Opportunistic Maintenance in Aircraft using Relevant Condition Parameter based Approach

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Abstract

Opportunistic maintenance has been an essential part of all systems-maintenance, implicitly if not explicitly. However, as systems become more expensive and complex, the decisions involving opportunistic maintenance activities become more complicated. In this paper, we discuss a few issues that arise while carrying out the opportunistic maintenance, and try to resolve them with the help of a popular optimization technique called Genetic Algorithms. We also present a few results concerning relevant condition parameter based maintenance, as it has a high potential to be an opportunistic maintenance in complex systems. A systematic methodology is designed to enable the maintenance crew in deciding which items to be maintained when an opportunity arose. The cost of premature replacement is compared with the cost of down time, in the optimization process using Genetic Algorithms.

Keywords: *Opportunistic Maintenance, Condition based Maintenance, Relevant Condition Parameters, Condition Monitoring, and Genetic Algorithms*

1. Introduction

Opportunistic maintenance plays a crucial role in systems that are maintained under both time-based as well as condition-based maintenance policies. In opportunistic maintenance, when a system or module is grounded for corrective or preventive maintenance, that opportunity is utilized to do maintenance on other parts of the module, which are found to be damaged or have started to deteriorate. On one hand, this improves the safety and reliability of the system, and on the other hand it reduces the downtime by avoiding un-scheduled maintenance. This in turn reduces the cost of maintenance, loss of revenue due to extra groundings, customer goodwill and so on. But,

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what is the criterion used to decide which parts to be considered for opportunistic maintenance and how far does one go? There is the engineering maxim, which says that, "unless it's broken, don't fix it!" Therefore, there are numerous factors that need to be considered before going ahead with opportunistic maintenance of a particular part. A detailed description of various situations that demand an in-depth analysis of advantages and disadvantages of carrying out the opportunistic maintenance is given below.

Maintenance cost has always been the most unappealing and at the same time the most unavoidable cost of a systems Life Cycle Cost (LCC). Especially in an airline industry, maintenance of an aircraft, commercial or defense, contributes a substantial amount of expenditure to the LCC. For example, the routine maintenance program of an aircraft itself is very extensive, and consists of maintenance checks like preflight before each flight, A and B checks, which are performed on a regular basis, once in every 150 and 750 flight hours respectively. In addition to these checks, major inspection and reconditioning are done through C and D checks, which come under heavy maintenance, every 3,000 and 20,000 flight hours respectively. The annual demand for heavy maintenance of a narrow body aircraft is 11,000 labor hours and for a wide body aircraft, it is 17,150 labor hours approximately [3]. In spite of this major inspection and maintenance schedules, aircraft still requires condition-based maintenance for most part of the engine and corrective maintenance in some cases. Although, most part of the engine comes under condition-based maintenance, in practice, it is very difficult to estimate the condition of the items with 'boroscopes' and 'intrascopes' [1], as only a part of the surface is visible and that too at a very oblique angel. Thus, most of this on-condition maintenance is carried out as an opportunistic maintenance, when the engine or any module of the engine is stripped down to part level during the shop visits and performance restorations. In such situations, if some safety significant items seem to have been damaged, then they are obviously repaired or replaced. But the difficulty arises, when some potential failures of non-safety significant items are detected. These failures, if and when they occur, would only cause small increase in vibration, reduction in thrust or specific fuel consumption etc., which may result in engine being run hotter to achieve the required performance. However, if there was no actual failure and these secondary damages do not measure up to the cost of the remaining life of the component, the maintenance crew is in an ambiguity as to carry out a premature replacement or not.

