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Failure models of mechanical objects

Key words

Physical degradation, mechanical object, reliability, failure.

Słowa kluczowe

Fizyczna degradacja, obiekt mechaniczny, niezawodność, uszkodzenie.

Summary

Mechanical objects are operated in the real world where the degradation of material components and the variability of processes managed by man are the main factors influencing its efficiency. Machine degradation is a long-lasting process concerning its material structure, components, and connections. The loss of machine operation is due to failures caused by wear and tear, fatigue, corrosion, overloading, material ageing, and many other destructive processes. A close relation between failure modes and reliability models is observed so that knowledge about failures may help analysts create reliability models and determine the best operational decisions. This paper discusses the 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 usually consisting of movable elements using energy and information to process or transform energy in order to perform work on mechanical principles [1, 2]. Machines are systems of solid, usually metallic, links (bars) connected to two or

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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 [1]. The main advantage of most machines is that it multiplies human efficiency, for instance, a driver moving tons of goods with high speed, or an aeroplane or ship transporting people or goods. Machines fulfil different tasks with high efficiency, precision or at lower risk, assuring comfort and safety.

1.1. Operational system of mechanical object

Machine operation requires that the operational system and process are defined [2]. The technical object performs its function with the support of mankind (crew, staff, operators, mechanics, and managers), in a properly prepared environment: territories, operational base, task or supply system. All elements that support operation create a system of operation (1):

$$SO = < SU, SM, R > \tag{1}$$

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 among system elements.

An object circulates between the operation and maintenance systems so that it requires all necessary resources consisting of an 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, recognising necessary adaptation to changes in external conditions” [3].

An object function that is designed to satisfy a customer’s needs is performed by changes of object states $S = \{s_1, s_2, ..., s_n\}$ in time sequence $t = \{t_1, t_2, ..., t_i, ...\}$. The function describing the distribution of time in states is called the operational process $S(t)$.

The operational process is a subsequent change of the state of the object and, according to the main function of the object, it is recognised as in an *up* or *down* state. The process jumps between up and down states in random moments. Failures and repairs (Fig. 1) determine the instant of jump.

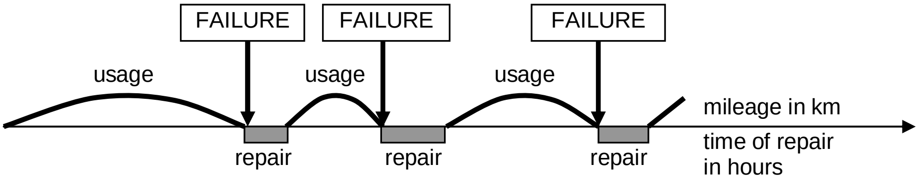

Fig. 1 Operational process of repaired object
Rys. 1. Proces eksploatacji obiektu naprawialnego

In an operational process, one may distinguish controlled and uncontrolled processes. Controlled processes are planned by man/management, depend on required tasks and 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 the above processes sometimes make these processes uncontrolled. We are usually forced 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 a desired function is in fault state [3].

The operational process starts by introducing an object in operation (purchase and installation) 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 catastrophic/disaster character causing the destruction of the object, and
- Purposeful operational decisions concerning a withdrawal from the use or thorough reconstruction of the object.

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

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

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

Safety is one of the most essential criteria, because events resulting in losses of human life constitute inadmissible object behaviour during operation and are classified by the European Organisation of Quality Control among critical object features.

In this connection, object degradation influences the object history in an uncovered or a hidden manner. 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 state of the object (its degradation degree), determined on the basis of evaluation measures according to assumptions, e.g. the total degradation degree q_{Σ}^{T} [4], permits one to define the decrease of its operation potential and residual life. In this case, a data bank containing information about the object becomes the basis for making operation decisions concerning the future of the object [5, 6].

