DEPENDABILITY OF SPECIAL EQUIPMENT

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Abstract

The typical features of advanced economics of industrial countries include robust scientific and technological development characterized by effort to achieve the most effective production and utilization. Effectiveness and public productiveness can be achieved through quality projects, designs, manufacturing machines and equipment and of course through high-class designers, constructors, technicians and workers.

Keywords: Reliability, failure, safety factor, lifecycle.

1 Introduction

In former times the price was decisive in sales; today mostly the quality determinates the price. The term of quality in EU countries is based on a supposition that a product is of high quality, providing that it meets requirements set by standards. The quality of a product is a set of features stating the capability of the product to fulfill functions it has been assigned for. The term of quality includes technical aspects (functional, utility features), economic features (purchase price and running costs), environmental features etc. Modern concept of quality is based on the fact, that an evaluation of utility features is left for effects by market mechanisms; however they are relatively strictly evaluated by authorized laboratories through a certification of security, hygienic and environmental properties of products. Extremely important are e.g. environmental features, protecting interests of a whole society. They include namely

- a possibility of a product disposal, its recycling and its return into a lifecycle,
- contents of expended energy and material – economy,
- environmental characteristics in proper sense (emission, waste, noise, vibrations, radiation burdens on environment etc.),
- toxicological characteristics – e.g. a level of a possible threat in accident environs etc.
- reliability, namely a long term failure less operation and a good sustainability without increased requirements for spare parts or without a need to replace a product and for additional consumption of raw material, materials, energy, human labor etc.

2 Effects Having Impact on Reliability

In analysis the reasons and major consequences of failures we always have to consider whether the consequences of failures are acceptable from a point of threat to a life, health or whether the failures do not result in large economic losses. The failures resulting in life menace fall under a significant component of reliability, which is called security. In some areas, e.g. army, air force, nuclear power engineering etc. is a minimum level of security defined by legislation, it is internationally unified and it is proved by state supervision authorities usually through a certificate proving that the requirements defining the minimum level of failure are met. From these points it is obvious, that a maximum level of failures, it means reliability is limited through requirements defining the minimum level of security and it cannot be exceeded, even at the price that the economic optimum will not be achieved. An example of a socially acceptable probability of failures is shown in Fig. 1. In stating the requirements on reliability of special equipment it is necessary to start from a system of operation, which is usually formed by three basic subsystems, namely: a man, an engine and environment. If we should express a philosophy of requirements on reliability and its legislative definition, we could note:

1. The catastrophic and critical failures must not exceed a defined level, or its socially accepted level is defined in such a way that a menace of catastrophic or critical failure is not higher or lower than in other areas (society, transport, industry etc.);
2. It means. e.g. that a rate of catastrophes or critical failures e.g. in air transportation must be lower than in areas of other kind of transportation;

3. It is desirable, that a trend in a rise of catastrophic failure is of decreasing trend in a time period, or in certain low stabilized rates of catastrophes or critical failures the constant levels can be admissible;
4. Probability of a rise of a catastrophic or a critical failure considered per an operational unit (km, motohour, standard hour, flying hour, etc.) related to a total lifetime of a technical system $F_k(t) \leq 10^{-7} - 10^{-9}$.

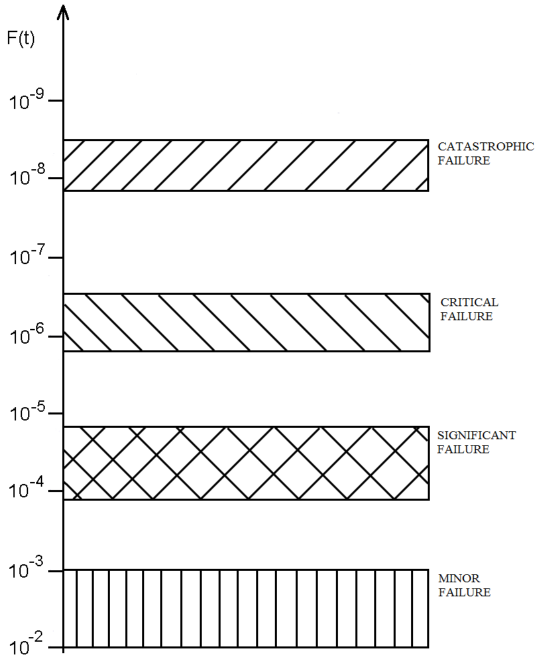

Fig. 1 *A possible statement of a socially acceptable level of failure of special equipment*

