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FEATURES OF DURABILITY CALCULATION FOR MACHINE PARTS AND STRUCTURAL ELEMENTS UNDER HIGH ASYMMETRIC LOW-AMPLITUDE LOAD CONDITIONS

The study has been conducted by means of physical, mathematical and computer modeling integrated method use. To prove the adequacy of the results obtained the experimental procedure on the existing equipment and laboratory facilities has been applied. The method of carrying out asymmetric stress cycles with mean stress of stretching to symmetric using the proposed piecewise – linear equations for evaluating the material sensitivity to asymmetry of the cycle has also been improved. It has enabled pipe column element durability under the condition of typical asymmetric low-amplitude loading calculation.

Key words: *stress reduction, the boundary toughness, the asymmetry of the cycle.*

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ОСОБЛИВОСТІ РОЗРАХУНКУ ДОВГОВІЧНОСТІ ДЕТАЛЕЙ МАШИН ТА ЕЛЕМЕНТІВ КОНСТРУКЦІЙ, ЯКІ ПРАЦЮЮТЬ В УМОВАХ ВИСОКОАСИМЕТРИЧНОГО НИЗЬКОАМПЛІТУДНОГО НАВАНТАЖЕННЯ

Дослідження об'єкта проводилось за допомогою комплексного методу, що полягає в сумісному використанні фізичного, математичного та комп'ютерного моделювання. Для підтвердження адекватності отриманих результатів використано експериментальні методи на діючому обладнанні та на лабораторних установках. Удосконалено метод приведення асиметричних циклів напруж4

ень з середнім напруженням розтягу до симетричних із використанням запропонованих кусково-лінійних рівнянь для оцінки чутливості матеріалу до асиметрії циклів. Це дає змогу проводити розрахунок довговічності елементів трубних колон в умовах дії типового для них високоасиметричного низькоамплітудного навантаження.

Ключові слова: *приведення напружень, границя витривалості, асиметрія циклу.*

Introduction. The process of loading for a large number of structures and machinery parts is characterized by a large scatter of asymmetrical stress cycles both along its length and in timeframe. To the full extent it also concerns the elements of the drill string, particularly when drilling deep holes. Therefore, the vast majority of experiments determinating the fatigue resistance parameters is carried out at a symmetric cycle of stresses as a required stage for calculating column elements strength and bringing asymatrical cycles to the symmetrical equivalent.

The analysis of the latest research papers. The vast majority of machine parts and subassemblies in the process of operation is subjected to random loading [1 – 3]. In this case, when calculating the durability in the schematization process [4], conducing of stresses with different asymmetry R ratio to the symmetric cycle is recommended. Such a cast greatly simplifies further calculations conducing single-ended voltages σ_{max} with $-1 \le R \le 1$ for the symmetric cycle to σ_{ekv} with the recommended equation [5]

$$\sigma_{ekv} = b\sigma_{max} - (ab-1)\sigma_{-1}, \quad (1)$$

where σ_{-1} – is the endurance limit at symmetric loading;

a i b – are odds cast;

$$a = \frac{2}{2-(1-\psi)(1+R)}, \qquad b = \frac{1}{\frac{V_0}{V_{-1}}(1+R)-R}, \quad (2)$$

where $\psi = \frac{2\sigma_{-1}}{\sigma_0} - 1$ – is the sensitivity ratio to the asymmetry of the load cycle;

σ_0 – are the limits of endurance of the load;

V_0, V_{-1} – is the characteristic angle of the left branch fatigue curve in the semilogarithmic system according to zero and symmetrical load.

The analysis of equation possible use (1) for bringing symmetric asymmetric cycles of loading processes and drill rod to equivalency has been made.

Lines of equal damage are constructed on the Haigh diagram of the cycles with a positive mean stress (1).

