RELIABILITY-BASED STRATEGY OF OPERATING TURBINE ENGINES, WITH CONSIDERATION TO SAFETY AND EFFECTIVENESS ISSUES

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Abstract

The future strategy of operating engineering objects such as turbine engines could be sought in combining various strategies of operational use of engines with consideration to the issues of reliability, safety, and effectiveness. The strategy has been based upon tracking of variations in adequate parameters of reliability, safety, and effectiveness, where account is also taken of the risk to fail performing the assigned missions (*operational tasks*).

Keywords: *operation, reliability, engine, safety*

1. Introduction

The strategy of technical equipment operation requires permanent tracking of relevant parameters related to reliability, flight safety and performance effectiveness. This is the future-oriented strategy as it needs extremely high reliability level of subassemblies and structural components with the probability of fault-free operation nearly as high as one (1) over the entire lifetime of the equipment.

In order to select the adequate strategy for operation of such sophisticated technical object as turbine engines one has to be familiar with the following issues:

- methods and criteria for assessment of technical conditions for specific units,
- shape of the curve for the function of technical condition or the area where the curve runs with the presumed probability,
- interrelations between frequency and “depth” (overall scope) of prophylactic and maintenance operations on one hand and reliability and safety issues on the other one,
- interrelations between the historical records for the equipment exploitation and the stream of faults that is generated by the specific object (a set of objects) with consideration to the effects of these faults,
- physical phenomena that serve as reasons for alteration of technical condition, symptoms of defects and states that directly precede catastrophic breakdowns,
- interconnections between reasons and results where alterations to technical condition components and subassemblies lead to definition of the entire object operability.
- progress of destructive processes (1^{st}, 2^{nd}, 3^{rd} and 4^{th} degree [4]) alterations to technical condition of components and subassemblies as a function of operational condition, total time of service, schedule of maintenance operations, external disturbances, etc.,
- risk factors that may occur during exploitation of the equipment and that are conductive to defects and failures

2. The problem of reliability

The method of estimating the maximum permissible probability of extending the parameter value beyond the established thresholds with respect to the parameter that quantifies the adopted exploitation strategy is reduced to checking the reliability-related parameters that vary during the service lifetime (the value vs. time functions). A series of reliability factors can be used for that purpose, including the number of recorded failures (defects), numbers of components or subassemblies exchange operations, number of recorded so called specific cases of failures (that sometimes can be spontaneously converted into breakdowns or catastrophic disasters), etc. For a defined parameter, e.g. number of recorded failures, where the maximum value of the parameter is $n_{\max}$, the maximum acceptable probability of the parameter value can be expressed by the formula [7]:

$$P_{dop} = \sum_{n=0}^{n_d} \frac{(\omega \cdot a \cdot T)^n}{n!} \exp(\omega \cdot a \cdot T), \tag{1}$$

where:

- ω – intensity of the stream of faults,
- T – number of operation hours for the technical object (operation lifetime),
- a – number of units under test,
- n_d – number of failures that is allowed for the unit under test with no exceeding of adjustment limits for working parameters.

Monitoring of the reliability level with permanent checking of such threshold level when individual parts or subassemblies reveal symptoms of hazardous failures requires thorough examination of the entire population of such components under real operational conditions. Such examination makes it possible to be in control of the manufacturing process quality and tune up quality of the maintenance, repair and overhaul processes in order to achieve goals of efficient prophylactic for the equipment exploitation.

The parameters that are most frequently used for reliability analyses include the mean time to the first failure *MTTF*[1] and the mean time to the first exchange *MTTE*[2]. However, estimation of those parameters is quite difficult during the initial period of new aircraft exploitation. Trustworthiness of these parameters' estimation increases only as the lifetime of the equipment goes by. That is why during the initial period of technical equipment operation other reliability-related parameters are used as well, including probability of fault-free operation $P(t)$, fault intensity $\lambda(t)$, probability of the need for restoration (exchange, repair, overhaul) $P_{Od}(t)$, restoration intensity $\lambda_{Od}(t)$, the gamma-percent resource T_γ. The analysis is carried out for the specified time interval Δt, which is defined as $\Delta t_i = t_i - t_{i-1}$ for the series of products (parts, subassemblies) $N_S(t_i)$ that exhibit the time of fault-free operation $t \geq t_i$. For such presumptions the reliability indices can be calculated by means of the following formulas:

$$\lambda(\Delta t_i) = \frac{n_S(\Delta t_i)}{\left[N_S(t_i) - \sum_{j=1}^{i-1} n_S(\Delta t_j)\right]\Delta t_i}, \tag{2}$$

