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RELIABILITY OF FLEET OF AIRCRAFT

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The importance of using information on the fatigue crack discovery for elimination of any fatigue failure in the fleet of aircraft of the same type and human factor influence has been studied. Numerical estimation of the influence of this information exchange has been obtained. The Monte Carlo method has been used for modeling the process of inspection of the aircraft fleet and calculation of fatigue failure probability as a function of inspection interval, number of aircraft in the fleet and intensity of the process of bringing in operation of new aircraft.

Keywords: Monte Carlo, inspection programme and approval test, fleet reliability

Introduction

Review of the problem of elimination of aircraft fatigue failure can be seen in [1]. It is solved using two main methods: by discarding the aircraft after the specified number of flight hours is reached (safe-life approach) or by implementing the periodic inspection programme, which allows finding the fatigue damage and repair or discard an aircraft from service before the damage exceeds regulatory mandated value (fail-safe approach). The main approach used today is the development of an inspection programme which is developed using the information on full-scale aircraft fatigue test.

Statement of the Problem

In previous investigation [1] the reliability of one aircraft was usually studied. Here we consider the reliability of a fleet of aircraft of the same type taking into account that if a fatigue crack is discovered in any aircraft then any fatigue failure in the fleet will be eliminated because of this and all the others aircraft (or certain structural significant item the failure of which is failure of aircraft) in the fleet will be discarded from service. Redesign of this type of aircraft will be made before new attempt to continue the service will be made. In [1] really the fatigue failure of one aircraft, p_{f1}, was studied, but reliability of fleet of N aircraft was calculated using equation of probability of independent events: $1-p_{f1N}=(1-p_{f1})^N$, where p_{f1N} is a probability of any failure in the fleet of N aircraft. This calculation corresponds to assumption that after discovery of a fatigue crack in any aircraft we make redesign (repair) only of this specific aircraft but the service of all other aircraft in fleet is continued without any changes, as if we do not do any exchange of information. In this paper we take into account the exchange of information about the crack discovery in any aircraft and take into account the human factor also. This mean that we take into account that the fatigue crack is discovered only with probability w, $w \le 1$, even if during inspection it has a detectable size. The reason of this can be a low level of labour discipline or any other combination of circumstances (human factor). The human factor is also not taken into account in [1].

It is supposed that a required operational life of the aircraft is limited by specified life, t_{SL}, when aircraft is discarded from service. We make assumption also that certain structural significant item, the failure of which is the failure of the aircraft, is characterized by a random ector (T_D, T_C), where T_C is a critical lifetime (up to failure), T_D is a service time, when certain damage (fatigue crack) can be detected. So if r inspections of one specific aircraft should be made in interval (T_D, T_C) and $T_c < t_{SL}$, then the fatigue failure of this aircraft can take only if in all r inspection the fatigue crack will not be discovered and probability of this event is equal to $p_{f1w} = (1-w)^r$. It is an implementation of random variable because r is an implementation of random variable which is the function of random vector (T_D, T_C). Mean value of this probability should be known.

As it is shown in [1], the following simple exponential model of fatigue crack in interval (T_D, T_C) could be used for approximation of its dependence on time: $a(t) = a_0 e^{Qt}$, where a_0 and Q are some parameters. In this paper we assume that Q is a random variable which has lognormal distribution but a_0 is a certain constant (see more general assumption in [1]). Then it can be shown that random variables $T_D = (\log a_d - \log a_0)/Q = C_d/Q$ and $T_C = (\log a_c - \log a_0)/Q = C_c/Q$, where a_d and a_c are fatigue crack sizes when it becomes detectable and critical (corresponds to failure), have lognormal distribution also. In this paper we consider the case when the parameters of these distributions are known [1]. This assumption allows calculating the probability of any fatigue failure in fleet of aircraft for specific inspection programme.

To prevent the failure in the fleet with information exchange, it is enough to find at least one crack before the failure of any aircraft in the fleet. Let ${T_{d_i}}^+ = t_i + T_{d_i}$ and ${T_{c_i}}^+ = t_i + T_{c_i}$ be the calendar time moments when fatigue crack can be discovered and aircraft failure takes place correspondingly for i-th aircraft, where t_i is the calendar time moment when service of i-th aircraft begins, $t_1 < t_2 < \ldots < t_N$, $i = 1, \ldots, N$. And let $I_{SL} = \{i: T_{ci} < t_{SL}, i = 1, \ldots, N\}$ be a set of indexes of aircraft the failure of which can take place if inspection is not provided. Let us define the calendar time of the first failure in the fleet of aircraft without inspection: ${T_f}^+ = \min\{{T_{c_i}}^+: i \in I_{SL}\}$.