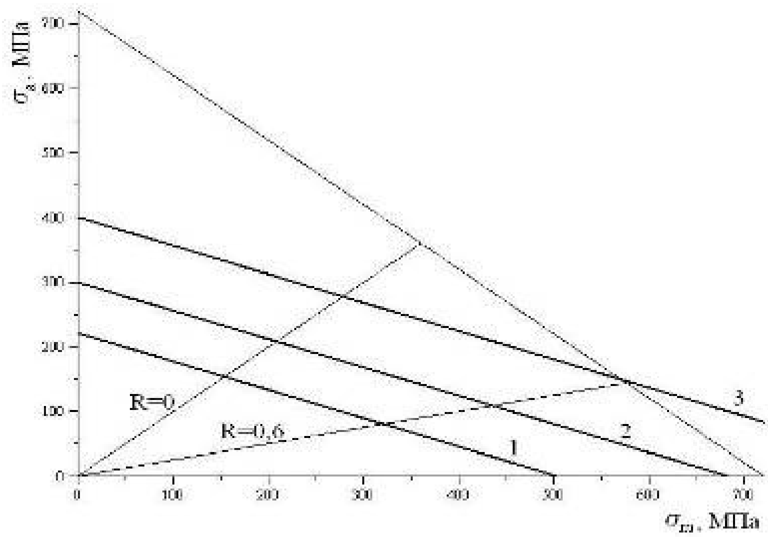

Figure 1 – The diagram with equal damage lines for samples made of drill locks material

On the graph line (Haigh diagram), which describes the cycle $R = const$, it is determined from equation (3)

$$y = \frac{1-R}{1+R}x \ , \tag{3}$$

where $R = 1$ is the x-axis, $R = -1$ coordinate axis, $R = 0$ – ray $y = x$.

Lines of equal damage are constructed in accordance with the equation (1) and data [6] for samples of steel 40XH, which is the material of drill pipe locks. Line 1 corresponds to the limit of endurance, line 2 is high fatigue and line 3 is low fatigue.

As it can be seen from Fig. 1, lines of equal distortion are in conflict with the real physical process for high asymmetric cycles with skewness 0.6 and above, which are characteristics for the load of the drill string upper part . So, lines 1, 2 may cross the x-axis in no case.

It can mean that a certain medium voltage level fatigue failure would occur for a certain number of cycles with infinitely small amplitudes that never happens in practice. Line 3 also has no physical meaning, because the outside of the diagram indicates a certain number of cycles before sample failures that are supposed to be broken down due to the stress exceeding tensile strength.

Therefore, it is necessary to adjust the corresponding equations (1) in case of asymmetrical stress cycles with high asymmetry. For this adjustment appropriate reduction equations have been developed [7].

In consequence, for aligning the asymmetric cycle asymmetry factor $-1 \le R < 0$, from the condition of invariance ψ of load levels ratio it was obtained [7] (4)

$$\sigma_{ekv} = \sigma_{max}\left(1 - \frac{(1-\psi)(1+R)}{2}\right) . \tag{4}$$

For conducing asymmetric cycles $0 \le R < 1$ the results of experimental studies of the asymmetry effect on the durability of materials and elements of aircraft structures given in [9, 1] (fig. 2) have been analyzed

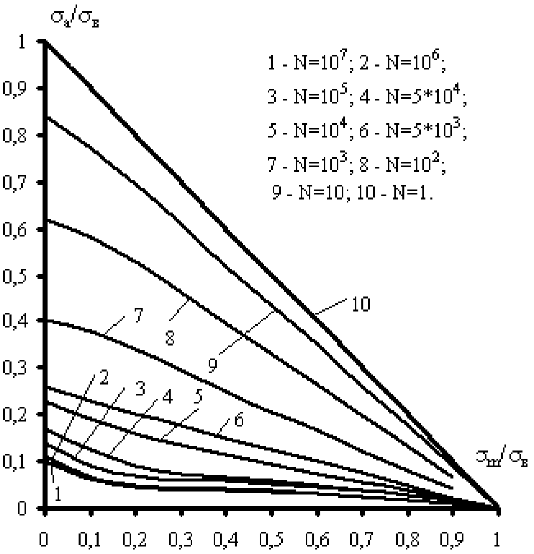

Figure 2 – Asymmetry loading impact on the durability of samples made of aluminium alloy 2024-T3 [7]

The authors have studied immense amount of information (over 1,000 experiments) which makes the results obtained extremely valuable and revealing under the conditions of inevitable statistical variance.