Another important factor that puts the maintenance crew in a dilemma during opportunistic maintenance is features like *hard life* (*hard time*) and *soft life* (*soft time*). *Hard life* is the age of the component at or by which the component has to be replaced. For example, at least 10% of parts in an aircraft engine consist of *Life Limited Parts* (LLPs), which are replaced at pre-determined time intervals, irrespective of their condition. Safety critical parts like discs and shafts are given *hard times* and come under LLPs, as they can cause the loss of aircraft if they burst. These parts are usually very expensive and any wastage of life remaining in a LLP will significantly add to the maintenance costs. But at the same time, an unscheduled grounding of the aircraft or removal of the engine, just to replace a few LLP's would cost the operators huge sums of money. A trade off would be to replace the LLP's during the regular shop visits for performance restorations or full overhaul [4]. However, since all the LLP's may not have same "hard times", it is always not feasible to wait until the complete useful life of an LLP is exhausted and hence at least few LLP’s are replaced prematurely during an opportunistic maintenance.

On the other hand, *soft times* are life thresholds for certain hot components of an engine, and usually determine the absolute limits for a performance restoration and full overhaul. Soft times are in fact the basis of on-condition engine maintenance. While some components may have reached their life thresholds, others may not and may also be in good working condition, so do not have to be repaired or replaced. Now the thousand-dollar question would be, how to decide whether to replace them now or not to avoid another engine removal in near future, when the soft times would have reached their thresholds. Another important aspect, which adds to the complexity of opportunistic maintenance, is the level of workscope required by the airline operators. Depending on their requirements, the airline may wish to have the engine overhauled either so that it remains on the wing for maximum time possible, or just the minimum work done to keep the engine serviceable for a shorter period at lower cost. This later practice is typical when an airline expects to keep the aircraft or engine in service for only a short time or it can acquire used engines on the market for a price lower than the cost of overhaul [3].

Condition based maintenance is replacing time based maintenance in modern aircraft, especially in case of mechanical components, which undergo degradation failure mechanisms like crack growth, corrosion etc. As mentioned earlier, 90% of the parts in aircraft engine undergo condition-based maintenance, which is carried out during scheduled shop visits. Now the question arises, when some expensive parts are found to be deteriorating, and there may be a potential failure in future. These parts are not always necessarily repaired or replaced, immediately after the deterioration is detected. For example, fracture critical hardware such as rotors and disks are assigned service limits for crack growth, where cracks are allowed to grow to a specified size before the hardware item is repaired or replaced [12]. There fore, items that fall under this category also need to be analyzed for cost of premature replacement against the cost of down time in future. Also, there is a possibility that there may be enough components with more or less equal useful lives left, which will collectively compensate the cost of down time for a future grounding. This is another factor that if optimized would result in a significant saving to the airline operators.

Thus, in the present paper, we mainly concentrate on two key issues. Firstly, as mentioned in the previous paragraph, condition-based maintenance is slowly but steadily taking over the traditional maintenance strategies like time-based maintenance (hard life). Hence, there is a need to develop various tools and techniques that not only monitor the condition of various components and subsystems, but also enable the maintenance crew to predict various reliability characteristics. Presently, many modern aircraft engines are equipped with Health and Usage Monitoring Systems (HUMS) to monitor various maintenance significant items. Strategies like Relevant Condition Parameter (RCP) based maintenance [8&9], which were developed mainly to model the degradation failure mechanisms, can be integrated into on-condition maintenance to predict the failures depending on the original condition of the components. RCP-based strategy is an effective way of condition based maintenance, which not only reduces the number of inspections and hence downtime [10], but also lends itself to opportunistic maintenance gracefully. The latter part can be attributed to the unique features of RCP-approach, like prior information and lead-time available to the maintenance crew regarding the eminent and potential failures of the components under observation.

Secondly, we develop a procedure to decide what components to be included in an opportunistic maintenance activity, using a popular optimization technique called Genetic Algorithms. In the following section we give a brief description of RCP-based maintenance.

