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EVALUATION METHODS OF AIRCRAFT FLIGHT SAFETY

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Abstract

The paper includes a method of probability and risk evaluation of technical damage to functional-relief (redundant) systems using the Poisson model. The paper raised the problem of diagnosis errors and erroneous usability evaluation and describes the example of a real event of an aircraft landing without the released landing gear as a consequence of an erroneous diagnostics. The rescue process in a situation of an aviation accident hazard was described briefly.

1. Introduction

By assumption, the aeronautics has high reliability requirements, which, in practice, are implemented through special inspection procedures and appropriate design solutions involving introduction of excesses of structure, strength, power, information, etc. The structural excess is characterised by elements or functional systems, basic and reserve-protective ones. After the damage to the basic system, protective systems join to functioning. This ensures a high level of aircraft flights safety, which is one of the most important issues in the air transport. Despite these protections and great efforts of technical services, failures causing accidents happen. The protecting systems constituting the reserve of basic systems significantly increase the production costs and reduce the overall performances, such as capacity, range, fuel consumption, etc. They also require special treatment in the operation of aircrafts, so that they have very high probability of correct functioning at the very low probability of use. The accuracy of continuous or periodic identification of a usability state is an important issue. The person stating the usability state of basic and reserve technical systems can make two types of errors:

– an error of the first type consists of qualifying the usable device as unsuitable;
– an error of the second type consists of qualifying the unsuitable device as usable.

The result of the erroneous qualification of the system activating the emergency release of the landing gear was the emergency landing of the PLL LOT plane, Boeing 767-300ER, on November 1, 2011, at the Warsaw Frederic Chopin Airport.

2. Estimating the probability of damages to the aircraft systems

Quantitative description and probability evaluation of the damage to the basic and protective systems of the aircraft can be executed according to the postulates of the Poisson point process.

Assuming that:

- the probability of damage is directly proportional to the length of the concerned time period and the number of operated aircrafts;
- the proportionality factor identifying the risk of damage is constant;

The following system of equations is legit:

$$
\begin{aligned}
&P_0(t+\Delta t)=P_0(t)(1-\lambda N(t)\Delta t)\\
&P_1(t+\Delta t)=P_1(t)\,(1-\lambda N(t)\Delta t)+P_0(t)\lambda N(t)\Delta t\\
&\vdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (1)\\
&P_n(t+\Delta t)=P_n(t)(1-\lambda N(t)\Delta t)+P_{n-1}(t)\lambda N(t)\Delta t \quad \text{for } n>0
\end{aligned}
$$

where:

$P_0(t, t+\Delta t)$ - probability of non-occurrence of damages to basic and protective systems in the time interval of Δt;
$P_i(t, t+\Delta t)$ (i = 1, ... n) - probability of the occurrence of the *"i"* number of damages in the time interval of Δt;
$N(t)$ - number of operated aircrafts, in which a considered damage may occur;
λ - proportionality factor that represents the damage risk;
Δt - adopted time interval of aircrafts operation (or the aircraft's flying time length).

By dividing the equations (1) by Δt and going to the boundary with $\Delta t \to 0$, we obtain the following system of equations:

$$\begin{aligned} P_0' &= -\lambda N(t) P_0(t) \\ P_1' &= -\lambda N(t) P_1(t) + \lambda N(t) P_0(t) \\ &\vdots \\ P_n' &= -\lambda N(t) P_n(t) + \lambda N(t) P_{n-1}(t) \end{aligned} \tag{2}$$

For the system of equations (2), the initial conditions are as follows:

$$\begin{cases} P_0(0) = 1 \\ P_n(0) = 0 \quad \text{for } n > 0 \end{cases} \tag{3}$$

The equations (2) are linear differential equations and they are solved recursively. First, we find $P_0(t)$. While knowing $P_0(t)$, we then set $P_1(t)$ and so on.

The solution of the system of equations (3) takes the form of:

$$\begin{cases} P_0(t) = e^{-\lambda \int_0^t N(t)dt} \\ \vdots \\ P_n(t) = \dfrac{1}{n!}\left[\lambda \int_0^t N(t)dt\right]^n e^{-\lambda \int_0^t N(L)dt} \end{cases} \tag{4}$$

The probability that in the time interval (0, *t*) occurs n of damages requiring launch of protection systems is described with the Poisson distribution, whereas the role of the expression " λt " is replaced with the following value $\lambda \int_0^t N(t)dt$ due to the low incidence of this damage type in the process of aircraft operation.

