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Physical and reliability aspects of failure in mechanical objects

Keywords

physical degradation, mechanical object, reliability, failure

Abstract

Mechanical objects are operated in real world where degradation of material components and variability of processes managed by a man are the main factors influencing its efficiency. Machine degradation is a long-lasting process concerning its material structure, components and connections. Loss of machine operation ability is due to failures caused by wear and tear, fatigue, corrosion, overloading, material ageing and many other destructive processes. It is observed close relation between failure modes and reliability models so that knowledge about failures may help analysts creating reliability models and determine the best operational decisions. In the paper it is discussed relation between physical phenomenon and theoretical models as a common platform of decision processes.

1. Machine and device- specifics of mechanical objects

Machines and mechanical devices are defined as technical objects consisting usually of movable elements using energy and information to process or transform energy in order to perform a work on mechanical principles [5], [9]. Machines are systems of solid, usually metallic, links (bars) connected to two or more other links by pin joints (hinges), sliding joints, or ball-and-socket joints to form a closed chain or a series of closed chains [5]. The main advantage of most machines is that it multiplies human efficiency like for instance driver moving tons of goods with high speed, or like airplane or ship captain transporting people or goods. Machines fulfill different tasks with usually high efficiency, precisely or at lower risk, assuring comfort and safety.

1.1. Operational system of mechanical object

Machine operation requires defining its system and process [9]. Technical object performs its function with support of man (crew, staff, operators, mechanics, and managers), in properly prepared environment: territory, base, tasks, supply system. All elements that support operation create system of operation (1):

$$SO = < SU, SM, R > \qquad (1)$$

where:

SU- usage subsystem (operation);

$SU = < \mathbf{UE}, R >$,

$\mathbf{UE} = \{UE_i\}$ - elements of usage subsystem,

SM- maintenance subsystem; $SM = < \mathbf{ME}, R >$,

$\mathbf{ME} = \{ME_i\}$ - elements of maintenance subsystem,

R- relations between system elements.

An object circulates between operation and maintenance system so that it requires all necessary resources consisting of operation and maintenance crew, infrastructure and environment.

1.2. Operational process of mechanical object

Operation is defined as "the combination of all technical and administrative actions intended to enable an item to perform a required function, recognizing necessary adaptation to changes in external conditions" [10].

An object function, that is designed to satisfy customer needs, is performed by changes of object states $S = \{s_1, s_1, ..., s_1\}$ in time. The function describing that changes is called operational process $S(t)$.

Operational process is a subsequent change of object state and according to main function of the object it is in up and down state. Process jumps between up and down states in random moments. Failures and repairs (*Figure 1*) determine the instant of jump.

In operational process, one may distinguish controlled and uncontrolled processes. Controlled processes are planned by man/management, depend on required tasks, management methods, and are usually more or less predictable. Timetables, schedules, plans of usage or scheduled maintenance are controlled processes. All unpredictable events that disturb above processes make sometimes these processes uncontrolled. We are usually faced to weather catastrophes (storms, hurricane winds, heavy snow, flood, etc.), technical catastrophes (crashes, collisions, building, bridges or machines collapses, explosions or fires) or human errors while operating an object.

Another classification criterion due to process definition is availability. An object being in the state in which it cannot perform desired function is in fault state [10].

Operational process starts by introducing an object in operation (purchase and installment) and finishes by withdrawal from operation.

In a practical approach, there are two kinds of decisive events for the moment of decommissioning of the object from operation:

- random events of disaster character causing the destruction of the object,
- purposeful operational decisions concerning a withdrawal from use or thorough reconstruction of the object.

A disaster is an event during which the destruction of the supporting structure and of the majority of sets and assemblies being essential for fulfilling object functions takes place. Generally, the result of a disaster is its withdrawal from use.

A decision concerning a thorough reconstruction (modernisation) or withdrawal from use is the consequence of diagnostic investigations and of an economical analysis.

These analysis determine further worthwhile and safety aspects of the object being operated.

Safety is here one of the most essential criteria, as events resulting in human losses or in an annihilation constitute an inadmissible object behaviour during operation and are classified by the European Organisation of Quality Control among the so called critical object features,.

