.[4]), low frequency vibrations (Friswell and Penny[5]), and transmittance function monitoring (Zhang et al.[6]), to name a few. Barros et al.[7] developed a simple optimization scheme to choose the optimal maintenance technology for a given structure.

Recently, Pattabhiraman et al.[8] quantified savings on lifecycle costs for CBM over scheduled maintenance. Also, Beral and Speckman[9] analyzed the beneficial effects of CBM over scheduled maintenance on various factors, including lifecycle cost and airplane weight. You and Meng[10] developed a framework to integrate CBM with scheduled maintenance for multi-component systems.

In practice, CBM has been implemented in military and space applications (Goggin et al.[11]), but it is yet to be implemented in commercial airplanes. Farrar and Worden[12] and Goggin et al.[11] summarized the challenges for SHM systems to be incorporated into commercial airplanes. Ikegami[13] noted the complexity of using SHM systems on commercial airplanes, but predicted technology to overcome this difficulty in the near future.

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One of the issues preventing widespread implementation in commercial airplanes is that CBM is often seen as too disruptive to traditional inspection and maintenance procedures, thus making it difficult to quantify potential advantages. It is then likely that CBM would benefit from working in tandem with scheduled maintenance. Fitzwater et al.[14] combined SHM with traditional scheduled maintenance to minimize the lifecycle cost of an F-15 fighter frame station 626 bulkhead. In the present article, the authors propose a strategy based on the use of CBM to complement scheduled maintenance and enable skipping maintenance when deemed unnecessary. This article also quantifies savings in CBM over scheduled maintenance for a short-range airplane (e.g. Airbus A320) in terms of the maintenance trips an airplane undergoes.

The effect on cost of CBM over scheduled maintenance is investigated using fatigue crack growth in fuselage panels, which remains a major driver of structural inspection and maintenance. At the time of scheduled maintenance, the airplane is taken to a hangar and undergoes a series of maintenance activities, including airframe and engine maintenance. Structural airframe maintenance is a subset of scheduled maintenance, and focuses on detecting and replacing cracks that would otherwise endanger the safety of the airplane. Since the maintenance schedule for commercial airplanes is designed for a low probability of failure (10^{-7}), there is a possibility of no critical cracks being detected on an airplane during a scheduled maintenance in the early life of the airplane. But, intrusive inspection of all panels in the airplane need to be performed, by non-destructive inspection (NDI) and detailed visual inspection (DVI), to determine the presence/absence of critical cracks that otherwise cause fatigue failure.

We propose that on-board SHM equipment could determine the current damage status of the airplane, at the time of scheduled maintenance. First, inspection by SHM equipment is much cheaper, once the SHM system is in place, than existing techniques like NDI or DVI. Second, inspection by SHM could detect when scheduled airframe structural maintenance is unnecessary owing to damage being non-existent or non-critical, thus avoiding time-consuming inspection processes based on manual NDI or DVI. This article focuses on the savings in lifecycle costs owing to skipping these manual structural inspections of the airframe.

The monitoring technique in this article considers crack detection probability as a function of crack size and location; i.e. the Palmberg model.[15] However, the detection capability of a SHM system is less than that of NDI. It is assumed that once the crack is detected, there is no error in quantifying its size. As this article limits itself to the benefits of skipping unwanted structural airframe maintenance, the effect of error in quantification of crack size is minimal, and deemed beyond the scope of this article.

The organization of the article is as follows. In 'Maintenance process for fuselage panels', the process of damage detection and replacement are explained. The different types of maintenance processes are also described in this section. A 'Comparison between different maintenance processes' is then described. 'Cost comparison illustration' focuses on the maintenance cost savings.

Maintenance process for fuselage panels

Corrective maintenance procedure

Repeated pressurizations during take-off and landing of an airplane can cause cracks in a fuselage panel to grow. The crack growth can be modeled in a myriad ways depending on the location and whether the critical site is subject to multi-site damage (MSD), wide-spread damage (WFD), two-bay criterion, or other types of fatigue damage. Romlay et al.[16] used the dual-boundary element method to model fatigue crack growth in MSD, while Harris et al.[17] used an analytical methodology to predict the onset of WFD in fuselage structure. Nilsson[18] used the Dugdale model with elastic–plastic crack growth interactions between a major crack and multiple small cracks. Based on airframe fatigue tests on various military aircraft, Molent et al.[19] concluded that a simple crack growth model, such as the Paris model, can adequately represent typical crack growth.

In the Paris model, the rate of crack growth is controlled by, among other factors, the initial crack size owing to manufacturing flaws, pressure differential between the cabin and atmosphere, and thickness of the fuselage panel. If left unattended, the cracks may grow to cause fatigue failure of the panel. In damage tolerance design, corrective maintenance is performed in order to maintain a desired level of reliability by repairing/replacing panels with large cracks.

Airplane maintenance is broadly classified into airframe maintenance and engine maintenance. The airframe maintenance that deals with maintenance of non-structural airframes, like electrical systems, upholstery, etc., is called non-structural airframe maintenance. The maintenance of airframe sections that develop cracks that can cause fatigue failure owing to excessive damage propagation is called structural maintenance. In this article, maintenance refers to structural airframe maintenance.

The size of cracks in fuselage panels in a fleet of airplanes is modeled as a random variable characterized by a probability distribution that depends on manufacturing and the loading history of the airplane. The corrective maintenance procedure changes this distribution by repairing large cracks as illustrated in Figure 1. The solid curve represents the damage size distribution of the airplane before maintenance. The maintenance process is designed to repair/replace panels with cracks larger than a threshold, a_{rep}. Since damage detection is not perfect, maintenance partially truncates the upper tail of the distribution, as represented by the dashed curve in Figure 1.

