Effects of Uncertainty Reduction Measures by Structural Health Monitoring on Safety and Lifecycle Cost of Airplanes

Sriram Pattabhiraman[1], Nam H. Kim[2], and Raphael T. Haftka [3]
University of Florida, Gainesville, FL 32608

In aircrafts, fuselage inspections are performed regularly to remove large damages that threaten the safety of the structure. Traditionally preventive inspections have been scheduled and performed leading to high costs over the lifecycle of an airplane. Recently, structural health monitoring techniques have been developed that uses sensors and actuators to detect damages on structures paving way for progressive inspection. In this paper, the cost effectiveness of progressive inspection over scheduled inspection is analyzed. The lifecycle of an airplane was modeled as blocks of damage propagation interspersed with inspection. The Paris model with random parameters is used to model damage growth, and detection probability during inspections is modeled by Palmberg expression. Monte Carlo Simulations delineate the process. SHM based progressive inspection are found to be 50% more cost effective than schedule-based preventive inspections. The sensitivity of the lifecycle cost to the inspection parameters has been studied. To accommodate critical panels which must be manually inspected, a hybrid model of inspection is also proposed. The hybrid model is found to have sufficient cost savings over scheduled inspection model.

Nomenclature

a	=	Half damage size
p	=	Pressure differential
t	=	Thickness of the fuselage
r	=	Fuselage radius
m	=	Paris Law exponent
C	=	Paris Law constant
$a_{h\text{-}man}$	=	Palmberg parameter for manual inspection w
β_{man}	=	Palmberg randomness parameter for manual inspection
$a_{h\text{-}shm}$	=	Palmberg parameter for SHM based inspection
β_{shm}	=	Palmberg randomness parameter for SHM based inspection
N_{man}	=	Frequency of manual inspections
N_{shm}	=	Frequency of SHM based inspections
a_{th}	=	Threshold crack length for sending the aircraft to maintenance in SHM based inspection
$a_{rep\text{-}man}$	=	Threshold for replacing panels in manual inspections
$a_{rep\text{-}shm}$	=	Threshold for replacing panels in SHM based inspections

I. Introduction

TRADITIONALLY, aircraft structures have been designed using the concept of damage tolerance (Hoffman, 2009 [1]) in which the structures are designed to withstand small damage, and large damage is repaired through scheduled inspections and maintenance. This concept turned out to be more cost-effective than safe-life design because airplanes designed based on safe-life would be much heavier. In damage tolerance design, it is important to inspect the airplane regularly such that all damages that can possibly threaten the safety of the structure should be repaired.

Scheduling inspections requires a trade-off between the structural safety and lifecycle costs. For example, if an airplane is inspected every flight, the safety can significantly be improved but the cost of inspections could be very high, so only visual inspection by the pilot is conducted. The current practice is a thorough intrusive inspection, also called the 'C' type inspection at every 6,000 flights [2], which is based on experience. Kale et al. (2008)[3] showed that this interval is close to optimal for fuselage panels and that the lifecycle cost is reduced by 30% compared to the

[1] Graduate student, Dept. of Mechanical and Aerospace Engg,.psriram85@ufl.edu. Student Member
[2] Associate Professor, Dept. of Mechanical and Aerospace Engg,.nkim@ufl.edu, AIAA Member
[3] Distinguished Professor, Dept. of Mechanical and Aerospace Engg,.haftka@ufl.edu, AIAA Fellow

safe-life design, at the same level of safety. The long interval between manual inspections is due to high inspection costs and downtime.

Recently, structural health monitoring (SHM) systems have become available using on-board sensors and actuators. These systems can perform inspections as frequently as needed without requiring much downtime and inspection costs (Boller (2000) [4]. Boller and Meyendorf (2008) [5] observes damage monitoring by SHM as a good tool to enhance inspection. However, the detectable damage size from most SHM devices is much larger than that of the manual inspections. The current technology of SHM allows to detect damage as low as 5 µm and to detect it at 20,000 cycles well before a panel's eventual failure at 46,000 cycles. (Papazian,et al (2009) [6]). These SHM devices can continuously monitor the damage growth and request for maintenance when damage grows beyond a threshold. In this process, many variables are involved to keep the airplane safe, such as the frequency of SHM inspections and the threshold for maintenance. In this paper, these variables are referred to as SHM parameters. The objective of this paper is to study the effects of these SHM parameters on the safety and lifecycle costs of airplanes.