In this connection, object degradation influence in an open or a hidden manner the object history. An open degradation image is observable by means of all kinds of diagnostic examinations, from simple organoleptic inspection to advanced measurement, metallographic, X-ray, gammascopy techniques etc. The object state (its degradation degree), determined on the basis of evaluation measures according to assumptions, e.g. the total degradation degree q_Σ^T, [4], permits to define the decrease of its operation potential and residual life. A data bank containing information about the object becomes in that case the basis for making operation decisions concerning the object future [7], [12].

A hidden degradation of the object can take place in situations of an insufficient supervision and of a not controlled, wasteful exploitation of the object. Then, there exist no procedures forcing continuous or periodical object diagnosing, and the more and more deteriorating technical state of the object can lead to a disaster, in a hidden way and without previous symptoms. The lack of information about the object state does not permit, in that case, to determine the time of exploitation interruption, nor to proceed to the withdrawal of the object from use. Thus, a lack of information concerning object degradation leads in an inevitable way to a catastrophe [4].

2. Concept of failure and fault in mechanical object

2.1. Failure as undesired event

Technical state of an object is described by set of selected technical parameters like: dimensions, displacement, force, moment, stress, power, velocity, pressure, temperature, etc.

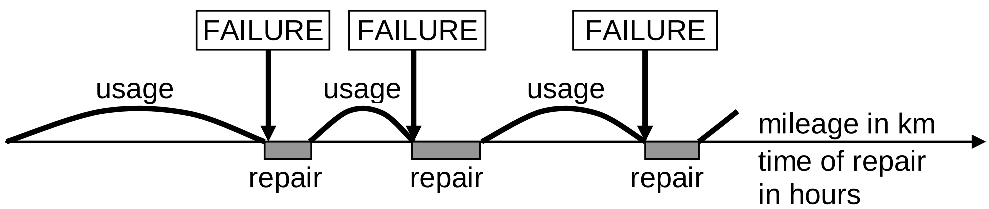

Figure 1. Operational process of repaired object

These parameters are designed according to object function, requirement and environment. They are kept during the operation (usage) in the assumed range of acceptance. Cross out of the limit threshold is equivalent to an event called a failure (*Figure 2*).

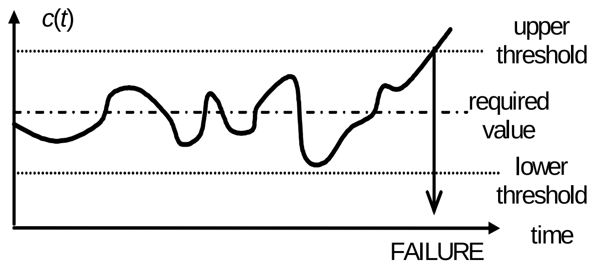

Figure 2. Variability of technical state parameter and failure moment

Definition of the failure states that it is "termination of the ability of an item to perform a required function" [10]. The failure is an event while after failure the item is in a state called fault.

There are two general approaches to the concept of failure in engineering sciences. The case when parameter $c(t)$ varieties randomly according to operational demands or monotonically changes (increases or decreases) (*Figure 3* a and b).

More precise analysis of the failure phenomena shows that the failure as an event occurs when active load over crosses strength of an object. Safety index represents ratio of load over strength and assures that at the design stage, with some level of confidence, undesired event (failure) should not happen in real world.