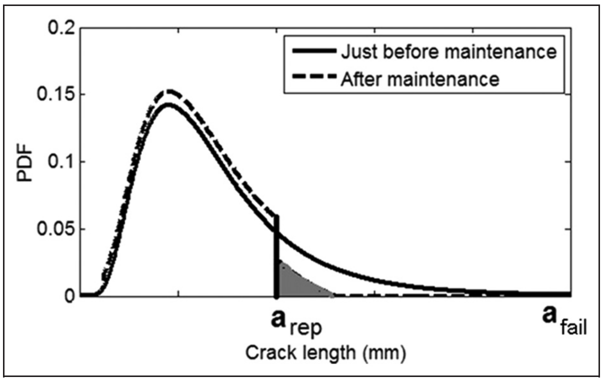

Figure 1. The effect of inspection and replacement processes on crack length distributions.
PDF: Probability density function.

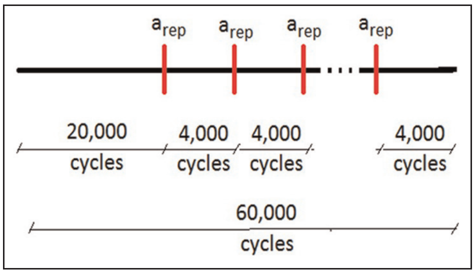

Figure 2. Schedule of the scheduled maintenance process. Cycles represent the number of flights.

The area under the dashed curve (gray) represents the fraction of panels missed during maintenance. Cracks missed during maintenance that grow beyond the failure damage size a_{fail} before next maintenance, affect the reliability of the airplane. The threshold, a_{rep}, is usually set to maintain a specific level of reliability.

In this article, four types of corrective maintenance procedures are discussed. In scheduled maintenance, as the name suggests, maintenance is scheduled at specific pre-determined intervals. In CBM, damage is continuously tracked using health monitoring systems, and maintenance is requested when damage size crosses a specified threshold. Sched-SHM and CBM-skip are techniques that form a hybrid model between the two, focusing on skipping the unwanted structural airframe maintenance by performing inspection of panels with an on-board SHM system.

Scheduled maintenance

Scheduled maintenance is scheduled at specific pre-determined intervals to perform corrective action that ensures the safety of the airplane until the next maintenance. Figure 2 depicts the scheduled maintenance schedule for a typical short-range airplane (e.g. A320). Scheduled structural maintenance is typically performed during C and D-checks of the airplane. In addition to engine and non-structural components maintenance, the airplane is checked for cracks that would cause fatigue failure before the next scheduled maintenance. During the maintenance process, the airplane is taken inside a hangar and an intrusive inspection of all panels on the airplane is performed using time-consuming techniques, like NDI, general visual inspection, and DVI. Cracks detected with a size greater than a threshold, a_{rep}, are repaired. The desired level of reliability can be achieved by setting a threshold value, a_{rep}.

Two parameters affect the lifecycle associated with scheduled maintenance. The maintenance interval determines the number of maintenance trips during an airplane's lifetime. The threshold for replacement (a_{rep}) affects the number of panels repaired/replaced (hence affecting cost) and the probability of a dangerous crack being left unrepaired (hence affecting safety). Thus, these two parameters affect both the safety and the lifecycle cost of an airplane undergoing scheduled maintenance.

CBM

In CBM, structural damage is monitored by the on-board SHM system using sensors and actuators. Structural airframe maintenance is requested when a detected crack size exceeds a certain threshold. It is noted that engine and non-structural airframe maintenance are still performed at the time of scheduled maintenance, while structural airframe maintenance may be carried out at these times or at any other time based on the condition of the structure.

Sched-SHM maintenance

Maintenance is scheduled with a low probability of failure ($\sim 10^{-7}$) for a panel until its end of life. This causes only a fraction of airplanes to undergo structural airframe maintenance at earlier scheduled maintenance times. But, in scheduled maintenance, an intrusive inspection of panels needs to be performed to ascertain the presence/absence of large cracks that affect the safety of the airplane. In Sched-SHM, inspection of panels for damage is performed by the on-board SHM system. The on-board SHM system can help skip structural airframe maintenance, if there are no life-threatening cracks on the airplane at the time of scheduled maintenance.

The schedule for Sched-SHM maintenance is exactly the same as for scheduled maintenance. The only difference is that the inspection of the fuselage panels is carried out by the on-board SHM system before the airplane enters the maintenance hangar. Figure 3 depicts the Sched-SHM maintenance process. If the maximum crack size detected in the airplane is less than the replacement threshold, a_{rep}, the SHM system recommends skipping the current structural airframe maintenance. Since damage assessment by on-board SHM is less accurate than NDI techniques used for

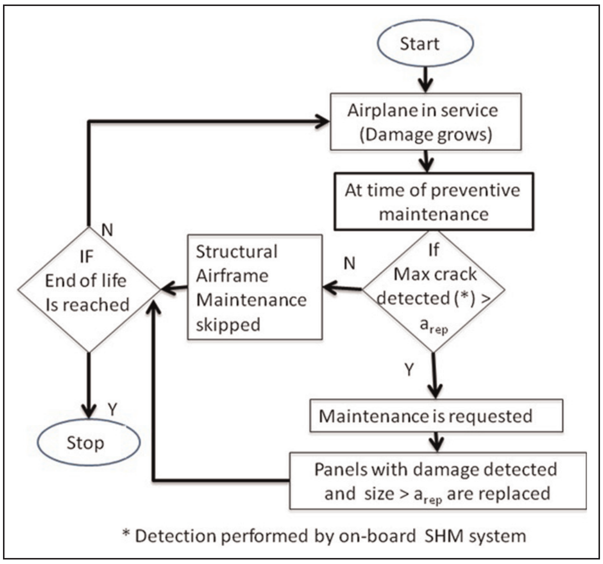

Figure 3. Flowchart of Sched-SHM maintenance process.

scheduled maintenance, Sched-SHM would lead to a lower level of reliability than scheduled maintenance.

