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Minimizing total lifecycle expected costs of digital avionics' maintenance

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Abstract

Continuous growth in modern avionics systems complexity allows the extension of the functionality of flight control and navigation systems and leads to an increase in operating expenses. Currently, avionics maintenance costs approximately 30% of the total aircraft maintenance costs. Great impact on the avionics maintenance cost has high rate of intermittent failures, which has been estimated as approximately 50% in military avionics. Here, a mathematical reliability model of continuously tested LRU subject to permanent and intermittent failures is developed. Mathematical expressions for availability of redundant systems are derived considering the spare part system sufficiency. A detailed analysis of the three different variants of the breakdown maintenance strategy (BMS) of modern avionics systems is presented. A criterion of optimizing the number of spare parts is proposed. Some considerations for choosing the optimum variant of the BMS are outlined.

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Keywords: Line replaceable unit; Breakdown maintenance; Permanent failures; Intermittent failures; No Fault Found; Failure rate; Lifecycle costs; Availability

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1. Introduction

At present, aircrafts such as B757, B767, B777, B787, A340, and A380 use digital avionics. Modern avionics comprise a set of redundant and easily removable LRUs. Each LRU includes several SRUs and has its own BITE. Modular design offers easy access to circuits and components for inspection or servicing. The LRUs operate up to the safe failures (permanent and intermittent), which are registered during flights or after landing. This type of maintenance strategy is called BMS. Dismantled LRUs can be retested and repaired either at the manufacturer or at the base airport facilities. In the last case, it is necessary to have ATE for retesting each dismantled LRU and detecting a failed SRU. Thus, the flight safety of modern aircraft is provided using redundant avionics systems, while the flight regularity is provided using a sufficient number of spare LRUs. However, the described maintenance strategy is ineffective in the case of high rate of NFF events because ATE does not confirm the fact of intermittent failures and the same intermittent failures may re-occur in the next flights. Aviation data suggest that there are more than 400,000 NFF cases per year, where a false alarm is given and no fault is detected after investigation [1]. As shown in [2, 3], the estimated NFF rates for avionics systems is between 20% and 50%. Theoretical calculations given in [4] show that the fleet, flying 30,000 hours per year, may have losses due to the NFF phenomena up to £500,000 annually. The impact of NFF on airlines includes an increase in service time, reduction of the regularity, and availability, as well as an increase in the spare LRUs, which ultimately leads to an increase in the lifecycle costs of avionics. Thus, when choosing the optimal variant of the BMS it is necessary to consider the effect of intermittent failures on the lifecycle costs of avionics.

The following references do not relate to avionics lifecycle costs, which is the subject of this study. However, these references are important for understanding the proposed reliability model of avionics LRUs.

Nakagava [5] analyzed inspection policy to intermittent faults where the test is planned at regular intervals to detect the faults. Exponential distribution of time to a permanent and intermittent failure is assumed. In [6], a communication system subject to intermittent faults is considered. Faults have an exponential distribution and are hidden. Faults become permanent failures when the duration in hidden state exceeds an upper limit time. In [7], a three state Markov model is

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considered for fault-tolerant systems by taking the effects of permanent and intermittent faults into consideration. The reliability of standby and duplex systems are analyzed. In [8], a reliability analysis is conducted for optimal periodic testing of intermittent faults that minimizes the test cost. A Markov model is used for the probabilistic modelling of intermittent faults. In [9], a model for studying the reliability of digital systems subject to both permanent and intermittent faults is considered. The model is based on a Markov model containing three states.

In this study, we consider an LRU subject to permanent and intermittent failures with an arbitrary law of failure time distribution. We assume that LRU is continuously tested and both types of failures are automatically detected by the BITE. When the LRU is rejected, a replacement (or as-good-as-new repair) is conducted. Dismantled LRUs are directed to repair facilities for retesting, and if necessary, repairing.