Let us define also ${T_{f_i}}^+ = \min({T_{c_i}}^+, {T_f}^+), i \in I_{SL}$ and $R = \sum_{i \in I_{SL}} R_i$ is a total number of planned inspections in aircraft fleet before T_f^+ ,where $R_i = max(\{[({T_{f_i}}^+ - t_i)/D] - [({T_{d_i}}^+ - t_i)/\mathrm{D}]\}, 0), i \in I_{SL}$, is a random inspection number of *i*-th aircraft from the set I_{SL} for inspection interval *D* (it is supposed a specific schedule of inspections for i-th aircraft: $t_i + D, t_i + 2D, \ldots;\ i = 1, \ldots, N$).

Random variable Q is a speed of fatigue crack growth in logarithm scale. It has a specific implementation for each aircraft and $Q_1, \ldots, Q_N$ are independent random variables. So probability of any fatigue failure in fleet of N aircraft

$$p_{fNNw}(D) = \int_{-\infty}^{\infty} \ldots \int_{-\infty}^{\infty} \left((1-w)^{r(q)}\right) dF_{Q_1}(q_1) \ldots dF_{Q_N}(q_n), \quad (1)$$

where $r(q), q = (q_1, \ldots, q_n)$, is implementation of a random variable *R*, $F_{Q_i}(.)$ is a cumulative distribution function of Q_i, $i = 1, \ldots, N$.

Using this equation we can get function $p_{fNNw}(D)$ and choose the inspection programme (in the considered case: inspection interval, D) under condition of limitation of the probability of any fatigue failure in fleet of N aircraft by some fixed small value.

Estimation of parameter distribution of both random variables T_d and T_c can be obtained processing results of full scale fatigue test of airframe. Taking into account that these estimates are random variables the minimax approach should be used for final decision [1] but this is a subject of another paper.

Numerical Example

For $N = 1$ very easy formula can be used for calculating (1) (see [1]) but for large N Monte Carlo method is more convenient. Example of Monte Carlo modeling of fatigue crack development in 10 fleets with 1 aircraft in every fleet is shown in Fig.1. For this case the information exchange about crack discovery does not take place. This means that after discovery of a fatigue crack during inspection of any aircraft all other aircraft of this fleet continue the service without any changes. So service of any single aircraft does take place independently of any other aircraft and we can consider every aircraft as a specific independent fleet. And for the Monte Carlo modeling of fatigue crack development we can suppose that all aircraft begin service simultaneously.

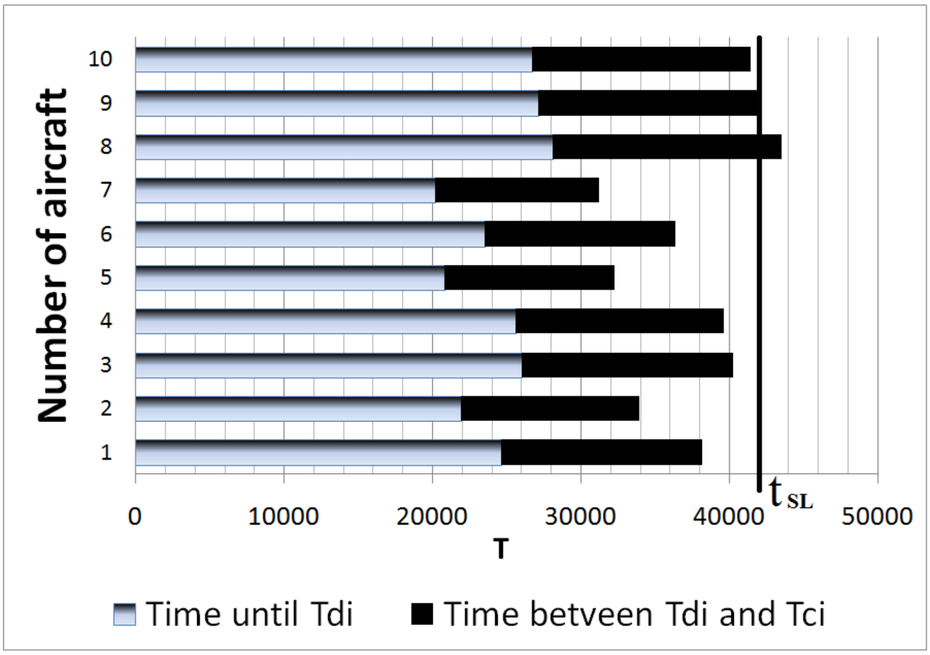

Figure 1. Example of Monte Carlo modeling of fatigue crack development in10 fleets with 1 aircraft in every fleet. Information exchange about crack discovery does not take place.