The integral $\int_0^t N(t)dt$ can be replaced with the following sum:

$$\int_0^t N(t)dt \leftrightarrow \sum_{i=1}^{N} t_i \tag{5}$$

where:

N – number of aircrafts operated at the considered time;

t_i – flying time of the aircraft operated at the considered time;

For a single aircraft, the probability of damages during the considered *t* flying time will be:

$$q_1 = 1 - e^{-\lambda t} \tag{6}$$

where:

q_1 – the probability of damage in one aircraft;

t – flying time of an aircraft.

Since the risk of the λ damage to both systems (basic and protective) that causes the failure is low, the expression $e^{-\lambda t}$ can be expanded into a power series.

Hence:

$$e^{-\lambda t} \cong 1 - \lambda t \tag{7}$$

By substituting (7) to (6), we obtain:

$$q_2 \cong \lambda t \tag{8}$$

One can estimate the probability of failure in a single aircraft with the dependency (8).

The probability of correct aircraft functioning is expressed by the dependency:

$$P_1 = 1 - \hat{\lambda} t \tag{9}$$

In order to estimate the average number of failures during a given period for the operated aircraft park, the following dependency can be used:

$$E[n] = \sum_{n=1}^{\infty} n P_n(t) = \hat{\lambda} \sum_{i=1}^{N} t_i \tag{10}$$

where:

t_i - flying time during a given period of the i-th aircraft

N - number of the operated aircrafts.

We are often interested in not only the probability of occurrence of n damages for a given flying time, but also in the value of the λ factor characterising the intensity (risk) of damage occurrence. In order to set the parameter λ estimator, we apply the maximum likelihood method. Suppose that we have observed and recorded the formation of the damages in several separate time intervals, when the aircrafts' flying time was: t_1, t_2, ..., t_i. As a result of the observations, the following was obtained:

- in the interval $(0, t_1)$, n_1 damages occurred;
- in the interval (t_1, t_2), n_2 damages occurred;

  ⋮
- in the interval (t_{i-1}, t_i), n_i damages occurred;

The probability of formation of the said number of damages, i.e. $n_1 + n_2 + ... + n_i$, during operation at the intensity of their formation equal to λ is expressed by the dependency:

$$L = \frac{(\lambda T_1)^{n_1}}{n_i!} e^{-\lambda T_1} \cdot \frac{(\lambda T_2)^{n_2}}{n_2!} e^{-\lambda T_2} \cdots \frac{(\lambda T_i)^{n_i}}{n_i!} e^{-\lambda T_1}$$

$$= \frac{\lambda^{n_1+n_2+...+n_i} T_1^{n_1} T_2^{n_2} \ldots T_i^{n_i}}{n_1! n_2! \ldots n_i!} e^{-\lambda(T_1+T_2+...+T_i)} \tag{11}$$

where:

$T_i = t_i - t_{i-1}$

The probability written above, considered as a function of the variable λ at the defined $n_1, n_2, ..., n_i, T_1, T_2, ... T_i$, is called the likelihood. We now find that value of λ for which the likelihood L takes the greatest value. For this purpose, we logarithm the dependence (11) and calculate the derivative in relation to λ, which we equate to zero. By solving the obtained equation in this manner, we find the dependence for λ.

Hence:

$$\hat{\lambda} = \frac{n_1 + n_2 + \ldots + n_i}{T_1 + T_2 + \ldots + T_i} \tag{12}$$

With the help of the dependency (12), we determine the estimator of the λ ratio with the maximum likelihood method.

Hence the dependency (11) takes the form:

$$\hat{q} = \hat{\lambda} t \tag{13}$$

where:

t – the aircraft's flying time within the year.

The dependence (13) makes it possible to estimate the probability of damages in a single aircraft during a given time interval.

3. Analysis of errors of diagnosis and to stating the usability state of technical systems

The aeronautics is characterised by specified ergonomic properties and a certain reliability. The reliability of diagnostic equipment and ergonomics of technical systems affect the errors committed by the operator. A person equipped with diagnostic equipment can make two types of errors, whose measurements are the occurrence probabilities marked with symbols α and β.