Condition-based maintenance procedure – skip (CBM-skip)

Using SHM, the damage status can be evaluated, not just at the time of scheduled maintenance, but as frequently as needed. The frequency of damage status evaluation (henceforth called maintenance assessment) is assumed here to coincide with A-checks of the airplane (~100 flights); i.e. a small maintenance task carried out overnight at the airliner's hub hangars. It would make sense to carry out the SHM-based maintenance assessment at the A-checks since only the sensors themselves would have to be embedded in the airplane. The monitoring system could be ground-based, thus reducing flying weight and monitoring system costs.

CBM-skip has the same objective as Sched-SHM in terms of skipping unneeded structural airframe maintenance. However, the frequent monitoring of the damage status would ensure the same level of reliability as scheduled maintenance. If a crack missed at the time of scheduled maintenance grows critical between two consecutive scheduled maintenances, CBM-skip recommends structural airframe maintenance to be performed immediately. This calls for unscheduled maintenance, which is more costly. The threshold for requesting unscheduled maintenance (a_{maint}), is set to prevent a crack growth beyond critical size between consecutive maintenance assessments.

Figure 4 plots the procedure for CBM-skip. The damage assessment is performed at a scheduled maintenance time, as well as in every 100 flights. CBM-skip is controlled by two parameters. The threshold for requesting unscheduled maintenance (a_{maint}) affects the safety of the airplane. This parameter, along with a_{rep}, controls the number of maintenance trips and number of panels repaired/replaced in an airplane, and hence, affects its lifecycle cost.

Comparison between different maintenance processes

In this article, a typical lifecycle of a short-range aircraft's fuselage (e.g. Airbus A320) is modeled, focusing on the fatigue life of panels owing to crack growth. A typical structural maintenance schedule for such an airplane is delineated in Figure 2. The life of the airplane

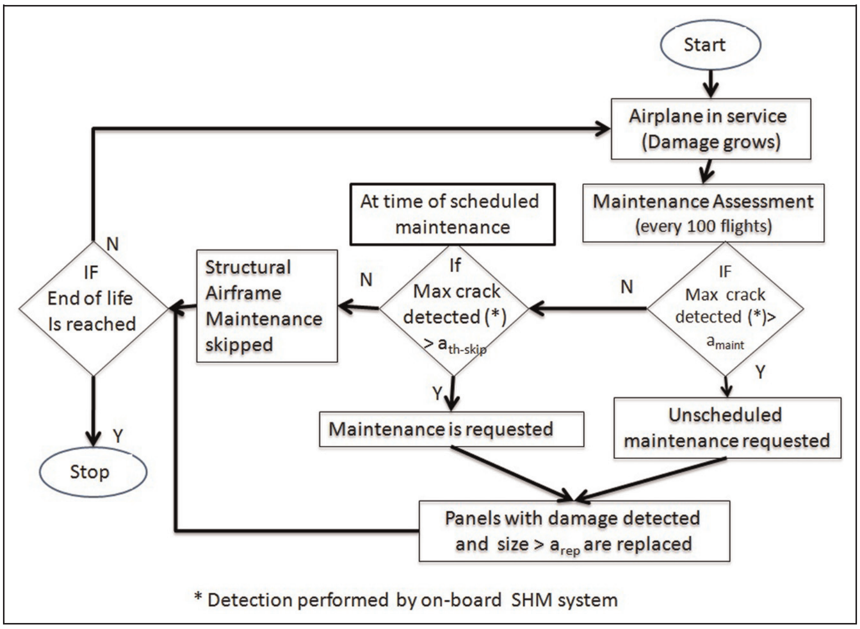

Figure 4. Flowchart depicting maintenance scheduling and assessment procedure for CBM-skip.

Table 1. Parameters of CBM processes and the constraints set to determine them.

Parameters	Value	Constraints
Threshold for requesting unscheduled maintenance ($2*a_{maint}$)	79 mm	To maintain Pf~10^{-8}, between maintenance assessments
Threshold for skipping a scheduled preventive maintenance ($2*a_{rep}$)	12 mm	To maintain a Pf~10^{-8} until next scheduled preventive maintenance

Pf: probability of fatigue.

Table 2. Comparison of different maintenance processes on the number of maintenance trips, percentage of panels replaced per airplane, and probability of fatigue failure of a single panel until the end of life.

Type	Average number of maintenance trips/airplane	Percentage of panels replaced/airplane	Average number of unscheduled maintenance trips/airplane	Pf of single panel until end of life
Preventive	10	6.6 (2.5)	—	1E-7
Sched-SHM	3.3 (1.0)	6.6 (2.5)	—	2.9E-6 (2E-6)
CBM-skip	3.3 (1.0)	6.6 (2.5)	0.02	1E-7
CBM	2.3 (0.7)	6.6 (2.5)	2.3	1E-7

Pf: probability of fatigue failure; SHM: structural health monitoring; CBM: condition-based maintenance. The number in parenthesis are the standard deviation of MCS.

is modeled as blocks of crack propagation interspersed with maintenance. In this article, we use the Paris model (see Appendix 1) to represent crack growth.