A hidden degradation of the object can take place in situations of insufficient supervision and of uncontrolled, wasteful exploitation of the object. Then, there exist no procedures forcing continuous or periodical object diagnosing, and the continuing deteriorating technical state of the object can lead to a disaster, in a hidden way and without previous symptoms. In that case, the lack of information about the state of the object does not permit one to determine the time of operation interruption or 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 a mechanical object

2.1. Failure as undesired event

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

These parameters are designed according to the object functions, requirements and environment. They are kept during the operation (usage) in the assumed range of acceptance [7]. Crossing the limit threshold is equivalent to an event called a failure (Fig. 2).

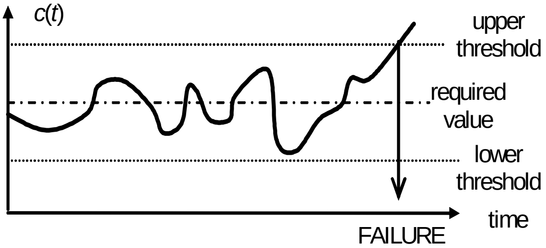

Fig. 2. Variability of technical state parameter and failure moment
Rys. 2. Zmienność parametru stanu technicznego i chwila uszkodzenia

The failure state is defined as the “termination of the ability of an item to perform a required function” [3]. The failure is an event, and 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*) varies randomly according to operational demands or changes monotonically (increases or decreases) (Fig. 3 a and b).

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

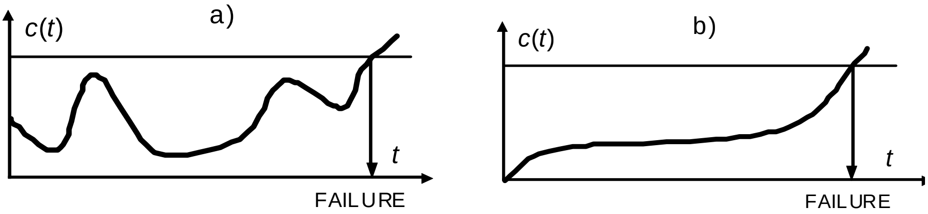

Fig. 3. Behaviour of technical parameter in operation,
a) random variation of parameter *c*(*t*), b) monotonic increase of parameter *c*(*t*) value
Rys. 3. Zachowanie parametru technicznego w eksploatacji
a) przypadkowa zmienność parametru c(t), b) monotoniczny wzrost wartości parametru c(t)

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 the current load does not exceed the strength of the element (2):

$$R = P(L < S) = \int_0^{\infty} F_L(s) f_S(s) ds \tag{2}$$

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 Fig. 4, than the safety margin *SM* is calculated as

$SM=\overline{S}-\overline{L}$. Applying $\sigma_m=\sqrt{\sigma_S^2+\sigma_L^2}$, the 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, 9].

Variability of technical state parameters may take place regarding the internal strength of the object as well as the external load applied during operation. These processes are usually classified as two main types, presented in Fig. 4. It gives four pictures of failure as a combination of the variability of strength and load. The case shown in Fig. 5d corresponds to level crossing with random bound [8].

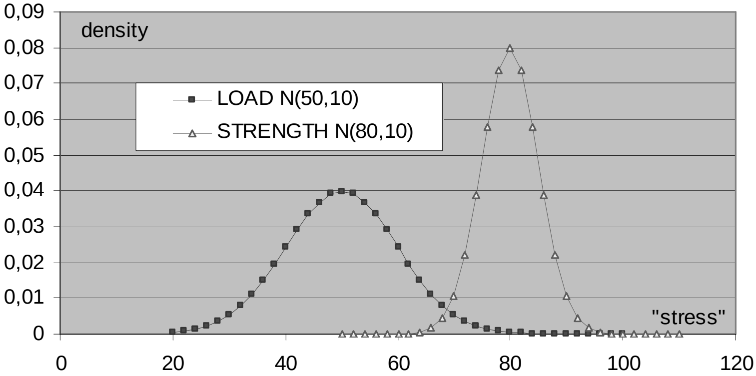

Fig. 4. Example of the relation between load and strength normally distributed
Rys. 4. Przykład relacji między obciążeniem i wytrzymałością opisanymi rozkładem normalnym.