The requirement expressed in point 4 is based on a general term of reliability applied for a risk of failures. We suppose a probability $P(x)$, expressing a fact, that a resistance to failure is equal or lesser than a certain value x. Likewise a probability, that an operational load causing failures is equal or greater than a certain value x, is $Z(x)$; the probability, that an operational load is ranging from x up to $x + \Delta x$, is then $Z'(x)$. For a certain value x the probability of a failure is equal to a probability, that an operational load is ranging from x up to $x + \Delta x$, multiplied by a probability, that a resistance to failures is lesser than x. A total probability of a failure is given by a relation [8]

$$F_x = \int_0^x P(x).Z'(x)dx \qquad (1)$$

An acceptable (limit) value of such understood probability is derived from a time development of a failure rate for particular areas (military, engineering, transport, etc.). It results from a relatively similar statistic information (namely in aviation, rail and road transport etc.) related to an operational unit that a rate of catastrophic and critical failures decreases over time. This fact is then used in practice to define socially accessible catastrophic and critical failures, casualties, intensities of subsystem failures etc. For an objective understanding of a catastrophic or critical failure is needed to distinguish the reasons resulting from a failure of a technical equipment, machine and reasons resulting from a failure by a human actor. From a relatively long-term statistics of reasons of catastrophes, critical failures and accidents (from aviation, traffic accidents) is known, that a decisive reason of such failure used to be a human actor. A man as a reason of failure is inherent not only in failures by an operator, maintenance faults, failing in management, but also in reasons which have not been explained. It seems that a human actor participates in up to 40 – 50% of reasons of failures, whereby the reasons caused by environment (traffic density, black ice, haze) are represented in about 10 – 20 % and proper technical failure, including servicing and unknown reasons form only 30 – 40% [9]. A human actor as a reason of unreliability, from practical reasons used to relate to a man as a subsystem of a given technical system (a vehicle, an aircraft, a nuclear power plant). However such definition is not fully correct and with a technical development, roboting and automation has been still specified. It seems that also the failures of a given inherent unreliability can be caused by a deficiency of a human actor in a whole lifecycle from assignment, designing, manufacture, installation until an operation itself, Fig. 2.

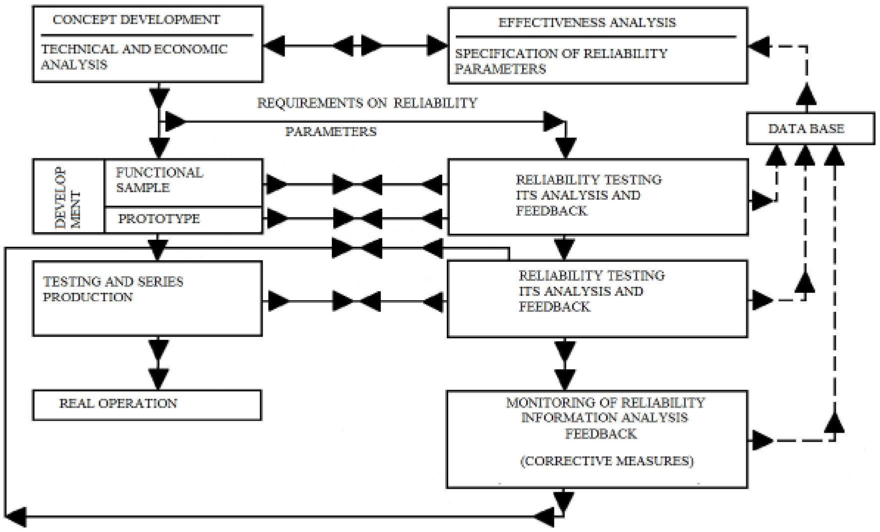

Fig. 2 *Interaction ensuring a level of reliability during a lifecycle of special equipment*