The values of the Paris model parameters are tabulated in Appendix 1 (Table 5). Uncertainty is considered for the loading condition and the Paris model parameters. The CBM processes follow the same damage growth model with parameters as described in Appendix 1 (Table 5).

Since modeling of the structural details of the fuselage is outside the scope of this work, we use a generic model for the fuselage panels and the corresponding damage growth. The parameters of this generic model are set to be representative of fuselage fatigue damage on real short-range aircraft. The panel thickness, initial damage size, correction factor for the stress intensity factor, and the damage replacement threshold are the parameters of our model we need to set. These are determined such that our model verifies certain constraints (such as probabilities of failure until end of life and between maintenance stops). A more detailed description of the constraints and the optimization processes to determine the parameters are given in Appendix 2. Table 1 tabulates crack size thresholds found to be representative of reality in the aforementioned sense. These thresholds were calculated using the direct integration procedure (see Appendix 5).

The lifecycle of the airplane is simulated using Monte Carlo simulations (MCS). A fleet of 2000 airplanes, with 500 panels per airplane, is considered. Each panel is assumed to contain a single crack. The equivalent initial flaw size (EIFS) and damage growth parameters (C, m) are sampled from their respective distributions and assigned to each panel. Maintenance processes are simulated according to the Palmberg

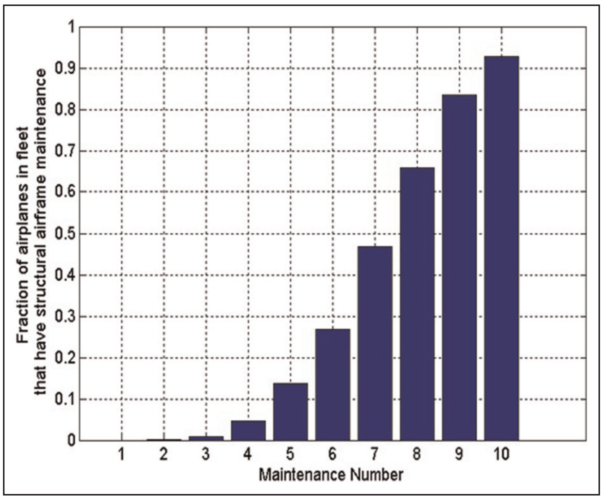

Figure 5. Fraction of airplanes undergoing structural airframe maintenance at each scheduled maintenance.

expression (Appendix 3), which provides the probability of detecting a crack as a function of crack length. MCS yield the number of maintenance trips and percentage of panels replaced in each airplane, until its end of life. For that equation, we assume that manual inspection have 50% chance of discovering a crack of 0.63mm, while for SHM the value is 5mm. Table 2 compares the different maintenance processes on the number of maintenance trips and the percentage of panels replaced per airplane.

Figure 5 plots the fraction of airplanes in a fleet that undergo structural airframe maintenance during a given scheduled maintenance. The fraction of airplanes requiring structural airframe maintenance is low earlier in the lifecycle and increases with life. Sched-SHM helps to skip unneeded structural airframe maintenance, and the result is reflected in Table 2. Figure 5 reveals that no airplanes require repair on the first scheduled inspection, which may indicate that the first inspection is set too early. However, this may reflect a limitation of the model or the number of airplanes in our fleet. We assume that the choice of first inspection reflects consideration by regulators, such as the FAA, who prefer to be conservative.

Owing to the poorer detection capability of SHM, Sched-SHM could miss cracks critical to an airplane's safety, when invoked only at the time of scheduled maintenance, causing a higher probability of failure than desired. However, frequent damage assessment in CBM and CBM-skip recovers the same level of probability of failure with scheduled maintenance. In order to maintain 1E-7 level of probability of failure, CBM-skip calls for about 2% of the airplanes to have an unscheduled maintenance trip per lifetime. On the other hand, all of the structural airframe maintenances requested by CBM are un-scheduled, but it does lead to fewer structural airframe maintenance trips per airplane, while maintaining the same level of reliability. It is worth noting here that the CBM-skip approach does not lead to any decrease in the conservativeness of the design since frequent SHM checks allow the detection of critical crack growth even outside the scheduled inspection. Since they maintain the same amount of conservativeness as in current practice, the CBM approaches may be looked at more favorably than probabilistic approaches that decrease the degree of conservativeness.

Cost comparison illustration

The information in Table 2 can be used to make decisions about the best maintenance approach with knowledge of only the costs associated with each option. To illustrate the process, a cost model based on literature and detailed in Appendix 4 is used to facilitate comparisons between the different maintenance processes, on the basis of their maintenance cost (including material and labor cost). In this model, the maintenance cost is the sum of airframe maintenance and engine maintenance cost, where structural maintenance is a subset of airframe maintenance. The engine maintenance and non-structural airframe maintenance are always performed at the time of scheduled maintenance intervals. Only structural maintenance is requested by CBM based on the current damage status.

Based on the empirical expressions and airplane parameters in Appendix 4 (Table 6), the airframe maintenance cost is \$1139/flight and the engine maintenance cost is \$258/flight. The aircraft makes 60,000 flights during its lifetime, and undergoes ten scheduled maintenances. Hence, the cost of one scheduled airframe maintenance (A) is \$6.84 million and the cost of one scheduled engine maintenance (E) is \$1.55 million. The cost for structural airframe maintenance (S) is assumed to be \$1.8 million.