The degradation of a technical object (deteriorating of strength) is a phenomenon consisting in the loss of its usability potential and is described as a stochastic process with respect to the real time of operational use. Degradation depends upon the lapse of time and operational and environmental conditions [10,4]. The object's technical state q can be described as a vector $\mathbf{q}(t)$ of selected criterion parameters $c_i(t)$:

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

which determines the instantaneous abilities of the object to perform assumed functions [11], [12]. Thus, object availability is a state in which each of the criterion parameters is included within intervals of admissible variability $C(t)=\left\langle c_i^{\min}(t),c_i^{\max}(t)\right\rangle$ (Fig. 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 (Fig. 5). With reference to 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, and other criteria.

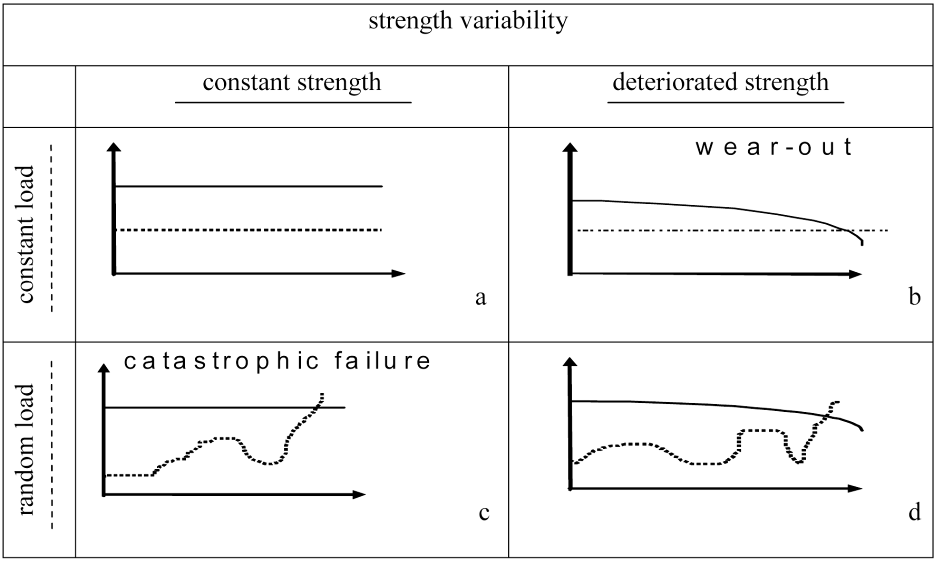

Fig. 5. Combinations of load and strength in operation
Rys. 5. Kombinacje obciążenia i wytrzymałości w eksploatacji

2.2. Typical fault modes

Fault mode is “one of the possible states of a faulty item” [3] and it is how we observe a consequence of a failure. It is the way of demonstrating the inability of performing 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 (Fig. 3) [12].

The most typical wear out failures in mechanical components are wear, fatigue, creep and corrosion, but there are also observed failures that are a 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 crews [13]. The wear out observed in a life time creates an increasing/decreasing monotonic process so that variables $c_i(t)$ reach a threshold limit value at some time.

Fig. 6 shows the simplest examples of wear-out and sudden failure. The complete loss of friction in a brake shoe block is probably due to poor maintenance. A connecting rod is torn by tensile impact during piston seizing (to the right).

An example of fatigue failure with a characteristic large fatigue zone, corroded before final fracture, and a glossy, instantaneous fracture zone are shown in Fig. 7.

The most complex failure is represented in Fig. 8. The bearing cap of an engine water pump is broken because of ball bearings released from seized bearing.

Analysis of the fault modes of the entire object usually concerns the inability of the main object to function. Fig. 9 and 10 show a design error resulting in an early crack of the deck transom of a river barge BP-500 [14].

