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Reliability Modelling of Automatic Gun with Pyrotechnic Charging

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Abstract:

This article deals with modelling and analysis of reliability of complex systems that use one-shot items during its operation. It includes analyses of an impact of reliability of used one-shot items on resulting level of reliability of the system as a whole. Practical application of theoretical knowledge is demonstrated on an example of a model of reliability of ZPL-20 aircraft gun that was used for optimization of the gun's design during its development and designing.

Keywords:

Complex systems, one shot items, reliability analysis, weapon

1. Introduction

The ZPL-20 aircraft gun was designed for the needs of the Czech Air Force and it was fielded into its armament as an onboard weapon for the L-159 advanced light combat aircraft. It refers to a 20-mm calibre twin gun, the automatic function of which is actuated by powder gases from its barrels.

A failure of the round of these automatic weapons will result in discontinuation of firing and a non-fired round remains loaded in a chamber of the gun. An external action is then necessary to eject a failed round from the chamber and to charge a new round in order to continue in firing. To this end the aircraft gun is equipped with special pyrotechnic cartridges. When a round fails, a pyrotechnic cartridge is automatically initiated and powder gases generated during its firing provide for an ejection of failed round and continuation of firing. A gun is a complex system that uses two types of one-shot items - rounds intended for the conduct of fire and pyrotechnic cartridges designed for re-charging of a gun after a failure of the round.

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A probability of accomplishment of a mission is the most important measure for assessment of reliability of a gun as a whole. A mission is considered as accomplished if it was possible to fire all rounds that were charged into the gun feed belt prior a mission.

From the description of the gun, it is evident that probability of accomplishment of a mission depends both on a reliability of used rounds and pyrotechnic cartridges. Of paramount importance that influences a probability of accomplishment of a mission is a quantity of pyrotechnic cartridges used in the design of the gun. The greater the number of pyrotechnic cartridges that can be applied during an accomplishment of a mission, the higher a probability of fulfilment of a mission. On the other side, a greater number of pyrotechnic cartridges brings about many problems – higher weight of a weapon, more complex design and more complicated fire control system, etc. A requirement during the development and design of this gun was to determine the optimum number of pyrotechnic cartridges that would ensure fulfilment of a mission. For this purpose a mathematical model of a dependence of probability of accomplishment of a mission on a number of used rounds and pyrotechnic cartridges and their reliability was presented.

1.1. Acronyms & Abbreviations

L-159	advanced light combat aircraft identification
MNRBF	mean number of rounds between failures
ZPL-20	aircraft gun identification

1.2. Notation

l	failure rate
k	number of one-shot items
m	number of pyrotechnic cartridges
n	number of rounds
p_r	probability of round failure
p_p	probability of pyrotechnic cartridge failure
p_i	reliability of i-th one-shot item
Q_s	probability of mission failure
Pr	probability
R_s	system reliability, mission success probability
R_w	weapon reliability
S	mission success
S_x	x-th scenario
X	counting random variable - number of rounds′ failures
x	reported number of round failures
Y	counting random variable - number of pyrotechnic cartridge failures
y	reported number of pyrotechnic cartridge failures

2. Reliability of One Shot Items

There is no universally accepted definition for a one-shot device or a one-shot system. According to DEF STAN 00-42 [3] a one-shot device “is an item which is required to perform its function only once during normal use. Such items will usually be destroyed during their normal operation and cannot therefore be fully tested. The reliability required from one-shot devices is normally high".

One-shot items are usually required to perform a function once only since their use is normally accompanied by an irreversible reaction or process, e.g. chemical reaction or physical destruction. The reliability of a one-shot item could be defined as the ability to perform the required function only once, and only when demanded, under stated conditions and for the specified period of time [3].

It follows from the definition that concerning one-shot items we can differentiate two basic types of failures - an item does not perform a required function when needed or an item performs the function of itself when not needed.

Reliability of a system where the item is used as well as its ability to complete a required mission is influenced by the first type of failure. System safety in particular is influenced by the latter type of failure because an inadvertent initiation of any one-shot item can lead to the hazard of personnel or equipment. In view of the nature of the problem being solved we focus upon the first type of failures only. They are the kinds of failures which may lead to a weapon function disruption.

