

Strategies for Structural Health Monitoring Implementation Potential Assessment in Aircraft Operational Life Extension Considerations

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Abstract. The commercial aircraft operational life extension considerations are increasing with more shorter and longer range aircraft operating than ever in history. Aircraft Maintenance Repair and Overhaul companies (MROs) serve a significant portion of the after-sales market. Though more aircraft are operating, the increasing after-sales market, particularly maintenance still remains very competitive. Cheaper labour forces existing in emerging economies and the arrival of next generation aircraft (Airbus A350 and Boeing 787 Dreamliner promising reduced maintenance costs) will cause additional pressures for MROs to operate efficiently and satisfy airline operators. One fundamental requirement for airliner operators will always remain apparent and that is the need to maximise their aircraft usage. State of the art, automated NDT applications for aircraft often also discussed within the context of structural health monitoring (SHM) are slowly developing and provide the prospect of reducing maintenance related down time, potentially increasing fleet usage. The questions of where and how these automated NDT and SHM technologies can be used on aircraft to bring about such benefits have yet to be fully addressed. The paper describes a method of analysing scheduled maintenance interval blocks to identify time critical areas. Automated NDT solutions with embedded sensors and faster decision support at such locations could contribute to elimination of unnecessary access and efficient information relayed to maintenance, repair and material handling teams. The method proposed was preliminarily applied to a short range aircraft across different types of scheduled maintenance interval blocks. Results highlighted significant benefits are likely to occur within shorter, more frequent scheduled maintenance intervals where inspections were intensive but specific to an area.

INTRODUCTION

Today, commercial aircraft operators are facing the pressures of keeping their fleet operational to survive in the current environment. "Aircraft Availability" has thus emerged as conventional vocabulary to operators and proves to be a significant factor for commercial operator fleets. By definition, Aircraft Availability is an aircraft's ability to remain operational (and generating revenue), rather than inoperable when under maintenance. The majority of aircraft operating today are predominantly made up of damage tolerant sub-structures. These structures have the ability to accommodate flaws safely until they can be repaired. The distinct advantage of damage tolerant structures are

their light weight attributes. However, to manage their potentially inherent flaws, regular scheduled inspections are mandatory.

A significant amount of inoperable time over an aircraft's life is accrued during these scheduled inspections. Inspecting the integrity of a structure is undertaken manually and is usually time intensive. A typical sub-structure inspection would initially involve an amount of effort to gain access. Additional preparatory work may be required (cleaning) before inspection is possible. Substructures are then inspected and findings are logged for engineering before any other procedures are performed. If corrective action is required, it is performed before the sub-structure is rebuilt.

Access and rebuild tasks may be intrusive, preparation could be lengthy (certain components require time for substances to penetrate cracks before inspection can even begin), inspections could be extensive (geometrically complex locations), and transferring health information to engineering could be tedious and in-efficient. From the above description, it is self evident that an extortionate amount of man effort and elapsed time could be accumulated along the process chain to inspect many sub-structures.

These extensive inspections have the possibility of being replaced by automated, in-situ Structural Health Monitoring (SHM) technologies where access and rebuild procedures could be eliminated, inspections are automated and unambiguous information is provided quickly to the engineer for repair scheme generation. But application of SHM will only be achieved if an overall cost benefit to the operator can be realised. A selective strategy is thus needed if SHM application is ever to be achieved.

Operational downtime is considered as the major cost contributor when an aircraft is inoperable. According to the ICAO [1] the average operating cost of a short range aircraft constitutes to approximately \$2500 per hour. Thus, SHM would be best applied to reduce downtime. In principle, mapping and analysing the elapsed time across inspection processes would identify "time critical" locations. It is those regions that influence the total duration of an interval and should be considered for SHM application.

The paper presents an approach that focuses on analysing these scheduled intervals to identify critical locations that have the prospect of being replaced by SHM such that a reduction in downtime can be achieved. Inspection processes are complex with many dependencies and uncertainties that can alter time critical inspection tasks; the method adopted accommodates for these by recommending "highly probable" critical locations during a scheduled 'block' of inspections.