The results are illustrated by the Haigh diagram with no dimension coordinates

$$x = \frac{\sigma_m}{\sigma_b}\ ; \quad y = \frac{\sigma_a}{\sigma_b}\ .$$

Curves 1-10 are ones of equal damage for a certain number of stress cycles to failure of samples ranging from static destruction ($N = 1$) through low and high fatigue endurance limit ($N = 10^7$).

The inclination of line passing through the points (0, σ_{-1}) i (σ_0/2, (σ_0/2), to the x-axis represents the ratio of sensitivity to the asymmetry load ψ and is determined by the equation (5).

$$\psi = -\frac{y(R=-1) - y(R=0)}{x(R=-1) - x(R=0)}\ . \tag{5}$$

From the analysis of the data shown in Fig. 2, it can be argued that the angle of inclination of the equal damage curves within multi cyclic fatigue ψ factor is satisfactorily described only if $-1 \le R \le 0$ and, $0 < R < 1$ provided the tilt angle increases with decreasing N. Therefore, it is suggested to approximate curves of equal damage for asymmetrical tension with the average tension stretch with two straight lines. For tensions from $-1 \le R \le 0$ the coercion will be just according to (7).

Since all curves of equal damage converge at a point with coordinates (1,0) on the Haigh diagram, it can be used to bring cycles with mean stress of stretching ($0 < R < 1$).

A diagram of the suggested cast is shown in Fig.3.

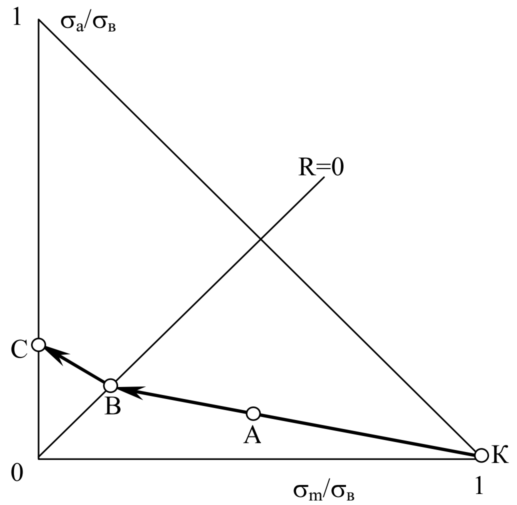

Figure 3 –The scheme of reduction to a symmetric cycle voltage with the average voltage stretch [7]

For example, let us consider the reduction to the symmetric loading cycle shown in figure 3 by point A (σ_m/σ_b, σ_a/σ_b). Through point A to the intersection with the straight line $R = 0$ (point B) we shall draw a ray, which is obtained from point K with coordinates (1,0). It was introduced a new coefficient specifying the influence of cycle asymmetry ψ_1. By analogy with (5) it is taken as (6)

$$\psi = -\frac{y(A) - y(K)}{x(A) - x(K)} = -\frac{y(B) - y(K)}{x(B) - x(K)} . \quad (6)$$

Considering the coordinates of points *A* and *K*, it is obtained (7).

$$\psi_1 = -\frac{\sigma_a}{\sigma_b - \sigma_m} , \quad (7)$$

$$y(B) = \psi_1 (1 - x(B)) . \quad (8)$$

Since $y(B) = x(B) = \sigma_{max}(B)/2\sigma_b$, from equality (8) it is obtained (9)

$$\sigma_{max}(B) = 2\sigma_b \frac{\psi_1}{1 + \psi_1} . \quad (9)$$

Given that *R(B)* = 0, further, the cast is performed according to (4). Obtained dependence is [7]

$$\sigma_{eq} = \sigma_b \psi_1 \frac{1 + \psi}{1 + \psi_1} . \quad (10)$$

Proposed rate ψ_1 is determined by the equation [7]

$$\psi_1 = \frac{\sigma_{max}(1 - R)}{2\sigma_b - \sigma_{max}(1 + R)} . \quad (11)$$

To justify the strength design of drill columns, the implementation analysis of the drill string operational load has been made using the Haigh diagram. Schematization of the loading processes has been carried out by the developed technique [4].

For instance, in (Figure 4) a general layout of the Haigh diagram with the imposed process of rod string columns loading is given.