One shot items can be used in the systems in different ways. The most common arrangement we can see in practice is the one of one-shot items arranged in series and the arrangement when a failure of every single item leads to a failure of the whole system. Regarding automatic arms actuated by powder gases for example a round failure causes a firing interruption and an external intervention is needed to renew the activity. During this process an un-shot round is removed from a gun chamber and a new one is inserted there. Relating to arms of a smaller calibre for instance the external intervention means to operate a gun manually.

Concerning some types of weapons the external intervention is not possible or very difficult to be carried out (regarding aircraft guns or ground guns with external carriage for example) in case the shooting is interrupted and operators do not have direct access to weapon control. Dealing with these weapons a failure of a one-shot item can lead to a default on the mission. That is the reason why various construction solutions are applied on these weapons and in case of a round failure the automatic activation of a gun is guaranteed by them (for example redundancy designs by duplication of explosive/pyrotechnic chains).

The reliability of a one-shot item or systems with one-shot items should normally be expressed or quantified as a probability of mission success [3]. And the conditions under which the mission is regarded as completed depend on many circumstances – on the nature of a mission, on one-shot items having been used, on the purpose of a system etc. Dealing with automatic weapons the mission is completed only in case we are able to shoot all the rounds placed in a magazine or in ammunition feed belt, and if this happens without any external intervention.

If one-shot item reliabilities are assumed to be statistically independent, the reliability of all one-shot items may be incorporated into the final calculation of the system reliability by multiplying the portion of the model representing the one-shot items by the portion representing other parts of the system [3]

$$R_s = R_w \prod_{i=1}^{i=k} (1 - p_i) \,. \tag{1}$$

The total reliability R_w of the system is represented by its partial items reliability and they are not an example of a one-shot item. Reliability of these items is time dependent - it means that probability of failure occurrence of these items rises with operating time. We describe the reliability R_w as the reliability of a weapon as a whole. On the other hand the reliability of a one-shot-item is regarded as time independent and it means that probability of a failure is unchanged with operating time [3].

Referring to fire arms the operating time is usually measured by a number of performed shots, and using the number of the shots we quantify relevant reliability performance measures. Mean time between failures for example is expressed as a mean number of rounds between failures *MNRBF* and a failure rate is related to a single shot. If we take into account an exponential distribution of time between failures, the failure rate can be put that way

$$l = \frac{1}{MNRBF} . \tag{2}$$

On the basis of these assumptions the reliability R_w can be described as a function of a number of rounds shot [1], [4]

$$R_w(n) = \exp(-l\,n) . \tag{3}$$

Let´s presume that for an automatic weapon we use rounds of the failure probability p_r and a magazine has a capacity of n rounds. Reliability of a system is described as a probability that all the rounds will be shot without external intervention and it can be put in the following formula using (1) and (3)

$$R_s = \exp(-l\,n)(1 - p_r)^n . \tag{4}$$

The formula shows that reliability of a weapon system depends mainly on failure probability of the rounds p_r and a number of the rounds n. The dependence is represented graphically in the diagram in the Fig. 1. The diagram demonstrates that despite relatively high reliability of rounds reliability of a system decreases rapidly with a growing number of rounds. Regarding each automatic weapon we have to take into account a possibility of a round failure then and to provide a recharging of a gun.

To describe reliability of a system with one-shot items it is important to be able to specify occurrence probability of a particular number of faulty items taken from a total number of used items. In most cases the initiation of single one-shot items might be regarded as a succession of mutually independent effects, and that is why we can use binomial distribution to describe the reliability.

