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THE INFLUENCE OF SHM TECHNIQUES ON SCHEDULED MAINTENANCE OF AIRCRAFT COMPOSITE STRUCTURES

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Abstract

Scheduled maintenance procedures for civil aircraft structures went through decades of evolution from hard time replacement to time-based inspection. Currently, different inspection tasks are carried out at predetermined intervals to check the condition of structural components. If the condition of the structure exceeds a certain threshold, repair activities are initiated. The two key parameters in scheduled maintenance are the inspection interval and the repair threshold. The development of new materials such as composites and the introduction of advanced Structural Health Monitoring (SHM) techniques, will have a profound effect on scheduled maintenance. Considering the current level of maturity of SHM technologies, several combinations of SHM and scheduled maintenance are proposed in this paper and a probabilistic analysis is performed to quantify the savings on maintenance cost.

1 Introduction

In the past 50 years, scheduled maintenance of aircraft structures has gone through several important transformations which can be reflected in the development of the Maintenance Steering Group (MSG) concept. The initial MSG-1, which was released in 1968, was used specifically for the Boeing 747 aircraft. In order to generalize the maintenance method, a more universal document MSG-2 was published in the 1970s, which follows a bottom-up and procedure-oriented logic. Since 1980, the decision logic was updated several times to be a top-down and task-oriented program, called MSG-3, in which maintenance tasks are scheduled based on predetermined inspection intervals to prevent any potential damage or failure of aircraft structures considering safety, operational and economic effects [1]. Nowadays, MSG-3 has been widely adopted by the commercial aviation industry for the development of minimum required scheduled maintenance for continued airworthiness [2]. However, the current MSG-3 is facing challenges with the development of the next generation aircraft. Advanced technologies have exerted a strong motivation to incorporate new concepts into MSG with a shift from preventive maintenance to prognostic maintenance.

One of the emerging technologies is Structural Health Monitoring (SHM), which refers to the process of structural damage identification via acquiring and analyzing data from on-board sensors so that the health state of the structure can be monitored on a continuous basis [3]. Taking advantage of the rapid development of advanced sensor technology and powerful computing capabilities such as data mining and data fusion, SHM is affecting the current maintenance philosophy by reducing time-consuming labor work on inspections and saving maintenance cost. In addition, SHM also has the potential of enabling new design principles such as reducing the safety factor in structural design, which will contribute to a more light-weighted aircraft.

Composite materials are increasingly used in aircraft structures. However, composite structures are susceptible to impact damage caused by runway debris, hail, tool dropping, etc. [4]. Different from single crack propagation in metallic structures, the damage tolerant design for composites follows a ‘no-growth’ approach as shown in Fig. 1.

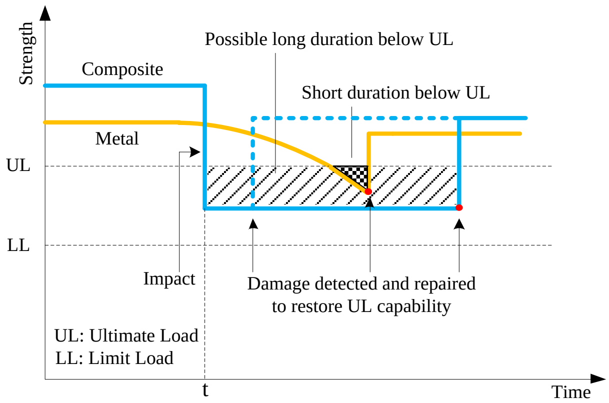

Fig. 1. Damage Tolerant Design for Metals and Composites

Generally, impact events are randomly distributed throughout the aircraft service life and may result in delamination or disbonding, which are difficult to predict and detect. Therefore, composite structures in particular will benefit from an effective SHM system.

However, SHM is still in its early development phase and has not been widely implemented on commercial aircraft. Despite many investigations into various SHM systems, several studies have begun to shift attention onto combinations between the current scheduled maintenance and SHM but they all focus on metallic structures [5-7]. This study investigates the effects of SHM on scheduled maintenance of composite structures.

