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PROBLEMS OF MILITARY AIRCRAFT CREW'S SAFETY IN CONDITION OF ENEMY COUNTERACTION

PROBLEMY BEZPIECZEŃSTWA ZAŁOGI WOJSKOWEGO STATKU POWIETRZNEGO W WARUNKACH PRZECIWDZIAŁANIA PRZECIWNIKA*

The presented paper consists outline of the probabilistic method of evaluation of military aircraft crew's safety, which took into consideration enemy counteraction. The specific attention was focused on estimation of durability of ejection seat, which is a means of pilot's emergency escape from aircraft. The basis of the presented model is probability of pilot's danger to life for single sortie caused by enemy. Formulated differentiation equation characterises process of increment of successful sortie number. The equation after transformation into partial differential equation served for establishing of successful sortie distribution function and subsequently for calculation of crew safety indicators.

Keywords: *military aircraft crew, safety, ejection seat, durability, probability.*

W artykule przedstawiono zarys probabilistycznej metody oceny bezpieczeństwa załogi wojskowego statku powietrznego uwzględniającej niszczące działanie przeciwnika. Największą uwagę skupiono na szacowaniu trwałości fotela katapultowego jako środka do awaryjnego opuszczania samolotu przez pilota. Podstawą prezentowanego modelu jest prawdopodobieństwo powstania zagrożenia dla życia pilota w pojedynczym locie statku powietrznego spowodowane przeciwdziałaniem przeciwnika. Sformułowano równanie różnicowe charakteryzujące w ujęciu probabilistycznym proces przyrostu liczby udanych lotów bojowych statku powietrznego. Równanie to po przekształceniu w równanie różniczkowe cząstkowe, posłużyło do wyznaczenia funkcji rozkładu udanych lotów bojowych, a następnie wskaźników bezpieczeństwa załogi.

Słowa kluczowe: *załoga wojskowego statku powietrznego, bezpieczeństwo, fotel katapultowy, trwałość, prawdopodobieństwo.*

1. Introduction

Military aircraft crew's safety is a very complex problem. The complexity of the problem emerges from necessity to rescue pilot's life in dynamic emergency condition, when time for making a decision is short [1, 8-9, 16-17,]. Therefore, element of "human factor", cannot be overlooked [3, 14]. World literature on this issue has an interdisciplinary nature and relates to these matters in a general way, often purely descriptive. In aviation, pilot's life rescue in emergency situation is realised with use of special devices which are called ejection seats. They are mounted only on military aircraft, what can restrict an access to information about their usage. Hence, specialised literature on this issue is not too extensive.

In Poland, studies of a practical and application nature in these field were mainly carried out in the Air Force Institute of Technology and years ago also in the Institute of Aviation, however analytical studies were performed in the Military University of Technology, Military Institute of Aviation Medicine and Warsaw University of Technology as well as other research centres worked on aerospace technology e.g. Rzeszow University of Technology.

World literature consist publication related to different areas of ejection process. Some of them raise anthropometric question connected with ejection [4], medical question as well as conditioning which may occur during ejection process [2, 3, 7, 10-14, 22-24]. Publications relating to collected combat experience also occur [13, 22]. One of the line of research is computer modelling of ejection process [5, 6, 9, 15, 25, 26], which enable to simulate various scenarios of the process, analysis of conditions of safety escape from an aircraft as well as examination of factors that affect pilot's organism in different situations of emergency escape. Huge diversity of the publications confirms interdisciplinarity of the subject area.

In the domestic literature, major part of the papers concern medical problems of ejection process and was published by scientists from the Military Institute of Aviation Medicine [23, 24]. Operating and maintenance manuals for particular type of ejection seats are also available. However, papers such as that on quantitative evaluation of crew safety with regard to ejection seat usage, are extremely rare [18].

