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

Introduction

As is known, the process of loading a large number of structures and machinery parts is characterized by a large scatter of asymmetrical stress cycles along its length and in time. In full measure it concerns the elements of the drill string, particularly when drilling deep holes. Therefore, the vast majority of experiments on the determination of the parameters of fatigue resistance is carried out at a symmetric cycle of stresses as a necessary step to calculate the strength of elements of columns, to bring asymmetrical cycles to the equivalent symmetrical.

The analysis of the sources of research and publications

It is known that the vast majority of machine parts and subassemblies in the process of operation is subjected to random loading [1, 2, 3]. In this case, the durability in the schematization process [4] recommended stresses with different ratio of the asymmetry R to the symmetric cycle. Such a cast greatly simplifies further calculations. For conducting single-ended voltages $\sigma_{\max}$ with $-1 \le R < 1$ for the symmetric cycle to σ_{ekv} with the recommended equation [5]:

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

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

where:

σ_{-1} – the endurance limit at symmetric loading,

a, b – odds cast,

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

σ_0 – the limits of endurance of the load,

V_0, V_{-1} – the characteristic angle of the left branch of the fatigue curve in the floor logarithmic coordinate system, respectively, from zero and symmetrical load.

The analysis of possibility of use of equation (1) to bring to equivalency symmetric asymmetric cycles of cycles of loading processes and drill rod.

Lines of equal damage are built on the Hey chart of the cycles with a positive mean stress (1).

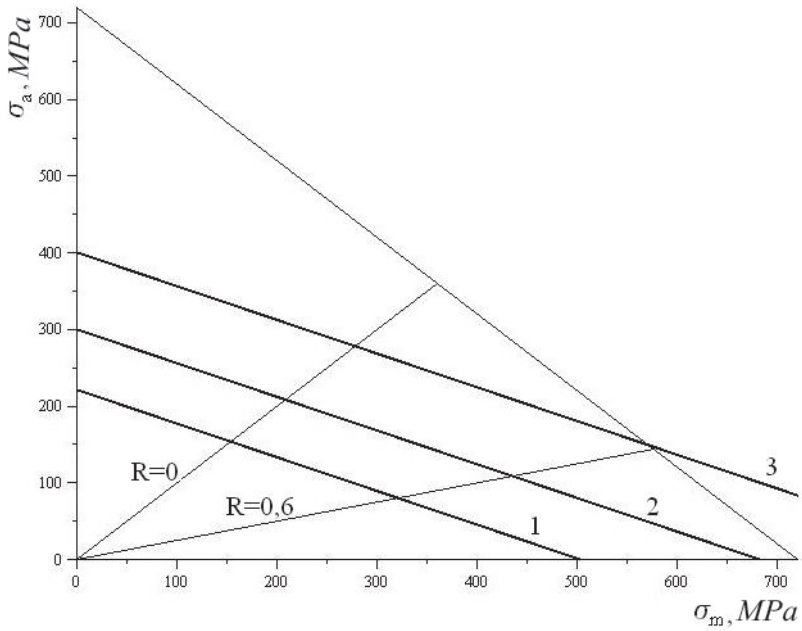

***FIGURE 1**. A diagram with lines of equal damage for samples made of material of drill locks*

On the graph line (Hey chart), which describes the cycle R = const, is determined from equation:

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

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

Lines of equal damage are built in accordance with the equation from (1) to (6) for samples of steel 40CrNi, which is the material of drill pipe locks. Line 1 corresponds to the limit of endurance, 2 – high fatigue, 3 – low fatigue.

As you can see from figure 1, for high asymmetric cycles with skewness of 0.6 and above, which are characteristic for the load of the upper part of the drill string, lines of equal distortion are in conflict with the real physical picture of the process. So in no way lines 1, 2 may cross the x-axis. This would mean that a certain medium voltage level fatigue failure will 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 chart indicates a certain number of cycles to failure for samples that are supposed to break down due to stress exceeding tensile strength.

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

Therefore, to align the asymmetric cycle asymmetry factor $-1 \le R < 0$, from the condition of invariance ψ of the ratio of the load levels we obtained [7]:

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

To bring asymmetric cycles $0 \le R < 1$ we analyzed the results of experimental studies of the effect of asymmetry on the durability of materials and elements of aircraft structures is given in figure 2 [9, 1].

The authors treated a very large amount of information (over 1000 experiments) that in the conditions of inevitable statistical variance make the results obtained extremely valuable and revealing.

The results are illustrated in the Hey diagram with no dimension coordinates $x = \frac{\sigma_m}{\sigma_B}$, $y = \frac{\sigma_a}{\sigma_B}$.

