NAFTA-GAZ

Nafta-Gaz 2022, no. 12, pp. 888–891, DOI: 10.18668/NG.2022.12.06

Methods for calculating the fatigue strength of machine parts

Metody obliczeń wytrzymałości zmęczeniowej części maszyn

Mahluqa S. Rahimova, Samira I. Mansurova

Azerbaijan State Oil and Industry University

ABSTRACT: Regardless of the operating conditions, a load acts on the parts of a machine in different directions. These loads in particular determine the required strength and resistance of parts and determine the study and selection of appropriate strength, resistance parameters for the parts. This can be determined by their impact on oilfield equipment and machine parts. Testing is done to determine the static flexibility, flow limit, tensile strength relative to flexibility, strength period limit, and plastic deformation coefficient. In some cases, when the limits of wear of machine parts are equal, elements with a larger coefficient of deformation are more convenient. These regularities should be used in those cases when it is possible to apply the methods of fracture mechanics or when there are direct experimental data on the development of fatigue cracks, which make it possible to carry out a probabilistic assessment of the durability of structural elements at the stage of crack growth and to substantiate the corresponding limitations on the service life of products. For the safety margins of machine parts, the starting points are as follows: longitudinal bending stress in the sleeve of a solid machine part made of a plastic material cannot damage the part. The length of the first crack can be taken to be equal to several millimetres, which is determined by the capabilities of the simplest means of observation, and by the fact that in some cases even a crack of such length can be critical from the point of view of a potential brittle fracture. In this regard, the fatigue resistance characteristics used in such a calculation should correspond to the point at which the first macroscopic crack appears.

Key words: machine parts, strength period limit, determine a connection, plastic material, oilfield equipment.

STRESZCZENIE: Niezależnie od warunków pracy na części maszyn działają obciążenia w różnych kierunkach. Obciążenia te w szczególności określają wymaganą wytrzymałość i odporność zmęczeniową części maszyn oraz determinują dobór metod badawczych oraz dobór odpowiednich parametrów wytrzymałościowych i odpornościowych tych części. Parametry te można określić poprzez ich oddziaływanie na urządzenia i części maszyn na złożach ropy naftowej, które są poddawane wyższym obciążeniom i odznaczają się wyższymi wartościami granicznymi zużycia. Badania wykonuje się w celu określenia elastyczności statycznej, granicy płynięcia, wytrzymałości na rozciąganie w stosunku do elastyczności, granicy okresu wytrzymałości oraz współczynnika odkształcenia plastycznego. W niektórych przypadkach, gdy wartości graniczne zużycia części maszyn są sobie równe, bardziej praktyczne w użytkowaniu są elementy o większym współczynniku odkształcenia. Prawidłowości te powinny być wykorzystywane w tych przypadkach, gdy możliwe jest zastosowanie metod mechaniki powstawania pęknięć lub gdy istnieją bezpośrednie dane doświadczalne dotyczące rozwoju pęknięć zmęczeniowych, które umożliwiają przeprowadzenie probabilistycznej oceny trwałości elementów konstrukcyjnych na etapie wzrostu pęknięć i uzasadnienie odpowiednich ograniczeń trwałości użytkowej wyrobów. W przypadku ustalania marginesów bezpieczeństwa dla części maszyny przyjmuje się następujące założenie wyjściowe: wzdłużne naprężenia zginające w wykonanej z tworzywa sztucznego tulei stałej części maszyny nie mogą spowodować jej uszkodzenia. Długość pierwszej rysy można przyjąć jako równą kilku milimetrom, co jest uzależnione od stosowanych metod obserwacji oraz faktu, że w niektórych przypadkach nawet rysa o takiej długości może być krytyczna z punktu widzenia potencjalnego wystąpienia pęknięcia kruchego. W związku z tym charakterystyka wytrzymałości zmęczeniowej, stosowana w takich obliczeniach, powinna odpowiadać punktowi, w którym pojawia się pierwsze makroskopowe pęknięcie.