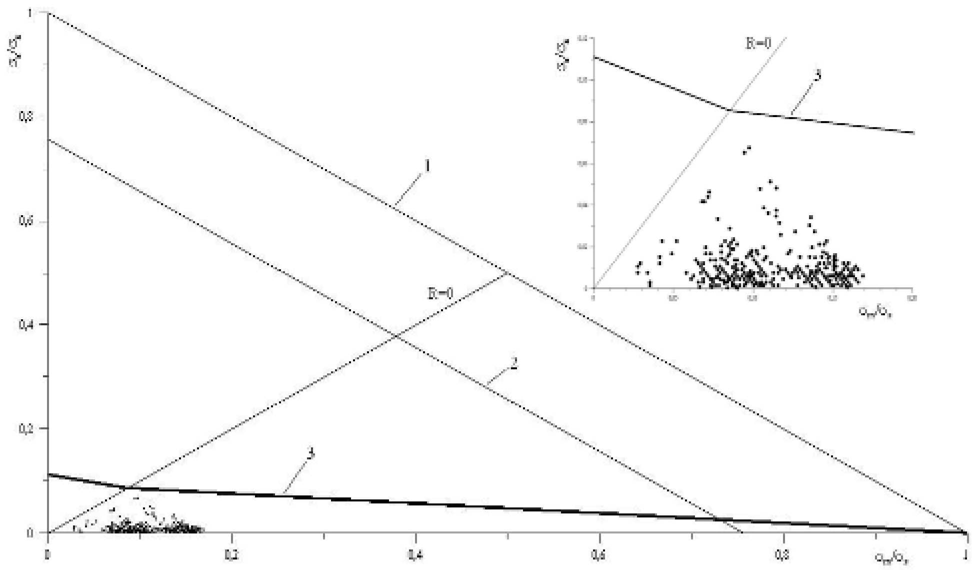

Figure 4 – A general layout of the Haigh diagram for the imposition of the process string rods columns loading

1 – static destruction $\sigma_{max} = \sigma_b$; 2 – line of border fluidity $\sigma_{max} = \sigma_m$;
3 – boundary line of endurance

In (Figure 5) treat processes over the drill string loading during lowering and for stitching during lifting are demonstrated.

It should be noted that in the case of stitches, the characteristic feature of all processes is the absence of cycles with stress amplitude above the corresponding border of endurance.

