New prognostics-based structural maintenance strategies for civil aircraft

Christian Gogu[1]

[1] *Université de Toulouse ; UPS, CNRS, INSA, Mines Albi, ISAE ; ICA (Institut Clément Ader)*
3 rue Caroline Aigle, 31400 Toulouse, France
christian.gogu@gmail.com

ABSTRACT

Currently, structural maintenance of civil aircraft is based on the scheduled maintenance strategy, where all the aircraft of a same model are inspected according to a predetermined schedule. Embedding sensors in aeronautical structures allowing to monitor their structural health can also open up new strategies for more efficient maintenance planning. A first possibility is to move from scheduled maintenance to condition based maintenance, where the current condition of the aircraft triggers specific maintenance policies. A further step is to not only use the current state of the damage but to also predict future damage growth and determine the maintenance policy accordingly. Both condition based as well as prognostics based strategies can be carried out independently or can be coordinated with other, scheduled, non-structural maintenances, which leads to a total of four new possible maintenance strategies. An application of these maintenance strategies to fuselage panels of a short range commercial aircraft is presented and their effectiveness and cost-efficiency is compared between them and with that of traditional scheduled maintenance. We show that large savings can be achieved, particularly when large variabilities are present.

1. INTRODUCTION

In order to comply with certification regulations aeronautical structures are designed using the concept of damage tolerance (EASA 25.571). This concept aims at guaranteeing the safety of airplane structures by imposing that the structure should withstand small damage and making sure that large damage is detected and repaired before becoming critical. It thus relies on regular inspections of the airplane's structure for detecting damage that may immediately threaten its integrity. Such inspections can range from the preflight checks done by the pilots and ground technicians before each flight and up to major overhauls occurring only a few times in the life-time of the airplane, where the structure is disassembled and inspected. Fatigue damage is one of the major types of damage that can threaten the structure. In order to detect and repair this type of damage each structural part of the airplane has a predetermined inspection interval which determines among other the overall inspection schedule of the airplane.

The damage tolerance strategy was found to be more cost-effective in terms of global life-cycle cost compared to safe-life design where the structure is designed such as to withstand potential damage without repairs (Kale and Haftka 2008). However, in spite of the advantages of this approach, there are numerous sources of uncertainty as well as inherent variability in the fatigue crack propagation problem, which affects the calculations of the inspection schedule. In damage tolerant design these are accounted for through safety factors on the inspection intervals, safety factors that can reach up to a factor of three. This leads to the inspection schedule being quite conservative in most cases, but it is required in order to guarantee the structural safety of the airplanes. There is thus a major economic incentive to decrease the conservativeness level of these structural maintenances in order to decrease maintenance costs.

Recently there have been significant research going into the development of structural health monitoring (SHM) systems based on embedded sensors that aim at detecting damage, thus paving the way for new structural maintenance strategies (Beral and Speckman 2003, Boller and Meyendorf 2008, Lopez and Sarigul-Klijn 2010). Such monitoring systems would allow to adapt the inspection schedule on demand such as to maintain the safety of the airplane thus having the potential to be much less conservative.

A first possibility of using SHM systems for improving maintenance strategies is to move from scheduled maintenance to condition based maintenance, where the current condition of the aircraft triggers specific maintenance policies. A further step is to not only use the current state of the damage but to also predict future damage growth and determine the maintenance policy accordingly. Both condition based as well as prognostics based strategies can be carried out independently or can be coordinated with other, scheduled, non-structural maintenances, which leads to a total of four new possible maintenance strategies.

In this presentation, we present and compare these four different structural maintenance strategies with the aim of finding the one which reduces most the conservativeness level and the lifetime structural maintenance costs.

In section 2 we provide an overview of a condition based structural maintenance strategy. In section 3 we describe a predictive maintenance strategy. Section 4 gives some elements of comparison. Finally section 5 provides concluding remarks.

2. CONDITION BASED MAINTENANCE STRATEGIES

The condition-based maintenance strategy tracks damage much more frequently (typically every couple of dozen or few hundred flight cycles) and requests maintenance whenever the damage is found to be large enough to threaten structural safety. In this paper, condition-based maintenance is assumed to be performed using embedded structural health monitoring. Figure 1 illustrates the flowchart for the condition based maintenance strategy.