In Fig. 1 example of Monte Carlo modeling of fatigue crack development only in 10 fleets are shown but, actually, one thousand modeling has been made in order to get precise calculation of p_{f1w} as function of the length of interval D for both w = 0.9 and w = 0.95. The result of calculation of this function is shown in Fig. 2 for initial data taken from [1]: mean value and standard deviation of random variable $\ln Q$ are equal to vector (-8.58733, 0.548084) for crack size unit equal to 1 mm, $\alpha_0 = 0.28613258$ mm, $\alpha_d = 20$ mm, $\alpha_c = 237$ mm and $t_{SL} = 42000$ flights.

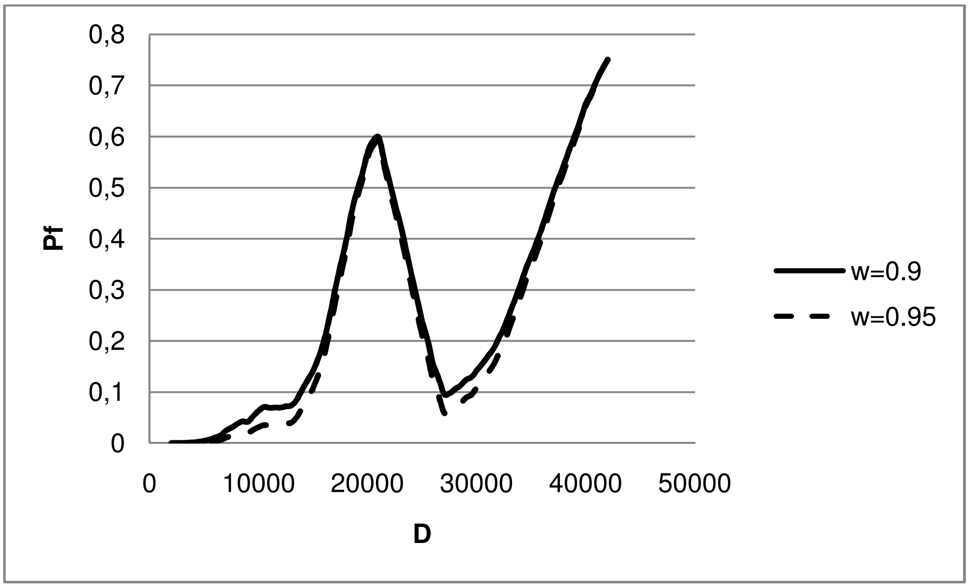

Figure 2. The dependency of failure probability on the inspection interval for one aircraft, $p_{f1w}(D)$

With an increasing inspection interval the probability of failure increases if it is small enough. Non-monotonous behavior of this function is explained in [1]. The interval between the inspections have to be chosen in first monotonous part of the curve with small value of p_{f1w}.

The result of calculation of fatigue failure probability of at least one aircraft for the set of 10 fleets with one aircraft in every fleet as a function of the inspection interval with service without information exchange, $p_{f1Nw}(D) = 1 - \left(1 - p_{f1w}(D)\right)^N$, is shown in Fig. 3.