Let´s presume we have a system made up of n rounds and failure probability of each round equals p. The following formula [5] demonstrates probability of a failure of the x particular rounds which might occur during operation of a system

$$\Pr(X = x) = \binom{n}{x} p_r^{\,x} (1 - p_r)^{n-x} . \tag{5}$$

Probability of a failure of at the most x rounds during operation of a system may be specified in a similar way [5]

$$\Pr(X \le x) = \sum_{i=0}^{i=x} \binom{n}{i} p_r^{\,i} (1 - p_r)^{n-i} . \tag{6}$$

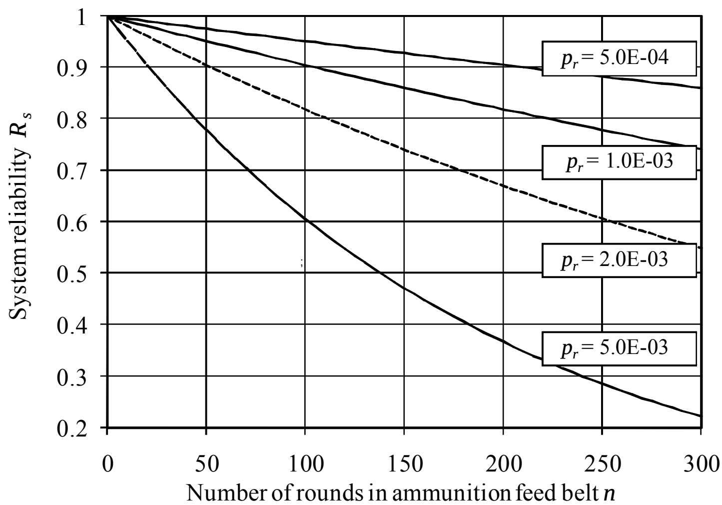

Figure 1 Weapon reliability as a function of rounds number

3. Model of Aircraft Gun Reliability

Regarding automatic guns actuated by powder gases one way how to guarantee to put the weapon into operation automatically in case a round breaks down is to use redundancy in the form of special pyrotechnic cartridges.

Relating to the weapon it is found out whether there was a shot or not after initiation of a round. In case there was not a shot after initiation, the system initiates automatically a pyrotechnic cartridge which makes a required amount of powder gases. They are used for throwing away a faulty round and inserting a new one into a round chamber of a gun. After this the system initiates a round and the shooting goes on. In case the pyrotechnic cartridge is not fired after the initiation, another pyrotechnic cartridge is initiated automatically.

The principle of the operation as described above was used when designing an aircraft gun ZPL-20 made for the purpose of Czech Air Force. When developing the aircraft gun there was a need to specify a number of pyrotechnic cartridges m which was supposed to be used in construction of the gun in the way to achieve required reliability of a system (probability of mission completion). In order to solve the task a model of aircraft gun reliability was designed as stated below.

The mission of an aircraft gun is determined by a number of rounds n placed in a gun feed belt. The mission is considered to be completed if all the rounds are used up, it means that after the mission is completed no round must be neither in a round belt nor in a gun chamber. In case of a failure of the round there is a total number m of pyrotechnic cartridges used in construction of the aircraft gun.

In general the condition under which the mission is completed may be defined this way – during the mission a number of round failures is equal to a number of working pyrotechnic cartridges. We can put the condition that way

$$X \leq m - Y \,. \tag{7}$$

It is obvious that during completing the mission a failure of the aircraft gun itself must not occur either. Probability of completing the mission can be put in the following formula

$$R_s = R_w(n)\Pr(X \le m - Y). \tag{8}$$

A mathematical model of aircraft gun reliability is based on analysis of possible scenarios of aircraft gun operation which lead to completing the mission. These particular scenarios are specified below and probability of their implementation is always determined.

The first scenario leading to completing the mission is a fully reliable function of an aircraft gun when no failure of a round occurs. Probability of implementation of the scenario is not influenced by reliability of pyrotechnic cartridges because the scenario does not take into account their operation. The scenario will be marked with S_0 and will be used for other purposes of the project. The subscript 0 means that no failure of a round, $x = 0$, is expected during implementation of the scenario. Probability of implementation of the scenario S_0 in keeping with the equation (4) can be expressed this way