2. Description of RCP based Maintenance

RCP-based maintenance is carried out in two parts. The first part is a systematic approach, with each step addressing a sequenced set of questions for each individual item of the system. The answers to these questions lead to the type of maintenance strategy that is most suitable to the corresponding item. The second part is a mathematical model, which is the implementation of RCP-based approach to maintenance planning. These are the four steps involved in the first part [2]:

- Identification of the maintenance significant items (SSI's)
- Determination of all condition parameters
- Identification of Relevant Condition Predictors (RCP's)
- Selection of condition monitoring techniques

Once the above steps are carried out, the next step is the implementation of RCP-based maintenance. The fundamental idea behind RCP-based approach is to integrate reliability of an item or a system into maintenance planning and to be able to predict the reliability of the system with the help of condition monitoring devises. In order to achieve this, an RCP for each maintenance significant item, which is at a risk of degrading, is being monitored with a suitable condition monitoring technique. For an item to be able to function satisfactorily its RCP should lie between certain prescribed limits, denoted by RCP^{in} and RCP^{lim} set by the manufacturers. Once the numerical value of RCP crosses these limits, the item is qualified as a failure. Therefore, in RCP-based approach, the reliability of an item or system at time *t* is defined as *the probability that the RCP lying between the prescribed limits RCP^{in} and RCP^{lim} at time t*, which can be given by the following expression [7].

$$R(t) = P(RCP^{in} < RCP(t) < RCP^{lim}) \qquad (1)$$

Depending on the nature of these limits, RCP may be divided into the following four categories.

1. Fixed $\mathrm{RCP}^{\mathrm{in}}$ and fixed $\mathrm{RCP}^{\mathrm{lim}}$
2. Fixed $\mathrm{RCP}^{\mathrm{in}}$ and distributed $\mathrm{RCP}^{\mathrm{lim}}$
3. Distributed $\mathrm{RCP}^{\mathrm{in}}$ and Fixed $\mathrm{RCP}^{\mathrm{lim}}$
4. Distributed $\mathrm{RCP}^{\mathrm{in}}$ and distributed $\mathrm{RCP}^{\mathrm{lim}}$

The reliability functions for each of the above mentioned categories and the cases involved within them are derived in Knezevic (1987), El-Haram (1995) and Saranga (2000) [8,9,2&10]. Once the reliability functions have been obtained for each maintenance significant item, depending on the nature of the limits, the next step is to plan the inspection intervals. In RCP-based approach, required reliability is considered as optimization criterion to maintain each significant item. Therefore, as soon as the reliability of an item reduces to its required level of reliability, maintenance actions needs to be carried out to restore the item to its original condition. In order to achieve this, the time to the first examination of each item *i*, denoted by T_i^1 is calculated using the following expression [Knezevic (1987b)] ,

$$R_i(T_i^1) = P(RCP_i^{in} < RCP_i(T_i^1) < RCP_i^{\lim}) = R_i^r \tag{2}$$

Where, R_i^r is the required reliability level for i^{th} item and $R_i(T_i^1)$ is the reliability of item *i*, at time T_i^1. Now, we measure the reliability of each maintenance significant item at time to the first examination, T_i^1 to see if the measured value M_{RCP_i}, is less than the critical value RCP_i^{cr}, where RCP_i^{cr} may be obtained from the manufacturers. For all the items, whose $M_{RCP_i} < RCP_i^{cr}$, the item is allowed to operate until the next time to the examination. And for all the items, whose $M_{RCP_i} \geq RCP_i^{cr}$, required maintenance actions be carried out to restore the items to their original condition. The next subsequent times to the examinations depend on the difference between the measured value of RCP at the previous time to the examination and critical value of RCP, and can be obtained using the expression [2],

$$\int_{T_i^{(j-1)}}^{T_i^j} f_{M_{RCP_i}(T_i^{(j-1)})}(\tau)d\tau = \int_{M_{RCP_i}}^{RCP_i^{cr}} f_{RCP_i(T_i^j)}(c)dc \qquad (3)$$

Where T_i^j is time to the j^{th} examination, T_i^{j-1} is time to the (j-1)$^{\text{th}}$ examination, $f_{M_{RCP_i(t)}}(\tau)$ is the probability density function of M_{RCP_i} at time t and $f_{RCP_i(T_i^j)}(c)$ is the probability density function of RCP_i at time T_i^j.

