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ANALYSIS OF PREVENTIVE MAINTENANCE PROGRAM IMPROVEMENT FOR IN-SERVICE AIRCRAFT

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Abstract

Excessive maintenance tasks and short maintenance intervals result in high cost and low operational availability. Reliability-centered maintenance (RCM) has been successfully applied to developing initial maintenance program for new aircraft. But it is difficult to apply this concept to in-service aircraft. This paper develops a method of revising preventive maintenance requirements for in-service aircraft based on the RCM philosophy. It consists of the following four steps: analyze the necessity of the maintenance tasks and cancel those for non-functionally significant items (NSI); identify and cancel those inapplicable or invalid maintenance tasks, and find those to be adjusted; analyze in detail the applicability and effectiveness of those maintenance tasks to be adjusted or added and determine the proper tasks and their intervals based on the Weibull Poisson process; and coordinate the maintenance tasks at all levels by prioritizing on-equipment tasks, reducing off-equipment tasks and minimizing duplication. Thus, preventive maintenance tasks and intervals are optimized with such a series of analyses. Good results have been achieved with its application to a type of in-service aircraft.

1 Introduction

Excessive preventive maintenance tasks and short intervals result in high cost and low operational availability of our in-service aircraft. On the one hand, reliability and maintainability have not been considered in their design. On the other hand, the empirical, traditional maintenance concept that more maintenance ensures safety prevails in maintenance analysis. The Reliability-centered Maintenance (RCM), which provides the basic principles and decision logic for a scientific approach to maintenance analysis, has been applied successfully to the development of initial maintenance documents for aircraft. However, when attempting to apply it to the revision of maintenance tasks for in-service aircraft, it turns out to be difficult and time consuming. Much of the huge amount of analysis work is unnecessary when there is a considerable experience. It is not very effective for modifying the numerous maintenance requirements that were empirically developed. It does not provide any scientific computing tools for quantitative analysis of available data. Therefore, based on the RCM theory, the authors develop a method for revising the preventive maintenance requirements in the process of maintenance analysis for a type of aircraft with expected good results[1]. Section 2 describes the basics of this method. Section 3 describes the computation of maintenance intervals with it.

2 Analysis for revision of maintenance tasks

The process of revising the maintenance tasks involves a decision logic and computation, with the analysis of existing maintenance tasks as the start-point. Tasks to be added are analyzed separately. The process consists of four steps: analysis of necessity of maintenance; verification of the applicability and effectiveness of original maintenance tasks; detailed analysis of maintenance tasks that are to be adjusted or added and computation of their intervals, and selection of new tasks or intervals; coordination of the maintenance tasks at all levels.

2.1 Analysis of necessity of maintenance

There are many unnecessary maintenance tasks in the preventive maintenance program of in-service aircraft. Therefore, cancellation of them by analysis of necessity can significantly reduce the workload.

By consequence, failures can be divided into functionally evident failures and functionally hidden failures. A functionally evident failure is one that can be detected by the aircrew with their senses during the normal performance of their duties. Otherwise, it is a functionally hidden failure. The consequences of a functionally evident failure are the direct consequences of a single failure, including the secondary failure that results from it. In contrast, a single functionally hidden failure does not result in any direct consequence, and its prevention is aimed at the prevention of any multiple failure. By criticality, the consequences of a functionally evident failure can be safety-related, mission-related, economical and non-significant. Safety consequences include death, severe injury, destruction or damage of aircraft. Mission consequences include cancellations, aborts, delays and premature returns. Economical consequences include the case that preventive maintenance costs less than repair after failure does. Otherwise, they are non-significant.

The maintenance tasks designed for failures with evident safety and mission-related or economical consequences or for functionally hidden failures necessitate further analysis. The analysis is terminated for those maintenance tasks designed for items with non-significant failure consequences. They are eliminated except those simple servicing and visual inspections, thus greatly reducing the maintenance tasks and their analysis.

2.2 Analysis of applicability and effectiveness of original maintenance tasks

Some maintenance tasks of the in-service aircraft do not follow the law of product reliability. A lot of hard time maintenance tasks are arranged for failures that are not subject to wear out over time. Others are too frequent, ineffective and unreasonable. By analyzing the applicability and effectiveness of the original tasks, those that are not suitable or effective are identified and cancelled, thus further reducing the maintenance workload and determining those tasks that require adjustment.