Yang and Trapp (1975) [7] appear to have first formulated the problem of the determination of the optimum inspection frequency as a constrained minimization problem. They indicated that various variables including inspection frequency and inspection quality can be adjusted in such a way so as to minimize a pre-defined cost function. Hellevik et al. (1999)[8] optimized the pipeline thickness together with the inspection regime to minimize the total operational cost. Kleyner and Sandborn (2008) [9] minimize lifecycle cost for an automotive electronics application considering product reliability and warranty return cost. Mizutani and Fujimoto (1993) [10] presented a sequential minimization method which aims to find an optimal inspection strategy so that the total cost expected in the period between the present inspection and the next is a minimum. Kassapoglou (1997)[11] minimized the cost and weight for manufacturing of stiffened panels.

Kulkari and Achenbach (2007) [12] optimize inspection schedule by minimizing the total cost function. They model crack propagation using Paris law but by assuming constant material properties. In this paper, fatigue crack propagation in fuselage panels under repeated pressurizations is modeled using the Paris model with uncertain parameters. The Palmberg equation is used to model the probability of damage detection during the inspection process with values, appropriate for SHM and manual inspection. Due to uncertainties of initial damage size and Paris model parameters, the damage sizes after a certain number of flights are randomly distributed. The inspection truncates the high tail portion of the distribution by detecting large damages and replacing the affected panels. Since it is extremely difficult to model the analytical distribution of damage sizes after propagation and replacement, Monte Carlo simulation (MCS) is employed for that purpose. Based on these procedures, the effects of SHM parameters on the safety and lifecycle costs of airplanes are studied using an estimated cost model for inspection.

The organization of the paper is as follows. In Section 2, the models for damage propagation, probability of damage detection during inspection, and cost estimation have been presented. In Section 3, the process of detection and replacement has been explained. Section 4 presents the data used for illustration. Section 5 compares the lifecycle costs for manual and SHM based inspection models. Section 6 presents a hybrid model and Section 7 summarizes the effects of SHM parameters on lifecycle costs.

II. MODELS

A. Fatigue damage growth due to fuselage pressurization

A through thickness center crack in a fuselage panel of an airplane is termed as damage in this paper. The life of an airplane can be viewed as damage propagation cycles, interspersed with inspection and repair. The pressure difference between the interior and the exterior of the cabin during each flight is instrumental in propagating the damage. The damage propagation is modeled using the Paris model, which gives the rate of damage size growth as a function of damage half - size (*a*), pressure differential (*p*), thickness of fuselage panel (*t*), fuselage radius (*r*) and the material specific Paris parameters, *C* and *m*.

$$\frac{da}{dN} = C\left(\Delta K\right)^{m}, \qquad \text{……………… (1)}$$

where $\Delta K = \frac{pr}{t}\sqrt{\pi a}$ ………………. (2)

B. Inspection model

In a SHM–based maintenance assessment or a manual inspection, the detection probability is modeled using the Palmberg equation given by,

$$P_d(a) = \frac{\left(\frac{2a}{a_h}\right)^{\beta}}{1+\left(\frac{2a}{a_h}\right)^{\beta}} \quad \text{………………. (3)}$$

The expression gives the probability of detecting a damage with size $2a$.In Eq (3), a_h is the damage size corresponding to 50% probability of deduction and β is the randomness parameter. The parameter a_h represents average capability of the inspection method, while β represents the variability in the process. In this paper, the above inspection model is used for both manual inspection and inspection by SHM, by using different values for the parameters. In the case of manual inspection, a_h will be small but β will be relatively large. On the other hand, inspection by SHM will have large a_h and small β .