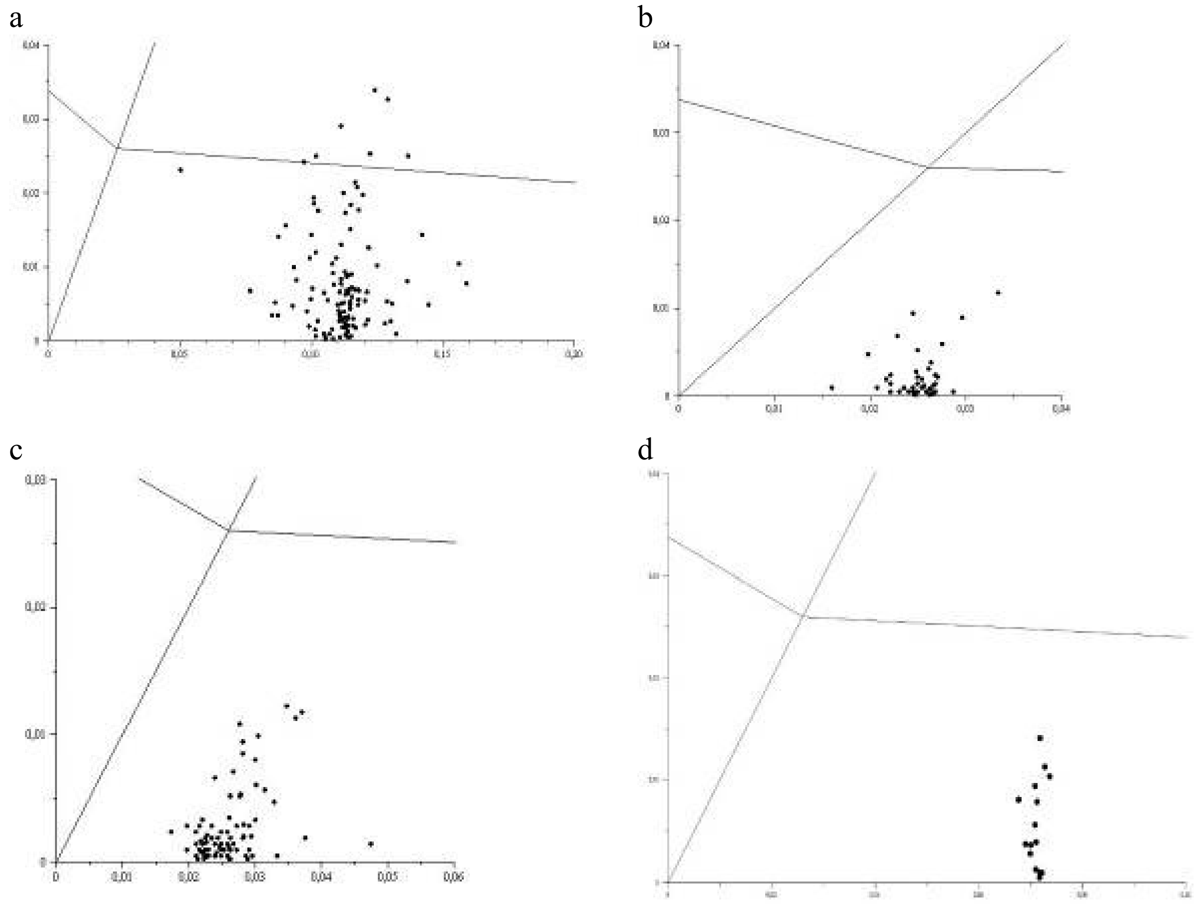

Figure 5 – The Haigh diagram with the process load of the drill string during lowering of the lifting operations

a – seams along the column length 500 m;
b – descent of the column length 190 m;
c – descent of the drill string length 500 m;
d – descent of the column length 1970 m

Generic problem unsolved parts selection. Thus, loading processes analysis occured under the operation of the drill string elements, shows that in the range of voltages the highest place is taken by low-amplitude voltage settings σ_{max}, R, which do not exceed the appropriate grants endurance σ_R. In this case, it is necessary to consider the inevitable reduction of the fatigue limit in the process of damage accumulation [8, 11, 12], caused by the action of the low amplitude voltages. So bringing σ_{max} to σ_{ekv} should extend to the stress cycles, which are smaller for the border of endurance. This again points to the particular importance of developing refined methods of bringing low-amplitude load cycles to assess drill string durability.

The use of equation (1) to bring $\sigma_{max} < \sigma_R$ has a significant limitation, namely, under the condition $\sigma_{max} < \sigma_R - \sigma_{-1}$ voltage σekv becomes less than 0. In this case, it is recommended not to consider this voltage as it is not producing any damaging effects [5]. But the neglect of low voltages under normal conditions (low amplitude loading) elements of the drill string is sure to have significant influence on their corrosion-fatigue life. It should be noted that the rejection of low voltage will lead to overestimation of the design life. It is also dangerous considering secure columns. The equations derived (4,11) also do not consider drill string loading elements specific.

The article goals. Therefore, the aim of this work is to develop the cast equations for asymmetric stress cycles drill string to the symmetric cycle with the features of their load.

Main material and results. For the development of such a refined method, it has been guided by the laws of low amplitude corrosion fatigue, characteristics and damage in Haigh diagram.

So, the decrease in the level of loading below the endurance limit reduces the sensitivity to unbalance loads. Damage accumulation is mainly due to dislocation mechanism, where the main factor is the amplitude. The effect of baushinger, which, presumably leads to a change in factor sensitivity of the load cycle asymmetry for the transition to exclusively tensile load on these stages is not completely working. But the accumulation of corrosion - fatigue fracture is not accompanied by decrease of kinetic endurance limit, which leads to the intensification of the process and the gradual increase of sensitivity to cycle asymmetry to typical cyclic fatigue level. Thus, for stress cycles below the fatigue limit, it is possible to make a model of the linear reduction factor in the sensitivity depending on the load level. The correctness of this model is confirmed by the fact that at low stress amplitude the damage line in Haigh diagram needs to be reborn in the x-axis.