In today's world, various types of ejection seats are employed in different types of military aircraft. The ejection seats differ in their design solution, dimensions (size, weight), established stabilisation system, survival equipment and accessory. [17, 19]. The direct inspiration for researching in the field of ejection seats development was necessity of perpetual modernisation of military aircraft towards performance and effectiveness improvement, which in turn involves indispensability of emergency escape subsystem perfection [21]. In the course of modernization, the question arises: how to assess pilot's safety for military aircraft equipped with particular rescue system?

Currently, about the idea of what type of ejection seat is installed in particular aircraft decides more often than not: type of an aircraft (who is a manufacturer), tactical and technical capabilities as well as

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** economic conditions. It also happens that, various types of ejection seat manufactured by different producers are installed on the same type of aircraft. Furthermore, each of producers have in his tender from several to over a dozen types of ejection seats, resulting significant diversity of possible technical solutions [19]. For an analysis of military aircraft crew safety, disparity of tasks in time of peace and war must also be count. Hence, further questions need answers: How to evaluate aircraft crew safety? What tool for such assessment apply? Thus, authors of present paper proceeded to study of the method (technique) which allows such an assessment, and is helpful in utilisation planning as well as aircraft and their rescue systems modernisation.

Presented method bases on probabilistic calculation, which take into consideration aircraft and ejection seat reliability. Carried out solutions do not exhaust the problem, but represents distinct progress in the quest for answers to the questions raised and provide the inspiration for formulation further questions connected with ejection seat usage for aircraft crew life rescue.

Ejection seats represents very complex technical objects, which are essential elements of the aircraft equipment and enable pilot to escape from an aircraft in very short time in emergency situation. So, it was assumed that pilot's safety during flight depends on:

1) aircraft reliability;
2) ejection seat reliability;
3) pilot health and calmness in emergency situation [1].

Additionally, in case of enemy counteraction, following elements have influence on pilot's safety:

1) military aircraft vulnerability;
2) ability to self-defense;
3) effectiveness of enemy impact on aircraft in order to destroy it during fighting;
4) quality of air traffic organisation (dynamic of operation) and crew's skills [18].

Pilot's safety was considered under the following assumptions:

1) on airfield (military base) possibility of aircraft destruction (as well as ejection seat) is negligible;
2) aircraft is destructed by enemy during combat mission;
3) probability of aircraft destruction during one sortie equals Q, and ejection seat remain operable (exist possibility to utilise the seat);
4) ejection seat durability is the same as aircraft durability.

The leading role in pilot's safety evaluation plays aircraft durability, which is defined as a number of sorties or flying time until destruction of aircraft in combat condition. „Lifetime" of the ejection seat can be measured by the number of the aircraft successful flights until destruction. The main subject of the presented paper was determination of the ejection seat durability in the above mentioned scope and assessment of crew's safety indicators.

2. Method of durability assessment with use of difference equation

This chapter presents method of determination of distribution of successful flight' number for assumed time range or for the whole aircraft's durability in terms of fighting. With the distribution of the number of successful flights considered one tried to calculate interesting parameters. The process of increment of the number of successful flight was considered as a function of time or number of sorties.

It was assumed that the sorties occurs randomly with a certain intensity λ. Therefore, for the range Δt following condition is fulfil:

$$\lambda\Delta t \le 1\,,$$

where: Δt can be considered as a duration time of one sortie. Above mentioned condition states that aircraft do not fly continuously but there are exist random intervals between consecutive sorties. For the sake of completeness, it was assumed that probability of aircraft's destruction during one sortie equals Q.

Let $U_{z,t}$ denote the probability that for the moment t the number of successful flights is z. For the applied symbols, the increment of the number of flights will be described in probabilistic way by the following difference equation:

$$U_{z,t+\Delta t} = (1-\lambda\Delta t)U_{z,t} + \lambda\Delta t(1-Q)U_{z-1,t}\,. \tag{1}$$

The difference equation (1) means what fallows: the probability that for the time t+Δt the number of successful flights amount to z is equal to the sum of probabilities of the following events:

- flight did not happen during Δt and aircraft have accomplished z successful flights until the moment t,
- successful flight was accomplished during Δt, aircraft' destruction did not happened and aircraft have accomplished $z-1$ successful flights until the moment t.

