A QUANTITATIVE INVESTIGATION OF ANTI-HAIL ROCKETS

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Abstract. The authors propose a multidisciplinary approach and algorithm for the study and evaluation of the reliability and performance quality of anti-hail missiles and their control system. When examining the objects and systems in question, it is necessary to have a priori information about the risk of a particular (catastrophic, emergency) situation causing danger, damage, loss of human lives and resources, etc. In the absence of such information, accelerated tests of the systems are carried out to ensure that they are adequate in terms of quality, reliability and operational risk (guaranteed by the manufacturer). The algorithm is implemented in a similar missile control system.

Keywords: anti-hail missiles, algorithm, quality, reliability, risk, evaluation.

1. INTRODUCTION

During designing and exploitation of technical objects and systems (TOS) such as electrical, mechanical, thermal, aircrafts, transport systems, eco-systems, etc., put under different kinds of loadings, is necessary to be determined their indices for reliability and quality of functional work. Among them are: probability of non-failure $P_{NF}(\Delta t)$ at an interval of control Δt; probability of failure $Q_o(\Delta t) = 1 - P_NF(\Delta t)$; probable density of flow of failures $f(\Delta t) = dQ_o(\Delta t)/dt$; intensity of flow of failures $\omega(\Delta t) = f(\Delta t)/P_{NF}(\Delta t)$ at an interval of control Δt; technical resource to the finish of exploitation, T_{RFE}, measured in hours, day, years, centuries; average time for operation up

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http://doi.org/10.7546/EngSci.LXI.24.01.05

to failure $\overline{T}_O$; coefficient of readiness for the functional work of the examined element, subject end/or system $K_{RF}(\Delta t) = \overline{T}_O/(\overline{T}_O + \overline{T}_R)$ for an interval of time Δt, where $\overline{T}_R$ is the average time for repair and recovery of subject during the process of its technical exploitation; middle risk of setting in dangerous damages (events, failures, etc.) $\overline{R_V}(\Delta t)$; quality of functional work of the object (the system) $\mathbf{QFWO}(\boldsymbol{\Delta}\mathbf{t})$ representing a function of reliability and risk of damages.

These basic indices of TOS are connected each other by the following mathematical-statistical formulae:

- The basic equation of reliability [1, 3, 4, 18]:

$$P_{NF}\left(\Delta t\right) + Q_o\left(\Delta t\right) = 1. \tag{1}$$

- The basic law of reliability [2, 17, 18, 19]:

$$P_{NF}\left(\Delta t\right) = \exp\left\{-\int_0^{T_{RFE}} \omega\left(\Delta t\right).dt\right\}, \tag{2}$$

where: T_{RFE} is the technical resource to the finish of the technical exploitation (TE);

- middle risk of setting in dangerous damage:

$$\overline{R_V}\left(\Delta t\right) = \sum_{i=1}^{n} P_i\left(A\right).V_i\left(A\right), \tag{3}$$

where $P_i\left(A\right) = Q_o\left(\Delta t\right)$ is the probability for rise of a damage (for example a failure of a subject from functional work) as a result of the influence of dangerous event (or events) A for time Δt; $V_i\left(A\right)$ is the authority of damage caused from the events (damages) A measured in relative units $(0 < V_i\left(A\right) < 1)$; n is the number of damages A [1, 5, 6, 10, 14].

During the realization of the condition for stationarity, simplicity and absence of consequences for the in intensity of the flow of failures (IFF) will follow $\omega\left(\Delta t\right) \cong \text{const}$ for the interval $\Delta\ t = t_2 - t_1$. This is the reason to be done the following mathematical transformations on the base of formula (2) for probability of non-failure (PNF) [1–4]:

$$P_{NF}\left(t_1, t_2\right) = e^{-\hat{\omega}(\delta t)\int_{t_1}^{t_2} dt} = \exp\{-\hat{\omega}(\Delta t).\tau_{\sum TE}\} = \exp\{-\tau_{\sum TE}/\overline{T}_0\}, \tag{4}$$