As it is known, the drill string is quite often subjected to the actions of asymmetrical stress cycles with high amplitudes, even to the level of yield stress, for example during the elimination of sticking [13]. Even a small amount of stress is necessary to be considered for the calculation of longevity. For such stress cycles, on the contrary to low amplitude loading, there is an increased sensitivity to asymmetry. The level of damage is primarily controlled by the maximum stress of the cycle. Fig. 2 shows that the coefficient of sensivity of the asymmetry to a high level of load increases to unity for a single fracture.

So, according to the damaging effects of asymmetrical load on the drill and rod columns, three areas should be distinguished: low amplitude, high amplitude and the area of conventional multi cyclic corrosion fatigue. For normal stress cycles, for example, in fig. 5a it is located above the border line. The use of equation (4) for cycles $a - 1 < R \le 0$ and (10) for $R > 0$ is recommened.

The corresponding equations for the other two regions are to be derived.

Assuming that low amplitude asymmetric cycle with a coefficient of skewness is to be reduced to the equivalent symmetric cycle $R \ge 0$ (point A in Fig.6).

In Fig. FED – is the line of endurance boundaries. Zero cycle equation (9) is used. Further enforcement conduct is a subject to linear reduction of the sensitivity coefficient to cycle asymmetry ψ_B depending on the load level

$$\psi_B = \psi \frac{OB}{OE} = \psi \frac{\sigma_{max}(B)}{\sigma_0} = \psi(1+\psi)\frac{\sigma_b}{\sigma_{-1}} \cdot \frac{\psi_1}{1+\psi_1} \quad . \tag{12}$$

Considering geometrical maintenance of coefficient sensitiveness to asymmetry of cycle in Haigh diagram according to (9), the equalization is obtained (13)

$$\psi_B = -\frac{y(C)-y(B)}{x(C)-x(B)} = \frac{\sigma_{ekv} - 0{,}5\sigma_{max}(B)}{0{,}5\sigma_{max}(B)} \quad . \tag{13}$$

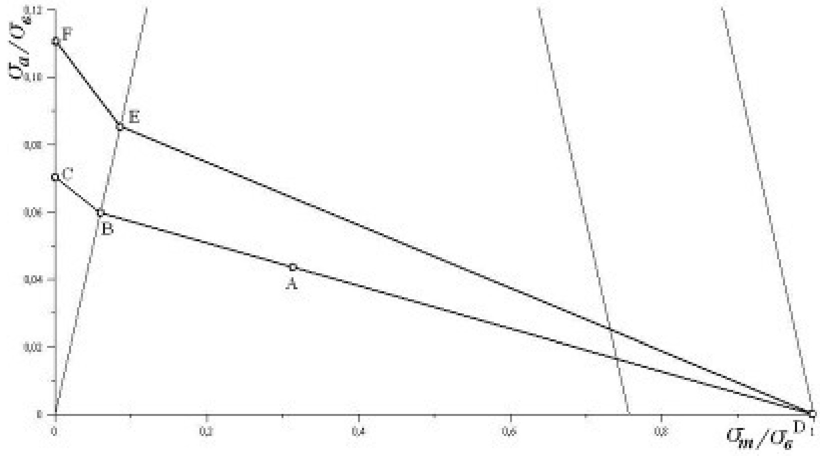

Figure 6 – A chart of bringing the amplitude asymmetric cycle with a coefficient of skewness $R \geq 0$

Thus it yields the final equation

$$\sigma_{ekv} = \sigma_b \psi_1 \frac{1+\psi_B}{1+\psi_1} \ . \tag{14}$$

where ψ_1 is determined by (10), and ψ_B from (12).

Given low amplitude asymmetric cycle with a coefficient of skewness $-1 < R < 0$ (the point A in Fig.7) is reduced to the equivalent symmetric cycle.