$$\Pr(S_0) = R_w(1 - p_r)^n . \tag{9}$$

A typical feature of the other scenarios leading to completing the mission is a failure which always occurs to a particular number of rounds and automatic recharging of an aircraft gun is done by pyrotechnic cartridges. These scenarios will be implemented only under the condition put in the formula (7) which says that a number of working pyrotechnic cartridges is at least the same as a number of round failures. The equation (7) will be transformed into the form which enables calculation of probability of completing the condition using the formula (6)

$$Y \le m - X . \tag{10}$$

Scenarios of this description will be marked with S_x and the subscript x stands for a number of round failures considered in the scenario. Only the scenarios which lead to completing the mission are considered, and that is why a number of considered failures can equal at best a number of used pyrotechnic cartridges x £ m. If there is a failure of more rounds than it is a number of used pyrotechnic cartridges, the mission will be always uncompleted.

Probability of implementation of the particular scenarios can be specified as a product of reliability of a gun itself R_w as well as probability of occurring exactly x round failures, and probability of occurring at most $(m - x)$ failures of pyrotechnic cartridges. This probability can be put in the following formula

$$\Pr(S_x) = R_w \Pr(X = x)\Pr(Y \le m - x). \tag{11}$$

Using the equations (5) and (6) we can transform the formula (11) into the form as written below

$$\Pr(S_x) = R_w \binom{n}{x} p_r^x (1 - p_r)^{n-x} \sum_{i=0}^{i=m-x} \binom{m}{i} p_p^i (1 - p_p)^{m-i} . \tag{12}$$

The formula mentioned above is universal for all the scenarios where $0 \le x \le m$. It is easy to demonstrate that if the scenario S_0 is considered, the equation (12) can be easily transformed by appropriate modifications into the form which is equivalent to the formula (9). For the scenario S_m, when there are a maximum permissible number of round failures $x = m$, the formula (12) can be adapted that way

$$\Pr(S_m) = R_w \frac{n!}{m!(n-m)!} p_r^m (1-p_r)^{n-m} (1-p_p)^m \ . \tag{13}$$

It follows from the analysis that an aircraft gun completes the mission only at that time if some of the scenarios mentioned above S_x are achieved. If the mission completion is marked as an event with S, the conditions under which the mission is completed can be expressed this way [2]

$$S = S_0 \cup S_1 \cup S_2 \cup \ldots\ldots \cup S_x \cup \ldots\ldots \cup S_m = \bigcup_{x=1}^{x=m} S_x \ . \tag{14}$$

In view of the fact that the particular scenarios present mutually disjunctive events, the probability of event occurrence S in terms of mission completion can be expressed as a sum of probabilities of single scenarios occurrence S_x [2]

$$R_s = \Pr(S) = \sum_{x=0}^{x=m} \Pr(S_x) \ . \tag{15}$$

Using the formula (15) we can also determine the probability of the fact that the mission will not be completed [2]

$$Q_s = 1 - R_s \ . \tag{16}$$

The formula (15) represents a mathematical model of reliability of the aircraft gun assessed by means of which we are able to analyse influence of all input parameters of the model on final reliability of a gun. The possibilities how to use the model in a practical way are shown in a next chapter.

4. An Example of Practical Application

A designed model makes possible to carry out an analysis which assesses systems´ sensitivity to changes of input parameters of the model. When calculating all the results stated below the reliability of a gun itself $R_w = 0.9999$ is considered. Final results of mission non-completion probability which are shown in the graphs below were calculated with the formulae (12), (15) a (16).

In the diagram in the Fig. 2 there is a dependency of mission non-completion probability on a number of pyrotechnic cartridges when considering rounds of different reliability. The diagram shows that the bigger number of pyrotechnic cartridges is used in a construction of an aircraft gun, the more sensitive reaction of a system is to a change of rounds´ reliability.

In the diagram in the Fig. 3 there is a dependency of mission non-completion probability on a number of pyrotechnic cartridges when considering a different number of rounds in an aircraft gun magazine. It follows from a course of dependencies that with a growing number of rounds which are supposed to be used during a mission a final effect of using pyrotechnic cartridges decreases.