Analysis of applicability is aimed at assessing whether the maintenance tasks follow the reliability law and maintenance features of a product so as to prevent its functional failures or their consequences. The original maintenance tasks are categorized into servicing, inspection, removal and discard. The servicing category refers to those servicing and lubrication that are required by design and help to reduce functional degradation of the item. Due to its low cost, it is effective as long as it is suitable. The inspection category includes operational checks and functional tests. Operational checks are qualitative against functionally hidden failures and are supposed to find if a function has failed. Functional tests are used to evaluate whether the performance parameters of a product are as specified, requiring that it takes a longer time for a potential failure to develop into a functional failure. The removal and discard category refers to hard time removals and discards. Hard time removals are designed for those items whose failures are difficult to find or prevent without removal. Hard time discards are applicable to those items that can not or uneconomically be repaired. It requires the items to have a definable period of wear out, before which there is a high probability of survival. As a result, in the process of analysis, it is necessary first to determine the failure mode that the maintenance task is designed for is related to wear out over time. If yes or it can not be determined, go on with the analysis. Otherwise, cancel the original hard time removal or discard and try to adjust it for an inspection task.

Go on to perform analysis of effectiveness for those maintenance tasks that follow the principle of applicability. Those that need to be adjusted are analyzed as described in Para. 2.3.

Analysis of effectiveness is designed to assess whether the maintenance tasks can reduce the probability of failures to an acceptable level so as to ensure the effectiveness of maintenance. This principle is applied to safety and mission critical items as well as economical items, considering the difficulty of obtaining the data of maintenance cost of these items. For functionally hidden items, the parameter of probability of multiple failure is controlled to ensure the required availability of the equipment. Provided that a maintenance task is effective, it should have a proper interval to avoid over frequent maintenance. If so, it can go directly to "coordination of maintenance tasks at all levels ". Otherwise, it is subject to adjustment for effectiveness.

2．3 Analysis for adjustment of maintenance tasks

Detailed analysis of applicability and effectiveness and computation should be conducted for those maintenance tasks that are chosen to be adjusted or added in Para. 2.2, so as to select a new maintenance task type and interval or make decision for redesign.

The selection of a maintenance task type is based on the features of the structure and failure of an item and by functionally evident failure and functionally hidden failure. It is selected among the 6 types of servicing, operational inspection, functional test, hard time removal, hard time discard and their combination as per Reference [3]. After the adjustment of maintenance task type, continue to perform analysis of effectiveness.

The effectiveness of an item may be controlled by its maintenance interval. A too short interval may increase the workload and cost of maintenance and make it difficult to implement. A too long interval may degrade the effectiveness of maintenance and can not even ensure mission and flight safety. Therefore, development of proper maintenance intervals can ensure the effectiveness of maintenance tasks while ensuring mission and safety. Otherwise, decision for design change can be made in the analysis when preventive maintenance tasks can not ensure mission or safety or prevent excessive economic losses.

Adjustment of maintenance intervals is conducted with a combination of quantitative and qualitative methods. A quantitative method is used when enough field failure and maintenance data is available, as described in Section 3. Otherwise, adjust the maintenance intervals by considering the maintenance and failure data, results of lead-the-force sampling, and experience of similar products.

Coordinate the maintenance tasks at all levels after the analysis for adjustment of maintenance tasks.

2．4 Coordination of maintenance tasks at all levels

The maintenance of our in-service aircraft is currently conducted at organizational, intermediate and depot levels. There is no preventive maintenance program as a top-level guide document for most of the aircraft types. Managed by different departments, each level of maintenance is based on maintenance manuals prepared independently. As a result, there are overlapping and duplicated maintenance tasks at the levels, causing unnecessary waste of resources.

In the process of analysis, it is necessary to first determine whether a maintenance task is duplicated at another level. If yes, the task at the level that costs more is usually cancelled and there is no more analysis for it. If no, the task is finally selected on the principle of putting priority on on-equipment maintenance and reducing off-equipment maintenance. Thus, some of the duplicated tasks will be removed to further optimize the maintenance tasks.

With all the analyses, the preventive maintenance tasks and their intervals can be effectively optimized and adjusted. It is noted that the analysis work is significantly reduced without complicated analysis for adjustment since most of the analysis is accomplished in the process of analysis for necessity, analysis for applicability and coordination among the levels.

3. Computation of maintenance intervals

This method is based on the statistical analysis of field reliability and maintenance data of aircraft items. Items are often not wholly replaced in field maintenance. Instead, they are lubricated, serviced, adjusted and partially replaced. The reliability of the sample is related before and after these maintenance tasks. It is no longer an independent, simple random sample of the same distribution, and can not be described with a common, traditional probability distribution function. Therefore, our method is primarily based on a Weibull Poisson process to construct a model for preventive maintenance intervals of items that are considered to have a tendency of wear out over time.