C. Cost model

In order to estimate the cost efficiency of the SHM systems, it is necessary to discuss about the cost model first. The lifecycle cost of an airplane, ignoring the cost of ownership, depends mainly on four factors, manufacturing cost, fuel cost, crew cost and maintenance cost (refer to Fig 2, Curran et al (2009) [12]). The crew cost depends on the mileage on the airplane and hence is ignored for the comparison intended in this paper. The effect of fuel cost is considered through weight penalty.

The approach of a weight penalty, given as the lifetime fuel burn cost per weight has been introduced in the work done by Kelly and Wang (2003)[14], Wang et al.(2002) [15] and Curran et al.(2004) [16]. The quantification of weight penalty however is not trivial. Kaufmann, et al (2008) [17]used a weight penalty of €1500 / kg or about $930 / lb over the life of an aircraft considering composite aircraft structures. An editorial by Kim, et al (2008) [18] refers to $200 savings over the life of an aircraft for every lb of weight saved. Based on the literature, two cases of weight penalties have been considered, the values of which are tabulated in Table 1. The manufacturing cost per lb of panel has been assumed to be $500.

The different maintenance operations performed on an airplane are classified in four categories, ‘A’, ‘B’, ‘C’,’D’, arranged in the increasing order of time spent for each type. Types ‘C’ or ‘D’ are the most time consuming and expensive of them all. This paper focuses on the ‘C’ type inspection.

The inspection and maintenance cost for an airplane depends on many factors such as number of labor hours, the revenue lost during the time the airplane is in the hangar and the cost for the facility and equipment. The B-737 of Lufthansa airlines [19] spends about four days on an average in the maintenance hangar for a ‘C’ type inspection and has about 1700 hours of labor, on an average, done on it during that period. Mcelroy (2006) [20] notes a labor rate of $60 /hr for inspection and maintenance work in the hangar and the industrial average revenue of $27,428 / day.

In SHM based inspection, the inspection would be done by sensors attached on board and hence, only the replacement / corrective action needs to be performed in the hangar. So, the number of days in the maintenance hangar for an airplane inspected by SHM has been assumed to be equal to one and the number of labor hours has been prorated from the information above. The inspection cost thus calculated is simply doubled to consider the effect of facility and equipment.

To replace a damaged panel, a cost of $500 / panel has been assumed. The cost of replacing simply the SHM equipment has been assumed to be 20% of the panel replacement cost. Table 1 show the cost model used in this paper. The downtime cost, inspection cost in the maintenance hangar, cost of replacing SHM equipment and the replacement cost constitute the inspection cost.

Table 1: Cost model

	Manual Inspection	**SHM based Inspection**	**Remarks**
Manufacturing Cost ($)	500 / lb	600 / lb	SHM installation costs 20% more
Fuel Cost ($)	Case 1: 200 / lb Case 2: 1000 /lb	Case 1: 240 / lb Case 2: 1200 /lb	SHM panel has a 20% extra weight.
SHM Installation Cost ($)	--	20 % of Mfg cost	
Maintenance Assessment Cost ($)	--	negligible	
Labor Cost in Hangar ($)	60/hr	60 / hr	
Downtime cost during Inspection ($)	27,428/ airplane/day	27,428 / airplane/day	
Time for Inspection in Hangar	4 days and 1700 hours of labor	1 day and 425 hours of labor	
Panel Replacement Cost ($)	500 / panel	500 / panel	
Replacing SHM equipment ($)	--	100 / panel	20% of Panel replacement cost

III. INSPECTION PROCESS MODEL

The inspection process monitors damage and replaces/repairs the fuselage panel when the damage reaches a critical size so as to threaten the safety of the airplane. In mathematical sense, the inspection process partially truncates the tail of the damage size distribution. The procedure is illustrated in Figure 1 for typical values.