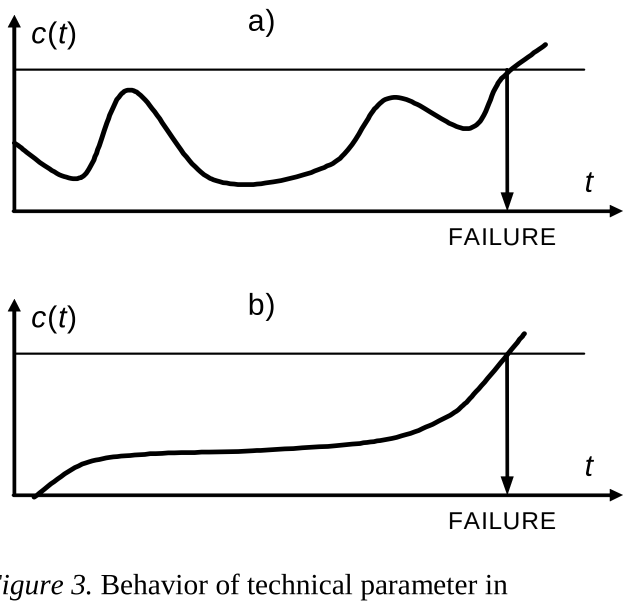

Figure 3. Behavior of technical parameter in operation,
a) random variation of parameter $c(t)$,
b) monotonic increase of parameter $c(t)$.

In fact, in real operation, both load and strength may be regarded as random processes and static reliability is defined [8], as the probability that current load does not excess strength of the element (2):

$$R = P(L < S) = \int_0^\infty F_L(s)\, f_S(s)\, ds \qquad (2)$$

where:
R- probability of safe relation between load L and strength S ($L<S$),
F_L- distribution function of load,
f_S- density function of strength.

If load and strength are both normally distributed, respectively $N(\overline{L},\sigma_L)$ and $N(\overline{S},\sigma_S)$ as shown in *Figure. 4*, than the safety margin *SM* is calculated as $SM = \overline{S} - \overline{L}$. Applying $\sigma_m = \sqrt{\sigma_S^2 + \sigma_L^2}$, reliability of an item is then defined as $P\left(\frac{\overline{S} - \overline{L}}{\sqrt{\sigma_S^2 + \sigma_L^2}}\right) > 0$ [8], [13].

Variability of technical state parameters may take place regarding internal strength of the object as well as external load applied during operation. These two processes are usually classified in two main types presented in *Figure 5*. It gives four pictures of failure as combination of variability of strength and load. The case shown in *Figure 5*d corresponds to level-crossing with random bound [8].

The degradation of a technical object (deteriorating of strength) is a phenomenon consisting in the loss of its usability potential and being described as a stochastic process with respect to the real time of operational use. Degradation depends upon lapse of time, operational and environmental conditions [2], [4]. The object technical state q can be described as a vector $\mathbf{q}(t)$ of selected criterion parameters $c_i(t)$:

$$\mathbf{q}(t) = \langle c_i(t) \rangle,\;\; i = 1, I;\;\; c_i(t) \in \chi_i(t) \qquad (3)$$

that determines the instantaneous abilities of the object to perform assumed functions [3], [14]. Thus, object availability is a state in which each of the criterion parameters is included within intervals of admissible variability $C(t) = \langle c_i^{\min}(t), c_i^{\max}(t) \rangle$ (*Figure 2*). That means, in the traditional damage model, that an excess of admissible values of at least one of the distinguished parameters is equivalent to the damage of the object and to its passage to the fault state. With reference to the real operational use, the model of unavailability can be generalised through an expansion of the area of technical criterion parameters by economical, safety, environment protection criteria etc.

