RELIABILITY, DIAGNOSTICS AND FAULT CORRECTION

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Summary

A brief survey of reliability theory is presented with special emphasis on the general concepts that are important for mechanical engineering systems. Reliability and its components are discussed and quantitative characteristics for various components of reliability are introduced. The basic concepts of diagnostics, testing and monitoring of engineering systems at all the stages of their life are surveyed. The trends and the perspectives of the theory and its applications are discussed in the context of the damage tolerance approach, monitoring and diagnostics that provide non-failure operation of mechanical engineering systems.

1. The Subject of Reliability Theory

Reliability is a term widely used both in day-to-day life and in engineering. To be reliable means to be sound, consistent, enduring, and to be of good quality and good character. Reliability in engineering is one of the components of quality for any engineering system. The problem of prediction, normalization and maintenance of reliability arises in mechanical, civil, power engineering, in any branch of engineering concerning life support such as energy and water supply, transportation, city infrastructure, etc. The general methodology is the subject of the multidisciplinary science named *theory of reliability*. In application to mechanical engineering we may say of the theory of reliability of machinery. However, the general theory of reliability covers a very wide domain of human activities.

The presentation further deals with engineering systems and their components. To be laconic, the term *engineering item* (briefly, *item*) will be used when no specialization is necessary. Reliability of an item is defined as its property to keep in time the ability to perform the necessary functions under the condition that all the prescribed requirements of exploitation are satisfied. Here the term *exploitation* includes not only the direct use and service, but also the maintenance, repair, storage and transportation. Sometimes the term *dependability* is also used, at the same time the term *reliability* is applied in a more narrow sense. Later on the term *reliability* is used both in the wide and narrow sense; the meaning of the terms will follow from the context.

The analysis of states and processes of engineering systems is based on appropriately chosen models. The essential factors are kept, and nonessential, secondary ones are neglected. There are two general approaches to the analysis, deterministic and stochastic (probabilistic, statistical). When a deterministic approach is applied, all the factors of the model, i.e. the parameters of the model itself, environmental factors, initial conditions, etc. are considered as completely definite, deterministic. The solution of a correctly stated deterministic problem is unique and, therefore, predicts the behavior of a real system uniquely. The conclusions based on the deterministic models may, however, differ from the results of observation or experimentation. One of the origins is that the behavior of real systems is controlled by a large number of various, poorly controlled, interacting and sometimes competing factors. This is the cause that the behavior of real systems exhibits an ambiguous, stochastic character. In the contrary to the deterministic approach, the stochastic approach takes into account the random factors giving the predictions that contain the probabilistic estimates.

The methodology for constructing stochastic models and developing probabilistic predictions is based on the concepts of the special mathematical discipline, *probability theory*. The basic concept of this theory is the concept of random event. Saying on an event, one means any qualitative or quantitative result of observation or experimentation performed under certain fixed conditions. An event is named *certain* if it inevitably occurs under the given conditions. It is named *impossible* if it inevitably cannot occur under the same conditions. An event that can occur and cannot occur under the given conditions is named *random event*.

Versatility of events signifies that there are factors situated beyond the frames of the given conditions that are either ignored or not supplied by the available information. A typical example is the failure of an engineering system or its component on a given time segment. Usually there is not enough information about the service conditions and the properties of the elements. Hence the failure is considered as a random event.

The application of the probabilistic methods to reliability problems implies methodological and psychological difficulties, especially when the unique items and the items manufactured in small series are concerned. Probability theory is based, in the first line, on the statistical interpretation of probability that is applicable to multiplex events and mass production items. The difficulties frequently arise even for mass production items when is difficult to obtain sufficiently reliable statistical data and verify the design models by tests and experiments. The above listed difficulties multiply in the application to the engineering systems of high responsibility when the estimated non-failure probabilities have to be very close to unity. There the extrapolation of predicted results into the area of rare events becomes necessary, and this procedure is, as a rule, unreliable.

In addition, there is an idiosyncrasy among the engineering community and general public against the probabilistic methods when the safety issues are concerned. This idiosyncrasy is of several origins. First, many practical engineers are not sufficiently educated in probability theory and mathematical statistics. Second, many engineers, especially those obliged with high responsibility, are not psychologically ready to accept the recommendations that contain uncertainties even they are presented in a probabilistic form. In the third, the public opinion (especially the people who are forming it) feels uneasy if the probabilistic concepts are used when the safety of people and environment is concerned.