Thus, for all those items, which did not need maintenance at the time of examination $T_i^{(j-1)}$, j=2,3… the time to the next examination will be T_i^j, where one of the above two decisions are made depending on their measured value $M_{RCP_i}(T_i^{(j-1)})$. For the items that have undergone maintenance at $T_i^{(j-1)}$, the time to the next examination will be T_i^1, as they are treated *as good as new* and the entire process starts all over again. An important point to note here related to opportunistic maintenance is that, although we know that the condition of RCP_i is critical once it exceeds RCP_i^{cr}, we still do not know exactly how much time it takes for RCP_i to reach $RCP_i^{\lim}$ i.e., to fail, from RCP_i^{cr}. And hence we do not know the time available for the maintenance crew in order to decide whether to ground it immediately or to wait until the system is available for maintenance in the immediate future. In such situations, it is helpful to know the *Residual Life* of the item, which is the mean remaining lifetime of the item that has survived up to time T_0 and can be obtained from,

$$MTTF(T_0) = \frac{1}{R(T_0)} \int_{T_0}^{\infty} R(t')dt' \qquad (4)$$

$$= \frac{1}{R(T_0)} (MTTF - \int_0^{T_0} R(t)dt)$$

Where $t' = t + T_0$. Thus, once the item reaches RCP_i^{cr}, we can calculate the residual life of the item in order to know as to how long the item will survive.

Thus the question that arises here, with regard to opportunistic maintenance is that whether the inspections or the maintenance activities can be carried out as a part of scheduled maintenance whenever there is an opportunity. The lead time and the prior information available to the maintenance crew regarding the nature of the potential or eminent failures enables them to plan the required preventive or corrective maintenance activities according to their convenience. But again, the comparison between the cost of grounding and the cost of premature replacement needs to be made even in this case.

3. Genetic Algorithms

In order to incorporate all the above-mentioned factors and like into the decision making process of opportunistic maintenance, one needs to come up with an efficient optimization tool that is robust enough. One such rapidly expanding optimization tool, recently being used for opportunistic maintenance strategies is Genetic Algorithms (GAs). Genetic algorithms are a subclass of Evolution Programs (EPs), which imitate natural selection process in searching for an optimum solution for an objective function called the fitness function. GAs were first proposed by Holland (1975)[7] and were further developed by his student, Goldberg and others in the 1980s. The GAs differs from most optimization techniques, due to their nature of searching a population of solutions, rather than a single solution. Savic *et al* (1995)[11&12] used genetic algorithms for optimum group replacement problem during opportunistic maintenance.

Following key features of Genetic Algorithms [6] lend themselves to use GAs as an optimization tool in the current context.

- Optimizes highly complex cost functions
- Optimizes with continuous or discrete parameters
- Simultaneously searches from a wide sampling of cost surface
- Deals with a large number of parameters
- Provides a list of optimum parameters, not just a single solution
- Works with numerically generated data, experimental data or analytical functions

Since, while talking about aircraft maintenance, we are dealing with thousands of unique parts, which involve numerous factors to be considered to be included in the opportunistic maintenance, GAs, being the best technique to model highly complex cost functions, will suite the present situation very well. The objective here is to be able to decide, whether the item under consideration should be replaced under opportunistic maintenance or not, purely depending on the basis of whether it is cost-effective to replace it now or not. Those items, whose hard or soft lives have been expired, are replaced without ambiguity. Question arises, only for items with useful life left in them, which most of the time are expensive, as otherwise are replaced prematurely whenever an opportunity arises, instead of grounding the system. The choice of replacing it now should be weighed between the cost of premature replacement and the cost of grounding the system in future, purely for the purpose of replacement.

Thus, with each item under question, we attach a cost or fitness function, and use Genetic Algorithms, to decide which ones to be replaced. We formulate the fitness function as follows:

Maximize

$$Z_{ij}[D_i * C_d - j * C_i] \qquad (5)$$

Where,

$$Z_{i,j} = \begin{cases} 1 & \text{If the item is replaced } j \text{ hours before the scheduled time} \\ 0 & \text{Otherwise} \end{cases}$$

D_i = Downtime due to replacement

C_d = Cost of Downtime per hour

C_i = Cost per hour for item i

At this point, it is important to note that, we have only considered the simplest case, just as an example, and the fitness function may be extended to incorporate various factors that play a crucial role in deciding whether an item should be replaced prematurely or not.