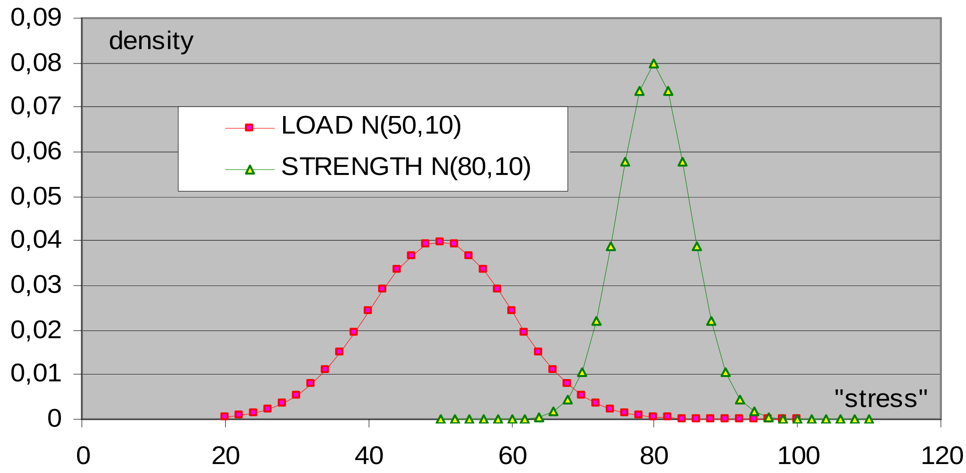

Figure 4. Example of relation between load and strength normally distributed

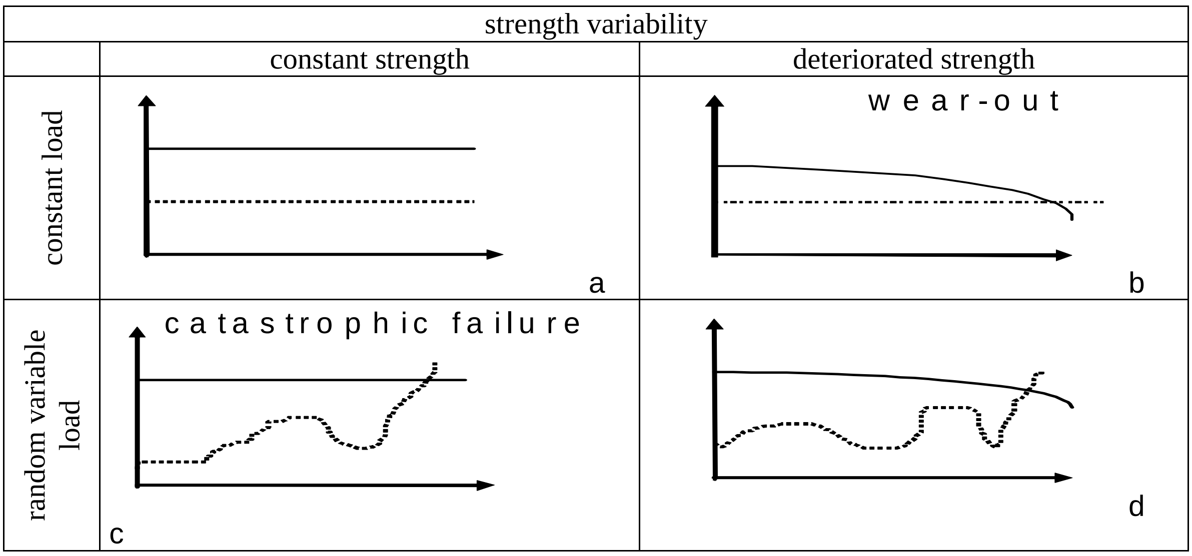

Figure 5. Combinations of load and strength in operation

2.2 Typical fault modes

Fault mode is "one of the possible states of a faulty item" [10] and it is how we observe a consequence of a failure. It is the way of demonstrating inability to perform a function like: rapture, bend, fracture, seizing, wear and many others. Physical processes that lead to failure classify fault models in two groups: wear out and overstress models (*Figure 3*) [14].

The most typical wear out failures in mechanical components are: wear, fatigue, creep and corrosion, but there are also observed failures being combination of the mechanisms mentioned above like: stress and electrochemical corrosion or degradation in strength due to stress variability or high temperature. It is also necessary to mention an influence of man as a failure cause. It is believed that about 80% of failures are introduced by operators or maintenance crew members [6]. The wear out observed in life time creates increasing/decreasing monotonic process so that variables $c_i(t)$ reach at some time a threshold limit value.

Figure 6 shows the simplest examples of wear-out and sudden failure. Brake shoe lost completely friction block probably due to poor maintenance.

Connecting rod is torn by tensile impact while piston seizing (to the right).
It is shown in *Figure 7* an example of fatigue failure with characteristic large fatigue zone, corroded before final fracture and glossy, instantaneous fracture zone.
The most complex failure represents *Figure 8*. Bearing cap of engine water pump is broken because of bearing balls released from seized bearing.