The red curve represents the damage size distribution when the airplane enters the maintenance hangar;i.e. before inspection. In the maintenance hangar, all damages detected and found to have a size greater than a_{rep} is replaced. Since the detection is also a random process, only a part of the tail of the damage size distribution is replaced. The partially truncated damage size distribution obtained after inspection is shown in green in Figure 1. This section discusses the different types of inspection processes considered in this paper

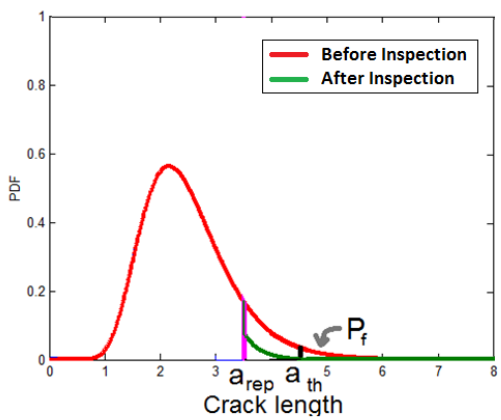

Figure 1: Explaining the Inspection and Replacement process through crack length distributions

A. Manual Inspection

Manual inspections are scheduled at specific pre-determined intervals. Let N_{man} denote the number of flights between inspections. Due to repeated pressurization, the damage propagates during those N_{man} flights. In damage tolerance design, the inspection schedule is designed in order to remove panels with large cracks that threaten the safety of the structure. At the time of scheduled maintenance, the airplane is sent to the maintenance hangar. At the hangar, the maintenance inspectors inspect all the panels in that airplane and replace those in which damage was detected and the damage size found to be greater than a particular threshold, $a_{rep-man}$. The rationale for having a threshold $a_{rep-man}$ is to prevent failure of panels in between the scheduled maintenance. The flowchart in Figure 2 depicts the scheduled maintenance process

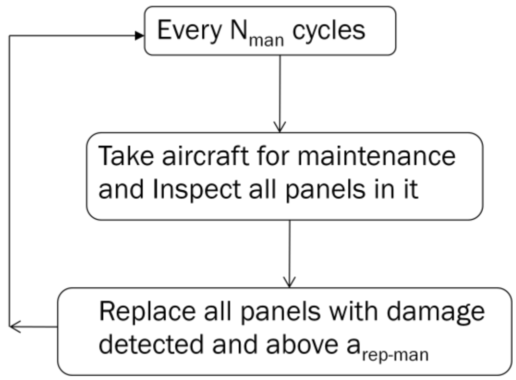

Figure 2: Flowchart of the scheduled maintenance process in manual inspection case

B. SHM-based Inspection

SHM-based inspection uses on-board sensors and hence, can be performed frequently without hampering the operational schedule. Let N_{shm} denote the number of flights in between scheduled maintenance assessments using SHM. It is noted that the value of N_{shm} can be as low as one or two cycles and the maintenance assessment costs for SHM-based inspection are quite negligible. The damage propagates in between the scheduled maintenance assessments due to repeated fuselage pressurization. During maintenance assessment, if damage is detected, and if its size found to be greater than a threshold value (a_{th}), the airplane is sent to a maintenance hangar. In the maintenance hangar, all the panels in the airplane are inspected by the on-board SHM equipment and those panels detected, and with damage size larger than another threshold value $a_{rep-shm}$, are replaced. The rationale for having another threshold, $a_{rep-shm}$ is to prevent sending the airplane back into the maintenance hangar at the next maintenance assessment.

Once inspected (and its damaged panels replaced), the airplane is brought back into service and repeated pressurization propagates damage for another N_{shm} flights till the next scheduled inspection / maintenance assessment. The flowchart in Figure 3 below depicts the maintenance scheduling procedure for SHM-based Inspection.