In the present paper, we discuss a step-by-step procedure to decide whether a particular component should be included in the opportunistic maintenance and suggest a method to decide when GAs can be used. To start with, we need to identify the points at which opportunistic maintenance can be performed. In general, for any complex system, the below mentioned timings provide an appropriate means to carryout opportunistic maintenance.

1. Scheduled maintenance intervals: these are predetermined times, at which scheduled tasks like overhauling, checks like A, B, C and D etc. are carried out.
2. Corrective maintenance: when a module is grounded to repair or replace a failed item.
3. Progressive inspection: if an inspection or examination of a condition monitoring devise needs to be carried out.

Once the opportunity arises, the next problem is to identify which components to be considered for repair or replacement amongst the components that are accessible and are at a risk of potential failure. At this point, one needs to divide the potential failures into age related and non-age related, and focuses only on age related failures. And also, we concentrate only on maintenance significant items, as the failure of non-significant items should not affect the system performance directly. The following flow chart diagram will be of great help in describing the procedure.

Notation:

MSI --- Maintenance Significant Item
TBM --- Time Based Maintenance
RCPBM --- Relevant Condition Parameter Based Maintenance
HT --- Hard Time
ST --- Soft Time
t --- time of opportunistic maintenance
t^1 --- time of next scheduled maintenance
RCP ---Relevant Condition Parameter

RCP_i^{cr} - - - Critical Value of RCP, for item i
$RCP_i(t)$ --- Value of RCP for item i at time t
GA --- Genetic Algorithm