Figure 6. Example of wear-out failure (brake shoe- to the left) and sudden disruption (connecting-rod – to the right)

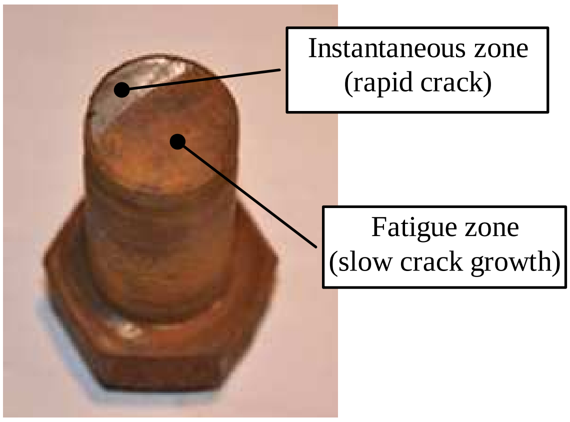

Figure 7. Fatigue crack: bolt ϕ 24mm.

Figure 8. Total, secondary destruction of water pump (car engine) due to primary bearing failure

Analyzing entire objects fault modes, it usually concerns inabilities of main object function. *Figure 9* and *Figure 10* show design error resulting in early crack of deck transom of river barge BP-500 [1].

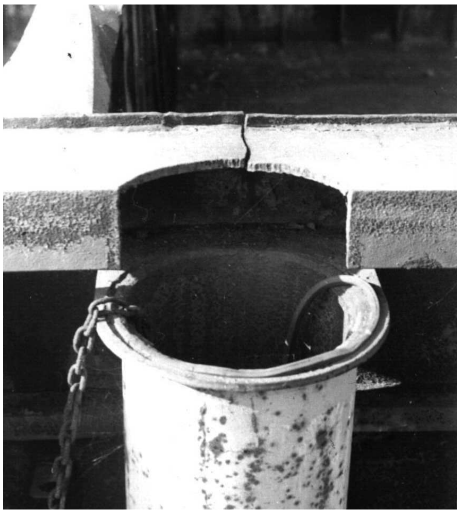

Figure 9. Crack of deck transom of river barge BP-500 (stress concentration, notch due to design error)

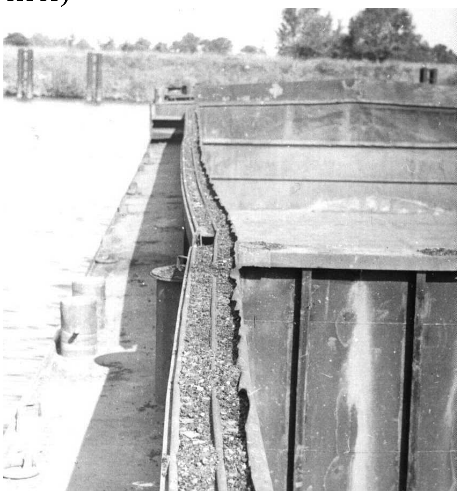

Figure 10. Example of macro notch of deck transom of river barge BP-500

Above pictures shows variety of fault modes and necessity of searching for failure cause to prevent future unexpected stops of mechanical objects. Knowledge concerning qualitative and quantitative failure assessment are important in the process of object improvement and modernization (design) as well as in setting good operational and maintenance practice.

3 Reliability characteristics of mechanical objects

Reliability is in present standards a part of wider concept known as *dependability*. It is the collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance. Dependability is used only for general descriptions in non-quantitative terms [10].

The most important among above definition is *availability* (performance) describing the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.

The *reliability* of a product is the probability that the product will perform an expected (designed) function without failure for a given time, at a desired confidence level under specified operating and environmental conditions.

Analysis and assessment of random disturbances of operation process requires working up a reliability model of the object operated in given circumstances. Main factors influencing variability of failure time are seen: deterioration, ageing, human abilities and infrastructure conditions [6], [7], [9]. Technical objects due to failure and repair classification are described in reliability theory by:

- maintainability, object abilities of being repaired (model of no repaired or repaired object: repaired with negligible repair time $\Theta \approx 0$, with any repair time $\Theta > 0$),
- complexity (design, functionality, reliability structure),
- quantitative assessment of failure (indexes and functions),
- failure description (cause, mode, consequence, way of repair),
- degradation processes analysis setting for instance: threshold state of the parameter (ageing, wearing out, fatigue, corrosion, fracturing, ...).

