Comparing structural airframe maintenance strategies based on probabilistic estimates of the remaining useful service life

Y. WANG[a], C.GOGU[b], N.BINAUD[b], C.BES[b]

a. INSA de Toulouse, Institut Clément Ader, yiwang@insa-toulouse.fr
b. Université Toulouse III, Institut Clément Ader, christian.gogu@univ-tlse3.fr
b. Université Toulouse III, Institut Clément Ader, nicolas.binaud@univ-tlse3.fr
b. Université Toulouse III, Institut Clément Ader, christian.bes@univ-tlse3.fr

Abstract:

Structural airframe maintenance is a subset of aircraft maintenance, which is often performed at scheduled intervals to detect and repair cracks that would otherwise affect the safety of the aircraft. With the progress of structural health monitoring (SHM) techniques, which uses on-board sensors and actuators to assess damage status, condition-based maintenance (CBM) is considered as an alternative to traditional scheduled maintenance. By applying SHM techniques, CBM can access damages status as frequently as needed and unscheduled maintenance can be asked once the damage exceeds a particular threshold. Due to the harsh working environment and sensor limitation, the measurement data acquired from SHM is often quite noisy. In this paper, Extended Kalman filter is used to filer the noise to provide an accurate estimation of crack size and crack growth parameters together with their associated uncertainty. This knowledge is used to obtain a probabilistic estimate of the remaining useful service life of the structure. Based on these estimates, two maintenance philosophies are developed and further compared in terms of maintenance stop number or replaced panel number. The results indicate that both these two strategies reduce considerably the maintenance stop number compared to scheduled maintenance.

Key words: Structural health monitoring, Scheduled maintenance, Condition-based maintenance, Extended Kalman filter, Remaining useful service life

1   Introduction

Aircraft maintenance can be classified into airframe maintenance and engine maintenance. The airframe maintenance that deals with non-structural items such as furniture and electronic systems is called non-structural airframe maintenance [1] while the one that concerns the cracks in the structural section (such as fuselage panels) which grows due to loading/unloading cycles during taking-off/landing and have the risk of leading to panel fatigue failure is called structural airframe maintenance. This paper focuses on structural airframe maintenance.

Traditionally, aircraft maintenance is scheduled. For a typical short-range commercial aircraft (e.g. A320, B737) the first maintenance occurs at 20000th flight cycle and consecutive maintenance is performed every 4000 cycles until its end of life, which is 60000 cycles. The maintenance schedule for commercial aircrafts is designed to be conservative to ensure a very low probability of failure, which implies that there are no critical cracks being detected on an aircraft's fuselage panels during the scheduled maintenance time in the early life of the aircraft.

With the progress of structural health monitoring (SHM) technique, condition-based maintenance (CBM) is considered an alternative strategy to scheduled maintenance. Through the help of on-board sensors and actuators of SHM system, CBM evaluates the damage status as frequently as needed and asks unscheduled maintenance whenever the crack size exceeds a particular threshold. One problem is that the crack size measurement data acquired from SHM system can be quite noisy due to the harsh environment and sensor limitations. An efficient filtering technique is necessary to filter the noise and get a much more accurate estimate for the crack size and the crack growth parameters. Extended Kalman filter (EKF) is proposed here since it is a commonly used algorithm for recursive nonlinear state estimation due to its excellent filtering properties.

In practice, CBM strategy is yet to be implemented in commercial aircrafts. One of the issues preventing its widespread implementation is that CBM is considered too disruptive to traditional maintenance process. Another downside of pure CBM is that damage assessment by on-board SHM is less accurate than NDI techniques used for scheduled maintenance, CBM would lead to a lower level of reliability than scheduled maintenance [2]. It is then likely that CBM would benefit from working in tandem with traditional scheduled maintenance. You [3] developed a framework to integrate CBM with scheduled maintenance. Fitzwater combined CBM with traditional scheduled maintenance and applied the proposed maintenance strategy on an F-15 fighter aircraft [4]. Pattabhiraman presented a hybrid maintenance strategy to skip unnecessary scheduled structural airframe maintenance using an on-board structural health monitoring system and argued that the hybrid strategy has the potential to lead to substantial cost saving over the lifetime of an aircraft [2]. The aim of the present paper is to propose and compare new structural airframe maintenance strategies based on a probabilistic estimate of the remaining useful servicing life of the structural airframe parts.