From a point of view of influence of a human actor on reliability it is needed to note, that a human psychic, its physical abilities result from a long-term evolution. He significantly differs in relation to modern equipment, equipment and devices, whose features and capabilities change and improve with each new type. Theoretical papers and practical experience show, that a fairly significant factor from a point of reliability is an interaction between a man – machine, and more over in a stress situation. From these facts four basic areas can be created [11], [12], which are in mutual interaction, they are interlinked and have a reciprocal influence and namely:

- A selective choice of qualified operators; it seems, that an additional influencing on a human actor is a complex process, which can be facilitated in a qualified selective choice from a set of candidates, whereby we start from inherent and gained capabilities of the applicants.
- Qualification training of operators; it is a long-term, systematic process, being held not only in period of a preparation for a profession, but during a whole period when performing a particular profession; such process includes not only a comprehensive theoretical training, achieving of practical capabilities skill, but mainly proper practical skills, including experience from nonstandard situations.
- Concept of machines and systems of their support; it relates solutions, leading to a situation when an operator is transferred from a position of a manual operating staff to a position taking-decision in non-computed situation of course having sufficient classified information and first of all into a control position; in controlling the machine, the threat of faults and failures must be minimized in a system way (the machines are to be designed using a so called “fool-proof” method, or “a machine resistant to faults“).
- Legislative – normative barriers; each system has its own restrictions, parameter limitations with a certain restrictions and limits; “a human actor“ subsystem must observe such restrictions defined as binding regulations, instructions, acts, measures, prohibitions, recommendations and other administrative restrictions; they should be documents, which do not “tie-up the hands” to an operator, but on the contrary, they form a set of important information necessary for meeting the mission and of a needed level of reliability.

Complexity and heterogeneity of a human factor meanwhile does not allow simulating theoretically nor in an experimental way all non-standard stress situations. Therefore up to now a decisive criterion is a real operation. The incentives then for corrective measures then stem from it and background papers to achieve a higher level of reliability in new generation systems. A need of obtaining objective information about a real operation stands out from these views. A logical modification of a term of responsibility can be found based on a preliminary monitoring of information from operation. [1], [8]: „A product is reliable if during its lifetime it follows a supposed rule of its behavior. In case of deviation, it is unreliable“. The issue of reliability from these viewpoints can be expressed by an interaction of free or more precisely four agents, namely: manufacturer, human factor as an operator and an important role of a state as a state supervisor, which is a guaranty of all-society interests.

A state supervision makes an influence on safety and reliability, namely through binding legislative papers in area of design, construction, production, testing, certification, operation, maintenance, including preparation and testing of manufacturing operators. For example in the field of aviation, nuclear plants, important industrial areas, transportation and others the state supervision must pursue a permanent monitoring of a level of responsibility of systems and to draw consequences from found deficiencies as against a manufacturer as against an operator. There are the consequences in maintenance resulting from these facts (RCM etc.) [10], which have to be dynamic and they must systematically respond to a found level of reliability as well as to financial costs. Objective systematic monitoring of the reliability state however leads to a detection of failures and in its consequences it decreases an ability to meet an operational task – a mission [5]. For these reasons they are looking for such methods, which can decrease the negative consequence of an objective detection and such failures, which can not affect a safety or a reliability of the task. Opinions on the admissibility of certain disorders are contained, for example used in standard design philosophy, as safe after a failure, as well, so called "fail - safe". Today, several methods are elaborated on the admissibility of certain failures for meeting a task, but opinions on them are not yet clear, and they vary considerably in different regions. If a fully objective assessment, of the likelihood of danger to the operation is possible with a with a broken part and if such assessment is made with relatively simple criteria and an acceptable confidence , then it will contribute significantly to the operative decision making in the operation and also to significant financial savings. It stems from those considerations that in complex systems, a complex fault as such is irrelevant but its consequences are decisive.