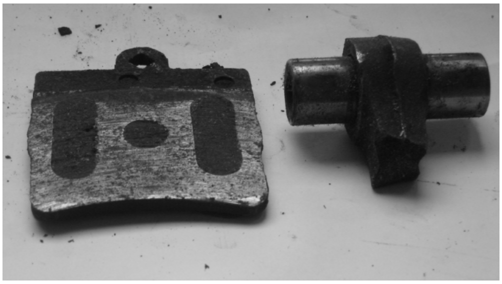

Fig. 6. Example of wear-out failure
(brake shoe- to the left) and sudden disruption
(connecting-rod – to the right)
Rys. 6. Przykład uszkodzenia zużyciowego
(okładzina hamulcowa – po lewej) i nagłego złamania
(korbowód – po prawej)

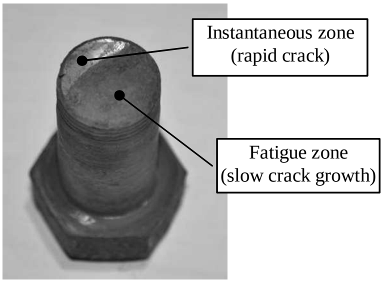

Fig. 7. Fatigue crack: bolt ϕ 24mm.
Rys. 7. Pęknięcie zmęczeniowe śruby
ϕ 24mm

Fig. 8. Total, secondary destruction of water pump (car engine)
due to primary bearing failure
Rys. 8. Całkowite, wtórne uszkodzenie pompy wody
(silnika samochodowego) z powodu pierwotnego uszkodzenia łożyska

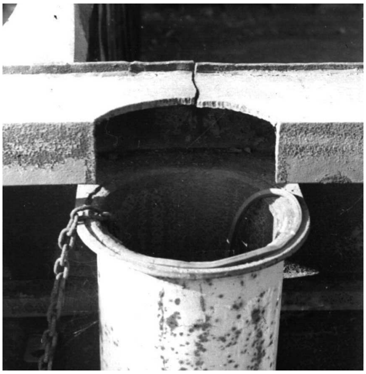

Fig. 9. Crack of deck transom of river barge BP-500 (stress concentration, notch due to design error)
Rys. 9. Pęknięcie pawęży barki BP-500 (koncentracja naprężeń w karbie spowodowanym błędem konstrukcyjnym)

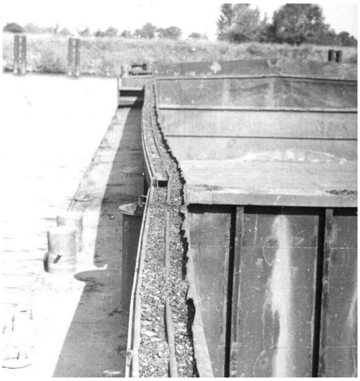

Fig. 10. Example of macro notch of deck transom of river barge BP-500
Rys. 10. Przykład karbu w skali makro pawęży barki BP-500

Pictures above show the variety of fault modes and the necessity of searching for the cause of the failure to prevent future unexpected stops of mechanical objects. Knowledge concerning qualitative and quantitative failure assessment is important in the process of object improvement and modernisation (design) and in setting good operational and maintenance practice.

3. Reliability characteristics of mechanical objects

Reliability in present standards is a part of the wider concept known as *dependability*. It is the collective term used to describe the availability performance and influencing factors: reliability performance, maintainability performance, and maintenance support performance. Dependability is used only for general descriptions in non-quantitative terms [3].

Availability (performance) describes 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. The main factors influencing the variability of failure time are deterioration, ageing, human abilities, and infrastructure conditions [13, 5, 2].

Technical objects, due to failure and repair classification, are described in reliability theory by the following:

- Maintainability, the reparability of an object (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);
- The quantitative assessment of failure (indexes and functions);
- Failure description (cause, mode, consequence, way of repair); and
- Degradation processes analysis setting, for instance, the threshold state of the parameter (ageing, wearing out, fatigue, corrosion, fracturing, etc.).