The paper is organized as follows. Section 2 introduces the crack growth model and the developed procedure for EKF estimation of the crack size and crack growth parameters based on noisy SHM data. Section 3 presents two maintenance strategies that are proposed that take advantage of the EKF estimations. Section 4 compares the two strategies in term of maintenance stops and number of replaced panels by a case study. Conclusions are drawn in section 5.

2.   Crack size estimation using EKF

During the lifetime of an aircraft, loading and unloading cycles occur due to repeated pressurization/depressurization of the fuselage and can lead to fatigue cracks in the fuselage panels. Cracks or damages in this paper refer to existing flaws on the fuselage panel of an aircraft. Typically, a fuselage is modeled as a hollow uniform cylinder while cracks in the fuselage panel are modeled as through-the-thickness center straight cracks in an infinite plate. This assumption is well verified if the crack size is small compared to the distance between fuselage stiffeners. For larger crack sizes the model can be adjusted by considering corrective terms in the calculations of the stress intensity factors to account for boundary conditions effect of stiffeners. The life of an aircraft can be viewed as consisting of damage propagation cycles, interspersed with inspection and repair. Crack propagation can be modeled in myriad ways depending on different phenomena to which the critical crack site is subject [5-7]. Based on airframe fatigue tests on various military aircrafts, Molent et al. concluded that a simple crack growth model adequately represented a typical crack growth [8]. In this work, the

celebrated Paris' law is selected to describe the crack growth behavior since it is commonly used for fatigue analysis due to its simplicity. The Paris' law is given by [9]:

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

where a is the half-crack size in meters, N is the number of load cycles. da/dN is the crack growth rate in meters/cycle. C and m are the Paris' law parameters which are associated with material properties. ΔK is the range of stress intensity factor in $MPa\sqrt{m}$, which is approximated in Eq.(2) as a function of the pressure differential (p), fuselage radius (r) and panel thickness (t). The coefficient A in Eq.(2) is a correction factor that compensates for modeling the fuselage as a hollow cylinder (thus ignoring the effect of stringers and stiffeners).

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

System dynamics is discretized such that a discrete-time EKF can be used. Euler method is employed to discretize Eq.(1). The discrete Paris' law can be written in a recursive form at each flight cycle k

$$a_k = a_{k-1} + C(\Delta K)^m$$
$$= f(a_{k-1}) + w_{k-1} \tag{3}$$

where w_{k-1} is the additional process noise. Here w_{k-1} is assumed to be 0.

Since the crack size is measured by sensors, the measured crack size always contains noise due to the measurement environment and sensor limitations. The measurement data is modeled as

$$z_k = h(a_k) + v_k \tag{4}$$

in which h is the measurement function and v_k is the measurement noise such that $v_k \sim N(0,R)$. In this paper, the measurement function h is identity. Eq.(3) and Eq.(4) are called the system equation and measurement equation respectively.

In the aforementioned crack growth model, m and C are the unknown parameters that need to be estimated. A two-dimensional parameter vector is defined as

$$\Theta = [m, C]^T \tag{5}$$

Appending Θ to the state variable, that is crack length a, the augmented state vector is defined as

$$x_{aug} = [a \; m \; C]^T \tag{6}$$

Using subscript *"aug"* to denote all the augmented variables, the extended system is represented in Eq.(7).

$$x_{aug,k} = f_{aug}(x_{aug,k-1}) + w_{aug,k-1}$$
$$z_{aug,k} = h_{aug}(x_{aug,k}) + v_{aug,k} \tag{7}$$

where $v_{aug,k}$ is the augmented measurement noise vector including $v_{a,k}$, $v_{m,k}$ and $v_{C,k}$, which represent respectively the uncorrelated measurement noise of each state variable with a zero mean and a variance of Ra, Rm, RC. The augmented measurement noise covariance matrix R_{aug} could be written as

$$R_{aug} = diag(Ra, Rm, RC) \tag{8}$$

The details of the EKF algorithm can be found in [10,11]. We use the symbol "$\wedge$" to represent an estimate and subscript "k" to denote the time step. Symbols "-" and "+" in the upper right corner are used to indicate a priori estimate and a posteriori estimate respectively. For example, $\hat{x}_{aug,k}^-$ represents the a priori estimate of the augmented state vector at time step k while $\hat{x}_{aug,k}^+$ denotes the posteriori estimate at the same time. Similar, P_k^+ is the a priori estimate for state error covariance matrix at time step k while P_k^- is the a posteriori one. The EKF algorithm will be used next to determine for each aircraft panel the associated material parameters governing crack growth m and C as well as their associated estimation uncertainty (P_k^+ covariance matrix). Given this uncertainty in m and C, various

possible simulations of the crack growth can be carried out, which will be used in the maintenance strategies that we propose next.