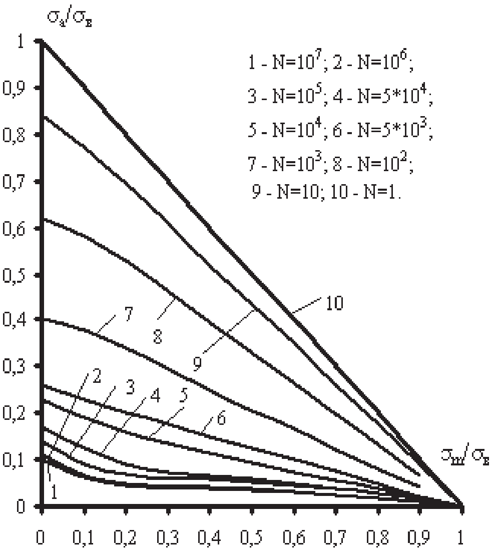

FIGURE 2. *Asymmetry loading impact on the durability of samples made of aluminium alloy 2024-T3 [7]*

Curves 1-10 are curves 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 slope of the straight line passing through the points (0, σ_{-1}) i ($\sigma_0/2, \sigma_0/2$), to the x-axis represents the ratio of sensitivity to the asymmetry load ψ, is determined by the equation:

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

From the analysis shown in figure 2 data, it can be argued that the angle of inclination of the curves of equal damage in the area of 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. It is therefore proposed that curves of equal damage for asymmetrical tension with the average tension stretch to approximate the 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 Hey chart, it can be used to bring cycles with mean stress of stretching ($0 < R < 1$).

A diagram of the proposed cast is shown in figure 3.

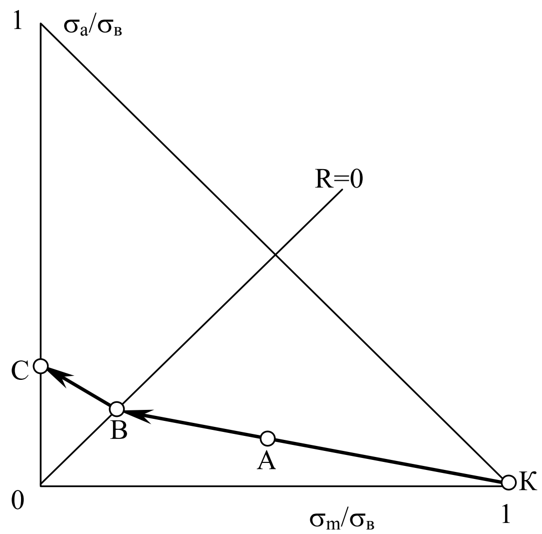

FIGURE 3. *The scheme of reduction to a symmetric cycle voltage with the average voltage stretch [7]*

For example, consider the reduction to the symmetric loading cycle shown in figure 3 by the point A $\left(\frac{\sigma_m}{\sigma_B}, \frac{\sigma_a}{\sigma_B}\right)$. Through the point A to the intersection with the straight line R = 0 (point B) draw a ray, which is obtained from the point K with coordinates (1,0). We introduce a new coefficient specifying the influence of cycle asymmetry ψ_1. By analogy with (5) we will have (6):

$$\psi_1 = -\frac{y(A)-y(K)}{x(A)-x(K)} = -\frac{y(B)-y(K)}{x(B)-x(K)} \tag{6}$$

Given the coordinates of points A and K, we obtain:

$$\psi_1 = \frac{\sigma_a}{\sigma_B - \sigma_m} \tag{7}$$

$$y(B) = \psi_1(1 - x(B)) \tag{8}$$

Since then $y(B) = x(B) = \frac{\sigma_{\max}(B)}{2\sigma_B}$, from equality (8) we obtain:

$$\sigma_{\max}(B) = 2\sigma_B \frac{\psi_1}{1+\psi_1} \tag{9}$$

Given that $R(B)$ = 0, further, the cast perform according to (4). The obtained dependence [7]:

$$\sigma_{eq} = \sigma_B \psi_1 \frac{1+\psi}{1+\psi_1} \tag{10}$$

The proposed rate ψ_1 is determined by the equation [7]:

$$\psi_1 = \frac{\sigma_{\max}(1-R)}{2\sigma_B - \sigma_{\max}(1+R)} \tag{11}$$

The proposed rate ψ_1 is determined by the equation [7].

To justify the strength design of drill columns the analysis of the implementation of the operational load of the drill string was made using the Hey chart. Schematization of the loading processes was carried out by the developed technique [4].

Though, on figure 4a general view over Hay diagram is brought with the imposed process of loading the columns of rod string.