The paper initially walks the reader through the different types of inspections current aircraft exhibit. The paper then moves onto how these inspections can be formulated into interval programs by using maintenance documentation. With a set of scheduled programs defined, an outline to how these can be mapped and analysed to identify time critical inspection locations is provided. Short range aircraft block interval examples were used as a test beds for the method. A description of the applied method is provided in these examples. Results are recorded and the paper is finalised with conclusions.

1. INSPECTION TASKS, THEIR TYPES AND BLOCK INTERVALS FOR CURRENT AIRCRAFT

Aircraft inspection tasks are derived from the type of aircraft design philosophy adopted to a sub-structure. Two types of design philosophy for a structure can exist. A safe-life design philosophy ensures that components survive a specific design life. After their lives, they are scrapped. Safe-life components are also disregarded if damaged. The design philosophy is usually applied to safety critical sections of an aircraft which generally carry a larger

payload and where hence a higher safety factor is required. As a result, inspection tasks for safe-life items would only occur if an unforeseen damage could have compromised the integrity of the structure.

The damage tolerant approach is contrasting to the safe life philosophy. Flaws (up to a certain design level) can safely be accommodated on a sub-structure, however must be complemented with regular inspections and repairs. They are usually lighter in design and applied to less critical sections of the aircraft. With these designs, regular checks are scheduled to ensure that the component is fit to perform its function.

SHM can influence aircraft availability by automating structural inspections for both safe-life and damage tolerant structures. Though SHM may have the prospect to automate and improve unscheduled inspections associated with safe-life sub-structures, the paper only concentrates on scheduled inspections of damage tolerant structures.

The complete database of past, present and future scheduled inspections is all contained in maintenance documentation. Understanding the function of these maintenance documents will initially allow the reader to distinguish the types of scheduled inspection interval blocks that exist and the role SHM could play in them.

1.1 Maintenance Planning Document

The MPD (Maintenance Planning Document) is issued by the manufacturer and provides the list of all the scheduled maintenance actions (inspection, servicing, repairs etc) necessary to keep the airframe airworthy. It not only contains structural inspections but a host of other maintenance items (servicing repairs and overhauls etc). The MPD is broken up into subcomponents and the associated maintenance actions are determined by MSG-3 (Maintenance Steering Group revision 3) logic. A threshold (first action) and interval (time between action) is generated for every maintenance action generated. For structural components the thresholds and intervals are calculated with fracture mechanic models.

Many of the generated maintenance actions can be clustered together to form periodic block programs of maintenance (MPD program). The MPD program fits largely to the letter check program that was previously adopted. The letter check philosophy would consist of repeating a series of standard maintenance blocks (running from A to D) over an aircraft's life.

Though the MPD program is similar to the old letter check philosophy, there are items that are listed with a threshold and interval frequency out of phase of the legacy letter check blocks. These are known as drop out blocks and have to be inspected in-between programmed blocks to satisfy aviation authority requirements. Increasing Aircraft Availability by substituting conventional inspections with SHM could be possible for both conventional letter check and drop out blocks.

The MPD also provides a description of the man effort for the generated maintenance actions, however this information is largely incomplete and the provided man hours are optimistic neglecting time for access and preparation and rebuild. The MPD is used as a valuable source of data that helps form MPD program blocks and helps identify drop out blocks.

1.2 Service Bulletins

As a result of in service experience and design corrections, inspections and other maintenance actions are usually assigned as Service Bulletins (SBs), or Airworthiness Directives (ADs) if mandatory. SBs are additional maintenance actions to the foundation MPD program. Therefore, depending on the threshold and interval frequency an SB can fit outside a conventional letter check block also becoming a drop out block. Service Bulletins

are usually included in an updated revision of the MPD to ensure all scheduled items are traceable.

1.3 Job cards

Job cards are documents specific to every inspection item listed in the MPD. They clearly provide all the steps needed to complete an inspection and provide comprehensive information regarding the geometries and location of the component/s inspected. These cards are given to the maintainer to perform the maintenance actions and are usually written by the airline operator or the maintenance provider. Job cards are a vital tool when an in-depth insight of the inspection process is required as well as assessing the cost benefit of applying SHM solutions.