During scheduled maintenance, most of the time is spent detecting cracks on the airplane and identifying the panels to be repaired/replaced. When maintenance is requested by CBM, the on-board SHM equipment assesses the current damage status of the airplane, and identifies the panels to be repaired/replaced. Hence, structural airframe maintenance requested by CBM will cost only a fraction compared with scheduled maintenance. The fraction is denoted as k_{SHM}, and a range of [0.3, 0.7] is assumed for k_{SHM}.

An unscheduled maintenance trip, requested by CBM, is more expensive than the scheduled maintenance, owing to less advance notice, as well as the fact that the structural airframe maintenance and the other maintenance (engine, non-structural) are not done at the same time. A factor, k_{unsch} (> 1) is set to denote the higher cost incurred for unscheduled maintenance, and a range of [1.2, 2] is chosen for k_{unsch}. Factors k_{SHM} and k_{unsch} are independent of each other and the cost of unscheduled airframe maintenance, requested owing to CBM, is the product of k_{unsch}, k_{SHM}, and the cost of one scheduled structural airframe maintenance (S). The total maintenance cost is given by

$$\text{Maintenance cost} = (E + (A - S)).N_p + k_{SHM}.S.N_{SA} + k_{unsch}.k_{SHM}.S.N_{unsc}$$

where E is the engine maintenance cost, A is the airframe maintenance cost, and S is the structural airframe maintenance cost. Hence, (A–S) is the non-structural airframe maintenance cost. N_p is the number of scheduled maintenance trips, N_{SA} is the number of times structural airframe maintenance is performed at the time of scheduled maintenance, and N_{unsc} is the number of unscheduled structural maintenance trips requested by on-board SHM.

Since both k_{unsch} and k_{SHM} are independent of each other, the best and worst case costs for each CBM process would be when parameters k_{unsch} and k_{SHM} are both at their lower and upper limits, respectively. Table 3 compares the best and worst case costs of different CBM processes against that of scheduled maintenance.

It is noted that even the worst case scenarios for different CBM processes lead to substantial savings in the maintenance cost. However, SHM uses on-board sensors and actuators, and they cause an increase in the weight of the airplane, and hence, cause an increase in fuel cost. An assumption on the mass of the on-board sensors and actuators, as a percentage of the fuselage mass, is considered. Based on these mass figures a lifetime fuel consumption was calculated based on preliminary design formulas from Jaeger et al.[20] These simple formulas stem from historical databases of aircraft parameters and performances on which regression models were fitted. Table 4 compares the fuel cost (calculated based on preliminary aircraft design formulas from Jaeger et al.[20]) between scheduled maintenance and CBM for different cases of fuselage mass increase owing to on-board sensors and actuators.

Table 3. Comparing the best and worst case costs of different CBM processes with the cost for scheduled maintenance.

Maintenance cost (M$)		
Type	$k_{unsch} = 1.2$, $k_{SHM} = 0.3$ (optimistic assumption)	$k_{unsch} = 2$, $k_{SHM} = 0.7$ (pessimistic assumption)
Scheduled	83.9	83.9
Sched-SHM	66 (0.5)	69.3 (0.6)
CBM-skip	67 (0.5)	70.1 (0.6)
CBM	67 (0.4)	71.7 (0.5)

SHM: structural health monitoring; CBM: condition-based maintenance.

Table 4. Lifetime fuel cost (based on $$/gal) for scheduled maintenance and CBM, for different cases of fuselage mass increase owing to on-board sensors and actuators.

Scheduled	With SHM (5% fuselage mass increase)	With SHM (10% fuselage mass increase)
210.5 M$	212.1 M$	213.8 M$

SHM: structural health monitoring.

Based on Table 4, CBM could cost about 3.5 M$ in excess over scheduled maintenance from the excess fuel, until end of life. But, based on Table 3, CBM could lead to at least 12 M$ in savings in maintenance cost over scheduled maintenance. Based on Tables 3 and 4, CBM is found to lead to substantial savings over the lifetime of the aircraft, considering maintenance and fuel costs. Considering the extreme case, "CBM", with $k_{unsch} = 2$ and $k_{SHM} = 0.7$ in Table 3, and SHM with 10% mass increase in Table 3, the savings for CBM is about 8 M$. If a SHM system can be installed on-board the airplane for less than this number, then the maintenance cost can be reduced by performing CBM.

Summary and conclusions

The savings in skipping unwanted structural airframe maintenance is quantified in this article. It has been observed that at the first few maintenance stops, structural repairs or panel replacements are not necessary for a large number of airplanes in the fleet. But using the current maintenance philosophy, an intrusive inspection of fuselage panels is nevertheless performed to ascertain that no critical cracks are present in the structure. Recently, SHM techniques have been developed. They use the on-board sensors and actuators to detect damage of the structural parts of the airplane. Several maintenance approaches were developed and presented in this article that aim at taking advantage of the SHM capabilities to reduce maintenance costs.

A first maintenance approach, Sched-SHM, was presented, wherein the on-board SHM is used to gage the damage status of the airplane at the time of scheduled maintenance. The method would skip structural airframe maintenance whenever deemed unnecessary, thus avoiding costly disassembling and inspections done by operators. A second approach, CBM-skip, was presented in which a regular tracking of panels is performed to prevent cracks from growing critical between scheduled maintenances. Finally, a simple CBM approach is also presented, which is advantageous if there is not much emphasis on timing the structural airframe maintenance together with the non-structural maintenance and engine maintenance. These three different approaches of CBM are compared in this article with traditional scheduled maintenance and it is found that, to different degrees, they all have the potential to lead to substantial savings over the lifetime of an airplane.

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Conflict of interest

Authors declare that there is no conflict of interest.