Randomness of uncontrolled operational processes turns tests, observations and analysis on variables describing mainly time to or between failures (TTF/TBF) and time to repair (TTR) time for whole objects, its subsystems, assemblies and elements. Statistical process of data concerning TTF and TTR leads to get probability distributions and in consequence reliability function R(t), failure distribution F(t), density function f(t), and hazard rate function λ(t).

Classical model of reliability function is given by Wiener formula (4) [2],[3],[14]:

$$R(t) = e^{-\int_0^t \lambda(\tau)d\tau} \qquad (4).$$

It combines reliability with hazard rate function $\lambda(t)$ which has close relation to fault mode (*Figure 11*). The relation is bidirectional i.e. knowing component fault mode one may predict shape of hazard rate function or on the other hand having calculated theoretical model of the failure than corresponding failure mode is possible to show.

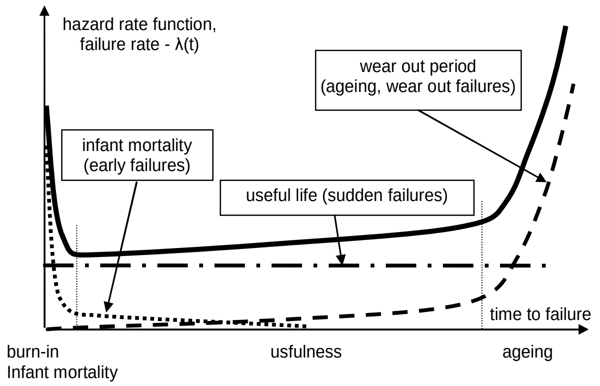

Figure 11. Hazard rate function and components of bath-tube curve

An important technical characteristic is B10 (10 percentile), which represents time to failure (durability) corresponding to 90% certainty that all objects should reach at least time T_{B10} or in other words that only 10% of the object may fail before time T_{B10}. Probability distributions taken usually as mathematical models of failure characteristics are Weibull model, Gauss (normal), log-normal, exponential, beta, gamma distributions [2],[3],[7],[14].

Special importance in failure analysis has an examination of failure cause and its mode. It is observed a high convergence between statistical model of time to failure and failure cause (*Figure 11*). Failures caused by natural phenomenon like ageing, wearing or fatigue described are, with high credibility, with Gauss distribution (time to failure has normal distribution). While sudden or catastrophic failures caused by external to object reasons are modeled by exponential distribution [7],[14].

4. Application of failure mode knowledge in operation and management

4.1 Automotive spare part stock management

Cause of failure knowledge let us assessing rough variability of entry to service stream (service demand). The problem appears in warehouse management when there are two antagonistic demands. It is necessary to keep in stock large amount of spare parts to maintain the service process continuous and on the other hand too high reserve charges expenses a warehouse. Components of natural or ageing failures (time to failure is described by normal distribution) are characterized usually by small variability index $\nu = \frac{\sigma_F}{\overline{T}_F} < 0{,}1$, where $\overline{T}_F$ is mean time between failures and σ_F is standard deviation of this variable. Components of sudden failures are usually described by exponential distribution and therefore are characterized by large variability $\nu = \frac{\sigma_F}{\overline{T}_F} = 1$, what means that demands on particular components may be expected very rarely as well as very often.

In *Figure 10* and *Figure 11* it is shown comparison of distribution functions having the same mean value $\overline{T}_F = 100000$. However, diversification in standard deviation of normal and exponential distributions makes great difference in B10 index, so that efficient stock for parts with exponential distribution should be much larger. One may observe that for exponential distribution 10% of objects will survive time below 20000 and for normal distribution about 80000 (B10 takes value 80 000 units of time for ageing failures and below 20 000 units for sudden failures). It gives a conclusion for further prediction that spare stock for elements of sudden failures is less anticipated and to maintain continuity of maintenance process should be kept on higher level.
Above issue deals only with uniform objects treated individually. In case of complex objects like vehicle, assemblies, subassemblies or park of various vehicles a stock does not undergo to above statement because it may be mixture of different variables. In that case some asymptotic models are applied.