The following descriptions have provided a brief insight into the origins of structural scheduled maintenance and their types. An outline of how maintenance items are documented has also been presented and elucidates how traceable scheduled inspection items are over the aircraft life.

3. A METHOD TO ANALYSE EXISTING INSPECTION INTERVAL BLOCKS

With the relevant maintenance documentation discussed, SHM could contribute to two types of scheduled intervals; drop out and standard letter check intervals blocks. The question is how can these documents be used to determine SHM potentials?

The objective is to find time critical maintenance tasks within an inspection block. Time critical items are those that influence the duration time of a block. A block would not only contain inspections, but other maintenance activities such as servicing and repairs are likely to be executed in parallel and must also be considered as any item could lie on the critical path. All items in a block can be determined from the MPD. Threshold and interval frequency allows us to find all tasks that belong to any interval block over any period of an aircraft's life.

All steps for to perform an inspection item must also be modelled to give an appreciation of the elapsed time. Every step is modelled in the correct order and is assigned to its stated resources (specific personnel). The elementary steps along with personnel information can be found in an item's job card. Mapping a block's processes provides a more accurate estimation of downtime and an in-depth insight into critical aircraft locations.

An interval block can be mapped computationally with a variety of modelling packages. Arena [1, 2], a discrete event simulation tool, was chosen to model interval blocks as the time for each action within the job cards was not specified. Arena has the ability to incorporate and analyse stochastic times easily. An estimate of the individual step times time and a probability distribution for modelling would suffice for the preliminary study.

Modelling the maintenance process in Arena is relatively straightforward with its graphical user interface. The processes can be constructed in a flow chart fashion and its entity's attributes can be monitored. However, initially it is important to plan the model before construction. Measuring the aircraft downtime is a key performance criterion to deciding where SHM would be applied. Following from this realisation, the entity that would move through the process would be the aircraft. As the aircraft moves along the steps, the duration time would alter. Time critical items would thus be traced by adopting this structure.

A process model in Arena must have a start and end. This is described with ‘create entity’, and ‘dispose entity’ modules respectively. Process blocks describe the work sequence and change key performance criteria. For modelling inspection interval blocks the major criterion was duration time. Modelling maintenance processes in Arena is common and has been used for many studies in the American Air Force Institute of Technology [3, 4].

The modelling and analysis procedure adopted is best explained with an example. Therefore as an aid, a short range aircraft’s maintenance procedure was used as a test case. The paper intends to model in Arena the impact SHM has on the heaviest D-Check block and a lighter drop out interval. The D-check was chosen for the study as it occupies a very significant portion of downtime and a large amount of man effort is dedicated towards structural inspections. Initial predictions were that the largest potential gains would be identified at D-checks.

4. SHM IMPACT FOR SHORT RANGE ‘D-CHECK’ AND DROP OUT INTERVAL BLOCKS

The objective of the study was to identify time critical structural locations and estimate the impact if SHM was employed at those areas, for the two intervals selected.

All items for the D-check analysis were sourced from the aircraft’s MPD. According to the short range aircraft maintenance program the first D-check would be approximately performed at 24000 flight cycles (FC) followed by a 24000 FC frequency. Over 1000 maintenance actions (MPD items) were performed at the initial D-check, for this reason it was impractical to have investigated every item’s job card. Approximate elapsed time durations were thus gathered by aircraft planners’ experience. Uncertainties were also elicited from personnel experience and were described with a mean and a probability density function. Each item in the D-Check was segregated into stages set by planners, and modelled in parallel as process modules within a stage. The five stages in a D-Check were segmented into:

- Stage 1: Removal
- Stage 2: Inspection
- Stage 3: Defect rectification and rebuild
- Stage 4: Paint
- Stage 5 : Final Checks

Figure 1 shows the structure of the D-check as modelled in an Arena model for greater clarity.