Słowa kluczowe: części maszyn, wartości graniczne wytrzymałości, określenie połączenia, tworzywo sztuczne, urządzenia naftowe.

Introduction

Actual loads and stresses occurring in machine parts are in most cases random functions of time, and the fatigue resistance characteristics of the part (lifetime, or endurance limit) are random variables characterised by significant scattering. The variability of the main factors that determine the strength of products under operating conditions is the reason for the variability in their durability, especially in relation to machines of serial and mass production (Ragimova, 2017).

Corresponding author: M.S. Rahimova, e-mail: *rahimova_mahluqa@mail.ru*

Article contributed to the Editor: 16.09.2022. Approved for publication: 18.11.2022.

Problem statement

Operating experience and the results of fatigue testing on significant batches of products and their parts indicate a significant variation in their service life before cracking or fatigue failure. Therefore, strength calculation methods should be based on the methods of probability theory and mathematical statistics.

Problem solution

Fatigue analysis by probabilistic methods can be used to determine the capability distribution function of a part as well as a connection between the service life of a part and its reliability, as estimated by the probability of no-failure operation. This function can be used to determine the average and percentage capabilities, i.e. capability corresponding to the probability of work without destruction γ in its scattering, etc.

The results of the calculation characterise the strength of the product in terms of reliability, taking into account the probabilistic assessment of the variability of the load and the fatigue resistance of the parts.

A representative sample of products made from metal of this grade, but with a large number of melts, has an inter-melt scatter of mechanical characteristics. This sample is will also be characterised by the actual dimensions of parts deviating from the nominal ones within limits, as a result of which the stress concentration level will become variable (eg., as a result of the radius value deviation of grooves, fillets, thread profiles, etc.) (Dunaev and Lelikov, 2000).

The spread of fatigue properties is also affected by possible deviations from the normal technological process (variations in the modes of thermal and mechanical treatment, welding, hardening processes, etc.). The endurance limits of parts should also be considered random. It was shown above that with sufficient accuracy for practice, the distribution of endurance limits can be assumed to be normal, and the endurance limit can be characterised by its σ_{-1} medium value with a coefficient of variation $\vartheta_{\sigma_{-1}}$.

The degree variability of loading and tension for a sample of products, characterised by the distribution function of stress amplitudes and the scattering indices of these functions' parameters, reflects the loading variability of the general set of products of serial and mass production.

These distribution functions describe the degree of variability in the loading of parts of machines of this type under various operating conditions for which reliability and durability are determined by the criterion of fatigue resistance. Such distribution functions are established by measuring the loading and tension in representative samples that are sufficient for statistical evaluation of the parameters of these functions in the characteristic range of operating conditions of a given type of machine or part.

Problem solution method

Methods of calculatin endurance under variable loads can differ depending on the stage of calculation and design, the level of expected reliability of the product, the amount of information available, the character of the changing loads and bearing capacity over time and certain other factors.

The least experimental information is available at the stage of technical design. However, even at this stage, it is possible to test models in order to study the stress state and strength, and to evaluate the characteristics of fatigue resistance and loads based on the results of tests on machines of similar designs, as well as calculations and analogue modelling using statistical dynamics methods.

The strength calculation in this case is carried out using the methods of material resistance by calculating the safety factors, usually without taking into account statistically described factors or equivalent stresses. If proper information about the loads and strength is obtained, statistical estimates of the capability are also possible at this stage (Aliyeva et al., 2021).

When fine-tuning a prototype of a machine on stands and at test sites, in some cases, information can be obtained by strain measuring the distribution function of stress amplitudes. Fatigue tests of the most critical structural elements are also carried out. The resulting data make it possible to estimate, as a first approximation, the capability distribution function of machine parts using probabilistic methods and to calculate the safety margins (Mordvinov et al., 2004).