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Appendix 1

Fatigue damage growth owing to fuselage pressurization

Damage in the fuselage panel of an airplane is modeled as a through-thickness center crack in an infinite plate. The life of an airplane can be viewed as consisting of damage propagation cycles, interspersed with inspection and repair. The cycles of pressure difference between the interior and the exterior of the cabin during each flight is instrumental in propagating the damage. The fatigue crack growth could be modeled in a myriad ways. Beden et al.[21] gives an extensive review of the crack growth models. Mohanty et al.[22] use an exponential model to model fatigue crack growth. The damage propagation, in this article, is modeled using the Paris model,[23] which gives the rate of damage size growth with the number of flight cycles (N) as a function of damage half size (a), pressure differential (p), thickness of fuselage panel (t), fuselage radius (r), and the Paris parameters, C and m

$$\frac{da}{d\mathrm{N}} = C(\Delta K)^m \quad (1)$$

where the range of stress intensity factor is approximated as

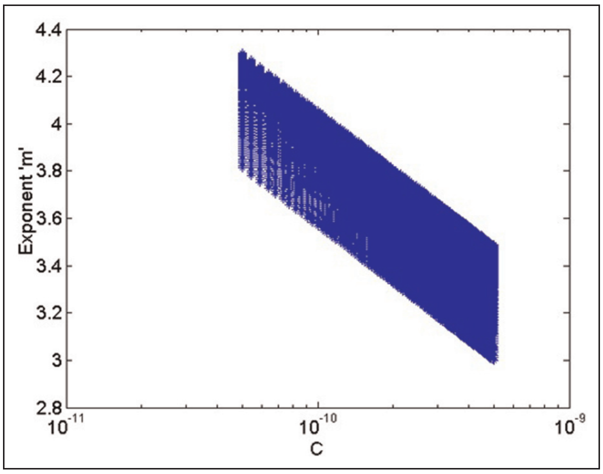

Figure 6. Possible region of Paris model parameters.

$$\Delta K = \mathrm{A}\frac{pr}{t}\sqrt{\pi a} \tag{2}$$

The coefficient 'A' on the stress intensity factor (SIF) is a correction factor intended to compensate for modeling the fuselage as a hollow cylinder, lack of stiffeners in the model, and for bulging effects. There is uncertainty in Paris parameters, and EIFS between fuselage panels. Generally EIFS are derived through back-projection to time zero of the flaw size using a mechanistic linear–elastic fracture mechanics model, and may bear little resemblance to any physical dimension. In this article, the uncertainty in the EIFS is modeled using damage size distributions. The random nature of the atmospheric pressure causes uncertainty in pressure differential. The damage size after N flight cycles of propagation depends on aforementioned parameters and is also uncertain. The values and distributions of the parameters are tabulated in Table 4.

Aluminum alloy 7075–T6 is considered as the material of the fuselage panels. Newmann et al. (Pg 113, Figure 3)[24] show the experimental data plot between the damage growth rate and the effective stress intensity factor for Al 7075–T6 with a center crack in tension. The Paris law parameters C and m are estimated from the intercept and slope, respectively, of the region corresponding to stable damage propagation in the figure.

The data points in the region of stable damage propagation do not lie on a straight line in the log–log scale plot. Hence, the region was visualized as bounded by a parallelogram with one edge parallel to the ordinate axes and the other edge parallel to the best fit straight line through the data points. The left edge of the parallelogram has a ΔK_{eff} value equal to one. As the region of the stable damage propagation can be bounded by a parallelogram, only the estimates of the bounds of the parameters, C and m, are obtained from the figure (Figure 3, Newmann et al.[24]).

For the same reason, for a given value of intercept C, there is only a range of slope (m) values permissible. To parameterize the bounds, the left and right edges of the parallelogram were discretized by uniformly distributed points, each assumed to be uniformly distributed. Each point on the left edge corresponds to a value of C chosen. For a given value of C chosen, there are only certain possible values of the slope, m. Figure 6 plots those permissible ranges of slope (m), for a given value of intercept (C). It can be clearly seen from Figure 6 that the slope, and log(C) are negatively correlated; the correlation coefficient is found to be −0.8065. Table 5 shows the parameters used.

Appendix 2

Optimizing parameters for damage growth model

In this article, damage/crack refers to damage in any location of the fuselage, and the crack growth is modeled using a simple damage growth model. The parameters of the damage model are set to satisfy certain constraints, in order to mirror realistic circumstances.

Following are the parameters of the damage model that need to be set.

- Thickness of the fuselage panel, t.
- Correction factor for the stress intensity factor, A.
- Replacement threshold for the preventive maintenance, a_{rep}.
- EIFS.

Table 5. Parameters and their values.

Parameter	Type	Value
Initial damage size (a_0)	Random	LN (0.2 mm, 35% COV)
Pressure (p)	Random	$LN(0.06, 0.003)$ MPa
Radius of fuselage (r)	Deterministic	1.95 m
Thickness of fuselage panel (t)	Deterministic	2 mm
Paris Law constant ($\log_{10}(C)$)	Random	$U[\log_{10}(5E\text{-}11), \log_{10}(5E\text{-}10)]$
Paris Law exponent (m)	Random	$U[3, 4.3]$
Correction factor for SIF (A)	Deterministic	1.255
Palmberg parameter for scheduled maintenance ($a_{h\text{-}man}$)	Deterministic	0.63 mm
Palmberg parameter for scheduled maintenance (β_{man})	Deterministic	2.0
Palmberg parameter for SHM-based inspection ($a_{h\text{-}shm}$)	Deterministic	5 mm
Palmberg parameter for SHM-based inspection (β_{shm})	Deterministic	5.0

SHM: structural health monitoring; SIF: stress intensity factor.