2 Integration of SHM into Scheduled Maintenance

Due to different developments in SHM technologies, differences exist in the definition and classification of SHM. Recently, ARP6461 was released by SAE to standardize and harmonize world-wide understanding of SHM [3]. Two technical terms are defined herein: S-SHM stands for Scheduled SHM, which is the act of using a SHM device at an interval set at a fixed schedule. A-SHM refers to Automated SHM, which is the use of any SHM technology without a pre-determined interval when maintenance must take place but relies on the system to inform maintenance personnel that action should be initiated.

It was in MSG-3 revision 2009.1 that SHM and S-SHM were first included but only at the conceptual phase. Considering different maturity levels for various SHM systems, a flexible integration of SHM into the MSG-3 logic procedure is shown in Fig. 2.

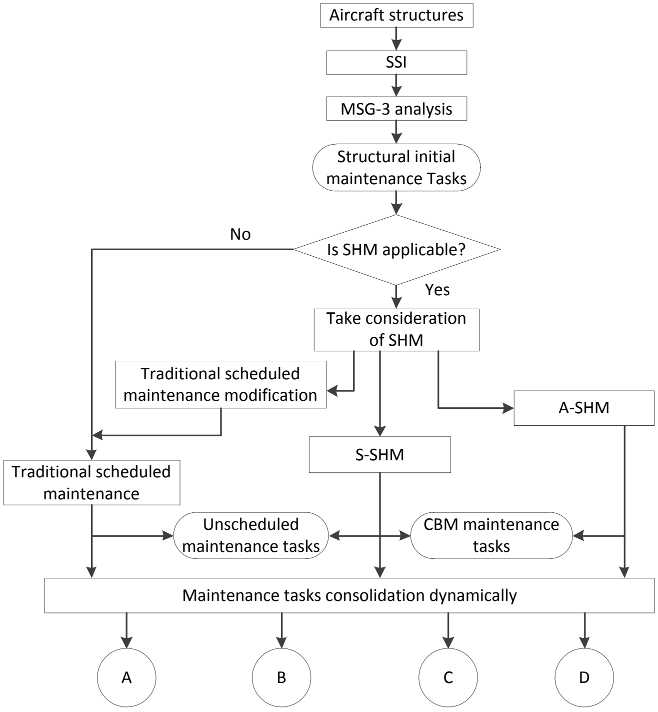

Fig. 2. MSG-3 Logic Diagram Considering SHM

A. Scheduled Maintenance

Scheduled maintenance is performed at predetermined intervals to address damages remaining undetected in normal operations. Non Destructive Inspection (NDI) is performed which often requires disassembling and reassembling structural components in locations hard to reach. Although time consuming, these detailed maintenance activities ensure aircraft safe operation until the next maintenance cycle. A typical logic procedure for maintenance of composite panels is shown in Fig. 3.