At the stage of operating an experimental series of machines, the volume of experimental information on loads and strength required for calculating experimental loads increases significantly, and data on failures in operation appear. All this makes it possible to clarify the design estimate of reliability in terms of fracture resistance.

The level of required reliability of the part is also important when choosing this or another calculation method. Let's consider two cases:

1. Suppose that the probability of failure of the part should be extremely small, for example, $P < 10^{-1} – 10^{-9}$, normal distribution $u_p < ((-6) - (-5))$. Such requirements are imposed, for example, on the elements of aircraft structures, spacecraft, or equipment that ensures the safety of operation of complex and hard-to-control systems. Reliably calculating such small probabilities requires such a large amount of

experimental information that it is practically impossible to obtain. In this case, it is proposed to calculate the margin of safety according to the formula:

$$n = Q_{\min} / L_{\max}$$

where: $Q_{\min}$ is the minimum possible strength value and $L_{\max}$ – is the maximum possible load value, found by statistical methods, taking into account possible random variations Q and L.

For n it is necessary to choose a minimum allowable value that would "guarantees unconditional reliability". The value (n) is proposed to determine on the basis of comparison of the calculation results with an assessment of the reliability of large sets of parts under operating conditions. The reliability of such a definition obviously depends on the estimated reliability of the strength of objects and the amount of available information about their reliability under operational conditions.

2. The probability of the part failing during its service life should lie at the level of $P \approx 10^{-2} - 10^{-5}$, $u_p = ((-2) - (-4))$. These limits usually contain the probabilities of cracking or failure in machines for which the replacement of damaged parts is allowed and which are controlled during operation.

In this case, an approximate estimate of probability becomes possible based on the amount of information available. The different nature of changing loading time of parts and the various requirements for the bearing capacity determine the choice of the calculation method. Of all the possible calculation cases, the following can be distinguished:

- Stresses change over time according to a periodic law (cyclical stresses), and the tension level of individual parts of the same type is random, due to the influence of a number of production and operational factors, but does not change over time.
- Stresses are cyclical, but over time, the stress amplitudes change slowly and monotonically. The fatigue limits of parts can also change as above time due to ageing, corrosion, relaxation of residual stresses, etc. (Kondakov, 1994; New elastomeric material, 2008).

  If the laws of these values' changing over time are known, then in the first approximation the calculation can be carried out as in that case according to the values of loads and safety margins corresponding to a given service life (if working conditions worsen over time). A more detailed consideration of this problem is based on a comparison of two monotone random processes.

  If the process of voltage change over time is random or is the sum of deterministic and random processes, then it is recommended to find the stress amplitude distribution function by processing stress oscillograms for a representative sample of parts using one of the systematisation methods described below. In this case, the most appropriate methods are the full cycle and the enlarged range methods.

  The resource distribution function can be calculated by two methods, depending on the total number of cycles over the service life with stress amplitudes exceeding 0.5 σ_{-1} (lower amplitudes do not have a damaging effect and are excluded from consideration).
- If $N_{tot} < 10^7 - 10^9$ cycles, then the calculation is carried out according to the linear hypothesis of the summation of fatigue damage with the introduction of corrections taking into account the influence of the shape of the amplitude distribution function.
- If $N_{tot} < 10^7 - 10^9$ cycles and stress amplitudes are predominantly less than the average value of the endurance limit σ_{-1} for this general population, then the calculation is carried out according to the method of taking into account the gradual decrease in the endurance limit due to cyclical overloads, possible variations in the endurance and loading limits (Joerres et al., 2005).

The division of the fatigue failure process into two stages (before the formation of the first macroscopic fatigue crack and from this moment to the final failure) can also be reflected in the fatigue calculations. However, despite the many works devoted to the study of patterns of fatigue crack developments, there are still no general methods for estimating the patterns of crack propagation depending on the number of cycles in a complex configuration of parts under random loading.