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[1] *MTTF* : Mean Time To Failures.
[2] *MTTE* : Mean Time To Exchange.

$$P(t_i) = 1 - \frac{\sum_{j=1}^{i} n_S(\Delta t_j)}{N_S(t_i)}, \tag{3}$$

$$\lambda_{Od}(\Delta t_i) = \frac{m_S(\Delta t_i) + n_S(\Delta t_i)}{\left[N_S(t_i) - \sum_{j=1}^{i-1} n_S(\Delta t_j) - \sum_{j=1}^{i-1} m_S(\Delta t_j)\right]\Delta t_i}, \tag{4}$$

$$P_{Od}(t_i) = \frac{\sum_{j=1}^{i} m_S(\Delta t_j) + \sum_{j=1}^{i} n_S(\Delta t_j)}{N_S(t_i)}, \tag{5}$$

$$T_{\gamma i} = P(t_i)\cdot 100 = \left[1 - \frac{\sum_{j=1}^{i} m_S(\Delta t_j) + \sum_{j=1}^{i} n_S(\Delta t_j)}{N_S(t_i)}\right]\cdot 100, \tag{6}$$

where:

m_s (Δt_i) – number of products that had to be exchanged due to prophylactic reasons,
n_s (Δt_i) – number of products that exhibited failures during the time period of Δt_i, starting from the moment when the equipment was put into operation, counted by the calendar time of tests.

$$\tau = [t = 0 \text{ to } t = t_i]. \tag{7}$$

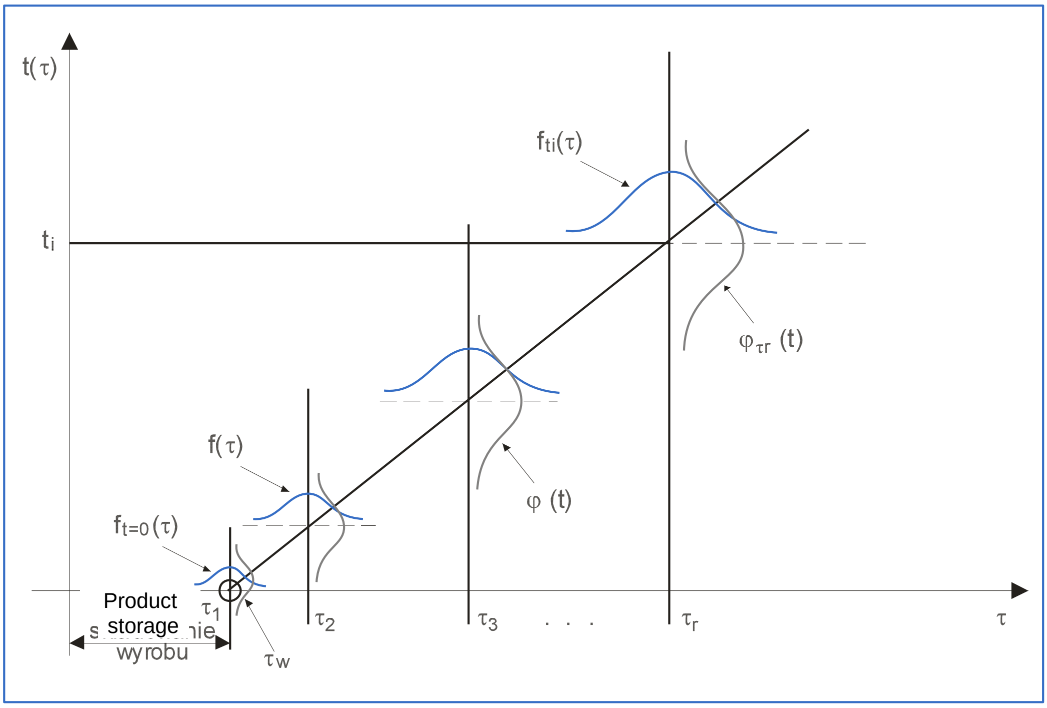

Fig. 1. Binomial process of the product operation time when the equipment is in service
t – operation time of the product; τ – calendar time; τ_w – moment when the product is put into operation

The above deliberations and analyses assume that the parameter of calendar time τ increases in a discrete manner with a specific increment and adopts the values of τ_1, τ_2, … τ_r. In general, variations of both t_i and τ_r are subject to random changes. In such a case they can be associated with the functions of densities $f_t(\tau)$ and $\varphi_\tau(t)$ that are shown on the example of the binomial process of the product operation when the equipment is in service (Fig. 1) [4].