3 Maintenance strategies

3.1 CBM

The condition-based maintenance strategy tracks damage as frequently as needed (typically every couple of dozen or few hundred flight cycles) and requests maintenance whenever the crack size is found to be large enough to threaten structural integrity. The damage status evaluation is called maintenance assessment.

Figure 2 illustrates the flowchart of the proposed condition based maintenance strategy. Maintenance assessment is implemented every 100 cycles. At each assessment, on-board SHM system acquires crack size data on each panel. Here EKF is employed to incorporate this noisy data into the Paris' law to output an optimal posterior estimate for crack size. If the maximal crack size of an aircraft panels exceeds a particular threshold (a_{maint}), unscheduled maintenance is asked immediately and this aircraft is sent to the maintenance hangar, in which place all panels on this aircraft are inspected and for each of them a decision of whether replacing or not (called IfReplace decision) is made. A straightforward idea for IfReplace decision is that panels with crack size greater than a second threshold a_{rep} are replaced [2]. In this case, a_{rep} should be assigned a small value (much smaller than a_{maint}), making the maintenance strategy too conservative. This is the basis of traditional condition based maintenance. Note however that the two material property parameters m and C are different from panel to panel, which imply that the crack in each panel will propagate with its own rate in the future flight cycles. Based on this fact we seek a less conservative probabilistic method to make a new IfReplace decision. Based on the existing knowledge of each individual panel at current flight cycle (i.e. crack size, m and C given by EKF), we predict for each panel the future crack size distribution after a certain number of flight cycles, say I_{SHM} flight. If we have, for example, 95% confidence that in the future I_{SHM} flight cycles the crack in a panel will not exceed a_{maint}, then this panel will not be replaced at the present maintenance stop. The selection for I_{SHM} can be determined in several ways. It is generally designed to maintaining a desired frequency of unscheduled maintenances or it can be just chosen based on the existing experiences of scheduled maintenance interval that recommended by certification authorities or aircraft manufacturers. The optimization of parameter I_{SHM} taking into consideration of boundary conditions like frequency of unscheduled maintenance and maintenance cost is the future work to be researched. In this paper, I_{SHM} is set to be 4000 for initial attempts referring to the scheduled maintenance interval of a short-range commercial aircraft. The detailed process of the new CBM maintenance strategy, called CBM new, is presented in Figure 1.

3.2 CBM-Skip based strategy

CBM-Skip is a hybrid strategy proposed in [2] that combines the scheduled maintenance with the traditional CBM approach. CBM-Skip has the same objective as pure CBM in term of reducing unnecessary maintenance stops. However, CBM-Skip ensures as much as possible that maintenance activities are carried out in scheduled maintenance interval. As in section 3.1 we propose to modify CBM-skip here to take into account the panel to panel variability and use a probabilistic estimate of the crack propagation to determine the necessary maintenance actions. The idea of CBM-Skip is described as follow. The maintenance assessment is carried out at scheduled maintenance time as well as every 100 cycles for unscheduled maintenance. At every scheduled maintenance stop, for each panel the crack size evolution from current stop up to next scheduled maintenance stop is predicted by using Monte Carlo simulation. If the 95% of percentile of crack size exceeds the threshold a_{maint} then this panel is replaced. The Flight cycles between two consecutive scheduled maintenance stop is noted by I_{sch}, which is generally selected from the scheduled maintenance interval according to the