α – means an error of the first type; it consists of qualifying the qualifying the usable device as unsuitable; the Institute of Mechanised Construction and Rock Mining

β – means an error of the second type; it consists of qualifying the unsuitable device as usable.

Making the error of the first type in the identification of an aircraft's usability may cause losses through an unplanned downtime and a repeated inspection. In the case of making the error of the second type, more dangerous consequences with the possibility of an aviation accident are often caused;

Three factors determining identification errors can be mentioned:

- monitoring susceptibility of a facility – it shows the extent, to which the object is adapted to the inspection and the inspection procedures identify the actual situation as well as what is the percentage of not inspected features;
- technical equipment of the operator inspecting the state of the facility and procedures of results interpretation;
- predispositions of the operator, his or her qualifications, personal characteristics;
- circumstances of the inspection, climatic conditions, time stress, information stress, etc.

As it results from the above considerations, the identification error is a parameter of systemic nature. The facility designer, the designer of diagnostic equipment, the operator equipped with diagnostic equipment of a sufficient quality, and the training of the operator conducting identification are responsible for the error of the facility condition identification. Despite the fact that the identification error depends on many factors, it is the person conducting the identification who is legally and morally responsible for the effects resulting from the identification error. Removal of responsibility from the operator follows the specified tests conducted by the specially appointed expert teams. These teams often include also experts from scientific and research institutions. These teams determine the causes of the erroneous qualifying of the facility condition. This results in a stressful situation for the operator, who does not always understand the essence of various sources of misidentification, blaming himself or herself for adverse events. The problem of errors of the first and second type during the identification of the usability state has a legal-moral, economical and technical aspect.

The source of the error is sometimes unreliability of diagnosing units equipped with the necessary equipment and procedures of stating the usability state. With regard to the facility, on which the condition is identified, it can be said that there are the following events on it:

A_{01} - An event involving the facility's being in the state of usability and its keeping this state during the identification. The probability of such an event is marked with P_{01}.

A_{02} - An event involving the occurrence of a damage detected during the identification in the facility until or during the identification. The probability of such an event is q_{02}.

A_{03} - An event involving the occurrence of a damage not detected during the identification in the facility until or during the identification. The probability of such an event is marked with q_{03}.

These probabilities meet the condition:

$$P_{01} + q_{02} + q_{03} = 1 \qquad (14)$$

The diagnosis process may include the following events:

A_{11} - An event involving the correctly conducted diagnosis and the flawless statement on the facility state. The probability of such an event is P_{11}.

A_{12} - An event involving the facility declared unsuitable regardless of its state. The probability of such an event is q_{12}.

A_{13} - An event involving the facility declared usable regardless of its state. The probability of such an event is. The probability of such an event is q_{13}.

A_{14} - An event involving the facility declared unsuitable, whereas in fact it is usable, and the facility declared usable, whereas in fact

it is unsuitable. The probability of such an event is marked with q_{14}.
These probabilities meet the condition:

$$P_{11} + q_{12} + q_{13} + q_{14} = 1 \qquad (15)$$

The probability of an event that the facility declared unsuitable is in fact usable, i.e. making the error of the first type, is given with the formula:

$$\alpha = 1 - \frac{P_{01}}{1 - \frac{q_{02}(P_{11} - q_{14})}{P_{11} + q_{13}}} \qquad (16)$$

The probability of an event involving the facility declared usable, whereas it is in fact unsuitable, i.e. making the error of the second type is given with the formula:

$$\beta = 1 - \frac{1}{1 + \frac{P_{01}}{1 - P_{01} + q_{02}\frac{P_{11} - q_{14}}{q_{12} - q_{14}}}} \qquad (17)$$

The influence of possible events is the process of diagnosis on the values of the errors of the first and second type results from the cited formulas.

4. Shaping of the errors of the first and second type by teaching the operator method

Fig. 1 shows the course of function α_m of reducing the error of the first type as a result of a m-fold repetition of actions performed by the operator or diagnosing team for different values of an experimentally determined factor $C(\alpha)$.

These errors in the function of the number m of tests are given with formulas:

$$\alpha_m = \alpha[1 - \alpha C(\alpha)]^{m-1} \qquad (18)$$

$$\beta_m = \beta[1 - \beta\, C(\beta)]^{m-1} \qquad (19)$$

The intensity of learning has a significant impact on the reduction of the errors of the first and second type. As a result of the training, the operator learns using the controls, reading instrument indications and interpretation of symptoms of the facility's usability and unsuitability. For the purposes of teaching the operator, the specific states are modelled. As a result of conducted research and analyses, coefficients $C(\alpha), C(\beta)$ characterising the quantitative progress of the training and the intensity of the error of the first and second type's reduction are determined.