After rearranging to the functional notation:

$$u(z,t+\Delta t) = (1-\lambda\Delta t)u(z,t) + \lambda\Delta t(1-Q)u(z-1,t)\,, \tag{2}$$

where: $u(z,t)$ is a probability density function of the successful flights' number for the moment t.

Taylor's expansion was used for above mentioned equation.

$$u(z,t+\Delta t) = u(z,t) + \frac{\partial u(z,t)}{\partial t}\Delta t + \frac{1}{2!}\frac{\partial^2 u(z,t)}{\partial t^2}\Delta t^2 + \frac{1}{3!}\frac{\partial^3 u(z,t)}{\partial t^3}\Delta t^3 + \frac{1}{4!}\frac{\partial^4 u(z,t)}{\partial t^4}\Delta t^4 + \dots$$

$$u(z-1,t) = u(z,t) - \frac{\partial u(z,t)}{\partial z} + \frac{1}{2!}\frac{\partial^2 u(z,t)}{\partial z^2} - \frac{1}{3!}\frac{\partial^3 u(z,t)}{\partial z^3} + \frac{1}{4!}\frac{\partial^4 u(z,t)}{\partial z^4} + \dots$$

For t it is two elements of expansion, and for z three elements. After transformation and rearrangement of the equation (2), there was obtained:

$$\frac{\partial u(z,t)}{\partial t} = -\lambda Q u(z,t) - \lambda(1-Q)\frac{\partial u(z,t)}{\partial z} + \frac{1}{2}\lambda(1-Q)\frac{\partial^2 u(z,t)}{\partial z^2}\,. \tag{3}$$

Let introduce the notations: $c = \lambda Q : b = \lambda(1-Q) : a = \lambda(1-Q)$.

Coefficient c indicates aircraft' destruction intensity. Then coefficient b and a despite the same description have somewhat different meaning, b is an average increment of the number of successful flights in the time range Δt, instead a is an average square of increment of the number of successful flights in the time range Δt. Convergence of the descriptions for a and b result from the fact that in the time range Δt can occur increase only by one flight, so an increment and square of increment are equal. Then:

$$\frac{\partial u(z,t)}{\partial t} = -cu(z,t) - b\frac{\partial u(z,t)}{\partial z} + \frac{1}{2}a\frac{\partial^2 u(z,t)}{\partial z^2}\,. \tag{4}$$

To present solution of equation (4) authors made use of equation's solution of the Fokker-Planck type [21] in the following form:

$$\frac{\partial \bar{u}(z,t)}{\partial t} = -b\frac{\partial \bar{u}(z,t)}{\partial z} + \frac{1}{2}a\frac{\partial^2 \bar{u}(z,t)}{\partial z^2}. \tag{5}$$

We search for the solution of the particular equation (5), which, by $t \to 0$ is concurrent to the so-called Dirac function: $\bar{u}(z,t) \to 0$ for $z \neq 0$ and $\bar{u}(0,t) \to \infty$, but in this way that the integral of function $\bar{u}(z,t)$ equals a unity for all $t > 0$. For above mentioned condition, the solution of equation (5) takes the form [21]:

$$\bar{u}(z,t) = \frac{1}{\sqrt{2\pi at}} e^{-\frac{(z-bt)^2}{2at}}. \tag{6}$$

Having taken account of these considerations one can present particular solution of equation (4) which takes the form:

$$u(z,t) = ce^{-ct}\bar{u}(z,t). \tag{7}$$

In order to verify the correctness of the solution, following transformations have been made:

$$\frac{\partial u(z,t)}{\partial t} = -c^2 e^{-ct}\bar{u}(z,t) + ce^{-ct}\frac{\partial \bar{u}(z,t)}{\partial t} = \left[-c - \frac{1}{2t} + b\frac{(z-bt)}{at} + \frac{(z-bt)^2}{2at^2}\right]u(z,t),$$

$$\frac{\partial u(z,t)}{\partial z} = ce^{-ct}\frac{\partial \bar{u}(z,t)}{\partial z} = -\frac{(z-bt)}{at}u(z,t),$$

$$\frac{\partial^2 u(z,t)}{\partial z^2} = ce^{-ct}\frac{\partial^2 \bar{u}(z,t)}{\partial z^2} = \left[-\frac{1}{at} + \frac{(z-bt)^2}{a^2t^2}\right]u(z,t).$$