In the diagram in the Fig. 4 there is a dependency of mission non-completion probability on reliability of pyrotechnic cartridges when considering a different number of pyrotechnic cartridges.

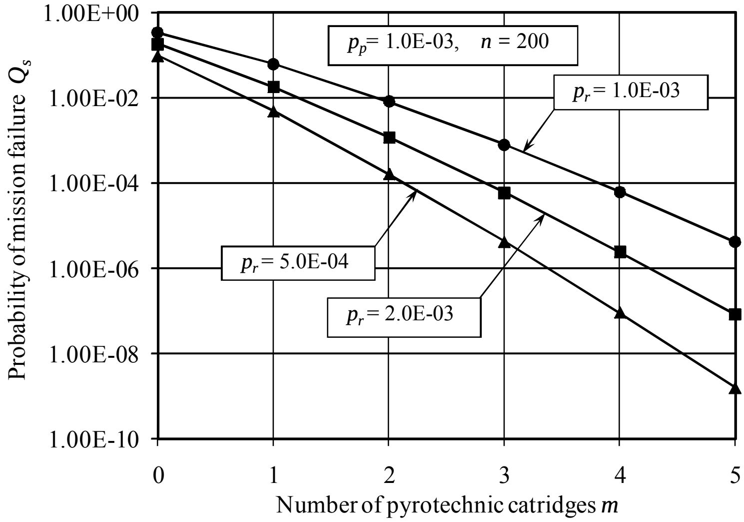

Figure 2 Influence of m and p_r on probability of mission failure

It follows from the diagram that a change of a level of pyrotechnic cartridges reliability influences final reliability of systems on a very limited scale. It results from this that extremely high requirements for reliability of pyrotechnic cartridges are not legitimate.

In the Fig. 5 there is a method how to determine an optimum number of pyrotechnic cartridges which are necessary to achieve reliability of a system required.

Let´s presume that relating to the system defined with the parameters R_w= 0.999, p_r = 0.001, p_p = 0.001, n = 200 it is required that $Q_s \leq$ 1.0E-04 means the probability of mission non-completion. The aim of the conception is to specify this number of pyrotechnic cartridges which guarantees that required reliability will be achieved.