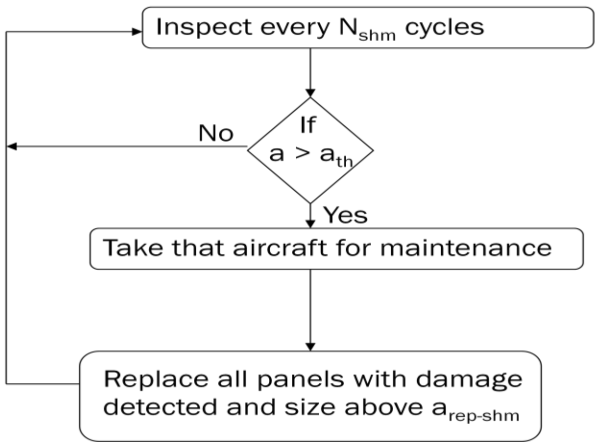

Figure 3: Flowchart depicting maintenance scheduling for SHM based Inspection

After inspection and maintenance, the tail portion of damage size distribution is partially truncated at a_{rep}. For SHM-based inspection, the distribution beyond a_{th} corresponds to the percentage of panels with high damage size, missed due to either infrequent inspection or randomness in the inspection process. Hence, in Figure 1, the area beyond a_{th} for the green plot is the fraction of high damage panels missed during the inspection and the difference between area beyond a_{rep} for the green and red plots gives the fraction of panels replaced during that particular inspection.

It can be seen clearly that for SHM based inspections, the safety of the airplane depends on the frequency of inspections (N_{shm}), the threshold for sending the airplane for maintenance (a_{th}), and the threshold for replacement for highly damaged panel in the maintenance hangar ($a_{rep\text{-}shm}$). These variables have been collectively called the SHM parameters. Since the inspection by SHM allows frequent inspections, the lifecycle cost is a more of an issue compared to the safety of an airplane. The effect of these SHM parameters on the life time cost of an airplane in studied in section VII.

IV. DATA USED FOR ILLUSTRATION OF COST MODEL

Aluminum alloy 7075 – T6 is considered as the material of the fuselage. All panels are of dimension 609.6mm × 609.6mm× 2.48mm and are assumed to possess a single crack at the center of the panel and subjected to tension. Table 2 shows the parameters used.

Table 2: Parameters and their values

Parameter	**Type**	**Value**
Initial damage size (a_0)	Random	LN(0.2, 0.07)
Pressure (p)	Random	LN(0.06,0.003)
Radius of fuselage (r)	Deterministic	3.25 m
Thickness of fuselage panel (t)	Deterministic	2.48 mm
Paris Law constant (C)	Random	U[5E-11, 5E-10]
Paris Law exponent (m)	Random	U[3, 4.3]
Palmberg parameter for SHM based inspection ($a_{h\text{-}shm}$)	Deterministic	5 mm
Palmberg parameter for SHM based inspection (β_{shm})	Deterministic	5.0
Palmberg parameter for Manual inspection ($a_{h\text{-}man}$)	Deterministic	0.63 mm
Palmberg parameter for Manual inspection (β_{man})	Deterministic	2.0

Newmann et al (1999) (Pg 113, Fig. 3)[21] shows 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. (Fig. 3, Newmann, et al (1999)).

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(Fig. 3, Newmann et al (1999)).

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 each discretized into 100 points. Each point on the left edge corresponds to a value of C chosen. For a given value of C chosen, there are 100 possible values of the slope, m. Figure 4 plots those permissible ranges of slope (*m*), for a given value of intercept (*C*). It can be clearly seen from Fig. 4 that the slope, and log(*C*) are negatively correlated; the correlation coefficient is found to be -0.8065.