In some cases, for a quantitative description of the development process of fatigue cracks, methods of linear mechanics are used with solutions of the corresponding boundary value problems on the stress state in the vicinity of cracks of a given configuration, oriented in different ways relative to the field of the main tension. The regularities of the growth rate and direction of fatigue cracks also need to be considered in the statistical aspect due to the random nature of the fracture processes.

These regularities should be used in those cases when it is possible to apply the methods of fracture mechanics or when there are direct experimental data on the development of fatigue cracks, which make it possible to carry out a probabilistic assessment of the durability of structural elements at the stage of crack growth and to substantiate the corresponding limitations on the service life of products.

In cases where it is difficult to assess the durability of a structure at the point when a crack develops, it is advisable to carry out fatigue calculations in the design under the conditions when the first macroscopic fatigue crack occurs.

The length of this first crack can be assumed to be several millimetres, which is determined by the capabilities of the simplest means of observation and by the fact that in some cases even a crack of such length can be critical from the point of view of a potential brittle fracture. In this regard, the fatigue resistance characteristics used in such a calculation should correspond to the stage when the first macroscopic crack appears. It should be noted that the endurance limits of parts found by the condition of crack formation and by final failure practically coincide at $\alpha_0 < 2 - 3$.

The amount of experimental information available on the characteristics of strength and loading determines the level of reliability in estimating the average values and scattering indices of the indicated values, and, consequently, the distribution function of the durability of the part calculated on their basis.

Practical recommendations for determining the number of products to be tested in order to obtain a given accuracy of durability estimates with a certain confidence probability during bench or life tests are given in manuals on mathematical statistics and test planning.

Conclusion

The results of the calculation characterise the strength of the product in terms of reliability.

If the amount of experimental information regarding the load and strength is insufficient, then it is necessary to calculate only the average capability of the details. In this case, indicators of capability scattering can only be evaluated indirectly by statistical data on of analogue machines.

References

Aliyeva S.Y., Damirova C.R., Abbasova S.M., 2021. Research of the problem of optimization and development of a calculation method for two-stage chain drives used in heavy industrial vehicles in conditions of economic efficiency. *EUREKA: Physics and Engineering*, 4: 105–112. DOI: 10.21303/2461-4262.2021.001930.

Dunaev P.F., Lelikov O.P., 2000. Designing units and parts of machines. *Proc. Allowance for Tech. Specialist. Universities. 6th ed., isp. Higher. Shk.*: 1–447.

Joerres M., Pilath C., Pischinger S., Sonntag H.D., 2005. Rechnergestütztes Verfahren zur akustischen Optimierung von Dichtungen. *MTZ Motortechnische Schweitzer*, 66: 386–393. DOI: 10.1007/BF03226742.

Kondakov L.A., 1994. Sealing and sealing equipment: *Machine building*. 1–445.

Mordvinov A.A., Zakharov A.A., Miklina O.A., Poluboyartsev E.L., 2004. Wellhead equipment of fountain and injection wells: Guidelines. *Ukhta: USTU*: 31.

New elastomeric material, 2008. New Elastomer material from Hintze and Kraft Stoff in Motiram. *MTZ*, 69(2): 1–115.

Ragimova M.S., 2017. Determination of the strength of machine parts of oilfield equipment. *Equipment and technologies for the oil and gas complex*, 4: 13–15.

Mahluqa Surxay kizi RAHIMOVA, Ph.D.
Assistant professor at the Department of Mechanics
Azerbaijan State Oil and Industry University
16/21 Azadliq Ave, Baku, Azerbaijan
E-mail: *rahimova_mahluqa@mail.ru*

Samira Ilyas kizi MANSUROVA. M.Sc.
Assistant professor at the Department of Oil and Gas Engineering
Azerbaijan State Oil and Industry University
16/21 Azadliq Ave, Baku, Azerbaijan
E-mail: *mansur_s74@mail.ru*