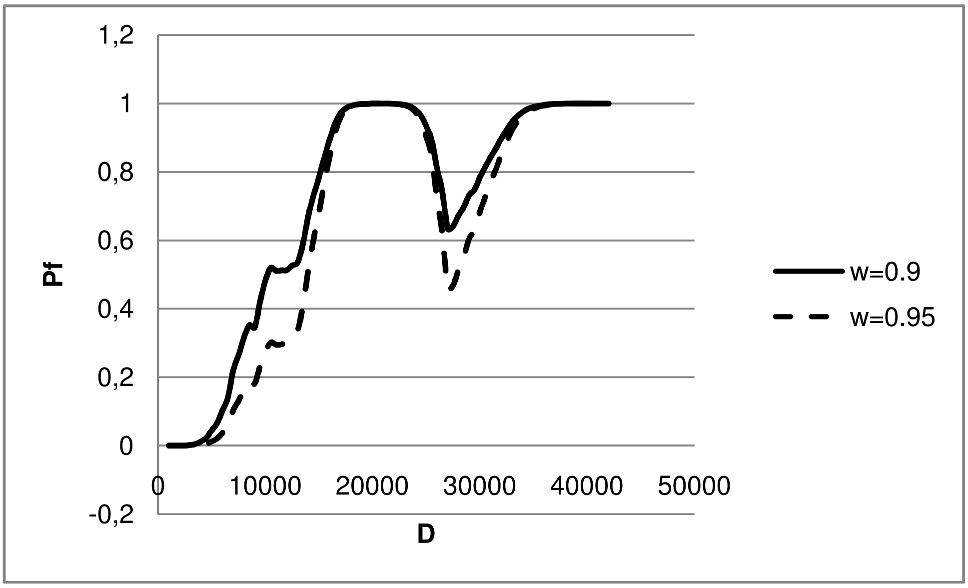

Figure 3. The dependency of failure probability of at least one aircraft for the set of 10 fleets with one aircraft in every fleet without information exchange on the inspection interval, $p_{f1Nw}(D)$

Example of Monte Carlo modeling of fatigue crack development in one fleet with 10 aircraft is shown in Fig.4 for the case of information exchange about discovery of any fatigue crack. We suppose that in this case time of service beginning of i-th aircraft $t_i = d(i-1),\ \ d \ge 0,$ corresponding to the calendar specified life $t^+_{SLi} = t_i + t_{SL},\ \ i = 1,2,...,N$, and that after discovery of fatigue crack in any aircraft all aircraft of this fleet are discarded from service.

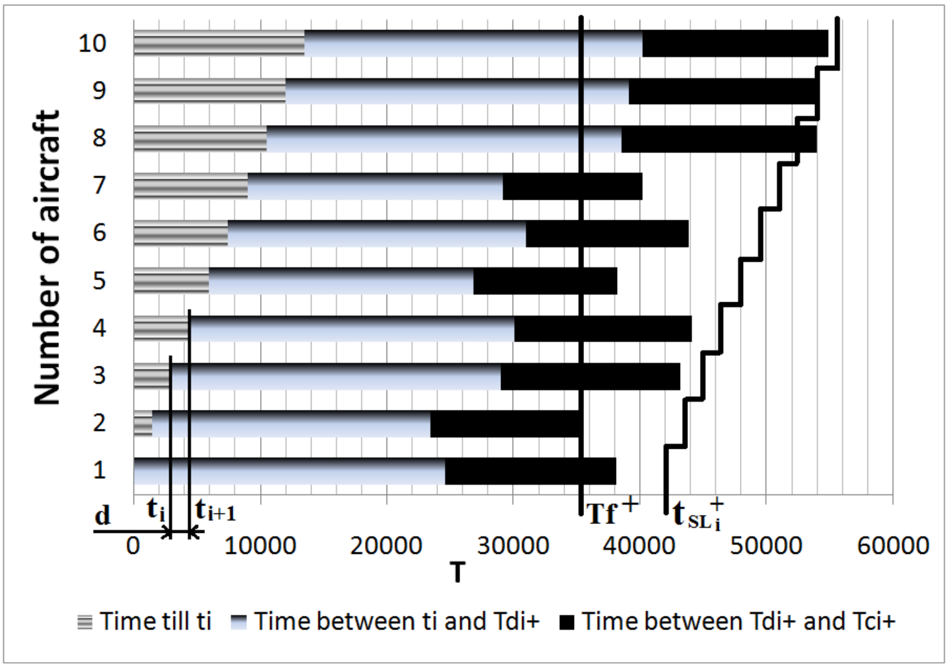

Figure 4. Example of Monte Carlo modeling of fatigue crack development in one fleet with 10 aircraft. After discovery of fatigue crack in any aircraft all aircraft of this fleet are discarded from service

Corresponding results of calculation of the function of probability of failure of at least one aircraft on the interval between the inspections, function $p_{fNNw}(D)$ (see (1)) for $d = 1500$ is shown in Fig. 5 again for both w = 0.9 and w = 0.95.