The Weibull Poisson process states that, in the process $\{N(t),t\geq 0\}$, the number of failures, $N(t_2)-N(t_1)$, in any time interval follows the Poisson distribution with a mean of $\int_{t_1}^{t_2} u(t)dt$, where the function of failure density is

$$u(t)=\lambda\beta t^{\beta-1} \qquad (t>0) \qquad (1)$$

Where β is the shape parameter, and λ is the size parameter. Thus, as u(t) varies with time *t*, the process mean changes accordingly, which describes the reliability-related features of the failure sample before and after the maintenance of the items.

The probability of the occurrence of more than n failures can be derived from the Weibull Poisson process:

$$P(N>n)=(\lambda t^{\beta})^{n+1}/(n+1)! \qquad (2)$$

Let the allowable probability of failures to be Pac(N>n), and the age corresponding to it is determined:

$$Tac=\{[Pac(N>n).(n+1)!]^{1/(n+1)}/\lambda\}^{1/\beta} \quad (3)$$

Before applying this equation, verify the Weibull Poisson process function, assess parameters λ and β, and determine the allowable failure occurrence probability, Pac, and allowable number of failures, n. The method of verification and assessment is given in Reference [2]. The allowable failure probability may be determined based on the criticality of failure consequences. For example, Pac=0.001 at a level of confidence γ=0.95 for safety-related items. It can be relaxed for mission-related and economical items. The allowable number of failures, n, can be computed with a binomial distribution as detailed in Reference[4].

So far, the formula for computing the intervals of main maintenance task types can be established by controlling the probability of failure occurrence to ensure safety, mission and economy. No intervals are developed for lubrication and servicing tasks, which are not costly or time consuming and can be conducted routinely.

3．1 Hard time removal and discard

When the allowable failure occurrence probability, Pac(N>n), and allowable number of failures, n, are determined and Weibull Poisson process parameters λ and β assessed, compute the age-based intervals as per equation （3）.

3．2 Functional test

First, identify the accuracy of the test equipment, R_E, give the allowable failure occurrence probability, Pac, and compute the number of tests with formula

$$k=lnPac/ln\ (1-R_E) \qquad (4)$$

Then, compute the operating time Tac for the failure occurrence probability to reach the minimum allowable with formula（3）. Assume that the operating time to the first failure is T_d, and the operating time between the first failure to the point when the failure occurrence probability reaches the minimum allowable is T, then $T=Tac-T_d$. This computation will not be needed if the time for a potential failure to develop into a functional failure, T, is known.

Finally, compute the interval of test with

$$T_C=T/k \qquad (5)$$

The time to the first test of an item is: T_d+T_C

In this way, it is ensured that the time to the first test is long enough to detect the evidence of deterioration of the item and that the repetitive test interval is short enough to detect the failure before the failure occurrence probability reaches the minimum allowable.

3．3 Operational check

Based on the allowable value of the multiple failure probability and the current reliability of the protected system, its required availability is determined and then its interval of maintenance is computed, as detailed in the following steps.

First, determine the value of the acceptable multiple failure probability P_{Hac}. Compute the probability of occurrence of one failure in one interval (0，t) for the protected system, $P_A(t)$, with equation (2). Compute the allowable failure occurrence probability of the protecting function with the following equation:

$$P_{Bac}(t)=P_{Hac}/P_A(t) \qquad (6)$$

The reliability of the protecting function is

$$R_{Bac}=1-P_{Bac} \qquad (7)$$

Since the protecting function is usually not repaired within the inspection interval, its allowable reliability equals its required availability, and the average availability of the protecting system is

$$\overline{A}=\frac{1}{Tc}\int_0^{Tc}A(t)dt=\frac{1}{Tc}\int_0^{Tc}R(t)dt \qquad (8)$$

From this, the approximate value of the average availability of the protecting function is

$$\overline{A}=[1+R_B(Tc)]/2=1-P_{Bac}(Tc)/2 \qquad (9)$$

There is no repair in an inspection interval, it is assumed to follow an exponential distribution for a complex system. Then

$$\overline{A}=\frac{1}{\lambda.Tc}(1-e^{-\lambda.Tc}) \qquad (10)$$

The interval of operational check for a functionally hidden item, Tc, can be computed if the average availability and λ are available.

The intervals of maintenance task types computed with the above method are usually verified by lead-the-force use in the field before being finalized.

It should be pointed out that this method can be used to compute the intervals of preventive maintenance for complex items and systems fairly satisfactorily. But it requires a quite large sample. If the sample is small, the failure distribution function is determined with a new mean ranks method, and the maintenance interval is obtained by smoothness processing, as detailed in Reference [4].

4. Ending remarks

This method was applied to a type of in-service aircraft, resulting in substantial economic benefits. 55 periodic maintenance tasks, up to one forth of the total, were cancelled. The intervals of 73 maintenance tasks, up to 33% of the total, were extended .

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