3 Safety against Faults

The model, which was represented by the equation (4), is defined by a failure probability. The model is based on the assumption that both the resistance (strength) design and the operating loads are random variables [6]. An important fact, e.g. in special technology, transport and others is that the load is usually specified by operational factors that are not operable by the operator, or are operable with considerable difficulties [7]. The failure probability can therefore only be changed by changing the distribution of the resistance of the structure. Increasing structural strength or feed distribution function to the high resistance value can reduce the probability of failure, and vice versa. Unfortunately, it is common for the probability function, either load or resistance, are not known to the extent that we could use this standard procedure, and therefore we usually work with a safety factor. In practice, there are considered in various fields various forms of safety factors and namely fatigue strength factor. Objective expression of safety relating failure is always the probability of failure. In practice, unfortunately, its application is possible only in limited applications, and then only on condition that we exactly know the load distribution and resistance of a particular construction. Therefore, there are various terms of security, based on the known statistical characteristics of the load and resistance. In engineering a conventional safety factor [8] expression and others have a simple form

$$k = \frac{\overline{x_p}}{\overline{x_z}} \tag{2}$$

The relationship in some applications (weapons systems, aviation etc.) is modified so that instead of using a mean of heavy load $\overline{x_z}$ the R_z limit load is taken and we can write

$$k = \frac{\overline{x_p}}{R_z} \tag{3}$$

Equation (3) can be further modified respecting a distribution of the load and to use the mean value of strength $\overline{x_p}$ defined by the minimum limit of strength R_p and then the expression applies

$$k = \frac{R_p}{R_z}\,. \tag{4}$$

For simplicity we assume that loads and resistance are normally distributed, and if we know their mean values and standard deviation we can express a probability of a failure free operation R(t) with the following correlation [9]

$$R(t) = \Phi\left(\frac{\overline{X}_p - \overline{X}_z}{\sqrt{\sigma_z^2} + \sqrt{\sigma_p^2}} \right). \tag{5}$$

where

$$\Phi = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2} \right) dx . \qquad (6)$$

Load and strength limits can be expressed by a multiple of the standard deviation, and then a relation is valid

$$R_z = \overline{X}_z + f_z . \sigma_z , \qquad (7)$$

and

$$R_p = \overline{X}_p - f_p . \sigma_p . \qquad (8)$$

Then, from these relations we can write an equation for the probability of failure-free operation of the equipment in a form

$$R(t) = \Phi \left\{ \frac{1}{\sqrt{1 + \left(\frac{\sigma_z}{\sigma_p} \right)^2}} \left[\frac{\overline{X}_p}{\sigma_p} \left(1 - \frac{1}{k} \right) + \frac{f_p}{k} + f_z \frac{\sigma_z}{\sigma_p} \right] \right\} . \qquad (9)$$

Equation (9) is expressed, provided that $\sigma_z = \sigma_p$, $F_z = F_p = 0{,}01$ is a risk of failure and in accordance with known features of the probability density for a standard normal distribution is $f_z = f_p = 2{,}33$. It is shown that the condition for achieving a constant level of a probability of a failure-free operation R (t) in a construction the change in a coefficient of the safety *k* is dependent on a value of a variation coefficient of strength, which is given by relation [10]

$$v_p = \frac{\sigma_p}{X_p} . \qquad (10)$$

Value of a safety factor, generally k > 1 in various engineering fields normally developed according to the increasing knowledge of the load and strength. The factor is based on the definition of two loads:

1. The maximum operational load, defined as the load, which is in normal operation of the machine achieved on average once in the technical life of the machine, so called extreme load R_Z ;
2. The load on an extreme load, which the construction must withstand without failure for a period specified in the operating (power) units (astronomical, numbers of worked hours, for example, flown hours, number of miles traveled, number of cycles, etc.) a load on an extreme bearing capacity level is calculated as the product of the operating load and safety coefficient according to equation (4), respectively (3).