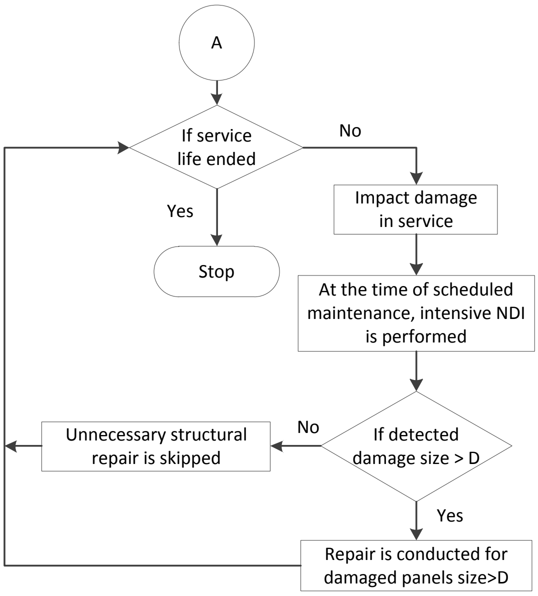

Fig. 3. Scheduled Maintenance Procedure

B. Scheduled SHM

In this scenario, an on-board SHM sensor system is implemented while the data collection and analysis system is ground-based. The SHM system can automatically detect damage without the need to remove components and therefore intrusive inspections are no longer needed. It is noted that the inspection interval and repair threshold remain the same as those in scheduled maintenance, i.e. the analysis of on-board SHM data is performed at every scheduled maintenance cycle. If damage exceeding the threshold is detected, repair activities are immediately initiated. Therefore, the use of scheduled SHM can be seen as an updated version of scheduled maintenance. A logic procedure similar to Scenario A is shown in Fig. 4.

C. Scheduled CBM

An alternative combination is designed to be a scheduled CBM procedure. With increasing maturity of SHM technologies, structures can be monitored more frequently at lower monitoring cost. The frequency of inspection in this scenario is increased by 10 times that of scheduled SHM (Scenario B). The threshold for repair can be increased due to the increased inspection frequency. This additional procedure is called maintenance assessment. In order to maintain a high safety level, scheduled SHM is requested at every scheduled maintenance cycle just as Scenario B and the repair threshold is adjusted to the original damage size. The logic procedure of scheduled CBM is shown in Fig. 5.

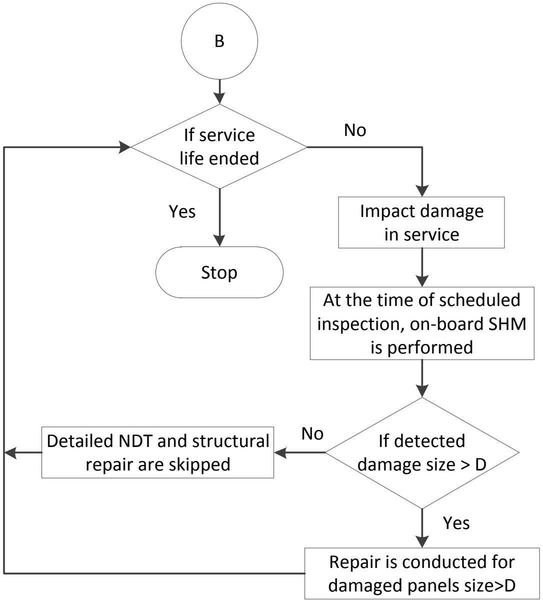

Fig. 4. Scheduled SHM Procedure

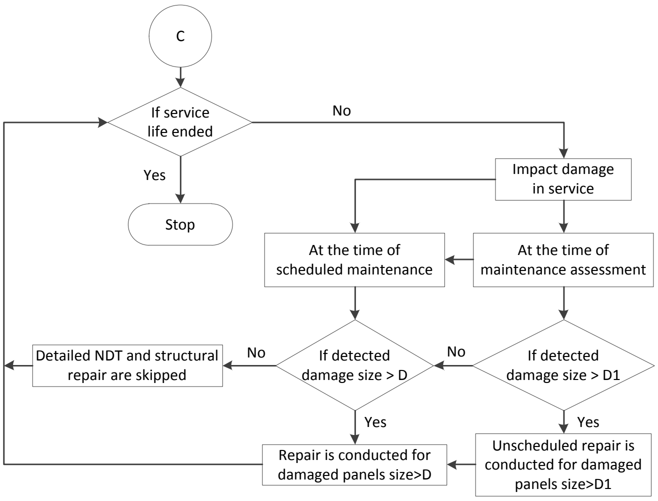

Fig. 5. Scheduled CBM Procedure

Between every maintenance assessment, unscheduled repair is conducted as long as the damage size exceeds the threshold D1 so the structure is repaired without waiting for the next maintenance cycle. Otherwise, the damaged structure will be kept in service until the next cycle which may compromise operational safety. It is noted that unscheduled repair is used in this context to distinguish from the repair performed at traditional scheduled intervals. However, since the threshold D1 in maintenance assessment is larger than D in scheduled maintenance, scheduled SHM should be carried out to repair the structure with damage larger than D so that the reliability of the structure is not impaired in the long term. This maintenance scenario can be seen as a hybrid model between scheduled SHM and CBM.