Nevertheless, the account for the randomness and uncertainties in the reliability analysis is now widely recognized. The probabilistic approaches are used even in the civil aviation and nuclear power industry where the safety requirements are very high whereas the systems and events cannot be treated as multiplex ones. On the other side, the adequacy of probabilistic models and trustworthiness of the used numerical parameters cannot be overestimated. The final numerical estimates, especially those relating to the rare events, must be considered only with a certain amount of tolerance. However, the probabilistic methods are useful even being applied to unique or small-series items. These methods allow us to find the weak, from the viewpoint of reliability, places of an item, to introduce additional factors including those absent in the deterministic analysis, compare the alternative schemes, etc.

The both extremes, the underestimation of probabilistic methods and their overestimation, are equally harmful. Now the engineers working in various branches of industry, mechanical engineering included, are approaching a balanced viewpoint on the reliability theory as a discipline based on probabilistic models. It is stimulated also by the progress in computers and computational mathematics. If a probabilistic model is not simple, the statistical simulation (*Monte Carlo method*) presents the only way to obtain numerical results. The method is based on the multiple numerical modeling of the item's behavior using the data that are the samples of certain random variables and random functions. The statistical treatment of sufficiently representative samplings gives the estimates for reliability measures. At the same time an engineer obtains a set of variants of the item's behavior. Each variant may be interpreted as a result of the solution of a corresponding deterministic problem. Thus, a more complete prediction of the item's behavior becomes available on the design stage.

There are two branches in reliability theory related both by ideology and by the common system of general concepts. There are no steady terms for these branches. First branch is *system, statistical* or *mathematical reliability theory*, the second branch may be named *physical reliability theory*. System reliability theory considers engineering items as the systems composed of elements interacting according to the logical schemes such as graphs and trees. The initial information consists of the results of the statistical treatment of tests and service data for elements composing a system. All problems in system reliability theory have to be solved in the framework of probability theory and mathematical statistics. The physical models of failures and physical processes controlled the item's behavior are not considered at all (see *System Reliability Analysis*).

The origin of physical reliability theory can be found in the earlier works dedicated to the statistical interpretation of safety factors in the design of structures (see *Mathematical Models of Physical Reliability Theory*). The essential feature of physical reliability theory is that the system's behavior and the occurrence of failures is considered as a result of interaction between the system and external actions, i.e. as a result of mechanical, physical, and chemical processes occurring in the system during its lifetime. Along with the tools of probability theory and mathematical statistics, the methods and models of natural and engineering sciences are widely used in physical reliability theory. The system theory is mainly applied in electrical and control engineering, computers and communications. The physical theory has been primarily developed in civil engineering, later on and in the lesser degree in aviation and naval engineering. Recently the models and methods of physical reliability theory became to be used in mechanical engineering, too (see *Reliability against Fracture and Fatigue*).

In general, there is no sense to search for the contradiction or competition between the two approaches to reliability theory. The basic concepts of the system theory are realized in the physical theory in the terms of corresponding physical models. Moreover, physical theory of reliability may be interpreted as an extension of the system theory by involving of physical models. The application area of the physical theory will extend in the future as far as our knowledge on the physics of failures in non-mechanical systems will be accumulated. The modern items of mechanical engineering include a large number of non-mechanical (electrical, electronic, etc.) elements and connections. Hence, the joint application of physical and system models is required.

2. Standardization in Reliability

All methods and procedures for the reliability design and maintenance are subjected to normalization. Standards and norms cover all the stages of the item's life beginning from the early steps of design and ending at the item's writing off or liquidation. There are national norms or standards on reliability as well as international documents that may be both compulsory and recommendatory. There are the documents of general character applied to all domains of engineering and the documents addressed to special branches and even special groups of engineering systems.

The standards on reliability form the basis for production of engineering items with the required reliability level and regulate the relations between the involved sides (designers, producers, suppliers and clients) on all stages of the item's life. The role of standards is especially high in respect to the items of national importance such as power production and power distribution systems, gas and oil pipelines, communication systems, and other systems of life support. The standards are especially important also in the application to the systems whose failure may endanger people and/or environment or produce a large economical loss. The standards on reliability regulate the maintenance and management for the support of the reliability level that is expedient from the economical viewpoint. The standards also regulate the methods of analysis for typical problems, methods of prediction, evaluation and support of the required reliability level.