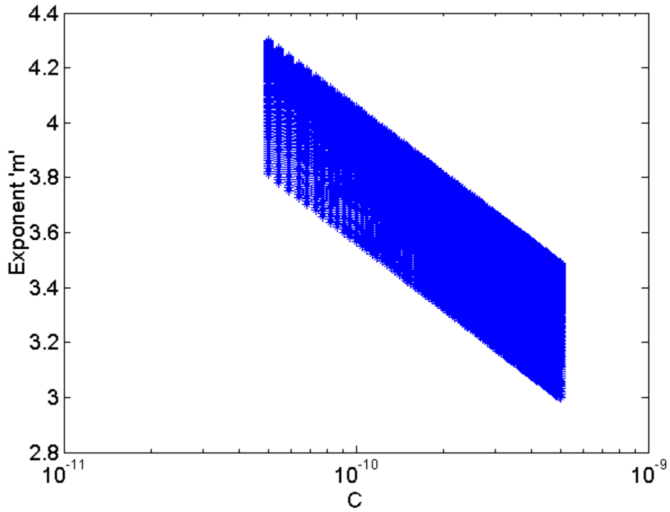

Figure 4: Correlation between Paris model parameters

V. COMPARING LIFECYCLE COSTS OF MANUAL AND SHM BASED INSPECTIONS

The lifecycle of the airplane is considered to be 50,000 flights. This section compares the total lifecycle costs for the manual and SHM-based inspection cases. For the manual inspection case, the scheduled maintenance for the airplane is every N_{man} = 6000 flights and the threshold for panel replacement in the maintenance hangar is $a_{rep\text{-}man}$ = 0.5 mm. For the SHM-based inspection, the maintenance assessment is performed by the on-board SHM equipment every 500 flights. Airplanes with damages detected during this assessment and found to have a damage size greater than a_{th} = 40 mm are sent to the maintenance hangar.

The above discussion assumed that the SHM equipment on-board has an infinite life or at the least, the equipment has same life as that of the airplane. In an attempt to be more realistic whilst staying conservative, a case of SHM-based inspection with a finite life of 12,000 flights for the SHM equipment is considered. For this case, the airplane needs to be sent to a scheduled maintenance after 12,000 flights to replace panels with worn-out SHM equipment in addition to its maintenance visits due life-threatening damage.

Since there is no analytical expression to model propagation of damage size distributions when replacements are involved, the process has been modeled using Monte Carlo Simulation (MCS). A fleet of 200 airplanes and 500 panels / airplane have been considered. A matrix of size 200*500 crack-size values realized such fleet in the simulation. The initial damage size (a_0) and the Paris law parameters (*C* and *m*) are randomly assigned to each panel according to their distribution parameters in Table 2. The pressure is also assumed to vary at each flight. The initial cracks grow according to the Paris law. In the case of manual inspection, all airplanes are sent to the maintenance hangar and all panels that have cracks greater than $a_{rep\text{-}man}$ are preplaced with new panels; these panels will have randomly assigned initial damage size. In SHM-based inspection, those airplanes that have cracks larger than a_{th} will be sent to the maintenance hangar, which can be realized by considering only those certain rows of the matrix.

The number of airplanes sent for maintenance (AM) and the number of panels replaced (PR) until the end of life, are calculated for a fleet of 200 airplanes. The inspection cost is calculated based on the cost model of Table 1.Since the Monte Carlo Simulation show sampling noise, Table 3 tabulates the noise associated with the output variables due to random sampling for the SHM based inspection case with life of equipment considered.

Table 3: Variability in the output variables due to random sampling for SHM based inspection case with life of the equipment considered for $200 / lb weight penalty

Case	No. of failed panels	Total no. of airplanes sent for maintenance (AM)	Total number of panels replaced (PR)	Mfg cost /panel ($)	Fuel cost /panel ($)	Main + Repl cost / panel ($)	Total cost /panel ($)
Mean	0	710	1800	3240	1300	760	5300
SD	0	9.4	35.1	0	0	10.2	10.2

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Table 4 compares the overall cost for these two different cases of inspections. It is noted that the total cost is the sum of fuel, manufacturing and inspection cost.

Table 4: Comparison of lifecycle costs for manual and SHM based inspection cases based on cost model in Table 1 for $200/lb weight penalty

Case	No. of failed panels	Total no. of airplanes sent for maintenance (AM)	Total number of panels replaced (PR)	Mfg cost /panel ($)	Fuel cost /panel ($)	Main + Repl cost / panel ($)	Total cost /panel ($)
Manual	0	1,600	23,800	2,700	1,080	6,900	10,675
SHM	0	7,10	1,800	3,240	1,300	760	5,300
SHM + life of equip considered	0	1,370	1,800	3,240	1,300	1,860	6,400

Since a fleet of 200 airplanes has been considered, an AM value of 710 would suggest that an airplane goes for maintenance about 3.5 times on an average throughout its life. Similarly a PR value of 1800 suggests that, on an average, 9 panels are replaced in an airplane until the end of its life. Table 3 suggests that replacing existing manual inspection model with SHM based inspection leads to about 50% reduction in lifecycle cost. It is noted that the main cost drivers are manual inspection and fuel. SHM required about 20% more fuel cost, but the cost of manual inspection is orders of magnitude higher than the fuel cost.