D. CBM

The most advanced scenario is presented to achieve real-time monitoring, which is based on a mature on-board SHM system and a well-developed air-ground data link system. Specifically, data relevant to structural health are well collected, transmitted and processed continuously. It is important that the maintenance decision-making module can perform autonomously and inform the operator in a timely manner when to take maintenance measures. Since the structural health can be monitored in real-time, the repair threshold can be set to D1. However, considering the reliability of the SHM system itself, it is necessary to assess the system frequently. The CBM logic procedure is shown in Fig. 6.

3 Probabilistic Model

Since impact events are randomly distributed throughout the operational service and composites have high scattered properties, traditional deterministic methodologies are not adequate to describe the life-cycle structural performance [8]. Instead, many probabilistic methods have been developed in the last two decades to address uncertainty in composite design, certification and maintenance. A probabilistic simulation flowchart is shown in Fig. 7 [9].

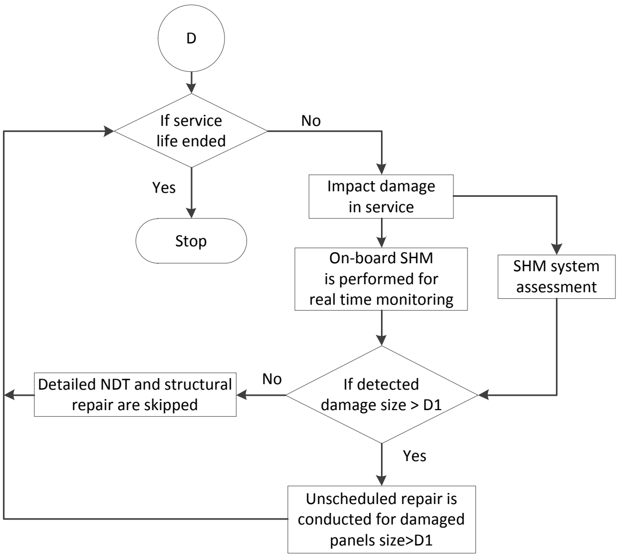

Fig. 6. CBM Procedure

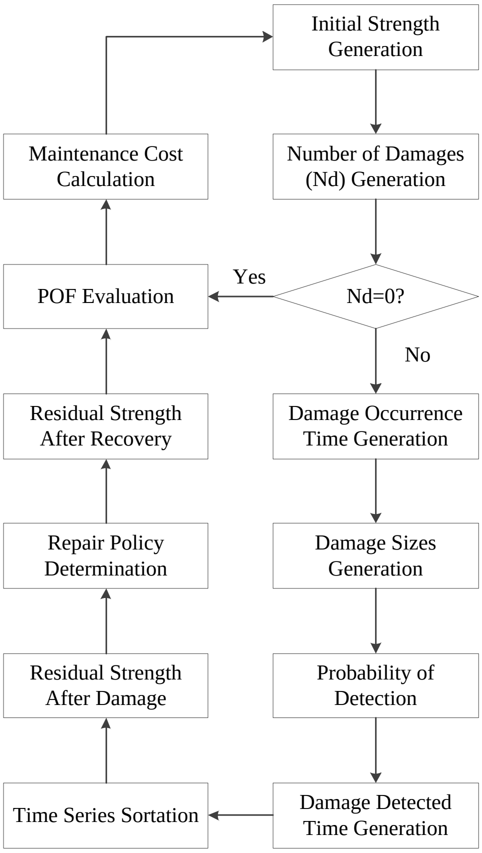

Fig. 7. Simulation Flowchart

The simulation procedure is illustrated as follows:

1. The first step is to generate the initial strength of the composite structure. Considering strength scatter introduced in the manufacturing process, a Gaussian probability distribution function (PDF) is used to describe the strength variation [10].