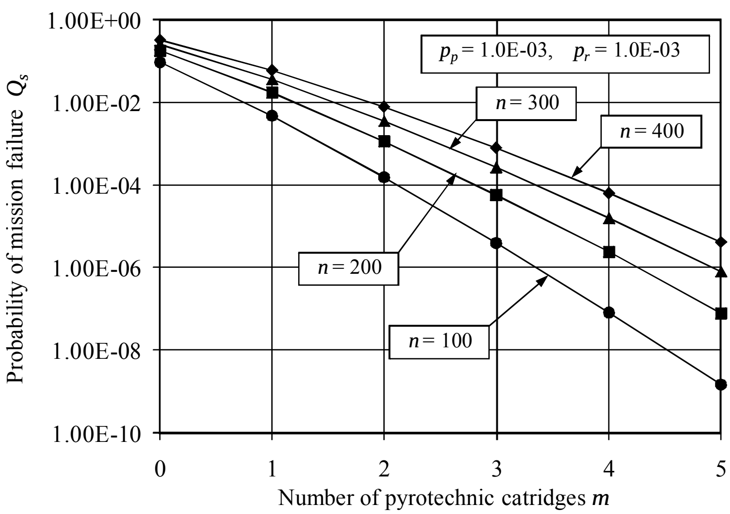

Figure 3 Influence of n and m on probability of mission failure

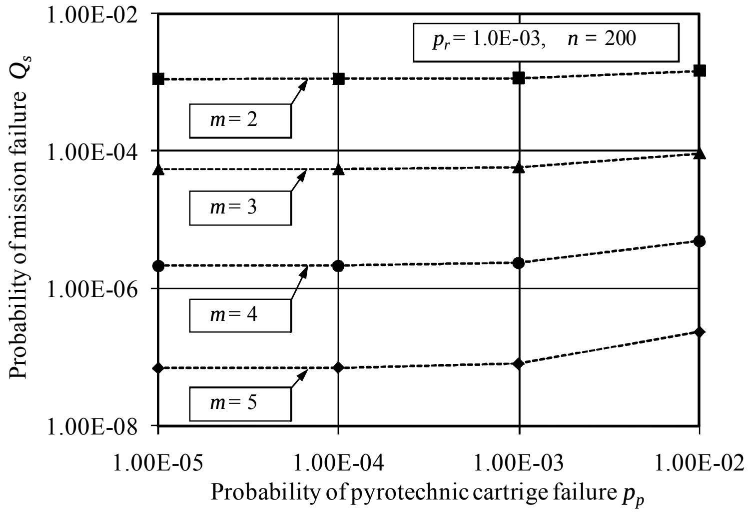

Figure 4 Influence of p_p and m on probability of mission failure

By means of input quantities and equations (13), (15), and (16) we put into the graph dependency of mission non-completion probability on a number of used pyrotechnic cartridges and required probability will be put into a diagram. The diagram in the Fig. 5 shows that a required level of reliability value will be achieved when using three pyrotechnic cartridges. Although we have to take into account the technical, operational and environmental conditions which also influence the total number of pyrotechnical cartridges required.

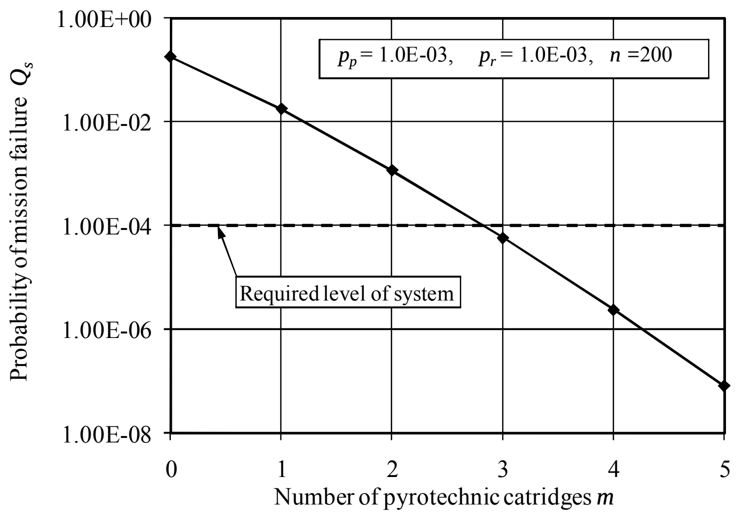

Figure 5 Influence of p_p and m on probability of mission failure

5. Conclusions

The example presented above represents the possibility of carrying out a precise analysis of influence of one-shot items and their reliability onto reliability of the weapon as a whole. Easy determination of an optimal number of pyrotechnical cartridges which is supposed to guarantee a required level of weapon reliability represents a significant advantage.

One of the most interesting results of this analysis is the fact that the total level of weapon reliability is not influenced by a level of pyrotechnical cartridges reliability. The effort for increasing the level of pyrotechnical cartridges reliability does not increase the level of total weapon reliability.

On the other hand we may observe that pyrotechnical cartridges application does increase a total value of weapon reliability and more over a relatively small amount of applied pyrotechnical cartridges does represent significant increase of total reliability value of the weapon.

One thing should be explained here. The situation in practise looks like that one pyrotechnical cartridge is used for the charging the first round into the chamber– before the shooting starts. That is why our analysis results in terms of the optimal pyrotechnical cartridges m should be increased by this one pyrotechnical cartridge ($m + 1$) to assure the successful fulfilment of a mission.

Due to concrete application of this developed model for a specific weapon type it is not impossible to utilise procedures mentioned above (after modifications needed) in order to estimate different weapons´ construction reliability.

Another possible way of this model application is the estimation of complex system reliability where one shot items are applied.

In such analysis we have to take into account a very sensitive thing which is a possible existence of failures dependencies (generally it means some events relationship). We presume in this analysis that some event occurrences are independent but when such a statement (we mean circumstance) is changed several consequences in analysis steps are supposed to be changed too.

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