The normalization and standardization in reliability is performed by a set of many multi-connected documents. The most known international documents are issued by the International Organization on Standardization (ISO) and the International Electrotechnical Commission (IEC). In the Russian Federation the reliability issues are regulated by the State Standards (GOST) issued under the supervision of the State Committee on Standardization (Gosstandart). The standards are built in three levels. The first level covers all the engineering area in the whole. The basic document is *GOST 27.002-89*. It is dedicated to the general concepts and their definitions. Other documents of the first level standardize the methods and procedures applicable in any branch of engineering. The second level of documents is dedicated to special branches of engineering and/or to large groups of engineering items. The third level deals with the reliability of special groups of homogeneous composition. The standards of the first and, partially, of the second level are harmonized with the international standards.

Another approach to standardization is practiced in the USA. The norms in mechanical engineering are prepared mainly in the framework of the American Society of Mechanical Engineers (ASME). This activity is maintained since 1884. Rigorously, this documentation is not compulsory even on the USA territory, though practically all the American private and governmental organizations follow it *de facto*. Some of these norms are applied, with minor modifications, in other countries or are used as a prototype for the corresponding national norms. As an example, the design norms for pressure vessels, piping and other components under high pressure may be mentioned. The *Pressure Vessel and Piping Code* with some amendments and supplements exists several decades.

Among other organizations with a significant contribution to norms and standards, the American Society for Testing and Materials (ASTM) is to be mentioned. The main activity area of the ASTM is developing the documents normalizing and standardizing the tests of materials, structural components and machinery parts. The recommendations of the ASTM are widely used not only in mechanical engineering, but also in aviation, naval and space engineering. One of the most known standards of the ASTM is dedicated to the experimental estimation of the fracture toughness of structural materials. This document becomes a prototype for a number of similar national standards.

3. Reliability and its Components

The concepts of reliability as well as the methods of prediction, evaluation, specification and support of reliability are applicable to any engineering items, machines, structures, life support systems and their subsystems, machinery parts, structural components, etc.

Sometimes the concept of an item includes not only a physical system, but also the information or its carrier. Considering a system machine - operator, *human factor* also enters the concept of an item.

The parametrical definition of reliability is used frequently. In this approach the ability of an item to perform required functions is described by a set of parameters that may be measured directly. Then reliability may be defined as the ability of an item to keep the magnitudes of these parameters in the prescribed limits during the prescribed time interval. Parameters characterizing kinematics and dynamics of a machine, the strength of its parts and connections, the precision of manufacturing, productivity, etc. are used to characterize the state of an item. These parameters vary in time, and when they attain a certain limit values, we say that a failure takes place. The parametric approach to reliability is not always expedient. The state of some simplest items can be characterized by the "yes-no" approach. Not all the properties of items, for example, of the systems machine-operator can be described qualitatively.

In the general case the concept of reliability includes several properties such as the ability to resist to failures, durability, availability and maintainability. The ability to resist to failures, i.e. the property of non-failure operation is usually named *reliability* (in a narrow sense). The combination of all listed properties is named also *dependability*.

Reliability is defined as the property of an item to keep the operating state during a prescribed time interval. The term *time* used in reliability theory may have various meanings depending on the type of an item and its operating regime. It may be the usual calendar time or pure operating time, for example, the flight time for an airplane. The time may be measured also in other units, for example, in kilometers of run for the surface vehicles. The time parameter may be also discrete, being measured in the number of operations or missions. In all these cases the time is a non-diminishing parameter similar to the natural physical time. The concept of reliability is usually introduced with respect to the operation of an item; but the preservation of non-failure properties is required also on the storage and transportation stages.

The concept of durability is connected with another concept of reliability theory, namely, with the concept of *limit state*. *Limit state* is defined as such a state for which the further functioning of an item becomes impossible or inexpedient in spite of the available maintenance and repair means. *Durability* is defined as the ability of an item not to attain the limit state during a sufficiently long time interval. By the way, an item can be considered as coming to the limit state even remaining in the operating state. It is a case when the further use becomes not admissible according to the requirements of safety, efficiency or economical reasons.

Maintainability is the property of an item to be supported in the operating state by means of maintenance and repair. Sometimes the term *repairability* is also used. Along with the opening to repair in the narrow sense, the concept of maintainability includes the possibilities to diagnose the current state of a system, to prevent and reveal the faults and approaching failures. More general term *supportability* is also used in the literature. This term includes a number of additional actions and facilities, in particular, an appropriate training of the personnel.