Changing the weight penalty affects simply the fuel cost and hence, the percentage savings obtained by SHM based inspection over Manual inspection. Table 5 below compares the cost saving between different weight-penalties

Table 5: Percentage cost savings for different cases of SHM based inspection over manual inspection for different weight penalties

Case	% cost savings over Manual Inspection	
	$200 / lb	$1,000 / lb
Manual	--	--
SHM	0.50	0.30
SHM + equip	0.40	0.23

VI. HYBRID INSPECTION MODEL

Some fuselage panels are either critical to the safety of the airplane (the panel at the intersection of wing and fuselage) or cannot be handled by SHM based equipment due to geometric constraints. Such panels, called the “critical panels”, have to be manually inspected. A hybrid inspection model is then proposed in which the critical panels are to be inspected manually, while the rest by the on-board SHM equipment. The critical panels are inspected manually during the scheduled maintenance every 6000 flights. The on-board SHM equipment performs maintenance assessment and requests maintenance when the damage size in the panel crosses a threshold. Even when the airplane is in the maintenance hangar for scheduled maintenance, the on-board SHM equipment is activated and the non-critical panels detected with damage size greater than a threshold $a_{rep\text{-}shm}$ are replaced. The cost of inspection for manual inspection is pro-rated based on percentage of critical panels in the airplane. For the same values of uncertainty reduction variables considered in the previous section, the lifecycle cost for hybrid inspection models with varying percentages of critical panels is tabulated in Table 6.

Table 6: Comparing lifecycle costs for different percentage of critical (manually inspected) panels in an airplane for $200 / lb weight penalty

% of critical panels	No. of failed panels	Total no. of airplanes sent for maintenance_SHM (AM_SHM)	Total no. of airplanes sent for maintenance_Manual (AM_Man)	Total number of panels replaced (PR)	Mfg cost /panel ($)	Fuel cost /panel ($)	Main + Repl cost / panel ($)	Total cost /panel ($)
100	0	-	1,600	23,800	2,700	1,080	6,900	10,675
75	0	160	1,600	8,300	2,840	1,134	5,390	9,360
50	0	280	1,600	6,000	2,970	1,190	3,910	8,070
25	0	400	1,600	3,900	3,100	1,240	2,430	6,780

In Table 6, AM_SHM refers to the number of airplanes sent to maintenance hangar in between the scheduled maintenance. For instance, when 75% of panels are critical, AM_SHM value of 160 panels means that each airplane had an unscheduled maintenance about 0.8 times on an average.

It is noted here that the lifecycle cost of an airplane reduces with the percentage of critical panels in it.

Table 7 compares the percentage cost savings over manual inspection for the different cases considered in Table 6 above.

Table 7: Percentage cost savings of different cases of SHM based inspection over Manual inspection for different cases of weight penalty

% of critical panels	% cost savings over Manual Inspection	
	$200 / lb	$1,000 / lb
100	--	--
75	0.12	0.07
50	0.24	0.14
25	0.36	0.22

VII. EFFECT OF SHM PARAMETERS ON COSTS

The lifecycle cost of an airplane is the sum of fuel, manufacturing and inspection costs. The number of airplanes sent for maintenance and the total number of panels replaced (PR) contribute to the inspection cost. All the variables discussed above that are instrumental in calculating the lifecycle cost of an airplane constitute the output variables.