Having put above relationships into (4), one gets:

$$\left[-c - \frac{1}{2t} + b\frac{(z-bt)}{at} + \frac{(z-bt)^2}{2at^2}\right]u(z,t) = \left[-c - b\left[-\frac{(z-bt)}{at}\right] + \frac{1}{2}a\left[-\frac{1}{at} + \frac{(z-bt)^2}{a^2t^2}\right]\right]u(z,t).$$

Then, after arrangement:

$$\left[-c - \frac{1}{2t} + b\frac{(z-bt)}{at} + \frac{(z-bt)^2}{2at^2}\right]u(z,t) = \left[-c - \frac{1}{2t} + b\frac{(z-bt)}{at} + \frac{1}{2}\frac{(z-bt)^2}{at^2}\right]u(z,t).$$

As seen, left side of the relationships is equal to right side, which proves the correctness of this solution.

Finally, the distribution of the number of aircraft successful flights was obtain:

$$u(z,t) = ce^{-ct}\frac{1}{\sqrt{2\pi at}} e^{-\frac{(z-bt)^2}{2at}}. \tag{8}$$

Function (8) has features of density function since:

$$\int_0^\infty \int_{-\infty}^\infty u(z,t)\,dz\,dt = 1.$$

Having determined the distribution of the number of aircraft successful flights (density function (8)) it is possible to obtain:

1) average value of the number of aircraft successful flights:
   a) for the lifetime;
   b) for the finite period of time;
2) for established number of successful flights z_1:
   a) probability that the number of successful flights is less than or equal to z_1;
   b) probability that the number of successful flights is greater than z_1 as a function of time.

Expected value of the number of successful flights for time less than t_1:

$$E[z] = \int_0^{t_1}\int_{-\infty}^{\infty} zu(z,t)\,dz\,dt = \frac{b}{c}\left[1-(1+ct_1)e^{-ct_1}\right] = \frac{(1-Q)}{Q}\left[1-(1+\lambda Qt_1)e^{-\lambda Qt_1}\right]. \tag{9}$$

If we take into account longer time period, i.e. time $t_1 \to \infty$, we received well known relationship which describe average value of the number of successful flights for the aircraft' lifetime:

$$E_T[z] = \frac{(1-Q)}{Q}. \tag{10}$$

Hence, the number of successful flights for finite range of time is described by equation (9).

Probability, that the number of successful flights is less than or equal to z_1 for time t_1 with possibility of aircraft' destruction is represented by:

$$P_{z_1}^{(1)}(t_1) = \int_0^{t_1}\int_{-\infty}^{z_1} u(z,t)\,dz\,dt. \tag{11}$$

Probability, that the number of successful flights is greater than z_1 for time t_1 with possibility of aircraft' destruction is represented by:

$$P_{z_1}^{(2)}(t_1) = \int_0^{t_1}\int_{z_1}^{\infty} u(z,t)\,dz\,dt. \tag{12}$$

Probability, that in the range of time $(0, t_1)$ aircraft will not be destroyed has following form:

$$\begin{aligned} P^{(3)}(t_1) &= 1 - \left(P_{z_1}^{(1)}(t_1) + P_{z_1}^{(2)}(t_1)\right) = 1 - \int_0^{t_1} ce^{-ct}dt = \\ &= 1 - \left[-e^{-ct}\right]_0^{t_1} = 1 - \left[-e^{-ct_1} + 1\right] = e^{-ct_1} \end{aligned} \tag{13}$$

It can be demonstrated that specified probabilities bring the total number to one.

$$P_{z_1}^{(1)}(t_1) + P_{z_1}^{(2)}(t_1) + P^{(3)}(t_1) = 1.$$

The equation (13) can be written down in the form:

$$P^{(3)}(k) = e^{-Qk}, \tag{14}$$

where: $k = \lambda t_1$ - number of sorties performed until time t_1.