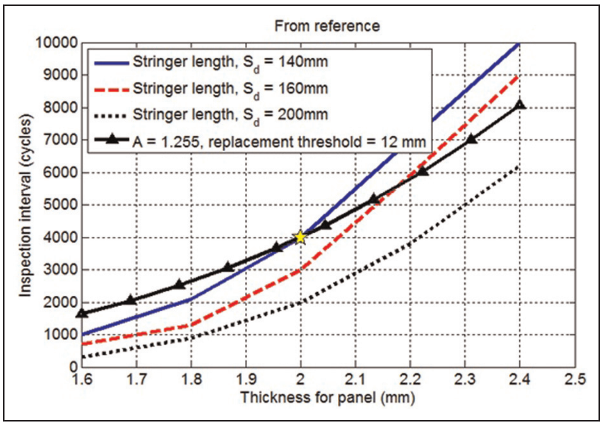

Figure 7. Comparing the sensitivity of inspection interval for an optimal set of parameters and reality.

The constraints that help mirror reality are:

- probability of failure of a panel at the time of first maintenance, for preventive maintenance = 10^{-8};
- probability of failure of a panel between successive preventive maintenance = 10^{-8};
- the sensitivity of inspection interval to fuselage panel thickness, for preventive maintenance must match reality;
- inspection interval = 4000 cycles (= preventive maintenance frequency).

Inspection interval is the time taken (in flight cycles) for a crack of size, 2^*a_{rep}, to grow critical with a probability of failure of 10^{-8}. The probability of failure is calculated by direct integration procedure (Appendix 5). A plot for the variation of the inspection interval as a function of panel thickness for various stringer lengths is obtained from Gaillardon et al.[25] The parameters of the damage growth model are set to maintain a similar sensitivity of inspection interval to panel thickness to mirror reality.

Parameters, thickness, t, and correction factor for SIF, A, control the rate of crack growth. These two parameters affect all four constraints. The EIFS parameter affects only the first constraint, i.e. probability of failure of a panel at the time of first maintenance, while the replacement threshold, a_{rep}, affects the other three constraints, i.e. probability of failure of a panel between successive preventive maintenance, inspection interval, and the sensitivity of inspection interval to the fuselage panel thickness, for preventive maintenance.

The panel thickness is set at t = 2 mm. The correction factor for SIF, A, and replacement threshold, a_{rep}, are optimized to satisfy constraint numbers 2, 3, and 4. Figure 7 compares the sensitivity of inspection interval to panel thickness for the optimized set of parameters and reality. It is noted that, for the optimized values of parameters, A, and a_{rep}, the inspection interval is equal to 4000 cycles at panel thickness = 2 mm, and the sensitivity of inspection interval to panel thickness is comparable to the case of 200 mm stinger length. The EIFS is later set to satisfy the first constraint, considering the optimal values of A and a_{rep}.

The optimal parameters are SIF correction factor, A = 1.255, replacement threshold (2^*a_{rep}) = 12 mm, and fuselage panel thickness, t = 2 mm. The EIFS distribution was computed to be LN(0.2, 0.07) mm to satisfy the first constraint.

Appendix 3

Inspection model

Packman et al.,[26] Berens and Hovey,[27] Madsen et al.,[28] Mori and Ellingwood,[29] and Chung et al.[30] have modeled the damage detection probability as a function of the damage size. In this article, in scheduled maintenance and in SHM-based maintenance assessment, the detection probability can be modeled using the Palmberg equation[15] given by

$$P_d(a) = \frac{\left(2a/a_h\right)^{\beta}}{1 + \left(2a/a_h\right)^{\beta}} \tag{3}$$

The expression gives the probability of detecting damage with size $2a$. In equation (3), a_h is the damage size corresponding to 50% probability of detection and β is the randomness parameter. The parameter a_h represents the average capability of the inspection method, while β represents the variability in the process. Different values of the parameters a, and β are considered to model the inspection inside the hangar for preventive maintenance and also for SHM-based maintenance assessment. Generally, the inspection technique for preventive maintenance is very thorough and would be quite capable of detecting large cracks. Hence, a truncated inspection model with truncation at ten times a_h is considered for preventive maintenance. Any crack present, with a crack size greater than the truncation limit, will always be detected, for preventive maintenance.

In this article, each crack is associated with a location probability. The location probability is set to be uniformly distributed between [0, 1]. A crack will be detected only if its probability of detection exceeds the location probability.

Appendix 4

Cost model

In order to estimate the cost efficiency of the SHM systems, it is necessary to discuss the cost model first. Trip-cost of an airplane includes, among others, fuel cost, airframe maintenance cost, and engine maintenance cost. These cost elements are given in terms of empirical expression in Kundu.[32]

Fuel cost is given as

$$\text{Fuel charges} = \frac{\text{block fuel} \times \text{fuel cost}}{\text{block time}} \quad (4)$$

The airframe labor cost is given as

$$\left(0.09 \times W_{airframe} + 6.7 - \frac{350}{(W_{airframe} + 75)}\right) \times \left(\frac{0.8 + 0.68 \times (t - 0.25)}{t}\right) \times R \quad (5)$$

where, $W_{airframe}$ is the maximum empty weight (MEW) of the airplane less the engine weight in tons, R is the labor rate in \$/hour, and t is the block time of airplane per flight.

The airframe material cost is given as

$$\left(\frac{4.2 + 2.2 \times (t - 0.25)}{t}\right) \times C_{airframe} \times R \quad (6)$$

where, $C_{airframe}$ is the price of airplane, less engine price, in millions of dollars.