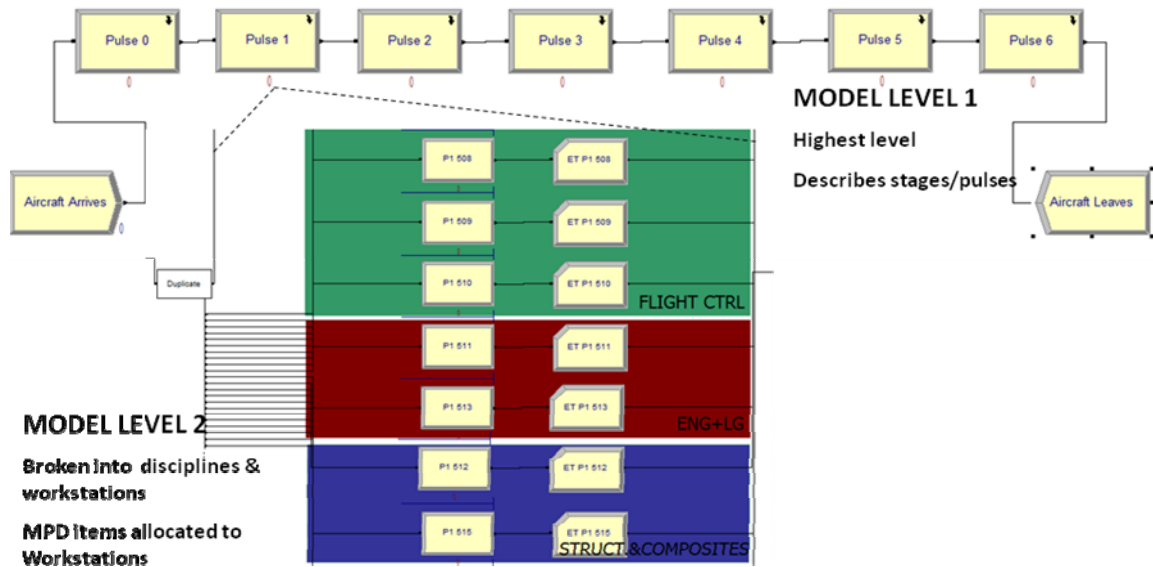


Fig.1. Structure of the D-check model. Level 1 shows the stages. A section of stage 1 has been expanded to show level 2. Here, items are broken in parallel to work stations.

Drop out items were obtained a little differently to the D-Check. The MPD program, which prescribes the scheduled downtime interval blocks, was generated with the MPD. MPD items that did not fit the conventional scheduled inspection blocks over the aircraft's life were considered drop out items. Drop out items with the same threshold and frequencies were then consolidated together to form a drop out interval block.

The MPD was accessible in MS Excel, allowing data to be manipulated relatively easy to form drop out block intervals. A number of drop out items that did not directly belong to the scheduled maintenance program were observed. A particularly interesting interval that has a high possibility of being a drop out interval was at 2400 FC. Three inspections were recommended at this interval, two were General Visual Inspections (GVIs) and one a Detailed Inspection (DI). A list of the items at the 2400FC interval is provided in figure 2 below.

Item 1	GENERAL VISUAL INSPECTION OF FORWARD PASSENGER/CREW DOOR SKIN, EXTERNAL SURFACE, LH/RH
Item 2	GENERAL VISUAL INSPECTION OF AFT PASSENGER/CREW DOOR SKIN, EXTERNAL SURFACE, LH/RH
Item 3	DETAILED INSPECTION OF UPPER CONNECTION AREA OF CENTER WING REAR SPAR FORWARD FACE BETWEEN RIBS 1 AND 2

Fig. 2. Items considered for 2400FC intervals

It was assumed that all 3 inspection items in the synthesised drop out block could be executed simultaneously. Two inspections (Items 1 and 2, see figure 3) were GVIs (General Visual Inspections) and one (Item3) was a DI (Detailed Inspection). The model at its highest level had all items executed in parallel. The jobs (obtained from job cards) were modelled as individual steps at lower levels in the model. Times were not available for the individual jobs set. Therefore statistical distributions were assigned to steps for a more representative case. Figure 3 describes the 2400FC drop out interval block construct for clarification.