Randomness of uncontrolled operational processes turns tests, observations and analysis on variables mainly describes the 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 probability distributions and, in consequence, the reliability function R(t), failure distribution F(t), density function f(t), and hazard rate function λ(t).

The classical model of the reliability function is given by Wiener's Formula (4) [10, 11, 12]:

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

It combines reliability with hazard rate function $\lambda(t)$, which has a close relation to fault mode (Fig. 11).

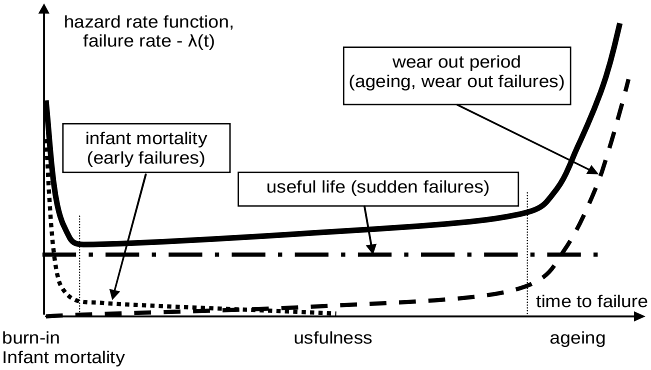

Fig. 11. Hazard rate function and components of bath-tube curve
Rys. 11. Funkcja intensywności uszkodzeń i jej składowe

The relation is bi-directional, i.e., knowing the component fault mode, one may predict the shape of hazard rate function, or, on the other hand, having calculated theoretical model of the failure, one can show the corresponding failure mode.

An important technical characteristic is B10 (10 percentile), which represents the 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's model, Gauss (normal), log-normal, exponential, beta, and gamma distributions [10,11,5,12].

The examination of failure cause and its mode is of special importance in failure analysis. A high convergence between statistical model of time to failure and failure cause is observed (Fig. 11). Failures caused by natural phenomenon like ageing, wearing or fatigue are described with Gauss distribution (time to failure has normal distribution) with high credibility. Sudden or catastrophic failures caused by reasons external to the object are modelled by exponential distribution [5,12].

4. Application of failure mode knowledge in operation and management

4.1. Automotive spare part stock management

Knowledge of the cause of failure lets us roughly assess the variability of entry to the service stream (service demand). The problem appears in warehouse management, when there are two antagonistic demands. It is necessary to keep in stock large amounts of spare parts to continuously maintain the service process and, on the other hand, cause high reserve expenses for a warehouse. A component of natural or ageing failures (TTF is described by normal distribution) are usually characterised by small variability $\nu = \frac{\sigma_F}{\overline{T_F}} < 0{,}1$, where $\overline{T}_F$ is the mean time between failures and σ_F is the standard deviation of this variable. Components of sudden failures are usually described by exponential distribution and are characterised by large variability $\nu = \frac{\sigma_F}{\overline{T_F}} = 1$, which means that demands on particular components may be expected very rarely as well as very often.

Figs. 12 and 13 show a comparison of distribution functions having the same mean value $\overline{T}_F = 100000$. However, diversification in the standard deviation of normal and exponential distributions makes a great difference in B_{10} 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 a 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). The conclusion is the prediction that spare stock for elements of sudden failures is less anticipated and, to maintain continuity of the maintenance process, should be kept at a higher level.