Probability that in the range of number of sorties *(0, k)* aircraft will be destroyed adopts the following form:

$$Q_k(k) = 1 - e^{-Qk}. \tag{15}$$

3. Outline of the pilot's safety assessment

In case of rise to loss of the ship hazard, pilot for the sake of saving one's own life is forced to trigger ejection seat. The success of ejection process depends mainly on the following factors [18]:

1) time to reach a decision about ejection;
2) course of ejection (including pilot's landing after ejection process);
3) conditions of the ejection process;
4) type of aircraft and type of ejection seat;
5) behaviours and skills of pilot during ejection process.

In real situations time for reaching decision about emergency escape is predominantly very short. Additionally, in this kind of situation pilot often tries to remedy the threat to aircraft. Great influence on making the right decision about ejection has "human factor" and other factors which determine pilot's mental state.

Taking decision about ejection necessitates the implementation of a series of activities which influence ejection process. These activities are more or less automated. Reliable performance of the operations has significant influence on the results of ejection. As mentioned in the introduction above, reliability of the emergency escape depends on aircraft's and ejection seat's type. Emergency escape does not always end successfully, to a large extent the results depends on conditions in which it occurred. Probabilistic evaluation of the pilot's safety can be, depending on the assumptions and simplifications, more or less accurate.

In this paper, model is limited by taking into account aircraft and ejection seat reliability. Reliability of an aircraft and ejection seat, by virtue of assumptions, are considered as a separate sets of events:

$$R_S(t) + Q_S(t) = 1, \tag{16}$$

$$R_F(\tau) + Q_F(\tau) = 1, \tag{17}$$

where: $R_S(t)$ - aircraft reliability in the time range (*0, t*);

$Q_S(t)$ - unreliability i.e. probability of the aircraft destruction for the time range (*0, t*);

$R_F(\tau)$ - ejection seat reliability at the time of its use;

$Q_F(\tau)$ - ejection seat unreliability at the time of its use.

The above equation (16) refers to the aircraft, and equation (17) to the ejection seat. Using formulas (16) and (17), probability of pilot's survive in the time range (*0, t*) can be determined in the following form:

$$\bar{R} = R_S(t) + Q_S(t)R_F(\tau), \tag{18}$$

where: $\bar{R}$ - probability that, in the time range (*0, t*), aircraft was not destroyed or the destruction of an aircraft occurred and pilot survived thanks to use of the operable ejection seat.

Probability of loss of pilot's life during sorties in the time range *(0, t)* takes the form:

$$\bar{Q} = Q_S(t)Q_F(\tau), \tag{19}$$

where: $\bar{Q}$ - probability of loss of pilot's life during sorties in the time range *(0, t)*.

Dependency (18) shows that pilot's safety depends on reliability of an aircraft and reliability of ejection seat. Dependencies (18) and (19), how easy it is to check, bring the total number to one, which proved the correctness of the above formulas for the assumptions made. Equation (18) for exponential distribution as a function of number of sorties has following form:

$$\bar{R}_k = e^{-Qk} + \left(1 - e^{-Qk}\right)R_F(\tau), \tag{20}$$

where: k – number of sorties.

4. Illustration of the calculations

Due to lack of available and reliable data relating to combat use of aircraft, which are indispensable for evaluation of required results, below hypothetical data were used.

Input data for the calculations:

– sorties intensity $\lambda = 2$ [$^1/_{day}$];
– probability of aircraft destruction during one sortie Q = 0,05 [-].

The input data illustrate situation, where sorties are curried out twice daily, and probability of aircraft destruction during one sortie equals 0,05.