Nomenclature

LRU	line replaceable unit
SRU	shop replaceable unit
BITE	built-in test equipment
BMS	breakdown maintenance strategy
ATE	automatic test equipment
NFF	no fault found
MTBF	mean time between failures
MTBUR	mean time between unscheduled removals
TLEC	total lifecycle expected costs
PDF	probability density function
IF	intermittent failure
PF	permanent failure
IFD	intermittent fault detector
WSPMS	warehouse spare parts management system
DME	distance measuring equipment

2. Mathematical model of LRU maintenance

2.1. Space of LRU states

When developing a mathematical model of the LRU maintenance, we assume that the interval of interest for LRU maintenance is infinite. In fact, this is true, because the MTBUR of an LRU is usually much less than the aircraft life expectancy. The state of the LRU is continuously tested by the BITE during time τ, where τ is the mean time between aircraft landings in the base airport. The behavior of the LRU in the time interval $(0, \infty)$ is described by the stochastic process $L(t)$ with finite number of states. The process $L(t)$ varies jump-wise. Each jump of $L(t)$ is caused by the transition of the LRU to one of the possible states. It is assumed that $L(t)$ is a regenerative stochastic process. Let $L(t)$ be defined as follows. Assume that the LRU permanent failure occurs at time ξ, where $k\tau < \xi \le (k+1)\tau$. Then, in an arbitrary time t the LRU can be in one of the following states: S_1, if at time t the LRU is in operable state; S_2, if at time t the LRU is not used and dismantled or mounted on the board of an aircraft; S_3, if at time t the LRU is not used waiting on the aircraft board for replacement by a spare LRU from a warehouse; S_4, if at time t the LRU with intermittent failure is repaired; S_5, if at time t the LRU with permanent failure is repaired.

The LRU, which was rejected by the BITE, would have to be replaced by an operable LRU from the warehouse. The LRU replacement time should be short enough so as not to violate aircraft flight regularity. Any delayed departure of the aircraft will be bound with economical losses. Therefore, the warehouse must have a sufficient number of spare LRUs. On the other hand, an excess of spare LRUs in the warehouse will also be bound with economical losses, since the cost of avionics is extremely high. Thus, there is a real problem of choosing the variant of BMS that minimizes the TLEC.

Let T_i be the time of staying of the LRU in the state S_i (i = 1, 2, …, 5). Obviously, T_i is a random variable with expected mean time $E[T_i]$. Let Ξ be the time to permanent failure. The uncertainty in the values that Ξ can take is described through the PDF $\omega(\xi)$. Analogically, we define the random variable Θ as the time to intermittent failure with PDF $f(\theta)$. The average duration of LRU regeneration cycle is determined by the following formula:

$$E\left[T_0\right] = \sum_{i=1}^{5} E\left[T_i\right] \tag{1}$$

2.2. Probabilities of intermittent failures

To determine the maintenance efficiency indicators, we use the joint PDF of random variables $\Xi, \Theta_1, \ldots, \Theta_k$, which we denote as $\omega_0(\xi, \theta_1, \ldots, \theta_k)$, where $\Theta_i = \Theta - (i-1)\tau$ is the remainder of the operating time to intermittent failure after $i-1$ flights ($i = 1, \ldots, k$). Using the multiplication theorem of the PDFs, we can write

$$\omega_0\left(\xi,\theta_1,\ldots\theta_k\right) = \omega\left(\xi\right) f\left(\theta_1,\ldots,\theta_k \left|\xi\right.\right), \tag{2}$$

where $f(\theta_1, \ldots, \theta_k|\xi)$ is the conditional PDF of random variables $\Theta_1, \ldots, \Theta_k$ under condition that $\Xi = \xi$.

To determine the expected mean times $E(T_i)$, $i = 1, \ldots, 5$, we introduce some conditional probabilities related to intermittent failures. The conditional probability of appearing the intermittent failure during ν-th ($\nu = 1, \ldots, k$) flight is formulated as follows:

$$P_{IF|O}\left(\overline{\tau,(\nu-1)\tau};\nu\tau\left|\xi\right.\right) = P\left\{\bigcap_{i=1}^{\nu-1}\Theta_i > \tau \bigcap \Theta_\nu < \tau\left|\xi\right.\right\} \tag{3}$$

The conditional probability of not having the occurrence of the intermittent failure during k-th flight is formulated as follows:

$$P_{\overline{IF}|O}\left(\overline{\tau,(k-1)\tau};k\tau\left|\xi\right.\right) = P\left\{\bigcap_{i=1}^{k}\Theta_i > \tau\left|\xi\right.\right\} \tag{4}$$

The probabilities (3) and (4) are determined by integrating PDF $f(\theta_1, \ldots, \theta_k|\xi)$ over the corresponding limits.