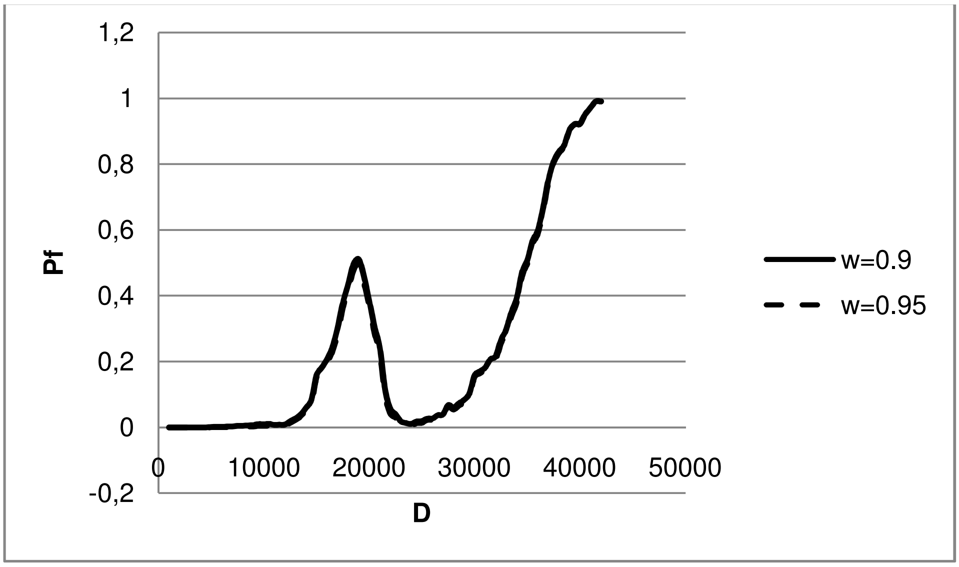

Figure 5. The dependency of failure probability of at least one aircraft of fleet with information exchange on the inspection interval for fleet of 10 aircraft

It is worth noting that influence of human factor is less in the fleet with information exchange than in fleet without information exchange.

Using functions $p_{f1Nw}(D)$ and $p_{fNNw}(D)$ we can choose the inspection programme (in the considered case: inspection interval, D) under condition of limitation of the probability of any fatigue failure in the fleet of N aircraft by some fixed small value ε for service without and with information exchange correspondingly.

For specific ε = 0.01 for N = 10 and w = 0.95 for the case of service without information exchange we should choose D=4900. For the same ε but for the fleet with information exchange we should choose D = 12200.

We see that it is necessary to make inspections more frequently to keep the failure probability on the same specified level for the case of service without information exchange.

Comparison of functions $p_{f1Nw}(D)$ and $p_{fNNw}(D)$ for $w = 0.95$ and different D is shown in Fig. 6.

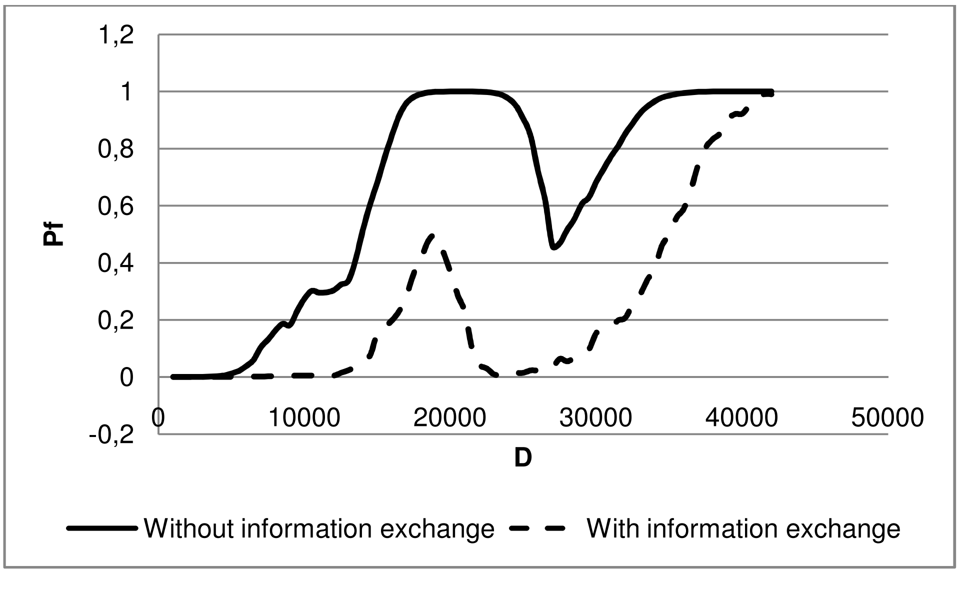

Figure 6. Comparison of failure probabilities of fleet with and without information exchange on the inspection interval for w = 0.95

Conclusion

Comparing service reliability of fleets with and without information exchange it is shown that for the same fleet reliability it is enough to make inspections less frequent for the fleet with information exchange, than for the fleet without information exchange. Equations and PC programme for calculation of probability of any fatigue failure in the fleet of aircraft have been developed. It allows choosing the inspection programme (interval between inspections) under condition of limitation of this probability taking into account the human factor.

References

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