where $\tau_{\sum TE}$ is summary time for technical or other kind of exploitation (TE) of the observed model articles in the interval of time Δt; $\overline{T}_0$ is the average time for operation up to failure for the interval of time Δt. For the interval of time Δt is valid the following formula:

$$\widehat{\omega}(\Delta t) = 1/\overline{T}_0. \tag{5}$$

2. AN ALGORITHM FOR MULTI-SUBJECT METHOD OF APPROACH

The algorithm of investigation is represented by a particular probable evaluation of the reliability of anti-hail rockets (AHR) used for the struggle against hails (hailstorms) in Bulgaria. The technical definition of reliability is used and it states: A spread out quality for functional work in time [2, 11, 16]. The definition of scientist Evgeniy Gindev for the multi-subject reliability is [3]:

“The reliability is a side of the objects, events, processes and systems characterizing the degree of effectiveness and stability of their realization, functional work and development, and possessing quantitative expression and this peculiarity that reaching a given limit it can pass in opposite, thus changing in that way the qualitative state of this or that system or process”.

The achievement in the work of the first author N. I. Petrov with title A Model of Technical Service and Exploitation of Aircrafts (AC) (manned and pilotless) presented in [17] allows to be suggested analogical evaluation of reliability of anti-hail rockets (AHR).

In Bulgaria, the method of delivery of reagent – artificial ice-forming nucleus (AgJ) in clouds by rockets has been adopted. It enables the direct and continuous dispersion of reagent in seeding cloud areas.

The hail suppression concepts define: seeding location – areas of large amount of supercooled water with weak updrafts and onset of impact – early stage of hail cloud development.

The strong vertical flows continuously supply the cloud with new amounts of supercooled water and carry the ice crystals to its upper part (the anvil). Therefore, it is necessary to import new quantities of artificial ice cores at short intervals throughout the period of urban activity.

The entry of a hail cloud in a mature stage of development within the range of the rocket sites leads to a reduction in the effect of the impact. The already formed city falls to the ground. In these cases, the impact reduces the strength of the process and losses of agricultural production. After each impact, with experts from the Regional Directorates of Agriculture, surveys are made for damage to agricultural production.

The overall hail suppression activity is carried out by the RAPIRA system. The system is designed to process and display the weather radar information from MRL5-IRIS, to process the aerological sounding data, to command and control the cloud seeding with seeding reagent and to command the anti-hail rockets launching. [22].

Fig. 1. A weather radar information processing and visualization system [22]

Analysis of the states of AHR is performed according to §2.2 of [17], shown in Fig. 2.

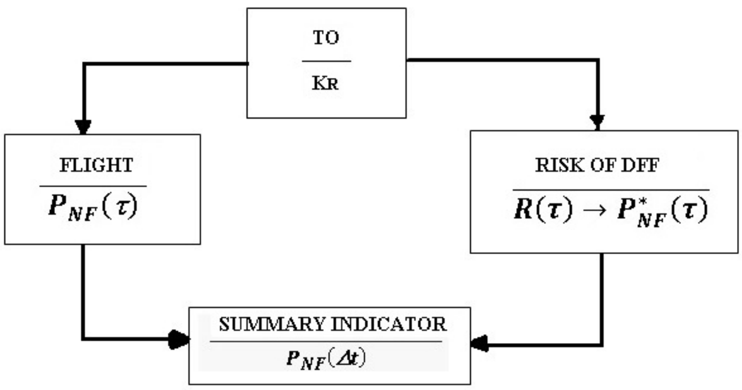

Fig. 2. Functional diagram of the states of AHR

From the analysis of the states of AHR follows the following formula for BNF for the respective interval of time Δt [17]:

$$P_{NF,AHR}\left(\Delta t\right) = K_R\left(\Delta t\right).P_{NF}\left(\tau\right).P^*_{NF}\left(\tau\right), \tag{6}$$

where $P_{NF,AHR}\left(\Delta t\right)$ is BNF of AHR in the process of technical service for the interval of time Δt (1 year), determined according the statistical analysis; $K_R(\Delta t)$ is the coefficient of readiness of AHR, calculated on the base of average time for operation up to failure for time 1 year $\overline{T}_0$ and average time for recovery T_R in the position for preparation of rockets at interval of 1 year according (2.1.30) from §2.1 [10, 17]; $P_{NF}(\tau)$ is BNF of AHR determined from failures causing non-executions of flying jobs (hail-carrying clouds shooting) at average time for before flying and flying mission τ [min]; $P^*_{NF}(\tau)$ is BNF determined from the setting in disastrous functional failures (DFF) or dangerous events for the civilian objects and/or persons at average time for before flying and flying mission τ [min].