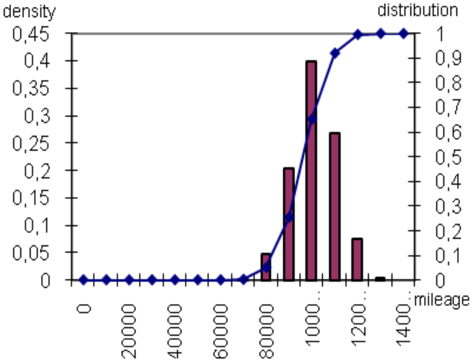

Fig. 12. Density and distribution function as normal distribution with $\overline{T}_F = 100000$ and $\sigma_F = 10000$
Rys. 12. Funkcja gęstości i dystrybuanta rozkładu normalnego $\overline{T}_F = 100000$ i $\sigma_F = 10000$

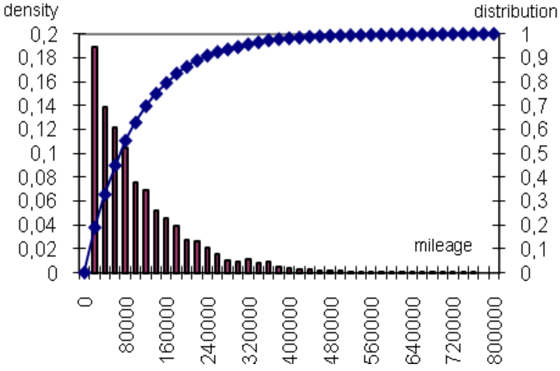

Fig. 13. Density and distribution function as exponential distribution with $\overline{T}_F = 100000$
Rys. 13. Funkcja gęstości i dystrybuanta rozkładu wykładniczego $\overline{T}_F = 100000$ i $\sigma_F = 10000$

The above issue deals only with uniform objects treated individually. In the case of complex objects like vehicle, assemblies, subassemblies of various vehicles, a stock does not undergo the 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 is extremely important in peacetime and during the war [15]. In the period of peacetime, all weapon system are stored or used as training objects. Both in real war service and during peacetime, there is an expected high availability, since they have to provide soldiers safety and fulfil military requirements. Tanks, as main land weapon, should therefore achieve its standard availability as soon as possible while used as training objects.

Reliability tests have been performed on a sample of 144 tanks in a period of over 3 years. The tanks were new, introduced to training system with the manufacturer warranty.

Collected data on 11 functional subassemblies of the tank TWARDY made the evaluation of 11 reliability functions possible. In 6 cases out of 11, a Weibull failure distribution function was obtained with shape parameter scientifically less then 1. It testifies that the period of observation was the burn-in period with the failures the manufacturer’s responsibility. Fig. 14 shows the decreasing hazard rate function of the fire control system. In the case of power transmission subassembly, the hazard rate was nearly constant (Fig. 15). It is suspected that failures observed due to that subsystem have the nature of incidents of overloading or human errors while operated by a trainee.

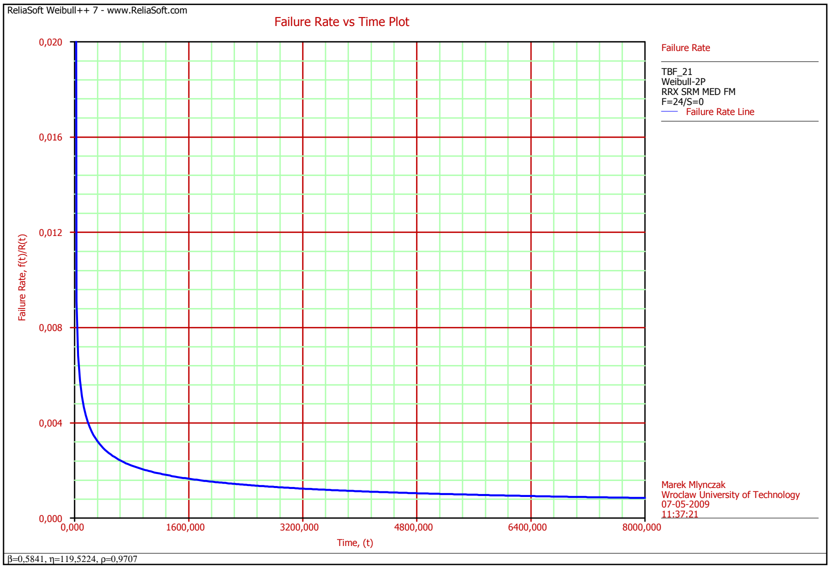

Fig. 14. Function of failure rate (decreasing) of fire control system in tank TWARDY
Rys. 14. Rosnąca funkcja intensywności uszkodzeń systemu uzbrojenia czołgu TWARDY