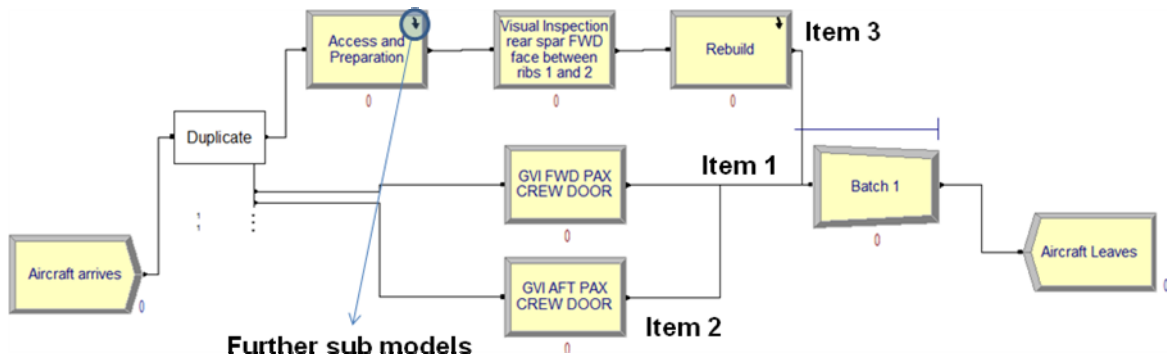


Fig. 3. 2400FC interval modelling in Arena©

Uncertainties were prevalent for both interval block models. Each uncertainty was described statistically and run 100 times according to suggestions from Kelton, et al [2, 5] to generate a mean duration. Additionally, for every replication, the critical path was assessed and a histogram of critical processes was presented. The impact of replacing critical items with SHM alternatives in terms of downtime saving was also assessed.

5. RESULTS

D-Check Interval

With 100 replications, the average duration was 413.4 hours (approximately 26, 16 hour working days). The model was validated with heavy maintenance planners who are responsible for planning aircraft in D-Checks.

There were many critical items that existed along the entire D-check interval. However, two processes were only SHM applicable processes. These were found within stage 1 of the model. Figure 4 shows a histogram for all processes that were critical. The number of hits represents the number of times a process was critical over the 100 simulation replications. Critical processes altered due to uncertainties in a process's duration time. Critical SHM applicable processes were highlighted in figure 4.

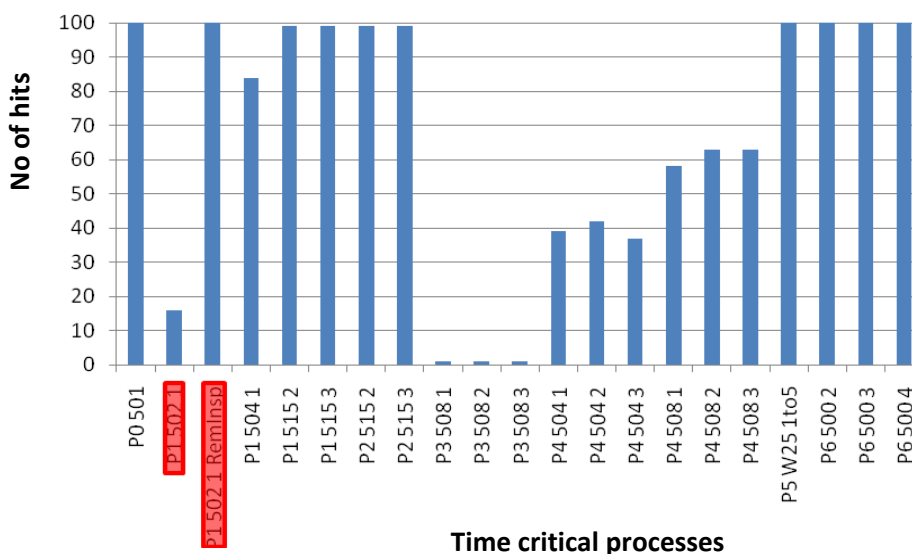


Fig. 4. Number of times a process is critical in 100 replications of D-Check simulation considering uncertainties. Highlighted processes (P1 502 1 & P502 1 RemInsp) are SHM applicable

Within these highlighted processes many sub processes (inspection items) were executed in parallel. In summary some of the driving items that caused the process to become critical were:

- GVI of flap transmission assemblies across the wing
- GVI of wing slat for connectors located over the wing
- DI of pressure deck membrane in the cabin over the upper surface
- Internal inspection of fuselage at various frames around the centre wing box region

Implementing SHM for these hot spot locations would eliminate the manual inspections saving time. However, at the processes highlighted, there were a number of SHM inapplicable (non inspections, larger visual checks) items that required identical access. Therefore, this access would be necessary even if a SHM alternative was made available. For this reason, time savings were lower than initial estimations.