The heavier regimes of flying and operation of the elements and aggregates, the complexity of the systems, the impossibility of reservation of some systems of AHR lead to significantly lower value of BNF $P_{NF}(\tau)$ for definite average time for before flying and flying mission τ [min].

The probability of non-failure $P_{NF}(\tau)$ (determined by failures causing the non-execution of hail-carrying clouds shooting) during duration of before flying and flying state τ [min] of AHR is determined according (2.2.2) from §2.2 [17]:

$$P_{NF}(\tau) \cong 1 - \tau/T_0. \tag{7}$$

The absolute error δ during the calculations of $P_{NF}(\tau)$ according formula (7) is determined by (2.2.3) of §2.2 [7, 16, 17]:

$$\delta < \frac{\tau^2}{2T_0^2}. \tag{8}$$

The coefficient of readiness $K_R(\Delta t)$, average time for operation up to failure $T_0(\Delta t)$, the average time for recovery of AHR in the position for preparation $T_R(\Delta t)$ for interval $\Delta t = 1\ \textit{year}$, and $P_{NF}(\tau)$ at $\tau = 6.6$ min for several AHR (**X, Y, Z, XYZ**) are represented in Table 1 [16, 17].

Table 1. Indices of reliability for AHRs used in Bulgaria

Article	$K_R(\Delta t)$ [%]	$T_0(\Delta t)$ [min]	$T_R(\Delta t)$ [min]	τ [min]	$P_{NF}(\tau)$
X	95.5	526	25	6.6	0.9875
Y	83.2	322	65	6.6	0.9800
Z	90.9	478	48	6.6	0.9862
X, Y, Z	83.8	280	54	6.6	0.9764

From (8) is determined the maximum error during the calculations of $P_{NF}(\tau)$ for the examined four articles of AHRs. This maximum error for article X has the value of $\delta_{\max} = 2.77 * 10^{-4}$.

In accordance of formula (2.2.4) from §2.2 [17] follows that BNF of AHRs determined from the setting in disastrous functional failures (DFF) or of especially dangerous events threatening civilian objects or human life at average time for before flying and flying mission τ [min] is

$$P^*_{NF}(\tau) = 1 - R(\tau).Q(K/O), \tag{9}$$

where $R(\tau)$ is the risk of setting in of DFF (or especially dangerous situation during flying) at average time for before flying and flying mission of AHR for flying time τ [min]; $Q(K/O)$ is a conditional probability for setting in of DFF (or a particular situation during flying) with AHR at failure of their respective system [7, 8, 14].

According to [10, 16, 17, 19] the norms of risk of setting in catastrophic functional failure (a particular situation during flying) are defined after the degree of responsibility of ANR and the time for development of eventual accident causing a fire on earth or a collision with another aircraft. They are the following:

$$R(\tau) \le 10^{-7}; \quad 10^{-6}; \quad 10^{-5}; \quad 10^{-4}; \quad 10^{-3}. \tag{10}$$

During the period of technical exploitation of ANR is necessary to be defined the conditional probability for setting in flying accident (damage) as a result of failure of the respective system of ANR (for example a fire in sown areas above which are available hail-carrying clouds that are an object of shooting with the goal chemicals to be spread in order the cloud to be split) $Q(K/O)$.

For the period from 1970 to 2020 in "Department of struggle with hails (hailstorms)" in Republic of Bulgaria where the concerned AHR are exploited, the number of the serious flying accidents caused by the pointed articles in Table 1 is 1–2% from the total number of fired AHR [6–9, 10, 11].