3. Problem of safety

Basic safety parameters for the adopted strategy of the equipment exploitation include the safety untrustworthiness factor Q_B and the safety trustworthiness factor R_B along with the factor of transition (event) intensity for the system untrustworthiness λ_B, expressed as

$$\lambda_B = \frac{\mathrm{d}Q_B(t)}{\mathrm{d}(t)} \cdot \frac{1}{1-Q_B} . \tag{8}$$

The formula (8) can be transformed to calculate the following form of the R_B factor:

$$R_B(t) = R_{BO} \exp\left[-\int_0^t \lambda_B(\tau)\mathrm{d}\tau\right] . \tag{9}$$

The next two safety indices are represented by the leading distribution function of safety untrustworthiness Λ_B and the expected value (mathematical expectation) for the system lifetime until its transition to the state with untrustworthy safety $\mathbf{E}(T_B)$:

$$\Lambda_B(t) = \int_0^t \lambda_B(\tau)\mathrm{d}\tau , \tag{10}$$

$$\mathrm{E}(T_B) = \int_0^\infty R_B(\tau)\mathrm{d}\tau . \tag{11}$$

where:

T_B – the random variable of the system operation time until its transition to the state with untrustworthy safety.

4. Problem of effectiveness

The aircraft exploitation practices show that failures can occur during a flight and are detected either at flight or during earth maintenance but the failure occurrence does not interrupt progress of the assigned task. Alternatively, failures can both occur and be detected on the earth and the total effect thereof is proportional to the sum of flight intervals. For the above presumptions one of the methods dedicated to selection of efficiency indices takes account for the following postulations:

- an aircraft is in operation until its limit (terminal) state occurs,
- purchase costs of the aircraft are taken into account,
- operational downtime periods result from aircraft failures,
- every failure is immediately repaired, just after it has occurred,
- duration of each repair is a direct result of the totalized time of repair operations,
- aircraft downtime due to the lack of the need to its use is also considered,

- every aircraft can only be in one of the following operational states: operable or non-operable,
- operational effect due to the equipment exploitation is totalized for its entire lifetime,
- failures of an aircraft and related operational downtime lead to the loss caused by the lack of expected effects as well as connected with rectification of faults and indirect results thereof,

Therefore, the relation (12) is justified for the model of operation under the above conditions as it expresses the expected value of performance effectiveness [2, 3].

During the process of exploitation any technical object switches between various exploitation states with different operational and maintenance parameters. Let us assume that P_i denotes probability that the object is in the i^{th} state of a complex Markov chain whereas T_i - the mathematical expectation for time duration when the object remains in the i^{th} exploitation state with probabilities of $P(t_i)$, $P_{Od}(t_i)$ and fault intensities $\lambda(t)$, $\lambda_{Od}(t)$. Thus the system reaches the values of performance effectiveness equal to a_i (a_i can adopt both positive and negative values) for individual states of exploitation. The average performance effectiveness per unit of exploitation time for a specific technical object (a set of objects) $\left(\overline{E}_f\right)$ is defined by the following formula:

$$\overline{E}_f = \frac{\sum_{i \in S} P_i \overline{T}_i a_i}{\sum_{i \in S} P_i \overline{T}_i}, \tag{12}$$

where:

S – set of exploitation states for the specific object.

4. Conclusion

The described strategy of technical equipment operation requires conjunctive tracking of relevant parameters related to reliability, flight safety and performance effectiveness (formulas 1÷6 and 8÷11). The parameters can be calculated on the basis of historical information stored in data banks [7, 8]. However, estimation of the risk associated with the adopted strategy [5] and untrustworthiness limits [1] still remains an essential and a very difficult problem.

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