2. Since damage occurs as a series of discrete and random events, the number of occurrence is best described by a Poisson distribution.
3. If no damage occurs, no repair actions are required except for scheduled inspections. The probability of failure (POF) and associated maintenance cost are evaluated. Then a new generation cycle is started.
4. If damage has occurred, the occurrence time is generated. A uniform distribution generator is used due to the randomness and accidental characteristics of impact damage.
5. After the generation of occurrence time, damage sizes are generated. The distribution model depends on damage statistics from real operational maintenance records.
6. The inspection efficiency is described by the probability of detection (POD). Generally there are three inspection levels in traditional scheduled maintenance: general visual inspection (GVI), detailed inspection (DET/DI) and special detailed inspection (SDI) [1]. For structures in different locations, an appropriate inspection level should be selected and the corresponding POD with a certain probability function is created.
7. With an appropriate POD, the time t to detect damage may be delayed to the subsequent inspection cycles and it is expressed as: $t = T \times n$ where T is the predetermined inspection interval and n is the number of inspections before damage is detected, which is generated by a geometric distribution.
8. The damage occurrence time and damage detection time are ordered in sequence to facilitate the description of residual strength variation with the assumption that down time is negligible.
9. The relationship of residual strength against damage size for a particular composite structure can be obtained through experiment or theoretical calculation. The damage size is converted to a reduction of residual strength.
10. Appropriate repair policies need to be developed to address detected damage. Normally, a threshold for repair is preset. If a damage size is smaller than the threshold, the damage can be kept until the next maintenance cycle. Otherwise, the damage is repaired immediately.
11. After repair, the structural strength is recovered to a level lower than the original strength. A recovery efficiency coefficient generated from a uniform distribution within a reasonable range is used to describe the recovery level.
12. The POF is calculated by:

$$POF = 1 - \prod_{i=1}^{N} [1 - P_f(S_i, t_i)] \qquad (1)$$

where t_i is the i^{th} time interval between $(i-1)^{th}$ and i^{th} activity (0 means the initial service time), S_i is the i^{th} residual strength between $(i-1)^{th}$ and i^{th} activity, N is the number of damages occurred in one life-cycle, and $P_f(\cdot)$ is the probability of failure for each interval with constant residual strength.

Failure occurs when the applied load exceeds the residual strength. Each time interval throughout the life-cycle with constant residual strength is assumed to be connected in series. The cumulative distribution function (CDF) of the maximum load per t_i is expressed as:

$$F_l(S_i, t_i) = e^{-H(S_i)t_i} \qquad (2)$$

where $H(x)$ is the frequency of the event exceeding the level x, which is described by different load exceedance curves after load cases are specified. A detailed illustration can be found in [11].

13. The last step of the simulation is to calculate the total maintenance cost including inspection cost, repair cost and risk cost caused by special events and is expressed as:

$$C_{total} = C_{inspection} + C_{repair} + C_{risk} \qquad (3)$$

where $C_{inspection}$ refers to cost induced by each scheduled inspection including consumption of manpower and equipment; C_{repair} is the repair cost considering labor, equipment, material and even spare part. C_{risk} denotes cost incurred by any special event or severe damage during operation having considerable impact on aircraft safety, e.g. a bird strike causing evident structural damage so that immediate repair needs to be conducted.

The operational life-cycle of a composite structure is simulated by the above 13 steps. Considering variable results due to Monte Carlo sampling, the simulation procedure should be repeated for manifold cycles to obtain mean values for both POF and maintenance cost.

With related data collected from the maintenance records of a particular aircraft fleet in a Chinese domestic airline, statistical analysis was performed to obtain inputs such as load cases, damage distribution, probability of detection, etc. The optimization result of the inspection interval and the repair threshold is shown in Fig. 8. The simulation results (15000 flight hours; 2 inches) coincide with the specified values in Maintenance Review Board Report and Structural Repair Manual for this type of aircraft, which demonstrates the effectiveness of the probabilistic model.