On a figure 5 treat processes over of loading the boring column are brought during lowering and for stitching during raising.

It should be noted that except 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.

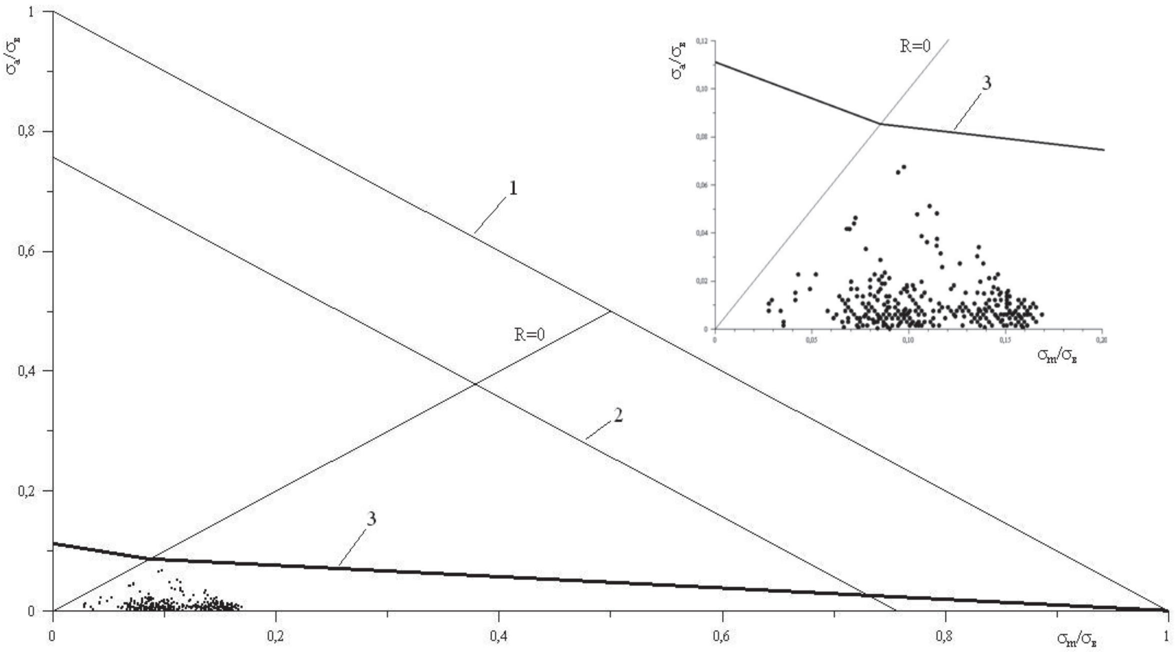

FIGURE 4. *A general view of the Heya chart for the imposition of the process of loading the columns of string rods: 1 – static destruction $\sigma_{max} = \sigma_B$, 2 – line of border fluidity $\sigma_{max} = \sigma_m$, 3 – boundary line of endurance*