From the adduced data for the numbered AHR in Bulgaria in Table 1 follows the information for $R(\tau) = 10^{-4}$; $Q(K/O) \cong 1 * 10^{-2} \div 2 * 10^{-2}$.

As an analogy between the deduced formulae and definitions giving the correlation between the reliability and the quality of functional work [17, 19] follows a formula described below (11) characterizing the quality of functional work of the object $QFWO(\Delta t)$ of anti-hail rockets (in a system with meteoric radars, bodies for guidance and hail-carrying clouds shooting, etc.):

$$QFWO(\Delta t) = K_{RF}(\Delta t).P_{NF}(\tau).\{1 - R(\tau).Q(K/O)\}. \tag{11}$$

According to (9) the value of BNF from DFF of AHRs and their system of control is $P^*_{NF}(\tau) = 0.999999 \div 0.999998$. Within one calendar school year ($\Delta t = 1$ year) the admissible $P_{NF,PER}(\Delta t)$ in the process of technical exploitation at $K_{R\ \min}(\Delta t) = 0.8$ for AHR is calculated after the formula (2.2.6) from §2.2 [17, 19] taking into account that:

$$P_{NF,PER}(\Delta t) = K_{R\min}(\Delta t).P^*_{NR}(\tau).P_{NF}(\tau) \\ = \exp\left[-\omega_{PER}(\Delta t).t_{\sum OF_i}(\Delta t)\right], \quad (12)$$

where: $t_{\sum OF_i}(\Delta t)$ is the total time for operation up to failure of the i-th AHR for the tome interval $\Delta t = 1$ year; ω_{PER} is the permissible maximum value of $\omega(t)$ in the process of TE of AHR for the interval Δt.

After calculations after formula (11) we get the range of change of BHF (the quality of functional work) of the enumerated AHRs in Table 1 for an interval of 1 year, technical and flying (anti-hail) exploitation, which is of the form:

$$P_{NF,AHR}(\Delta t) = QFWO(\Delta t) = 0.7812 \div 0.7900.$$

From formula (12) the permissible maximum value of $\omega(t)$, $\omega_{PER}(\Delta t)$ for a concrete AHR, respectively, can be determined using the approved in the modern technological standards formulation for relative constancy of $\omega(t)$ in the intervals of control Δt for the whole period of service and exploitation [2, 9, 19–21].

This formulation directly determines the uniform spending of the resource of AHR in this period. The formula for $\omega_{PER}(\Delta t)$ is:

$$\omega_{PER}(\Delta t) = -\frac{1}{t_{\sum OF_i}(\Delta t)}.\ln\left[\frac{T_0}{T_0+T_R}.(1-R(\tau).Q(K/O)).(1-\frac{\tau}{T_0})\right]. \quad (13)$$

On the base of (13) a computing programme for the calculation of the permissible maximum value of the intensity of flow of failures of AHR $\omega_{PER}(\Delta t)$ for interval of time of TE equal to 1 year [16, 18] is done.

CONCLUSION

An algorithm for the investigation of the reliability and quality of functional work of AHRs is designed as it is represented by a concrete probable evaluation of the RAPIRA system for ant-hail defense in Republic of Bulgaria.

A formula for the determining of the permissible intensity of the flow of failures of AHR (violations, damages) $\omega_{PER}(\Delta t)$ for calendar time $\Delta t = 1$ year is suggested.

The suggested formula is introduced in the exploitation of analogous rockets used in Bulgarian Air Force. It is suitable also for the field of the educational organizations as a social criterion for intelligence and quality.

REFERENCES

[1] I. Popchev, Turbolentnost, reshenia i aforizmi, *Nauka, Obrazovanie, Kultura*, ISSN 1314-717X, 21–32, (2016).

[2] B. Gnedenko, Y. Belyaev and A. Solovev, Matematicheskie metody v teorii nadezhnosti: Osnovnye harakteristiki nadezhnosti i ih statisticheskiy analiz, Librokom, ISBN 978-5397057615, (2017).