corresponding aircraft type. If no panel needs to be replaced at this scheduled time, then CBM-Skip recommends skipping this structural airframe maintenance. If a crack missed at the time of scheduled maintenance grows critical between two consecutive scheduled maintenances, CBM-Skip will recommend structural airframe maintenance to be performed immediately when this crack exceeds the threshold a_{maint}. This calls for unscheduled maintenance, which is costlier but guarantees safety. The number of flight cycles from current unscheduled maintenance until next scheduled maintenance stop is denoted by I'_{SHM}. At each unscheduled maintenance stop, we predict the crack propagation in the future I'_{SHM} cycles by Monte Carlo method. If the 95% of percentile of crack size exceeds a_{maint} then this panel is replaced. Note that I'_{SHM} is distinct from I_{SHM} that was used in the CBM strategy. In CBM strategy, I_{SHM} is optimized satisfying some certain constrains like a desired reliability level and lowest cost. Once it is determined, it keeps constant. While in CBM-Skip, I'_{SHM} is a variable depending on how many flight cycles are left from current cycle to next schedule maintenance time. The new CBM-Skip procedure, called CBM-Skip new, is shown in Figure 2.
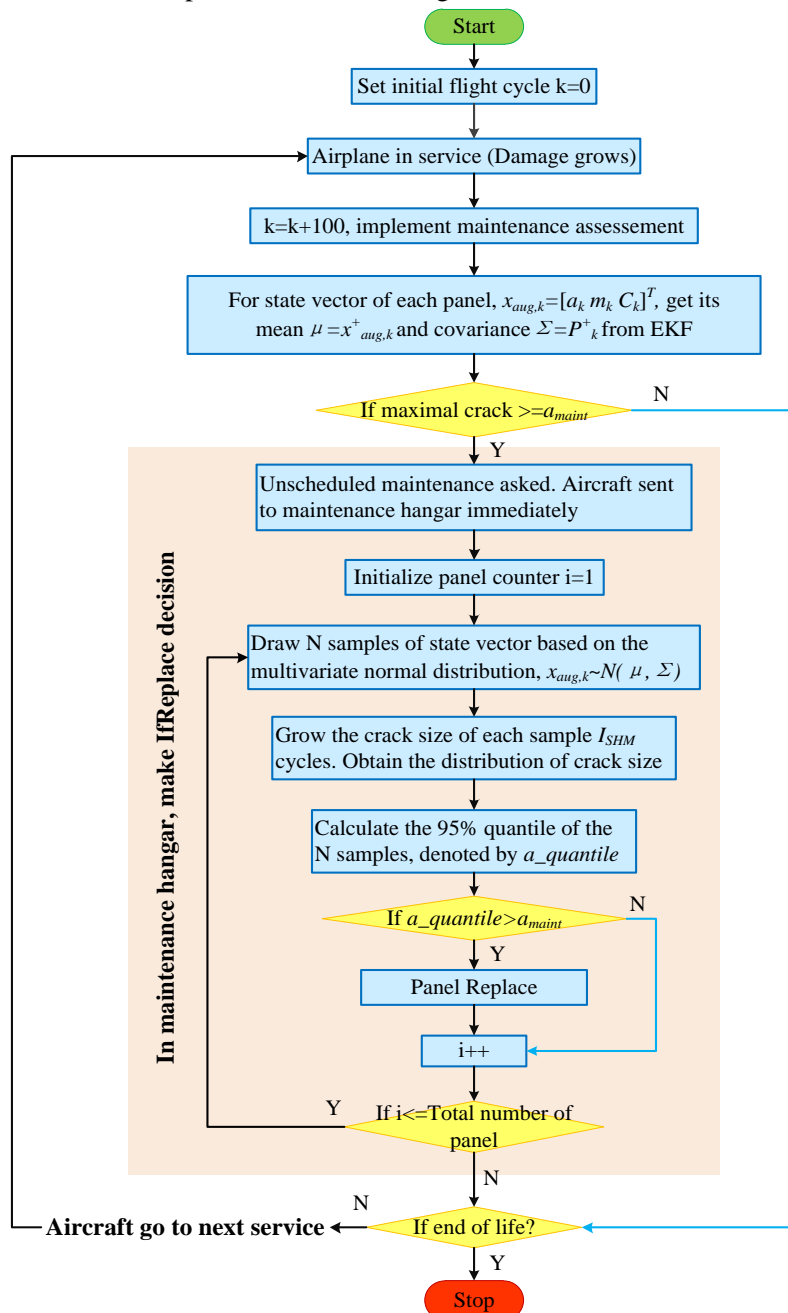