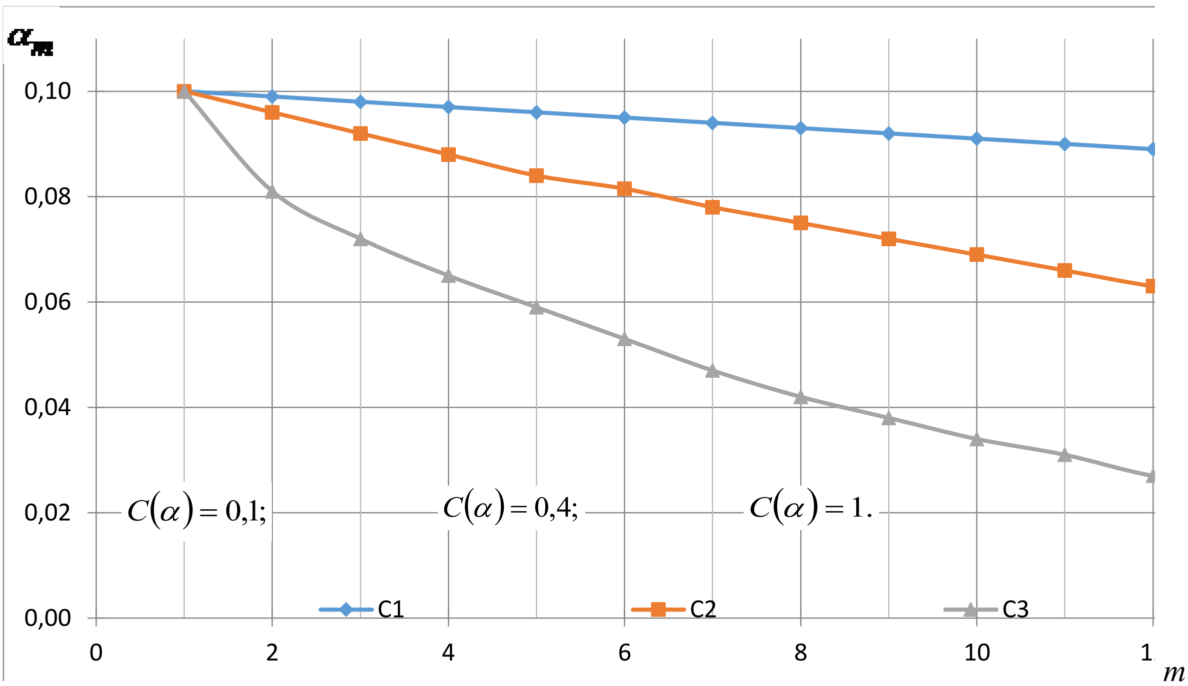

Fig. 1. Course of function α_m for different values of $C(\alpha)$ for $\alpha = 0,1$.

5. Example result of an erroneous diagnosing

The fact of some error in diagnosis can be stated on the example of the above-mentioned emergency landing of the PLL LOT plane, Boeing 767-300ER, on November 1, 2011, at the Warsaw Frederic Chopin Airport. We would remind that the Boeing 767-300 of the Polish airlines LOT departed from the Newark airport (USA) after midnight on November 1, 2011. After c. 30 minutes after the departure from Newark, the crew of the Polish plane signaled a failure of the central hydraulic system. The machine had another system, an emergency one, which could eject the landing gear. After the departure, the plane was filled with fuel and despite the fault, it would not be justified to fly around over the U.S. territory for many hours because only after fuel consumption it would be possible to check the operation of the system extending the landing gear and to try to land. The captain made the decision to continue the flight, although he could not be sure as to the usability of the emergency system – he was going to check the operation in Poland. Over Warsaw, it proved that the usability of the entire landing gear control system was evaluated erroneously because its extension failed, although the flaps had extended. Then the decision to execute an emergency landing was made. The result of the incorrect evaluation of the situation described above was the failure of the plane, which is a rare event in the operation of aircrafts.