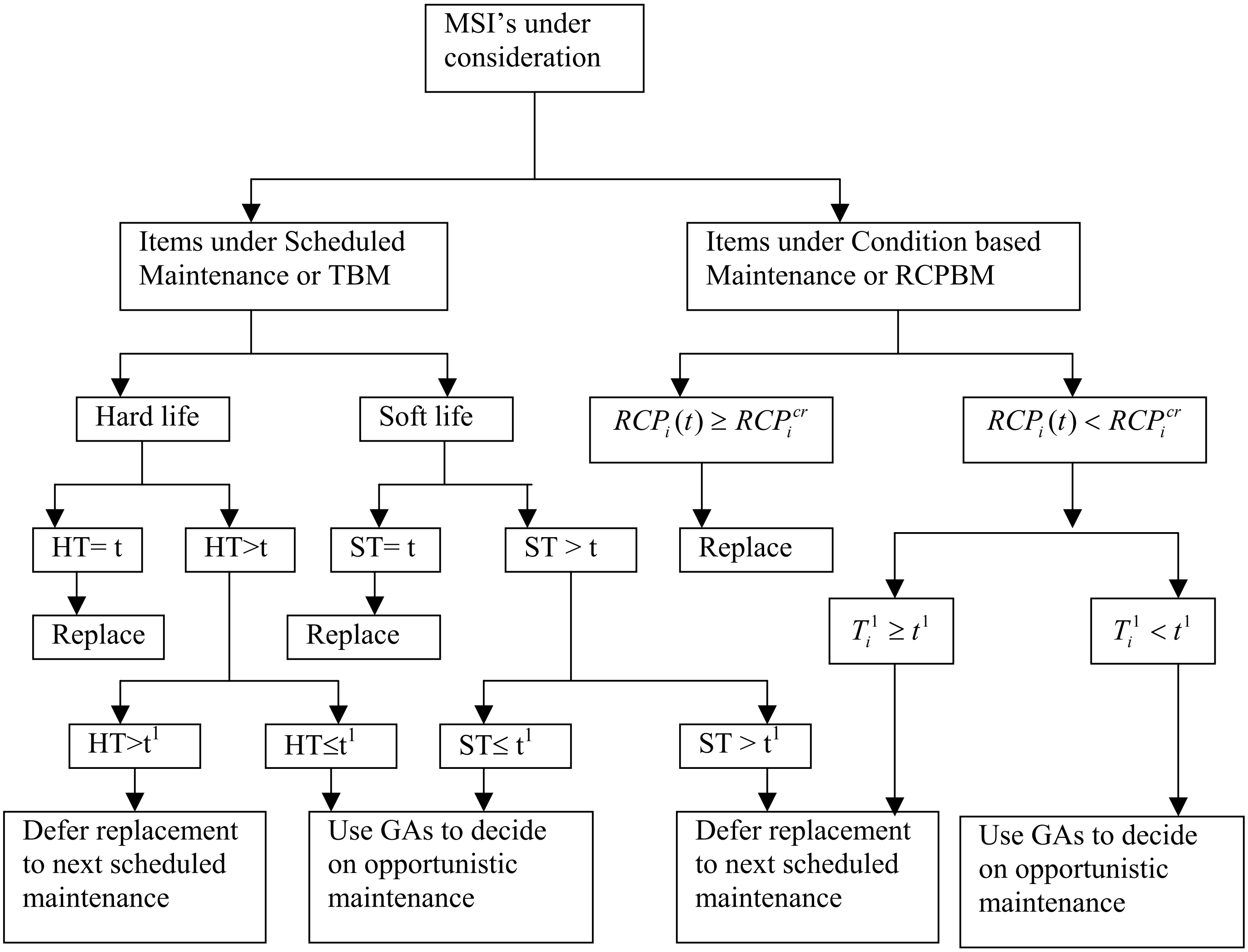

Figure 1. Flow Chart Description of the procedure to decide on opportunistic maintenance

As one can see from the flow chart, the MSI's accessible for opportunistic maintenance have been divided between time-based maintenance and condition-based maintenance, depending on how they are being maintained. For all the items that fall under TBM, we have to further divide them into hard life and soft life, depending on what times are allotted to them. At the time of opportunistic maintenance, all those items, whose hard life or soft life has elapsed, would any way be replaced. For those items, whose hard life or soft life is remaining, depending on how much life is remaining, the decision to defer the replacement to the next scheduled maintenance, t^1 or to replace now has to be taken. If the life remaining is more than t^1, then obviously, the replacement is deferred to t^1. If the life remaining is less than t^1, then the decision of whether to replace now, or ground the system when it is required, is taken using Genetic Algorithms.

Similarly, for items under condition-based maintenance, especially, in case of relevant condition parameter based maintenance, the decision to replace now or not, is taken depending on the value of RCP^{cr}. If the value of RCP for item i, at the time of opportunistic maintenance, t is equal to the critical value, then the item is replaced. If $RCP_i(t)$ is less than the critical value, and if the time to the next examination, T^1 is greater than the time to the next scheduled maintenance, t^1, then the replacement can be deferred to t^1. And if the time to the next examination, T^1 is less than the time to the next scheduled maintenance, t^1, then Genetic Algorithms is used to decide whether to replace now or to ground the system whenever the requirement arises.

4. Conclusions and Limitations

The significance of opportunistic maintenance in fields like aircraft engine maintenance, where complex systems are involved has been emphasized. There are numerous factors to be considered, while deciding on whether a particular component should be replaced or repaired when an opportunity arises. An effective condition-based maintenance, called relevant condition parameter based maintenance, has a great potential to be integrated into aircraft engine maintenance and adopts gracefully for opportunistic maintenance with its unique features. Genetic Algorithms is introduced, as an optimization tool, to compare the cost of premature replacement with the cost of downtime if grounded for the sole purpose of replacement.

This paper was an initial attempt to use Genetic Algorithms for opportunistic maintenance in complex systems. Much work needs to be done in this area, and numerous other relevant factors needs to be incorporated for a comprehensive study. A case study involving a practical application of Genetic Algorithms to real life data, would bring about the practical difficulties involved, but was not carried out here. This was just a preliminary research done to integrate the two areas of opportunistic maintenance and relevant condition parameter based maintenance and to explore the scope of Genetic Algorithms as an optimization tool in this respect.

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