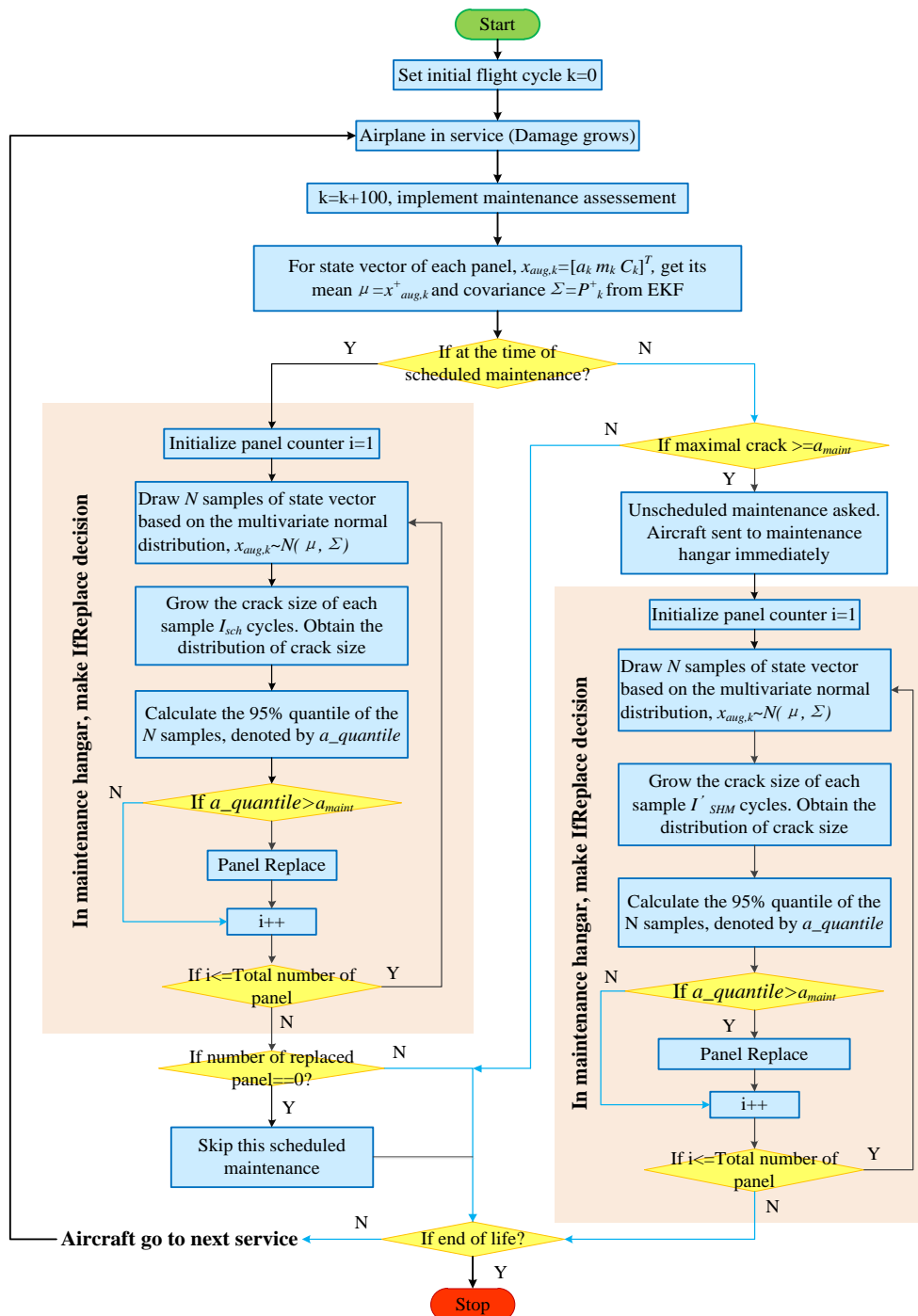**Figure 1 Flowchart for the CBM new strategy**

Figure 2 Flowchart for CBM-Skip new strategy

4   Comparison between CBM and CBM-Skip based strategies

In this section, the two maintenance strategies will be compared in terms of the number of maintenance stops and number of panels replaced. A typical short-range commercial aircraft (e.g. A320, B737) is considered here. The schedule maintenance for this kind of aircraft is that the first maintenance happens at 20000 flight cycle and consecutive maintenance is implemented every 4000 cycles until its end of life, which is 60000 cycles. A fleet of 100 aircrafts is simulated. Each aircraft is assumed to have 500 fuselage panels and each panel is assumed to have an initial crack. The values in Table 1 are used in this case study. The comparison results are shown in Table 2.