However an existing safety factor in essence covers uncertainty for loads higher than the operating one and uncertainties of possible reduction of structural strength due to strength variance, level of production, operation and strength degradation of uncertainty in the calculations and tests. The current safety factor is related to the load on an extreme bearing capacity level, i.e. in principle to this load, including, does not admit any malfunction. This statement shows that the current safety factor does not determine the level of security at loads higher than operational ones; it requires only avoiding failures when these loads are close to the extreme bearing capacity level. A deficiency is that possible non-linearity is not respected, which may significantly affect the operation of construction, operation and subsystems.

Based on these considerations, it is obviously necessary to exclude from the classical safety factors the area related with loads higher than operating one and instead to assume that certain maximum load occurs in the same structures operated in the same conditions.

In case of such load the readiness factor higher e.g. by about 25% can be used. The maximum load is defined as an extremely sparse load, which is expected to occur less than once in a lifetime for a statistically significant file of the construction. Any failure should occur for all real loads between the operational and the extreme ones that would prevent the construction from serviceability. It stems from a listed definition of the extreme load that this is an extended concept of construction which is safe after the failure in area of the fatigue strength into the area of static strength. What is a new approach to express the security in terms of fatigue strength? The approach is based on the application of linear hypothesis [10], [11], [12] on the accumulation of fatigue damage, which assumes that the fatigue failure (crack, etc.) occurs if

$$U_{pstř.} = \sum \frac{n_i}{N_i} = 1, \tag{11}$$

where

$U_{pstř.}$ … fatigue damage for the failure probability *F (t) = 0.5,*

n_i … the number of load cycles, achieved when the amplitude of the i-th load amplitude,

N_i … the number of load cycles until a failure during the i-th load amplitude.

Load range is a function of time, o S – N on a Wöhler´s curve we suppose, that it is not a function of time. Knowing the load range for a time unit T_z, we can find partial fatigue damage for this time unit and it applies

$$U(T_z) = \sum \frac{n_i(T_z)}{N_i}, \tag{12}$$

and from it then the mean lifetime *(for F (t) = 0.5)* until a fatigue failure

$$T_{stř.} = \frac{T_z}{U(T_z)}, \tag{13}$$

where

T_z … time unit to determine a load range,

$n_i(T_z)$ … the number of load cycles, obtained during the i-th amplitude of the load over the period, T_z,

$U(T_z)$ … partial fatigue damage during T_z period,

$T_{stř.}$ … a mean technical life until fatigue failure.

Safe life design can then be defined by two ways respecting the course of smarminess curve S - N and its variance. The difference is in the fact that in the low-cycle fatigue is considered scattering in the direction of the axis of load cycles N, expressed in standard deviation σN, and in the high-cycle fatigue scattering amplitude in the direction of the axis of strain, expressed standard deviation σS [13], [14], [15], [16].
The difference is in the fact that in the low-cycle fatigue there is variation considered in the direction of the axis of number of load cycles N, expressed in standard deflection σ_N, and in the area of high-cycle fatigue the variance in the direction of the axis of strain, expressed by a standard deviation σ_S.
In the low-cycle fatigue is a safe fatigue life is determined by a quotient of a mean fatigue life $T_{stř.}$ according to (13) and the coefficient of safety of the structure k_b according to relation

$$T_{bezp.} = \frac{T_{stř.}}{k_b}. \tag{14}$$

Whereby the factor k_b respects the load variance with a factor k_n and a variation S – N in a scattering coefficient of the load factor and scattering S - N curve of Wöhler´s coefficient Wöhler´s curve with a factor k_N, whereby $k_b = k_n.k_N$, $k_n = f(\sigma_n)$ and $k_N = F_x(\sigma_N)$. The both factors k_n and k_N are seen in the direction of the axis of the number of cycle’s n, respectively N. A factor respecting a variation coefficient curve S - N is dependent on the number of samples tested experimentally and their results, [17], [18]. In the high-cycle fatigue area there is determined a working S - N curve and the working range of the load, and then directly a safe fatigue life according to the relations (11) and (13). A working curve (Fig. 16) is a so called mean S - N curve (for F (t)

