A PROBABILISTIC ASSESSMENT OF THE RELIABILITY OF AVIATION SYSTEMS

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Abstract: *The technological risk which involves running of actions/processes in operation, leads to exposing and compromising systems operations developed by advanced technologies. The application of risk analyzes in conjunction with probability theory becomes the framework for reliability studies based on the classical structural theory described by Freudenthal and others, considering that the probabilistic and statistical calculation is a solid pillar for the risk assessment methods used in the reliability theory.*

Keywords: *reliability, risk, probabilistic assessment, cumulative probability, RPAS*

1. INTRODUCTION

Aviation was a precursor for reliability analyzes since it managed to outline an average of operating failures, statistics revealing that in the 1940's, a period located at the boundary of the technical era and the human factor era, corresponding to the evolution of the flight accident analysis methods, the fault ratio traduced into an accident at 10^5 flight hours [5].

Probabilistic perception of reliability treats failures as random events, but fitting within certain limits and patterns is useful for highlighting different classes of unexpected/sudden failure or with a progressive evolution [1].

As a probability element, reporting to a fault previously produced establishes classes of failures, connections and chaining of events, since the probability of failure depends on the stability and dependence of the systems, as defects may be influenced by variations and previous states of the system. In this respect, the failures will be classified into: dependent and independent faults, thus determining their causes and influences [8].

The classical approach to the probabilistic evaluation of a failure takes into account the failure rate of a component λ, the exposure time T and the repair time τ. This is also used in the analysis of a fault tree (FTA), a frequently used technique for reliability and safety analysis, which considers the primary events of the arboreal structure as faults whose probabilities are used further to calculate the next probabilities of the events in the upper part of the intermediate structure and afterwards, the top event.

$$P = \begin{cases} 1 - e^{-\lambda T} \\ \lambda\tau / (1 + \lambda\tau) \\ c \end{cases} \tag{1}$$

c - constant probability

Error modeling based on a reliability theory approach makes a classification based on the stages or phases in which they can occur, the importance and the consequences attributed [10]. Impairment of the system's reliability affects safety as a response, hence, a reactive analysis of previous accidents and a predictive approach by anticipating errors and uniformity of operations are essential to maintaining a high level of safety.

Despite the need for an overall approach to a remotely piloted aircraft system that will be analyzed below, it must be considered that at the level of any constituent component, a relative independence should be established in respect to the rest of the elements.

2. A CUMULATIVE PROBABILITY APPROACH FOR RELYABILITY

In the probabilistic hypothesis, the expression of reliability notion specifies the probability that the fixed parameters of a system maintain their set values within the range of $[0,t)$; this probability characteristic to operational safety being framed by the values 0 and 1.

$$0 \le P(t) \le 1 \tag{2}$$

The $\langle E_i, p_i, X_i \rangle$ trio designates the probabilistic computational framework of a risk, therefore it can be seen as an interpretation of the degree of realization of E_i events [1]. If an event (malfunction) noted E_i occurs with the probability p_i, it will have consequences X_i (losses) with different nature and will verify the relations:

$$\begin{gathered} i = 1 \ldots n \\ X_i = (X_1, X_2, \ldots, X_n) \end{gathered} \tag{3}$$

Assuming that:

$$X_1 \le X_2 \le \ldots \le X_n \tag{4}$$

If the events are identified, then the sum of the probabilities attached has a unitary result.

$$p_1 + p_2 + \ldots + p_n = 1 \tag{5}$$

Thus, the cumulative probabilities (which can be ascending or descending cumulative probabilities), whose form is (for an event E_i):

$$P_i = p_i + \ldots + p_n \tag{6}$$

Cumulative probability takes into account events in a sequence and represents the probability that a random variable’s value is considered within a specified range [4].

So, the cumulative probability:

$$Cumulative\,\mathrm{Pr} = \begin{cases} P_1 = p_1 + \ldots + p_n \\ P_i = p_i + \ldots + p_n \\ \quad P_n = p_n \end{cases} \tag{7}$$

Considering the before noted relations $p_1 + p_2 + \ldots + p_n = 1$, the probability P_1 becomes $P_1 = p_1 + p_2 + \ldots + p_n = 1$, so the cumulative probability transforms into:

$$Cumulative\,\mathrm{Pr} = \begin{cases} 1 \\ P_i = p_i + \ldots + p_n \\ P_n = p_n \end{cases} \tag{8}$$

For example, considering an inspection for one of the remotely piloted aircraft system developed by NASA and used for government surveillance interests, the most common malfunctions revealed at routine check could be: damage of lithium batteries produced by overheating, normally caused by solar radiation and a short circuit of the hydrogen cells.