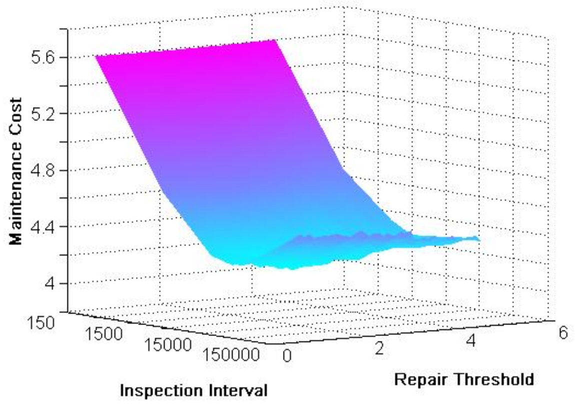

Fig. 8. Optimization of Inspection Interval and Repair Threshold

4. Case Study of Four Maintenance Scenarios

A new type of aircraft is assumed to have a composite wing consisting of 10 panels made of CFRP and has the same design life as the aircraft in the previous survey. A generic model is used only considering the structural strength reduction against damage size shown in Fig. 9.

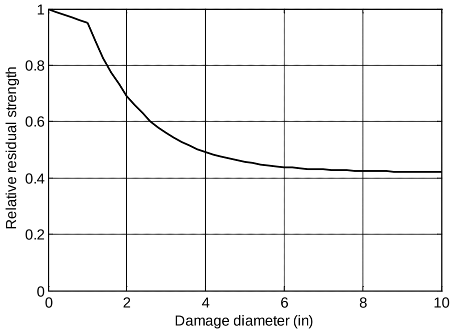

Fig. 9. Residual Strength Reduction against Damage Diameter

Other necessary statistical inputs such as frequency of damage occurrence, damage distribution, etc. are obtained from the statistical analysis of the maintenance records.

For scenario C and D, a new threshold D1 is specified for unscheduled repair due to more frequent inspections by on-board sensors. Structures with a larger damage size can still be accepted for a short period of time with the same safety level. Therefore, a maximum damage size 3.6 inches is obtained as the threshold for unscheduled repair to ensure the POF in scheduled maintenance is at 10^{-7} level.

A uniform reliability of the SHM system is assumed to be 80% and maintenance for the SHM system is called SHM assessment in scenario D.

Maintenance cost consists of four parts: inspection cost, scheduled repair cost, unscheduled repair cost and risk cost, which is calculated by Equation 4.

$$C_{total} = C_{inspection} + C_{repair} + C_{unsched\_repair} + C_{risk} \quad (4)$$

where C_{total} is the total maintenance cost; C_{risk} is any cost incurred by possible operational interruption once POF exceeds a predetermined threshold.

In terms of repair cost, for scenario A (Scheduled Maintenance) and B (Scheduled SHM), all maintenance tasks including inspection and repair are carried out at every scheduled maintenance cycle and thereby C_{repair} is incurred. For scenario D (CBM), repair tasks are initiated based on the health condition of the monitored structure and therefore, only $C_{unsched\_repair}$ is generated. For scenario C

(Scheduled CBM), both C_{repair} and $C_{unsched\_repair}$ are incurred since repair can either happen at scheduled maintenance or at maintenance assessment time.

For the last two scenarios, structures are monitored more frequently. In order to improve the safety level compared to B, Scenario C performs maintenance assessment every 0.01 life-cycle, which is every 1500 flight hours. A maintenance assessment is usually carried out overnight, when the SHM system is checked and structures are inspected to fix damages larger than D1. Alternatively, Scenario D (CBM) requires an SHM system assessment activity every 150 flight hours in case of any SHM component failure.

Assumptions of values for specific cost items are tabulated in Table 1.

Table 1. Maintenance Items Quantification

Maintenance Cost Item	Value
$C_{inspection}$	200 per aircraft
C_{repair}	100 per panel per time
$C_{unsched\_repair}$	200 per panel per time
C_{risk}	1000 per panel if POF>10^{-2}
k_{SHM}	0.2

Note: units are neglected for simplicity. The coefficient k_{SHM} denotes the proportion of inspection cost by SHM in the inspection cost by NDI.