4.2 Analysis of tank ageing data

Knowledge about reliability characteristics of weapon systems are extremely important as well in peacetime as during the war [11]. In the period of peacetime all weapon system are stored or used as training objects. Both in real war service and during peacetime it is expected high availability since they have to provide soldiers safety and fulfill military requirements. Tanks, as main land weapon, should therefore achieve its standard availability as soon as possible while used as training objects.

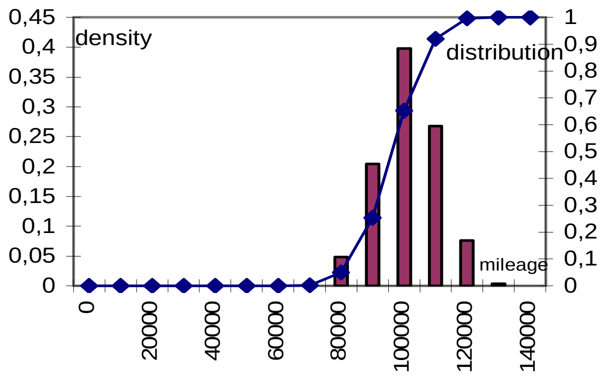

Figure 12. Density and distribution function of normal distribution with $\overline{T}_F = 100000$ and $\sigma_F = 10000$

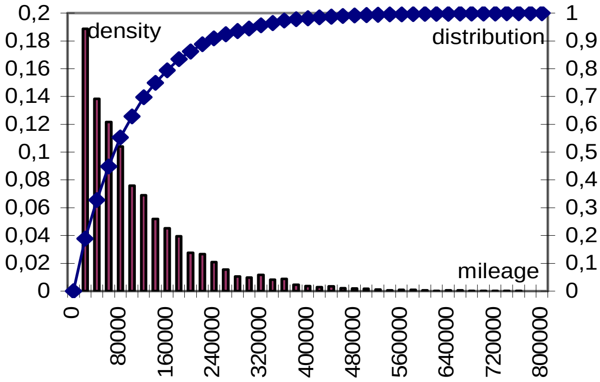

Figure 13. Density and distribution function of exponential distribution with $\overline{T}_F = 100000$

Reliability test has been performed on the sample of 144 tanks in the period of over 3 years. Tanks were new, introduced to training system under supervision of the manufacturer.
Collected data made possible evaluation of reliability functions for 11 functional subassemblies of the tank TWARDY. In 6 cases out of 11, it was obtained Weibull failure distribution function with shape parameter scientifically less then 1. It testifies that the period of observation was the burn-in period with the failures of manufacturer responsibility. It is shown in *Figure* 14 decreasing hazard rate function of fire control system
In case of power transmission subassembly hazard rate was nearly constant (*Figure* 15). It is suspected that failures observed due to that subsystem have the nature of incidents of overloading or human errors while operated by trainee.

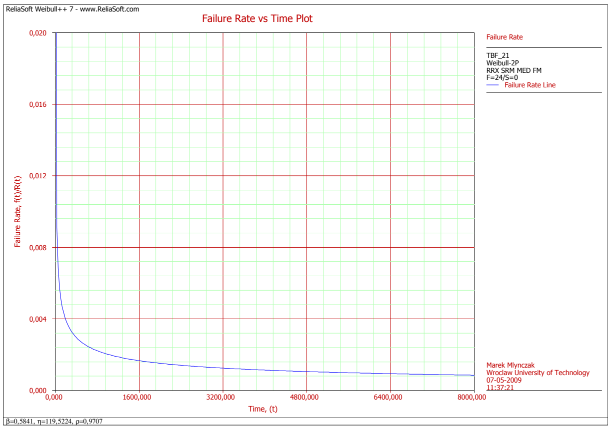

Figure 14. Function of failure rate (decreasing) of fire control system in tank TWARDY