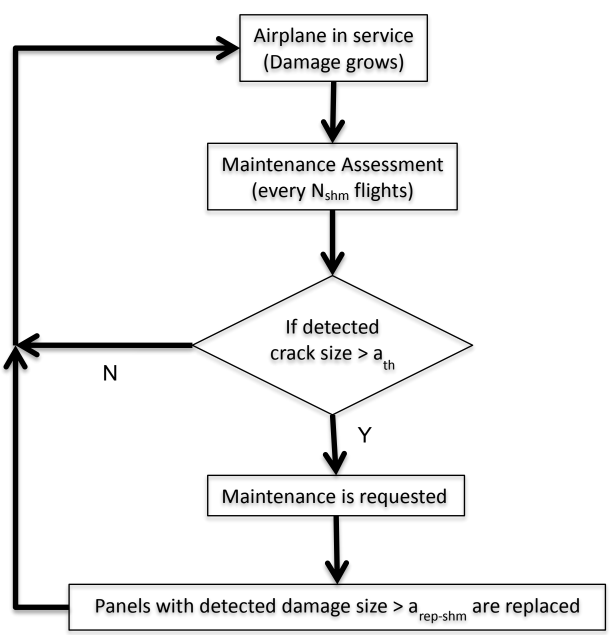

Figure 1. Condition based maintenance strategy

After damage assessment via the embedded SHM system, maintenance is requested if the maximum damage size in an airplane exceeds a particular threshold (a_{th}). The threshold for requesting maintenance (damage size, a_{th}) is chosen to maintain a desired level of safety until the next scheduled damage assessment (i.e. for the next N_{shm} = 100 cycles). Once maintenance is requested, all panels on the airplane are inspected for damage using the on-board SHM equipment, and panels with a crack size greater than a second threshold $a_{rep\text{-}shm}$ are repaired. This second threshold is imposed in order to prevent overly frequent maintenance requests which may become cost-inefficient due to too frequent immobilization of the aircraft.

Note that this condition based maintenance strategy can be carried out either independently or in tandem with other scheduled maintenances. The advantage of independent maintenances is that it allows to track more closely the desired repair strategy. The drawback is that it is then totally disconnected from other required maintenances (i.e. engine, non-structural maintenances) and can thus be more disruptive of traditional maintenance policies. Carrying out the maintenance in tandem requires some changes to the above strategy, which will not be detailed here.

The reader interested in more details on the condition based maintenance policies implemented here is referred to Pattahabiraman et al. (2012).

3. PREDICITVE MAINTENANCE STARTEGIES

In the predictive maintenance strategy, the damage measurement data from the SHM system is used not only trigger maintenance but also to characterize the damage propagation parameters of the specific crack under question. Extended Kalman filtering is used to estimate the state vector $(a,m,C)_{current}$, which consists of the damage size a and the damage propagation parameters (m,C). The state vector and the corresponding estimation uncertainty (covariance matrix) are thus estimated based on the SHM system's data and used in order to predict the future crack evolution. The decision of which panels to repair is based on the quantile of the predicted crack size evolution, as illustrated in Figure 2, and is aimed at avoiding that damage threatens again the safety of the aircraft before the next I_h flights. A variation of this maintenance strategy is also possible when seeking to carry out all the maintenances in tandem with other maintenances on the aircraft e.g. engine, non-structural maintenances).

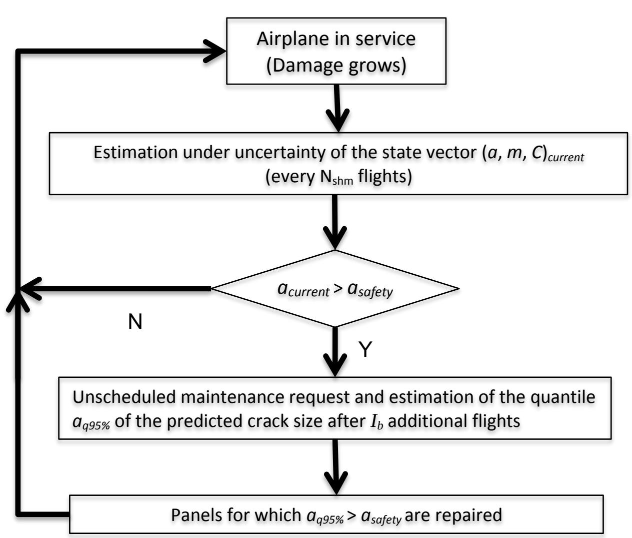

Figure 2. Predictive maintenance strategy.