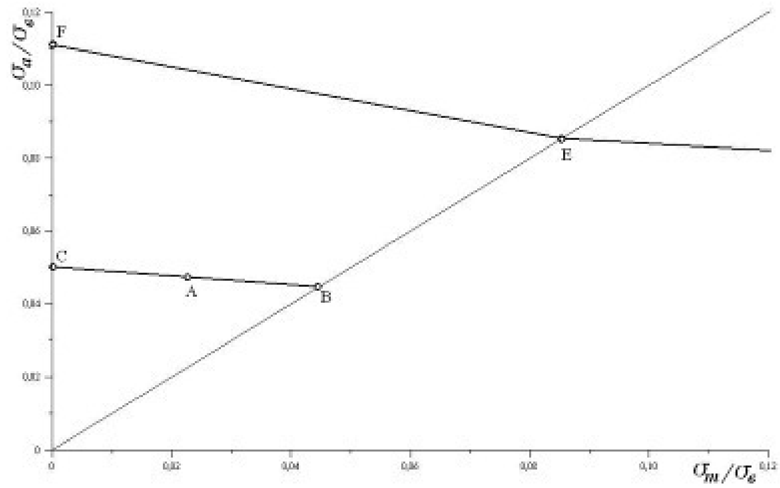

Figure 7 – Scheme of bringing the small-amplitude asymmetric cycle with a coefficient of skewness *-1 < R < 0*

In this case

$$\psi_B = -\frac{y(A)-y(B)}{x(A)-x(B)} = \psi \frac{x(B)}{x(E)} .$$

If $\psi = \psi\ x(B)/x(E) = k \cdot x(B)$ and $x(B) = y(B)$, the resulting quadratic equation with unknown $x(B)$. The solution has the form

$$x(B) = -\frac{k \cdot x(A) - 1 \pm \sqrt{[1 - k \cdot x(A)]^2 - 4k \cdot y(A)}}{2k} .$$

The analysis shows that the physical sense has the solution with the sign « + ».

Given (13), it is finally obtained

$$\sigma_{ekv} = k \cdot x(B) \cdot (1 + x(B)), \qquad (15)$$

where $x(B) = -\dfrac{k \cdot x(A) - 1 + \sqrt{[1 - k \cdot x(A)]^2 - 4k \cdot y(A)}}{2k}$;

$k = \psi \dfrac{1+\psi}{\sigma_{-1}}$;

$x(A) = \sigma_{max} \dfrac{1+R}{2}$;

$y(A) = \sigma_{max} \dfrac{1-R}{2}$.

In the case of high-amplitude load $\sigma_{max} \geq \sigma_m$ it is got the same equation cast with just a little difference in definition ψ_B. From the condition of sensitivity coefficient linear increase to load level cycle asymmetry of, the following equation is

$$\psi_B = \psi + \frac{\sigma_{max}(B) - \sigma_m}{\sigma_b - \sigma_m}(1 - \psi). \qquad (16)$$

To justify the proposed method of asymmetric construction of the curves -1 < R < 1 the object of study was 40XH steel, which is used as the material of the tool joints of drill pipes.

The results of the study by V. Ivasi for samples of steel 40XH yielded such parameters of fatigue curves [14]:

σ_{-1} = 408 MPa; V_{-1} = 29,82 MPa;

σ_0 = 662 MPa; V_0 = 54,91 MPa;

$N_0 = 2 \cdot 10^6$ cycle; ψ = 0,22·

Fig. 8 shows the curves based on experimental studies as well as the curves constructed according to equations (4) and (10).

As it can be seen, the results correlate quite strongly. It demonstrates the effectiveness of the developed method of bringing asymmetrical stress cycles to equivalent destructive actions and the fatigue curves parameters determination under asymmetric loads.

To assess the reliability of the suggested casting method and other critical structural elements operating under conditions of corrosion fatigue, the results have been analyzed on samples of steel 17G1S. The parameters of fatigue curves are:

σ_{-1} = 141,9 MPa; V_{-1} = 30,87 MPa;

σ_0 = 247,1 MPa; V_0 = 51,83 MPa;

$N_0 = 5{,}207 \cdot 10^5$ cycle; ψ = 0,209·.