= 0, 5), set at a confidence level of 90%, shifted by the safety factor, expressed as functions of the number of standard deviations σ_s for the selected probability [19]

$$F_x = f(\sigma_s) \tag{15}$$

eventually

$$F_x = anti\log(\log S_0 + f.\sigma_s)\,. \tag{16}$$

The working range of the load of the relevant operational (power) units has magnified amplitude of load multiplied by a factor F_n

$$F_n = f(\sigma_n)\,. \tag{17}$$

The fatigue damage is determined from working curves by an abovementioned procedure in operational units *Tz*, for which a load range has been defined

$$U(T_z) = \sum \frac{n_{ipr.}}{N_{ipr}} \tag{18}$$

and a fatigue life

$$T_{bezp.} = \frac{T_z}{U(T_z)}\,. \tag{19}$$

These procedures apply to safe life constructions, so-called "safe - life" that we can call structures with a limited life. In terms of security strategy, however, these structures are not convenient because the risen failure can have disastrous consequences, and to ensure a high level of security we need to work with high factors of safety, which is very expensive [20], [21], [22], and [23]. Therefore there are quite clear attempts to apply, wherever possible, a safe design strategy after a so called "fail - safe" failure. A fail-safe design is usually defined by two requirements:

1. After a fatigue failure, the remaining part of the structure have sufficient strength (rigidity) to transfer the load, which may be supposed to occur;
2. Failure must be reliably detectable by conventional diagnostic methods and repairable, so that the structure after the repair has initial properties.
   This means that the structure safe after a failure has characteristics ensuring that when a failure occurs (deformation, damage, fatigue cracking, burning, etc.), the probability of a catastrophic failure before diagnosis is extremely small.

If we accept this strategy we can find some essential possibilities of ways to realize a safe construction being safe after the failure, for example [24]:

1. Structure back-up (active, passive);
2. Construction with a load decline after a failure (transferring the load to the adjacent structural element, etc.);
3. dual design elements;
4. Appropriate choice of material with low speed of spread of fatigue cracks;
5. Self-diagnosis of potentially dangerous elements of the structure,
6. Etc.

4 Conclusion

The submitted text outlines a possible systemic approach to reliability and durability of special equipment and their structures, which can be, in various specific applications differently modified, which always depends on the consequences of any critical or catastrophic failures. Everyone is aware of the fundamental differences in the consequences of failure for special equipment, aircraft equipment, nuclear facilities or conventional machinery. This shows also a vulnerability of a quantification of admissible probability of a critical or a catastrophic failure and its legislative expression. The reason is that in some applications in special equipment, as well as air transport, etc. is the probability of catastrophic failure actually the probability of death of people. Development of technology, however, needs the quantification of critical and catastrophic failures, and in the sense that it uses such probability, which corresponds to less than one disaster in the life of the entire file structure under consideration as e.g. for transport airplanes means $F(t) = 10^{-7}$. We note, however, that it is a probability of occurrence in a highly complex mechatronic complex system, from any, usually in the present state of knowledge, exactly unobservable causes. It follows that the probability of catastrophic failure of the subsystem should be in order of $F(t) = 10^{-8}$ respectively $F(t) = 10^{-9}$ or even smaller. Probability of catastrophic failure $F(t) = 10^{-9}$ is so small that its experimental demonstration represents an extremely extensive tests which are currently unfeasible and that are not yet implemented only in exceptional cases (shuttles, especially important weapons systems, etc.).

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