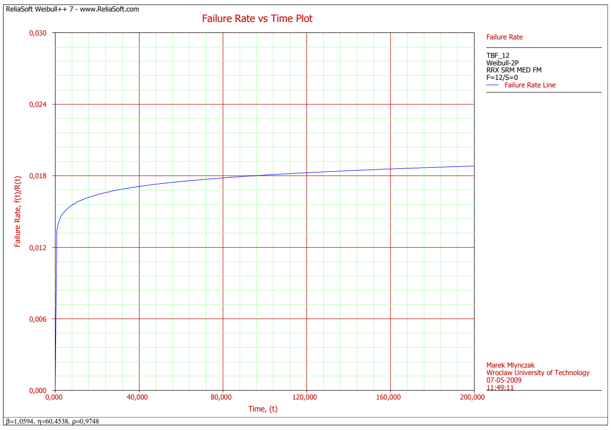

Figure 15. Function of failure rate (nearly constant) of power transmission system in tank TWARDY.

Conclusion

Real operation of mechanical objects provides everyday a lot of examples of failures due to design, manufacture and operation. Some failures are embedded in the object (hopefully not intentionally) and they appears usually in the beginning of operation process (burn-in failures with decreasing hazard rate function). Long lasting correctly managed operational process may bring failures of sudden, catastrophic character related to exponential distribution of time between failures. They are hardly predictable but intensity is of such events is very low. Last part of object life assuming that it survives to that time is related to ageing, wear out failures due to degradation of object material. Depredating processes become more rapid with operational time and finally lead to failure. Corresponding failure rate is modeled by monotonically increasing function. Appropriate mathematical model is Weibull distribution with shape parameter larger than 1, practically, about 3,3.

References

[1] Augustynowicz, J., Dudek, D., Dudek, K., Figiel, A., Młyńczak, M., Nowakowski, T. & Przystupa, F.W. (2001) *Struktury patologiczne maszyn.* KONBiN'2001. Seria Monograficzna ITWL, Szczyrk.

[2] Bentley, J.P. (1999). *Introduction to Reliability and Quality Engineering*. Addison-Wesley Longman Ltd., Edinburgh Gate, Harlow.

[3] Blischke, W. & Murthy, D.N.P. (2000). *Reliability. Modeling, Prediction, and Optimization.* John Wiley & Sons, Inc. New York.

[4] Dudek, D. (1996). Degradacja maszyn roboczych. Teoria czy sztuka. *Problemy Maszyn Roboczych.* Z.7/96. Instytut Technologii Eksploatacji, Radom.

[5] Encyclopædia Britannica® Online. http://www.britannica.com.

[6] Fragola, J.R. (2001). Human reliability analysis procedure. Tutorial Notes. *Proceedings of the European Conference on Safety and Reliability ESREL'01 Safety & Reliability*. Torino.

[7] Gercbach, L.B. & Kordoński, Ch.B. (1968). *Modele niezawodnościowe obiektów technicznych*. WNT. Warszawa.

[8] Ushakov, I.A. & Harrison, R.A. (1994). *Handbook of Reliability Engineering*. Ed. John Wiley&Sons Inc. New York.

[9] Hubka, V. & Eder, W.E. (1988). *Theory of Technical Systems, A Total Concept Theory for Engineering Design.* Springer Verlag. Berlin, Heidelberg.

[10] IEC 60050–191. *Dependability and quality of service -, Amendments 1 & 2. International Electrotechnical Vocabulary* (IEV 191).

[11] Kowalski, K. Młyńczak, M. (2009). Issue of availability of weapon systems in early operation phase. *Reliability and Maintenance,* Lublin (in edition).

[12] Młyńczak, M. (1999). Maintenance modeling of degrading objects. *Proceedings of ESREL'99*. A.A. Balkema Monachium.

[13] O'Connor, P.D.T. (1985). *Practical Reliability Engineering.* John Wiley & Sons. A Wiley-Interscience Publication. Chichester, New York, Brisbane, Toronto, Singapore.

[14] Smith, D.J. (2007). *Reliability, Maintainability and Risk.* Oxford: Elsevier.