Fig. 9 shows curves 1 and 2, constructed in accordance with the specified parameters according to the equation [12]

$$N = N_0 \cdot ln\left\{1 + \left[exp(\frac{\sigma_{max} - \sigma_R}{V_R}) - 1\right]^{-1}\right\},$$

as well as the curves 3 and 4, obtained by casting using Oding equation $\sigma_{np} = \sqrt{\sigma_{max} \cdot \sigma_a}$ [9] and equation (4), respectively.

Special software has been developed for such 'reversed' curves.

The suggested method is almost fully consistent with the results of the experiment in contrast to the widely applied method using the Oding equation.

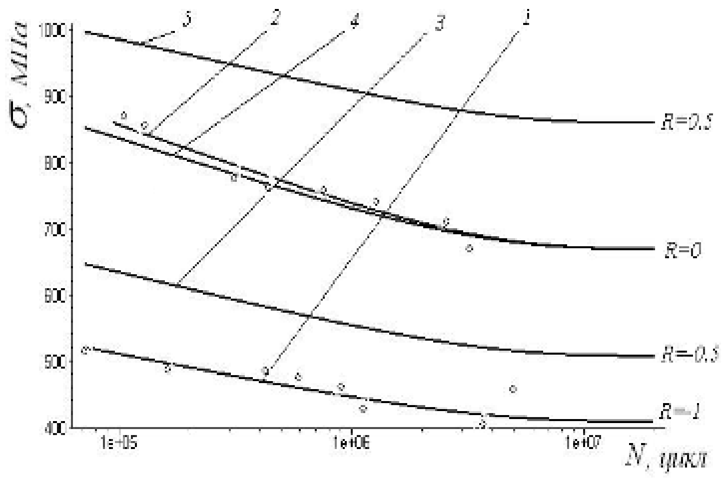

Figure 8 – Curves for the samples on steel 40XH:
1 – is experimental for symmetrical loading; 2 – is experimental with a pulsating load;
3 - is given by equation (4) (R=0); 4 – is given by equation (4) (R=-0,5);
5 – is given by equation (10) (R=0,5)

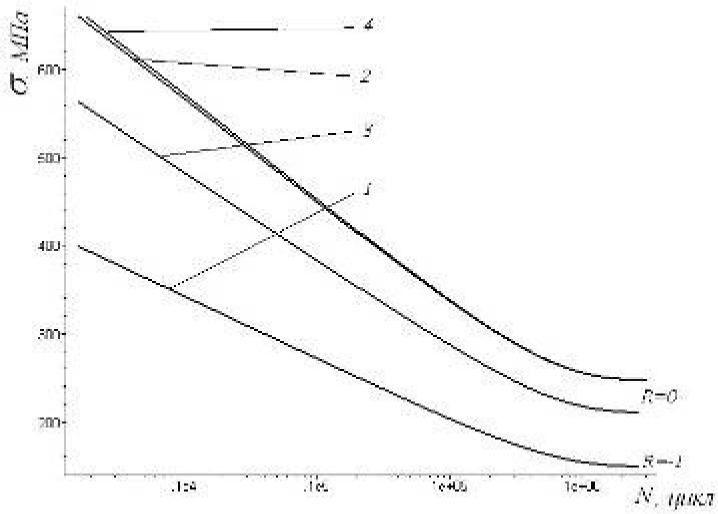

Figure 9 – Curves for samples of steel 17G1S [7, 15]:
1 – experimental for symmetrical loading; 2 – experimental with pulsating loads ;
3 – given in accordance with the Oding equation; 4 is given by equation (4)

Conclusions. Using the developed equations and software it can be built curves with symmetric loading and the coefficient of sensitivity to determine the parameters exactly. It is only necessary to consider the parameters of fatigue curves under symmetrical loads.

It greatly decreases the number of costly and time-consuming experimental studies that are required to assess the durability of the drill stem elements, operating in conditions of asymmetrical loading with mean stress of stretching. In the process of analyzing the load of the drill string at the stage of its reduction to an equivalent symmetric process there should be asymmetrical voltage range of the load.

The following research will focus on identifying features of the load during lowering-lifting operations in deep drilling using computer modeling and experimental studies of the durability of natural samples at high asymmetrical loads.

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