Figure 1 presents changes over time of an average value of the number of successful flights $E[z]$ (calculated according to (9)) and dashed line presents stationary value $E_T[z]$ pursued by $E[z]$ (calculated according to (10)). $E_T[z] = 19$.

While, figure 2 presents changes over time of probabilities $P_{z_1}^{(1)}(t_1)$, $P_{z_1}^{(2)}(t_1)$, $P^{(3)}(t_1)$ calculated according to the equations (11), (12) and (13).

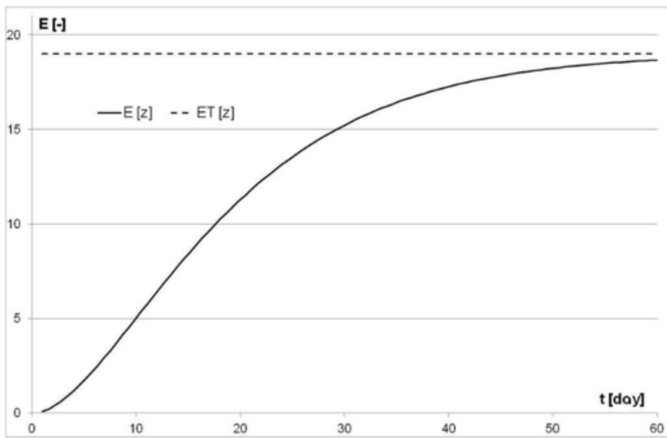

Fig. 1. Average value of the number of successful flights

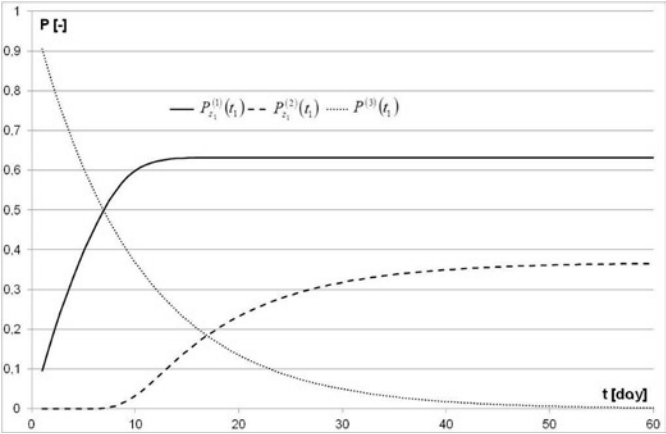

Fig. 2. Graphs of calculated probabilities: $P_{z_1}^{(1)}(t_1)$ – probability, that the number of successful flights is less than or equal to z_1=19 for time t_1, $P_{z_1}^{(2)}(t_1)$ - probability, that the number of successful flights is greater than z_1=19 for time t_1, $P^{(3)}(t_1)$ - probability, that in the range of time (0, t_1) aircraft will not be destroyed

5. Summary

The requirements of the modern battlefield in the field of aircraft engineering forces us to seek reliable (not only intuitive) answers to important questions: what effect should be expected on battlefield as a result of activity of specified type of one's own or enemy aircraft, and how aircraft engineering should be formed in order to achieve a goals for assumed probability and under particular conditions. Furthermore, very important aspect of effectiveness evaluation of military aircraft usage is assessment of aircraft durability and crew safety during combat mission [20]. It seems that presented method of crew safety evaluation in terms of the enemy counteracting can be used for the preliminary assessment of pilot safety with specific rescue system applied to the aircraft. Additionally, the method supports decision-making during combat mission as well as facilitates obtaining required indicators in the field of safety and reliability for combat use of aircraft.

With the use of distribution of the number of successful flights obtained in presented work it is possible to determine average value of the number of successful flights (as presented at figure 1) as well as probability of achievement established number of successful flights and probability of aircraft endurance for specified time (figure 2). Presented numerical example shows possible utilitarian aspects of use the method outlined in the work.

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