The reader interested in more details on the predictive maintenance policies implemented here is referred to Wang (2017).

4. STRATEGIES COMPARISON

Traditional scheduled maintenance, condition based maintenance and predictive maintenance were compared in terms of number of unnecessary repairs (i.e. conservativeness level) and maintenance costs associated with the corresponding strategy.

It was found that condition based maintenance doesn't decrease the number of unnecessary repairs but allows to significantly decrease the maintenance costs since fewer maintenance stops need to be carried out compared to scheduled maintenance. Basically this strategy allows to better group panels to be repaired in fewer maintenances, without compromising safety.

It was also found that the predictive maintenance strategy allows to both decrease the number of unnecessary repairs and further decrease the cost of the maintenances. This is achieved by using the prediction and its uncertainty in order to decide which panels need repair.

Extensive results of this comparison can be found in Wang 2017 and Wang et al. 2017.

5. CONCLUSION

Current scheduled maintenance practice for aeronautical structural maintenance was reviewed and the various sources of conservativeness elaborated. In order to decrease this conservativeness level and maintenance costs we proposed tow strategies making use of structural health monitoring data: condition based maintenance and predictive maintenance. We found that both these strategies can reduced maintenance costs, but the predictive strategy allows achieve greater gains by significantly reducing the number of unnecessary repairs while simultaneously reducing the number of maintenance stops.

ACKNOWLEDGEMENT

The author would like to thank the conference organizers for their invitation to give this invited talk. The author would also like to acknowledge following students and colleagues for their contribution to the topics presented: Christian Bes, Nicolas Binaud, Raphael Haftka, Nam Ho Kim, Sriram Pattabhiraman, Yiwei Wang.

REFERENCES

Beral, B., Speckman, H., Structural Health Monitoring (SHM) for Aircraft Structures: A Challenge for System Developers and Aircraft Manufacturers", *Structural Health Monitoring*, DEStech Publications, 2003.

Boller, C., Meyendorf, N., "State-of-the-Art in Structural Health Monitoring for Aeronautics", *Proc. of International Symposium on NDT in Aerospace*, Fürth, Germany, December 3-5, 2008.

European Aviation Safety Agency (EASA), *Certification specifications*, Part 25, Airworthiness Code: Large Aeroplanes, Sec. 25.571, Damage-tolerance and fatigue evaluation of structure.

Kale. A., Haftka, R.T., "Tradeoff of Weight and Inspection Cost in Reliability-Based Structural Optimization", *Journal of Aircraft*, Vol. 45, No. 1, 2008.

Lopez, I., Sarigul-Klijn, N., "A review of uncertainty in flight vehicle structural damage monitoring, diagnosis and control: Challenges and opportunities", *Progress in Aerospace Sciences*, Vol. 46, 2010, pp. 247-273.

Pattabhiraman, S., Gogu, C., Kim, N.H., Haftka, R.T., & Bes, C., "Skipping unnecessary structural airframe maintenance using an onboard structural health monitoring system", *Journal of Risk and Reliability*, 226(5), 549-560, 2012.

Wang, Y., "Development of predictive structural maintenance strategies for aircraft using model-based prognostics", PhD dissertation, Université de Toulouse, 2017

Wang, Y., Gogu, C., Binaud, N., Bes, C., Haftka, R. T., & Kim, N.H. A cost driven predictive maintenance policy for structural airframe maintenance. Chinese Journal of Aeronautics, DOI: 10.1016/j.cja.2017.02.005 , 2017

BIOGRAPHY

Christian Gogu is Associate Professor in the department of Mechanical Engineering at Universite Toulouse III (France). He received his Master degree in Mechanical Engineering from the Ecole des Mines de Saint Etienne (France) in 2006 and his PhD in 2009 as part of a joint PhD program between the Ecole des Mines de Saint Etienne and the University of Florida. He has been granted an award for outstanding academic achievement as part of his PhD on Bayesian identification of orthotropic elastic constants identification. His research interests include design under uncertainty, multidisciplinary design optimization, structural health monitoring and surrogate modeling with applications mainly to aerospace structural design.