The CBM is completely random in nature, meaning that maintenance stop can occur any time within the lifetime of the aircraft. The proposed CBM new strategy indicates that on average an aircraft

undergoes very few maintenance stops during their lifetime compared with scheduled maintenance (10 maintenance stops). However, the pure CBM strategy always requires unscheduled maintenances, which can be quite disruptive of the airline's traditional service planning and can thus be quite costly. CBM-Skip has a little higher average maintenance stop than pure CBM, however it has almost no unscheduled maintenances. This strategy incorporates the advantages of scheduled maintenance and CBM. It reduces the maintenance stops and reduces the cost of unscheduled maintenances compared to CBM because the number of unscheduled maintenance is negligible here.

Table 1

Parameter	Notation	Type	Value
Panel-to-panel uncertainties			
Initial crack size	a_0	Lognormal	LnN (0.2e-3, 35%COV)
Mean value of m	μ_m	Deterministic	3.8
Standard deviation of m	σ_m	Deterministic	0.27
Mean value of C	μ_C	Deterministic	$Log_{10}(1.5e\text{-}10)$
Standard deviation of C	σ_C	Deterministic	0.16
Correlation coefficient of m and C	ρ	Deterministic	-0.8
Paris' law parameter	m_0	Multivariate	$N(\mu_m, \sigma_m, \mu_C, \sigma_C, \rho)$
Paris' law parameter	C_0	normal	
Individual panel uncertainties used in EKF			
Estimated initial crack length	$\hat{a}_0$	Uniform	$U[a_0\text{-}25\%\,a_0,\ a_0\text{+}25\%\,a_0]$
Estimated initial m	$\hat{m}_0$	Uniform	$U[m_0\text{-}25\%\,m_0,\ m_0\text{+}25\%\,m_0]$
Estimated initial C	$\hat{C}_0$	Uniform	$U[C_0\text{-}25\%\,C_0,\ C_0\text{+}25\%\,C_0]$
Initial error covariance matrix	P_0	Deterministic	$diag\ (1e\text{-}4,1,1e\text{-}10)$
Measurement noise variance	Ra	Deterministic	$(30\%\,a_0)^2$
Measurement noise variance	Rm	Deterministic	$(50\%\,m_0)^2$
Measurement noise variance	RC	Deterministic	$(50\%\,C_0)^2$
Aircraft geometry parameters			
Fuselage radius	r	Deterministic	1.95
Panel thickness	t	Deterministic	2e-3
Correction factor	A	Deterministic	1.25
Parameters related to maintenance			
Unscheduled maintenance threshold	a_{maint}	Deterministic	39.5e-3
Parameter in SHM strategy	I_{SHM}	Deterministic	4000
Parameter in CBM-Skip strategy	I_{sch}	Deterministic	4000

Table 2 Comparison of the two maintenance strategies

Maintenance strategy	Average No. of maintenance stops per aircraft	Average No. of unscheduled maintenance stops per aircraft	Average No. of panel replaced
CBM new	1.28	1.28	3.4
CBM-Skip new	4.64	0	6.7

5   Conclusions

This paper presents two kinds of condition-based maintenance strategies based on structural health monitoring. The measurement uncertainty of SHM system is considered and the noisy SHM data is incorporated into a deterministic Paris' law model using extended Kalman filter to improve the accuracy of the crack size estimation. Based on the estimated crack size, new CBM and CBM-Skip strategies are developed. The proposed CBM new strategy is designed completely random without

considering scheduled maintenance time. Unscheduled maintenance can be required at any time in the aircraft's lifetime. This strategy is thus much more disruptive to traditional maintenance organization. CBM incurs much fewer maintenance stops than that of scheduled maintenance but the aircraft safety has been reduced. By contrast, CBM-Skip new incorporates both the advantages of CBM and scheduled maintenance, which reduces unnecessary maintenance stops (although a little bit higher than CBM but still much lower than scheduled maintenance) as well as guarantees aircraft safety. Furthermore, by applying CBM-Skip, almost all maintenance stops occur during one of the ten scheduled interval when engine and non-structural maintenance are implemented. This is likely to have a beneficial role in terms of lifetime maintenance costs.

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