The airframe maintenance cost per flight is given as a sum of airframe labor and airframe material cost. Engine labor cost is given as

$$0.21 \times R \times C_1 \times C_3 \times (1 + T)^{0.4} \quad (7)$$

where, T is the sea level static thrust, in tons,

$$C1 = 1.27 -^{0.2} * BPR^{0.2}$$

where, BPR is bypass ratio of the engine

$$C3 = 0.032 * n_c + K$$

where, n_c is the number of compressor stages, K = 0.50 for one shaft, 0.57 for two shafts, and 0.64 for three shafts.

Engine material cost is given as

$$2.56 \times (1 + T)^{0.8} \times C_1 \times C_2 \times C_3 \quad (8)$$

where

$$C2 = 0.4 * (OAPR/20)1.3 + 0.4$$

where, OAPR is the overall pressure ratio of the engine

The engine maintenance cost (labor + material) per flight, is given as

$$N_e \times (\text{engine labor cost} + \text{material cost} \frac{(t + 1.3)}{(t - 0.25)} \quad (9)$$

Parameters affecting the cost model are obtained from aircraft preliminary design formulas[33] and engine specifications.[34] Parameters affecting the cost model are tabulated in Table 6

Fuel cost is calculated on the basis of \$126.1/barrel of jet fuel.[34] A barrel houses 42 gallons of jet fuel and the density of jet fuel is 6.8 lb/gallon.

Table 6. Airplane parameters affecting cost.

Parameter	Value
MWE (tons)	51.6
Engine wt (tons)	13.0
Labor rate (\$/h)	63
Block time (h)	1.1
W_airframe (tons)	38.6
Cost_airframe (M\$)	83
Sea level static thrust (tons)	24.6
Engine bypass ratio (BPR)	6
Number of compressor stages (n_c)	9
K	0.57
Overall pressure ratio (OAPR)	31.3
Number of engines (N_e)	2
Block fuel (kg)	3604.3
Fuel cost (\$/kg)	0.9

MWE: Maximum empty weight.

Appendix 5

Direct integration procedure

The direct integration procedure is a method used to compute the probability of an output variable with random input variables. In this article, the direct integration process is used to compute the probability of having a specific damage size. The damage size distribution is a function of initial damage size, pressure differential, and Paris model parameters (m, C), which are all random

$$f_N(a) = h(a_0, f(p), J(C, m)) \quad (10)$$

where a_0, $f_N(a)$, $f(p)$ represent the initial damage size, the probability density functions of damage size after N cycles and pressure differential, respectively. $J(C, m)$ is the joint probability density of the Paris model parameters (m, C). The probability of damage size being less than a_N after N cycles is the integration of the joint probability density of input parameters over the region that results in a damage size being less than or equal to a_N; that is

$$\Pr(a < a_N) = \int_{C_{a_N}} a_0.J(C, m).f(p).dC_{a_N} \quad (11)$$

where C_{a_N} represents the region of (a_0, C, m, p) which will give $a < a_N$.

Based on preliminary analysis, the effect of the random pressure differential was averaged out over a large number of flight cycles. Therefore, the average value of the pressure differential is used in the following calculation. Hence, equation (12) reduces to be a function of m, C, as

$$F_N(40) = \iint_A J(C, m).dC.dm \quad (12)$$

where A represents the region of $\{C, m\}$ that would give $a_N < 40$ mm for a given initial damage size, a_0.

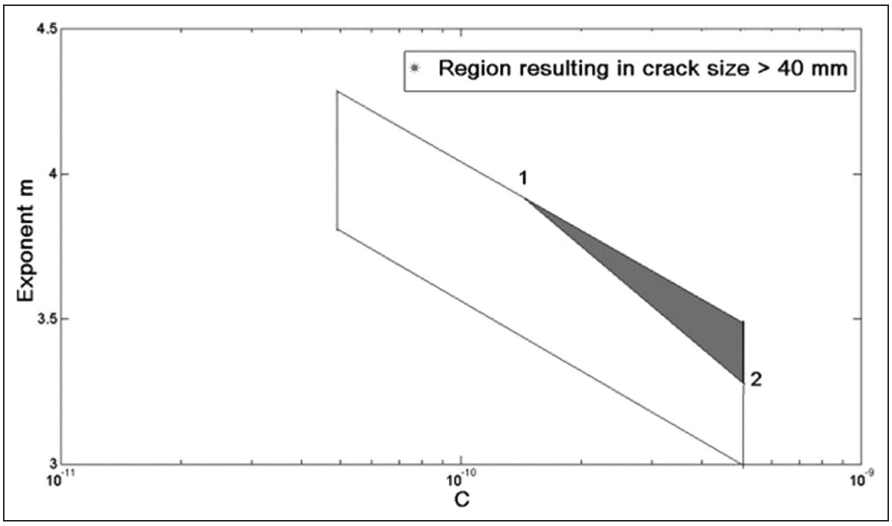

Figure 8. Regions of $\{C, m\}$ for N = 50,000 and a_0 = 1 mm.

Figure 8 plots the region of $\{C, m\}$ for initial damage size, $a_0 = 1\,\text{mm}$ after N = 50,000 cycles. The parallelogram represents all possible combinations of $\{C, m\}$. The region in gray results in a damage size $(a_N) > 40\,\text{mm}$. The points 1 and 2 that define the gray region are computed first using the analytical expression of the Paris model and the area of the polygon is computed from basic geometry.

If the initial damage size is distributed, then the integrand is evaluated at different values in the range of the initial damage size, and the trapezoidal rule is used to compute the probability at the desired damage size.