The members of the government committee investigating the circumstance of the emergency landing showed that the emergency system was efficient but the crew did not use it because one of the key fuses, which secured several aircraft's systems, including the emergency landing gear extension system, was disabled. If the fuse had been enabled, it the dramatic landing at the Warsaw's Okęcie would not have happened.

6. Process of saving of a critical situation

In the considered flight, there occurred an event involving consideration of the activating element as usable regardless of its state and not diagnosing it. An unaware classification of the unsuitable device as usable without diagnosing is the system error of the second type.

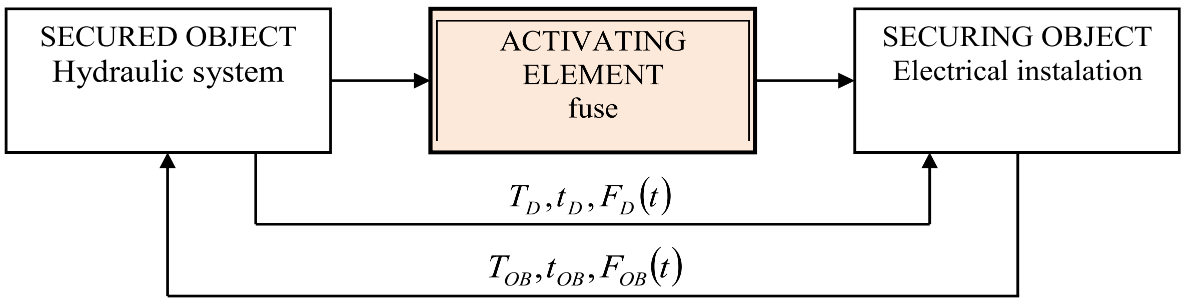

Fig. 2. Model of a relief system with a security system.

In the model representing the situation of the emergency landing on November 1, 2011, you can highlight the following elements (fig. 2): secured object – the landing gear extension system, the securing object – emergency system of landing gear extension and the activating element.

In fig. 2, probabilistic characteristics of the time of security task and available time were marked.

T_{OB} – random variable of the securing task execution time,

$F_{OB}(t)$ – distribution function of the random variable of the securing task execution time,

t_{OB}, – execution of the random variable – time of flight over the airport and the search for a solution,

T_D – random variable of available time – time of flight limited with remnants of fuel,

$F_D(t)$ – distribution function of the random variable of available time,

t_D – execution of the random variable of available time – maximum time of flight limited with remnants of fuel,

Available time designates a reasonable time necessary to prevent a dangerous situation. In general, this time may be determined with, for example, a fuel resource, a resource of an active substance or any other type of energy extending the system operation.

The analysis of the situation and taking actions at available time can be described as follows:

- receiving information about a hydraulic system leak;
- making the decision to continue the flight;
- initiation of the landing procedure;
- receiving information about a faulty security system (electrical system);
- analysis of the obtained information and search for a solution;
- making the decision about the emergency landing on the aircraft fabric covering;
- implementation of the made decision;
- inspection of the made decision.

After receiving the information about a defective security system (electrical system) and inability to release the landing gear, there was the search for solutions, which had to take place at the available time – T_D. After recognition of the erroneous evaluation of the emergency system, the only solution left was the use of a different emergency protective system in the form of the fuselage designed for this purpose. Thanks to the pilot's wise action, great skills and precise action, the implementation of the made decision of the emergency landing was successful. This type of situation can be described with the salvage equation (20), which designates the probability of the danger defuse at the available time through the convolution of distribution functions of random variables of the available time and execution time of the rescue task.

$$P(T_{OB} < T_D) = \int_0^{\infty} F_D(t+\tau)\,dF_{OB}(t) \qquad (20)$$

The continuous variable of the available time depends on the type of event. For example, for a survivor at sea, it will be the time of survival dependent on circumstances (temperature of the water and his or her own equipment); for the aircraft, the remained flight persistence; for the parachutist, remaining height, etc. The continuous variable of the execution time of an intervention task also depends on many factors – the type of the task, the degree of the rescue team or system's readiness, action efficiency.

In the cited example, making the right decision and the precise landing proved to be the right security action before the crash. The executions of random variables in the considered event in the relationship (t_{OB} < t_D) have fulfilled the salvage condition.

The presented analysis of the diagnosis errors and the rescue process model were presented in a shortened version due to the limited scope of the paper.

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