Figure 5 shows that the average saving between the existing process and the improved process with SHM resulted in average savings of nearly 3 hours per interval. The average total saving was less than the minimum saving, as the highlighted critical processes were not critical 100% of over the 100 simulation replications. Considering replacement for only a handful of hot spot areas in D-Check would yield very small savings.

	AV. tot time (hrs)	Min. tot time (hrs)	Max. tot time (hrs)
Existing	413.5	371.8	460.8
SHM hot spots	410.6	367.2	451.4
Savings	2.9	4.6	9.4

Fig. 5. Comparison of the two simulation durations. One modelling the existing process and the other replicating if identified hot spot regions were eliminated.

Drop out interval 2400 FC results

The drop out item selected for analysis presented different results. The average interval duration was approximately 14 hours after 100 replications. Item 3 was critical in all 100 runs. The access and preparation for item 3 was specific i.e. no other region required the same access during the interval. Therefore, if SHM could be applied to item 3, it would eliminate both the access, inspection and rebuild steps for the item.

Assuming that the other two external GVIs were of negligible duration and a SHM inspection of the area could be executed remotely within a transit stop, then the entire drop out interval could be eliminated resulting in potential savings of 13.8 hours per maintenance interval. The inspection interval is far more frequent than the D-Check investigated, resulting in potentially larger savings over the life of the aircraft. Assuming that all 2400 FC intervals were outside the letter check program and were needed over the span of the aircraft's life then a saving of approximately 280 hours could be realised. However, there is a possibility that a 2400 FC interval falls into a larger programmed interval at some point over the aircraft's life. Thus the benefit quantified is an upper estimate. The results have been summarised in Figure 6.

Interval (FC)	Max. time(hrs)	Avg. times (hrs)	Min. time(hrs)	No. of Intervals.*	Tot. duration(hrs)
2400	15.9	13.8	11	20	276

*Assuming aircraft designed for 48 000 FC

Fig. 6. Calculated savings per interval and over the aircraft life to the 2400 FC drop out interval

SUMMARY & CONCLUSIONS

There are great prospects for SHM solutions to contribute to maintenance processes by reducing scheduled downtime, a significant cost driver for commercial airliners. However, recognising where to place SHM to realise these benefits is needed. A method was proposed that analyses maintenance intervals and distinguishes where critical maintenance inspection items exist in scheduled intervals.

This was achieved by initially classifying MPD data into scheduled interval blocks. The processes within these blocks were modelled with the objective of monitoring duration time. As part of a study to highlight the approach two types of scheduled intervals were used. A conventional D-check (still adopted today) was modelled with a discrete event simulation tool called Arena. Savings of 3 hours per D-check interval could be realised by placing hotspot monitoring to a set of locations highlighted in the paper. This would equate to 6 hours saved over the life, which may be insufficient to justify investment of SHM technologies. Results show that aircraft maintenance processes for damage tolerant design are well optimised from an initial design perspective and that the high degree of an aircraft disassembly required may only provide very limited potential for SHM within the frame of current aircraft initial structural design. However, aircraft structures are likely to fracture at locations other than those initially predicted once they come into the ageing aircraft category. Those damages known as drop outs lead to specially directed inspections which are likely to fall outside of the conventional maintenance program and hence can become comparatively costly. The example of a 2400 FC interval only provided here has three items of which the critical item was a detailed inspection that remained on the critical path despite fluctuations in uncertainties. Substituting for a SHM centred process could save up to 280 hours over the aircraft life. With the cost of operation at \$2500 per hour, application of SHM to drop out intervals to further optimise maintenance processes could certainly justify future investment.

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