For the manual inspection model, the scheduled maintenance is every 6,000 flights [11]. Choosing a $a_{rep\text{-}man}$ replacement threshold size of 0.5 mm is found to have been effective in preventing failure at 10^{-3} reliability until the next scheduled maintenance. Failure is defined when the damage size exceeds 100 mm. Table 8 below tabulates the average number of failures for 9 runs until the end of life for different cases of $a_{rep\text{-}man}$

Table 8: The average number of failures for 9 runs until the end of life for different cases of $a_{rep\text{-}man}$

arep-man	Mean number of failures for 9 runs
1	0.9
0.9	0.1
0.8	0.1
0.7	0.1
0.6	0.1
0.5	0.0

It is noted that at 10^{-3} reliability, no failures were observed and hence $a_{rep\text{-}man}$ value of 0.5 mm was chosen for the analysis.

For the SHM based inspection model, the threshold for sending the airplane to maintenance (a_{th}), the threshold for replacing panels in the maintenance hangar (a_{rep}) and the frequency of inspections are the parameters that affect the inspection cost. As the inspection and maintenance cost dominates the replacement cost, a large difference between the two thresholds will results in fewer trips to the maintenance hangar and hence, would be cost effective. The threshold for sending the airplane to maintenance, a_{th} has been chosen as 40mm based on psychological constraints. The effect of the two remaining uncertainty reduction variables on the lifecycle cost is analyzed by Fig. 5. Figure 5 plots the variation of total cost / panel with the threshold for replacement at the hangar ($a_{rep\text{-}shm}$) for different values of frequency of maintenance assessment (N_{shm}), when the weight penalty is \$200 / lb. Figure 5 shows that the lifecycle cost increases with a_{rep} as that would warrant frequent maintenance. The variation with respect to the frequency of inspections remains fairly constant.

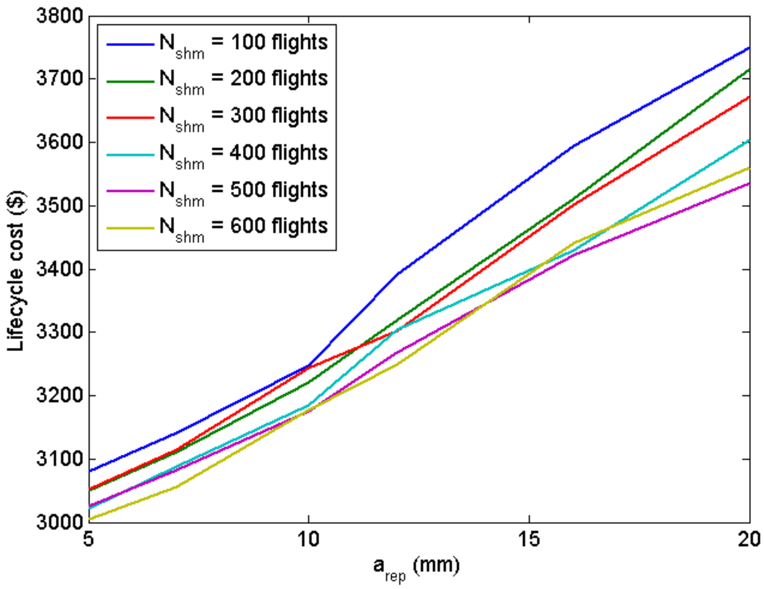

Figure 5: Variation of total cost / panel with N_{shm} and $a_{rep\text{-}shm}$ for weight penalty = \$200 / lb

VIII. CONCLUSIONS

- The paper focuses on studying the effects on life time cost and safety of aircrafts, when the inspections are performed using structural health monitoring.
- Since SHM-based inspection would be performed by on-board equipment, it can be performed frequently. Inspection cost for such model will simply have an installation cost and very negligible operational cost.
- SHM based inspection model could lead to about 50% in savings over the manual inspection model
- To cater to the need of critical panels that could be inspected only manually, a hybrid inspection model is proposed and is found to be economical than manual inspection model
- The effect of SHM based inspection parameters on the lifecycle cost has been analyzed. It is found that the effect of inspection interval on the total cost is very small because independent of inspection interval, the existing damages will grow. On the other hand, the effect of replacement threshold is significant on the total cost because intermediate sized damages between a_{th} and a_{rep} are allowed to exist without being replaced.

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