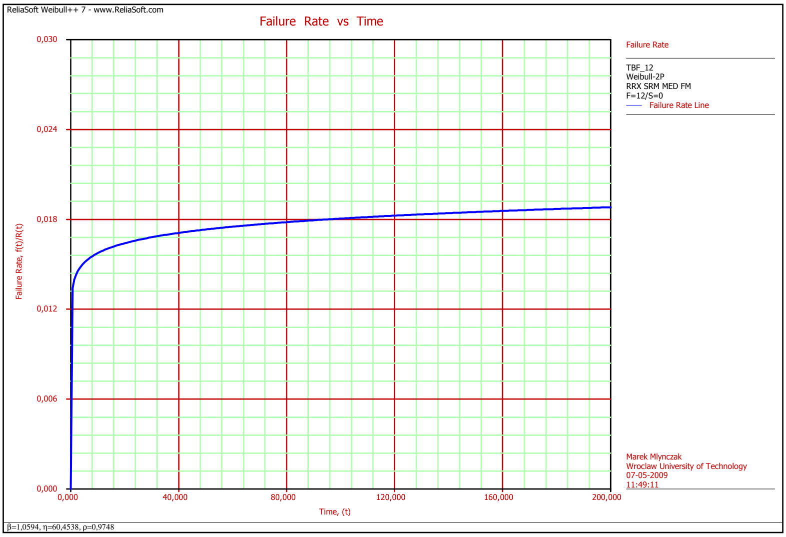

Fig. 15. Function of failure rate (nearly constant) of power transmission system in tank TWARDY
Rys. 15. Bliska stałego przebiegu funkcja intensywności uszkodzeń systemu napędowego czołgu TWARDY

Conclusions

The real operation of mechanical objects provides everyday many examples of failures due to design, manufacture, and operation. Some failures are embedded in the object (hopefully not intentionally), and they appear usually in the beginning of operation process (burn-in failures with decreasing hazard rate function). Long lasting correctly managed operational processes may bring failures of a sudden, catastrophic character related to exponential distribution of time between failures. They are hardly predictable, but the intensities of such events are very low. The last part of an object's life, assuming that it survives to that time, is related to ageing and wear failures due to the degradation of materials of the object. Depredating processes become more rapid with operational time and finally lead to failure. The corresponding failure rate is modelled by a monotonically increasing function. An appropriate mathematical model is Weibull's distribution with a shape parameter larger than 1.0, practically, about 3.3.

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Modele uszkodzeń obiektów mechanicznych

Streszczenie

Obiekty mechaniczne są eksploatowane w rzeczywistych warunkach, gdzie głównymi czynnikami wpływającymi na ich efektywność są zjawiska degradacji materiału elementów obiektu oraz zmienność procesu eksploatacji sterowanego przez operatora. Degradacja jest długotrwałym procesem dotyczącym materiału struktury konstrukcyjnej oraz połączeń elementów. Utrata zdatności użytkowej maszyny wynika z uszkodzeń spowodowanych tarciem i zużyciem, zmęczeniem, korozją, przeciążeniem, starzeniem materiału i innymi procesami destrukcyjnymi. Można zauważyć bliski związek między postaciami uszkodzeń a modelami niezawodności. Wiedza o uszkodzeniach wspomaga analityków w tworzeniu modeli niezawodnościowych i wskazuje optymalne decyzje eksploatacyjne. W pracy omówiono związki między zjawiskami fizycznymi i teoretycznymi modelami tworzące wspólną platformę dla procesu decyzyjnego.