The considered aircraft was a Helios prototype developed as part of an evolutionary series of solar electric and fuel-cell-system-powered unmanned aerial vehicles, designed to operate at high altitudes for long duration flight. It was a long-term, high-altitude aircraft made by NASA in order to perform different research tasks [2].

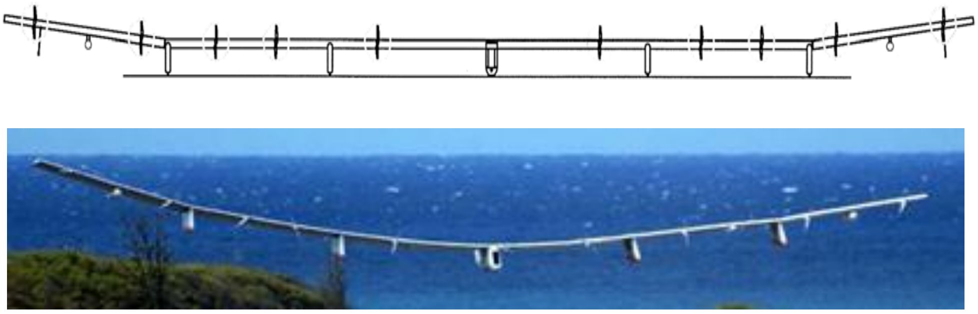

FIG. 1. Description of remotely piloted aircraft system developed by NASA

In structural failures, eighty to ninety percent of the occurrences [11], [12] are caused by human error [13]; so, the analysis of the likelihood of a failure will have to take into account both the rate or frequency of production and the contribution of the human factor and possible implications.

Problems generated by the human factor refer to the human-machine-environment trio, which is often only seen by the first two components, the latter being treated as a framework for producing the accident scenario. However, the following studies will not take into consideration human errors, but the malfunctions (i.e. damage of the lithium batteries, short circuit of the hydrogen cells, a defective piece of the hydrogen tank placed in the center of the wing) of the particular structure of a complex unmanned aerial vehicle (a propeller-driven aircraft flying under guidance of ground-based controllers [2]), produced by NASA in the early 2000.

If considering two successive inspections, it can be analyzed what is the probability that the damage of the lithium batteries caused by overheating would not produce or will produce one or two times.

Using cumulative probabilities, the result will be the sum of the probability of the event not producing and the probabilities that the damage of the lithium batteries will produce once and two times.

Table 1. Probabilities and cumulative probabilities of considered case

Number of events	Probability	Cumulative Probability
0	$2.5 \cdot 10^{-1}$	$2.5 \cdot 10^{-1}$
1	$5 \cdot 10^{-1}$	$7.5 \cdot 10^{-1}$
2	$2.5 \cdot 10^{-1}$	1

In this case, the probabilities of the consequences are calculated as the sum of the probabilities values that appear before the targeted element (inclusive), being a cumulative probability.

$$P(X \le 1) = P(X = 0) + P(X = 1) \tag{9}$$

$$P(X \le 1) = 2.5 \cdot 10^{-1} + 5 \cdot 10^{-1} = 7.5 \cdot 10^{-1}$$

$$P(X \le 2) = P(X = 0) + P(X = 1) + P(X = 2) \tag{10}$$

$$P(X \le 2) = 2.5 \cdot 10^{-1} + 5 \cdot 10^{-1} + 2.5 \cdot 10^{-1} = 1$$

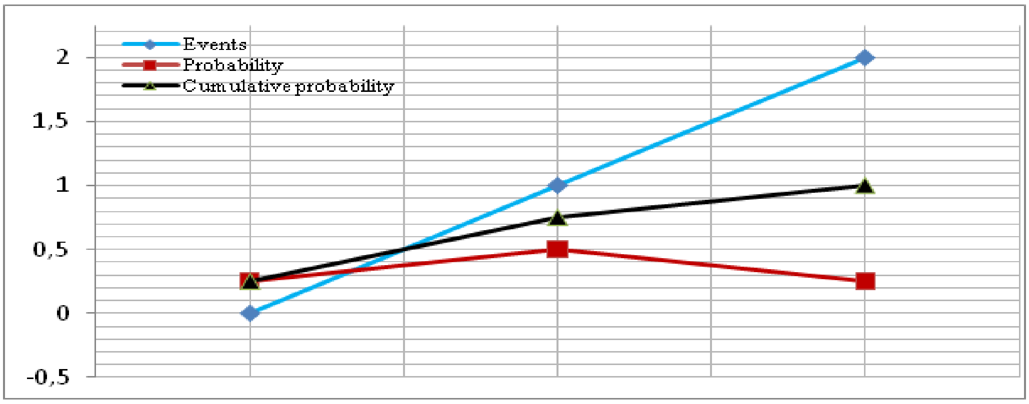

FIG. 2. Events, probabilities and cumulative probabilities of considered case

In this manner, the cumulative ascending frequency function can also be established (represented by the sum of all values that occur up to and including X).