When engineering items are on the storage and/or on the transportation stage, they are subjected to various actions such as temperature, vibration, moist air, etc. As a result, an item may enter a non-operating or even the limit state. In the ideal, an item has to reserve the same quality as before being put to storage and transportation. The ability of an item to follow this pattern is considered as a part of the general concept named *availability*.

The significance of the components entering the concept of reliability (in the wide sense) depends on the type of an item, the regime of its use, etc. If an item is non-repairable, its most important quality is the non-failure performance, i.e. reliability in the narrow sense. For repairable items, their maintainability becomes of primarily importance.

There is a rather complex relationship between the concepts concerning reliability and safety of engineering systems. *Safety* is the property of an item not to endanger people and/or environment on any stage of its life, being both in operating and non-operating states. Usually, safety is not included into the components of reliability. There are several reasons of such a situation. In particular, the different groups of specialists and different agencies are responsible for safety and reliability. As a rule, the safety requirements are subjected to special codes and regulations. However, safety and reliability are the related concepts. First, a failure can be a source of danger, and the reliability of an item with the respect to such a failure may be considered as a component of safety. Second, the measures of safety are similar to some measures of reliability, and a similar methodology is applied for the evaluation of both types of measures.

Some new tendencies are observed in the last decades bridging the concepts of reliability and safety. For example, *fail-safe* performance means the property of an item to oppose to the development of critical failures from non-critical failures, local defects and damages. Some faults are admitted when they are not dangerous at the time being, and their evolution is surely predictable. In those cases, one says on *damage tolerance* approach. To characterize the fail-safe approach with respect to human errors, the term *fool-proof* property is used.

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Biographical Sketches

Bolotin Vladimir V., was born on March 29, 1926, Tambov, Russia. He graduated from the Moscow Institute of Railway Engineers as the Civil Engineer (Bridges and Tunnels) in 1948. He received from the same Institute the Degree of Candidate of Sciences in 1950 and the Degree of Doctor of Sciences in 1952.

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He has authored/coauthored about 300 research papers and 20 monographs, textbooks and handbooks. Among them are : Dynamic Stability of Elastic Systems (in Russian 1956, translated into English, German, Japanese and Chinese); Nonconservative Problems of the Theory of Elastic Stability (in Russian 1961, translated into English and Japanese). Statistical Methods in Structural Mechanics (in Russian 1961, 1965, translated into English, German, Japanese, Polish, Czech, Hungarian and Portuguese). The latest books are published in English: Stability Problems in Fracture Mechanics, John Wiley, 1996; Mechanics of Fatigue, CRC Press, 1999.

Chairman of the Council on Structural Mechanics of the USSR/Russian Academy of Sciences, Deputy Chairman of the Council on Reliability and Safety of the Russian Academy of Sciences, Member of the Board of the National Committee on Theoretical and Applied Mechanics. He is on the Editorial Boards of 8 national and international journals on structural safety, mechanics of solids and structures.

He is an Elected Member (academician) of the USSR/Russian Academy of Sciences, Russian Academy of Engineering, Russian Academy of Architecture and Structural Sciences, Foreign Fellow of the USA National Academy of Engineering.

USSR National Prize and Russian Government Prize in Science and Technology, Award of the International Association of Structural Safety and Reliability, the Alfred Freudenthal Medal from the American Society of Civil Engineers, a number of other national and international awards.

Klyuev Vladimir V., was born on January 2, 1937, Moscow, Russia. He graduated from the Moscow State Technical University named after Bauman in 1960 and Received the Degree of Candidate of Technical Sciences in 1964 and the Degree of Doctor of Technical Sciences in 1973. Professional Employment: 1960-1964, engineer of the Moscow State Technical University named after Bauman; 1964-1970, Senior Researcher, Head of Laboratory, Head of Department at the Institute of Introscopy; 1970 – present, General Director of the Moscow Scientific Industrial Association "Spectrum".

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President of the Scientific Council on Automated Systems of Diagnostics of the Russian Academy of Sciences, President of the Russian Society for Non-Destructive Testing and Technical Diagnostics, Member of Editorial Board of journal "Defectoscopiya", Editor-in-chief of Journal "Testing. Diagnostics."

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