Logic procedures in other three maintenance scenarios with different SHM synchronizations are incorporated into the probabilistic model. A fleet of 100 aircraft each having 10 composite wing panels is simulated and outputs are tabulated in Table 2.

Table 2. Comparison of Four Maintenance Scenarios

Scenario	Percentage of panels repaired per inspection	No. of unscheduled maintenance	Probability of Failure (POF)	Maintenance Cost
A	0.189	-	1e-7	406000
B	0.158	-	1e-6	344900
C	0.134	636	1e-8	616800
D	-	718	1e-7	269600

5 Discussion

With an increasing usage of SHM from Scenario A to D, repair work at conventional scheduled maintenance cycle has transferred to unscheduled maintenance cycle due to shorter inspection intervals or even real-time monitoring. Meanwhile, SHM can help skip unnecessary time-consuming labor work for NDI. As to safety, the relatively higher probability of failure in Scenario B is because of the consideration of SHM reliability. Although SHM can save great manpower, it is less reliable than human intervention at a long inspection interval. In comparison, Scenario C with more frequent inspections and smaller repair threshold has the highest safety level.

In terms of the maintenance cost, distributions of each cost item from Scenario A to D are shown in Fig. 9. It is noted that the areas of the pie charts are proportional to the total cost and so does each cost item.

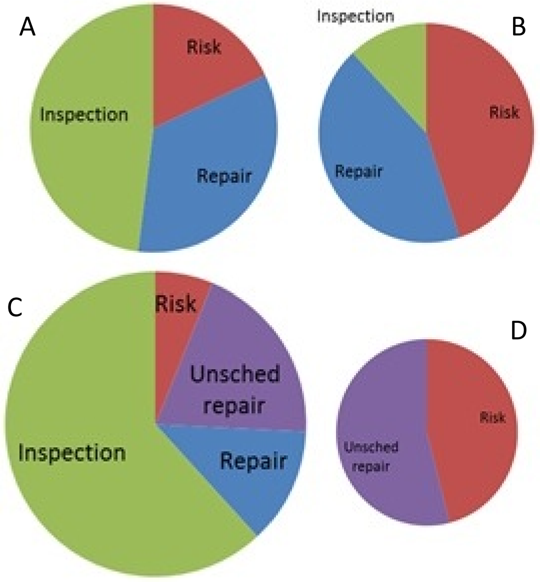

Fig. 9. Cost Distribution for Scenario A and D

Compare Scenario D with A, CBM can achieve the same POF level as traditional scheduled maintenance but reduce the maintenance cost significantly by 33.6%. Inspection cost in Scenario A takes up almost half of the total cost. For Scenario D, the unscheduled repair constitutes a major part of the total cost.

As a simple updated version of scheduled maintenance, traditional scheduled inspection is replaced by on-board sensors and ground-based data analysis equipment in Scenario B. The maintenance cost can be reduced by 15% by eliminating intrusive NDI. However, due to the reliability of the SHM system and infrequent inspections, the aircraft has a higher POF level, which is reflected in the distribution of cost items with a small proportion for SHM inspection and a large proportion for risk cost. Scenario C has the largest maintenance cost. This is because the inspection cost reduced by SHM still cannot neutralize the cost incurred by more frequent inspection times.

6. Conclusion

In this paper, an integrated maintenance logic diagram was established based on MSG-3 considering SHM technologies. Four scenarios of maintenance procedures were developed as A (Scheduled Maintenance), B (Scheduled SHM), C (Scheduled CBM) and D (CBM), which incorporate SHM tasks with an increasing maturity level. A probabilistic model was developed to simulate the structural strength variation in an operational life-cycle addressing impact damages in assumed composite wing panels.

The influence of SHM on scheduled maintenance for composite structures is examined from both safety and economic aspects through the adjustment of the two key parameters: the inspection interval and the repair threshold. The maintenance procedure and the probabilistic model developed in this study have the potential of assisting aircraft manufacturers and airlines to achieve the most efficient maintenance strategy by determining to what extent SHM can be integrated with scheduled maintenance.

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