$$F(X) = \sum_{X_i \le X} f(X_i) \tag{11}$$

The experiments described in the probabilistic studies are random, and if an event E has been produced m times from n possible times, the relative frequency oscillates around the probability of E:

$$0 \le m \le n \tag{12}$$

$$\forall n, 0 \le \alpha \le n$$

α -absolute frequency

$$\forall n, 0 \le f_n \le n \tag{13}$$

$$f_n(E) = \frac{\alpha}{n}$$

f_n - relative frequency

Table 2. Evaluation of probability and consequences by frequency and the probability of failure

Criterion	Probability evaluation	Consequence evaluation
Frequency	Per time interval	Components/equipment with defects/malfunction
Probability	Per solicitation	Length of unavailability

Statistical data on reliability that were processed over time have become necessary for a good definition and understanding of the phenomena treated by reliability laws and also for the comprehension of system behavior and evolution in order to make accurate predictions for failures [1].

Mathematical models for reliability analyzes are applied to multiple interconnections between elements/components of the system. Since system's interactions mirrors in the possible states of operation, the accuracy of reliability calculations implies uncertainty modeling which starts by eliminating incorrect/poor knowledge of different conditions.

Throughout this paper, risk and reliability analyzes are considered a framework for risk management, for identifying weaknesses in the remotely piloted aircraft system. Yet, for modeling uncertainty, probabilistic methods, statistics and complex mathematical operations are used.

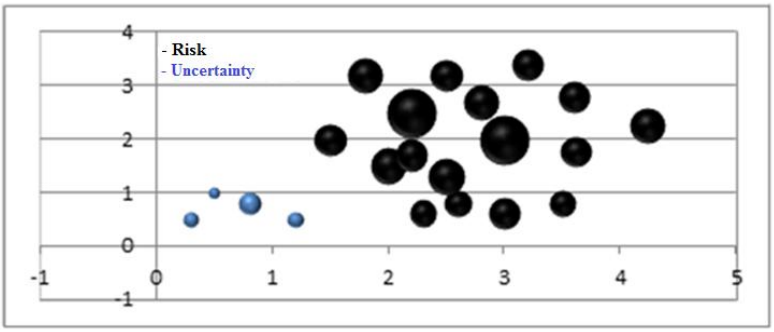

FIG. 3. Level of information regarding risk evaluation

In this case, the probability of a failure is modeled with risk and reliability studies outlined by reasoning and judgments that suppresses/annuls unclear evidence or analyzes, so the level of uncertainty and clarity regarding risk assessment tools will be framed by existing information [1].

3. A CASESTUDY ON A RPAS DEVELOPED BY NASA

Taking into account the dynamic nature of the system analyzed, since the designed levels may differ from those achieved, in a reliability/non-reliability study is necessary to consider the characteristics and performance of the remotely piloted aircraft system and the compliance with the specifications in order to be able to achieve a clear understanding of the evolution and the level of malfunctions.

The continuity in operation is not necessarily an attribute of reliable systems, but is related to service life; in spite of the malfunctions, a system may run for a period of time (treated as a random event) indicated by the "medium repair time". This is considered true if the parameters do not exceed certain imposed limits and/or the system retains its operational features [9].

Maintainability is aimed at easily keeping (or rehabilitating, if necessary) a system, this is a concept mirrored in future maintenance activities [6].

$$M(t_r) = P(t_r \le T_r) = 1 - \exp[-\int_0^{t_r} \mu_r(t_r)dt_r] \tag{14}$$

$M(t_r)$ - maintainability function

t_r - restoration time (re-commissioning)

T_r - the limit imposed for the re-commissioning time

$\mu_r(t_r)$ - rate of repair

The average repair time is MTR.

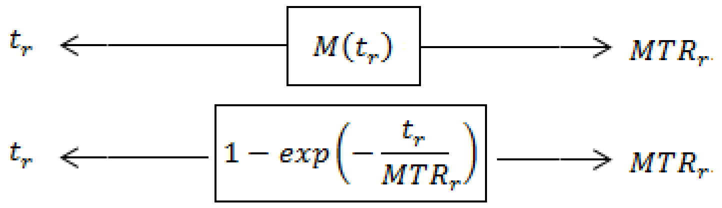

FIG. 4. The relationship between the maintenance function, the restoration time and the average repair time

Re-commissioning a system with cascade faults or failures (caused by various combinations of malfunctions depending on their nature) will be achieved with greater difficulty, as the loss of control is at an alert pace.