[3] E. Gindev, Nadezhdnost na Slozhni Sistemi, ISOR, BAN, Sofia, (1976).

[4] E. Gindev, Uvod v Teoriyata i Praktikata na Nadezhdnostta, Chast 1, Osnovi na Prilozhnata Nadezhdnost, Prof. Marin Drinov, Sofia, (2000).

[5] I. Popchev and I. Radeva, Risk Analysis, An Instrument for Technology Selection, *Engineering Sciences* (2019) **LVI** (4) 5–20, https://doi.org/10.7546/EngSci.LV.19.04.01.

[6] I. Popchev, I. Radeva and I. Nikolova, Aspects of the evolution from risk management to enterprise global risk management, *Engineering sciences* (2021) **LVIII** (1) 16–30, ISSN:1312-5702 (Print) 2603-3542 (Online), https://doi.org/10.7546/EngSci.LVIII.21.01.02.

[7] I. Popchev, I. Radeva and V. Velichkova, Blockchains in Enterprise Global Risk Management, in: Proceedings of International IEEE Conference Automatics and Informatics 2021 – ICAI'21, Varna, Bulgaria, IEEE Xplore, (2021) pp. 282–287, https://doi.org/10.1109/ICAI52893.2021.963-9500.

[8] I. Popchev, R. Ketipov and V. Angelova, Risk averseness and emotional stability in e–commers, *Cybernetics and Information Technologies* (2021) **21** (3) 74–84, Print ISSN: 1311–9702. DOI: 10.2478/cait-2021-054.

[9] I. Popchev and I. Radeva, The New Paradigm and Risk in the Relationship Human- Digital Environment, Journal of BAS (2019) **5** 72–77.

[10] N. Petrov, Izsledvane na Operatsiite po Osiguryavane na Nadezhdnostta na Riskovi TIS, ISBN 978-954-322-790-7, Sofia, (2014).

[11] N. Petrov, Nadezhdnostta Kato Tehniko-Ikonomicheski Problem pri Kibernetizatsia na Obshtestvoto, Chernorizets Hrabar, (2015).

[12] N. Petrov, Deskriptivni Statistiki pri Upravlenie na Nadezhdnostta i Riska, Zhelyo Uchkov, ISBN 978-954-391-141-7, (2020).

[13] N. Petrov, Catastrophe and risk theory, TU–Sofia, DiagalPrint, ISBN 978-954-92761-3-8, (2011).

[14] N. Petrov, Expert risk assessment. Study guide, RL G. Rakovski, Yambol, ISBN 978-954-92960-7-5, (2015).

[15] N. Petrov, Reliability studies of risky technical systems, Yambol, ISBN-10: 954-9978-76-1, ISBN-13: 978-954-9978-76-6, (2006).

[16] N. Petrov, Reliability's Investigations of Risk Technical Systems. BG 005-632.02, Joint Small Project Fund at the Bulgarian-Turkey Border, Cross Border Co-operation, Edirne, ISBN 954-9978-55-9, Turkey, (2006).

[17] N. Petrov, Operational reliability of risky technical systems. University "Prof. Dr. Asen Zlatarov", 2002, ISBN 954-9978-26-5.

[18] N. Petrov, V. Dimitrov and V. Dimitrova, Reliability of Technology Systems in Industrial Manufacturing, Monograph, New Delhi, (2019).

[19] N. Petrov, Quality: A function of reliability and risk, *Science, Education, Intelligence* (2023) **17** 11–54, ISSN 2603-476X.

[20] N. Petrov, K. Keremidchieva, K. Dimitrova, M. Vasilev and M. Laskova, Security of control in computer and transport systems, *Science, Education, Intelligence* (2021) **13** 31–42, ISSN 2603-476X.

[21] N. Petrov, K. Dimitrova and Y. Zhelyazkov, Dialectic on Principles of Reliability, 2023 58th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST), Nis, Serbia, (2023), https://doi.org/10.1109/ICEST58410.2023.10187256.

[22] Hail Suppression Agency, News, online: https://iabg.government.bg/?p=19.

Received January 31, 2023