As known, fault manifestations depends on the following factors: the failure mode, the location of the fault, the nature/type of failure, the intensity of the fault, the moment of failure producing and the type of equipment considered [14].

Case study:

In the case of the RPAS mentioned above, a piece of the hydrogen tank placed in the center of the wings, which has been established at the last inspection to be defective, must be replaced.

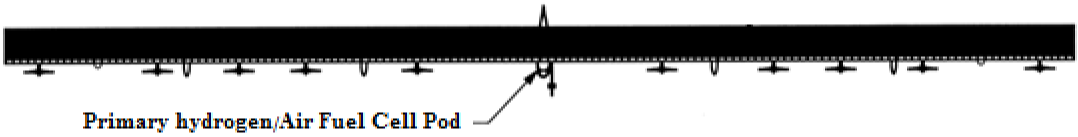

FIG. 5. RPAS configuration

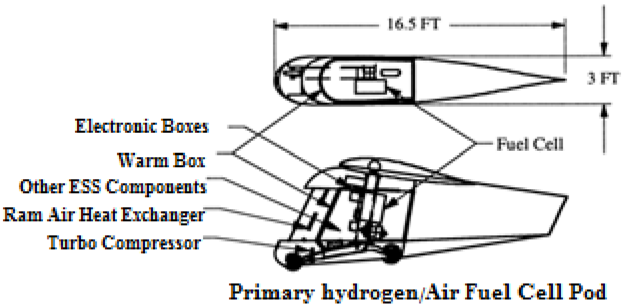

FIG. 6. RPAS primary hydrogen tank configuration

As the temperature sensor is located outside the tank, it does not require the tank to be purged in order to extract the sensor (i.e. there is no risk of leakage), so the time for changing the piece is low [1].

Although in the maintenance manual was specified that that considered piece could be replaced in $0.8h$ ($MTR = 0.8h$), supposing the time available in hangar for the replacement must be lower, for example, between $0.6h - 0.7h$, $t_r = 0.6h$ or $t_r = 0.7h$ [1].

Since the rate of repair (μ_r) is (generally) constant and equal to MTR^{-1} if MTR is given according to an exponential distribution law, the following formulas will be applied:

$$\mu_r(t_r) = \mu_r(ct) \tag{15}$$

$$\mu_r(t_r) = MTR^{-1} = ct$$

$$M(t_r) = 1 - \exp(-\frac{t_r}{MTR}) \tag{16}$$

Therefore, for the next cases:

Case 1:

$t_r = 0.6h \quad MTR = 0.8h$

$$M(0.6) = 1 - \exp(-\frac{0.6}{0.8}) = 1 - 0.472366553 = 0.527633$$

$$M(0.6) = 0.527633 \cong 0.53$$

Case 2:

$t_r = 0.7h \quad MTR = 0.8h$

$$M(0.7) = 1 - \exp(-\frac{0.7}{0.8}) = 1 - 0.416862 = 0.583138$$

$$M(0.6) = 0.5831383 \cong 0.58$$

The obtained results indicate that in the first case, the situation prior the malfunction can be fully restored in 53% of the cases ($M(0.6) = 0.5831383 \cong 0.58$) by replacing the component, and in the second case in 58% ($M(0.6) = 0.5831383 \cong 0.58$) of the cases.

Surely, the technical parameters must show a good relationship between the designed (required) characteristics and the resulting ones; the functional technical properties must have values in accordance with the technical standards and documentation [7].

Knowing the system's particularities, in this case the specific features of an unmanned aerial vehicle with the hydrogen tank placed in the center of the wing, understanding the premises of producing a fault and identifying the causes by observing/analyzing thoroughly, will result in imposing corrective measures to limit/avoid system malfunction.

The causes and occurrences of the malfunctions are not the only issues of interest in the reliability studies performed; the analysis of the failure mechanisms and ultimately, combating them creates a safety loop in the treated remotely piloted aircraft system.

CONCLUSIONS

The performance of remotely piloted aircraft system has been designed to provide acceptable levels of safety. In this context, aspects relating to the performance of equipment and, in particular, structural elements were necessary to be highlighted in order to determine the fault-generation framework.

In-service/operation safety analyzes include control methods and risk identification, involve modalities to allocate the resources needed to manage risks; and reliability analyzes, resistance calculations, evaluation of reliability parameters and maintainability studies complements them. Consequently, reliability studies are an important element in making safety policy decisions.

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