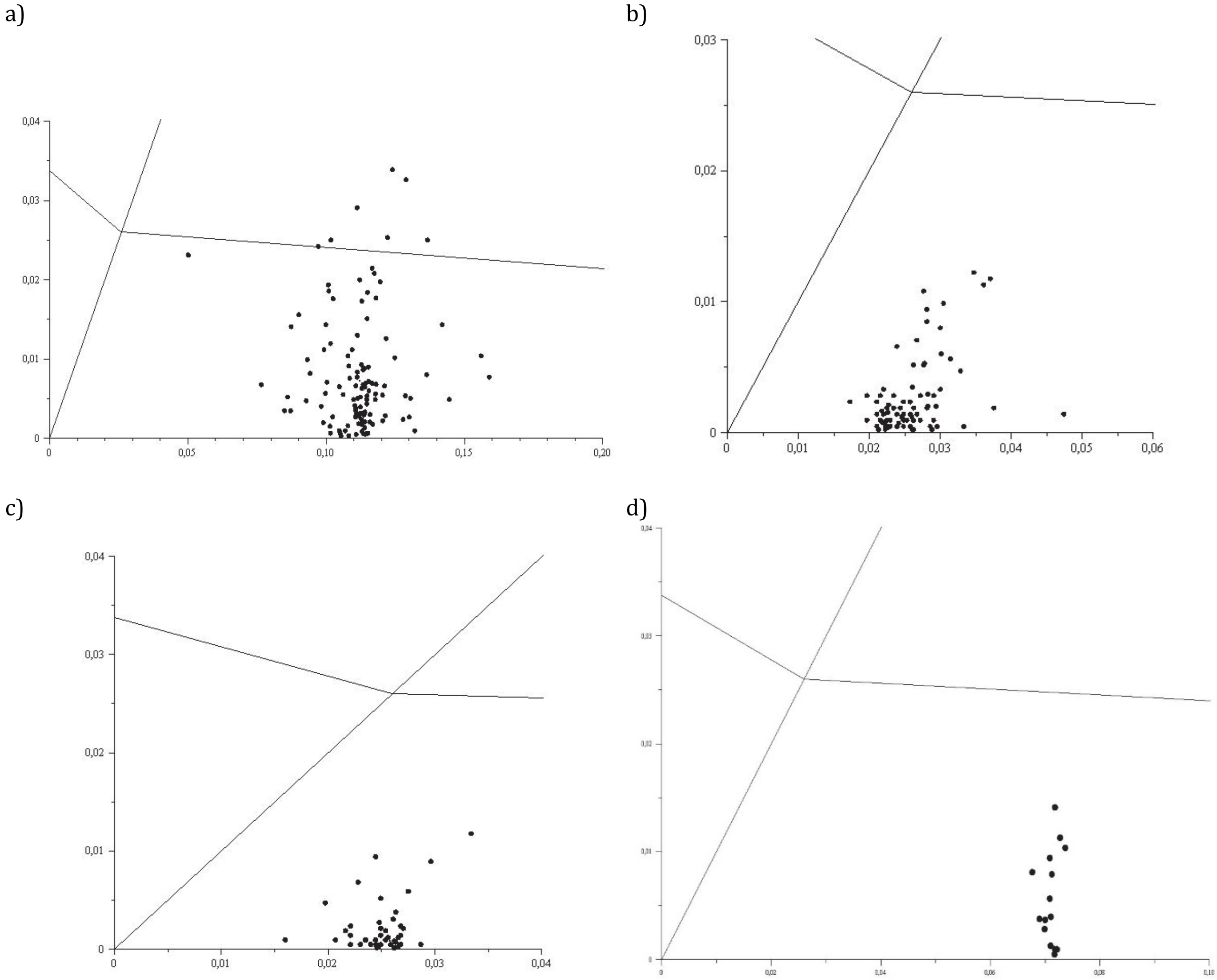

FIGURE 5. *Hay chart with the process load of the drill string during lowering of the lifting operations: a) seams along the column length 500 m, b) descent of the length of the column 190 m, c) descent of the length of the drill string 500 meters, d) descent over the length of the column 1970*

Selection of the unsolved parts of generic problem

Thus, the analysis of processes of loading, which arise under the operation of the elements of the drill string, shows that in the range of voltages the highest place is occupied by low-amplitude voltage settings $\sigma_{\max}, R$, which do not exceed the appropriate grants endurance σ_R. In this case, it is necessary to take into account the inevitable reduction of the fatigue limit in the process of accumulation of damage [8, 11, 12], caused by the action of the low amplitude voltages. So bringing $\sigma_{\max}$ 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 the durability of the drill string.

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 σ_{ekv} becomes less than 0. In this case, it is recommended not to drop the voltage from consideration as not making the damaging effects [5]. But the neglect of low voltages under normal conditions (low amplitude loading) elements of the drill string will exert a significant influence on their corrosion-fatigue life. It should be noted that the rejection of low voltage will lead to an overestimation of the design life. It is dangerous to view secure columns. We also derived equations (4, 11) that did not fully take into account the specifics of loading elements of the drill string.

The article goals

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

Main material and results

For the development of the refined method, we adhered to the laws of low amplitude corrosion fatigue, characteristics and damage on the chart Hay.

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 asymmetry of the load cycle 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 a decrease of kinetic endurance limit, which leads to the intensification of the process and the gradual increase of sensitivity to cycle asymmetry to a level typical of a lot of cyclic fatigue. 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 on the graph Haye needs to be reborn in the *x*-axis.

As is known, the drill string is quite often subject 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 take into account for the calculation of longevity. For such stress cycles on the contrary, on the contrast to low amplitude loading, there is increased sensitivity to asymmetry. The level of damage is primarily controlled by the maximum stress of the cycle. Figure 2 shows that the coefficient of sensivity of the asymmetry to a high level of load increases to unity for asingle fracture.

So, according to the damaging effects of asymmetrical load on the drill and rod columns one should distinguish three regions: low amplitude, high amplitude and the area of conventional multi cyclic corrosion fatigue. For normal stress cycles, for example, figure 5a located above the border line we recommend the use of equation (4) for cycles a $-1 < R \leq 0$ and (10) for $R > 0$.

Derive the corresponding equations for the other two regions.

Assume low amplitude asymmetric cycle with a coefficient of skewness for the equivalent symmetric cycle $R \geq 0$ (point *A* in figure 6).

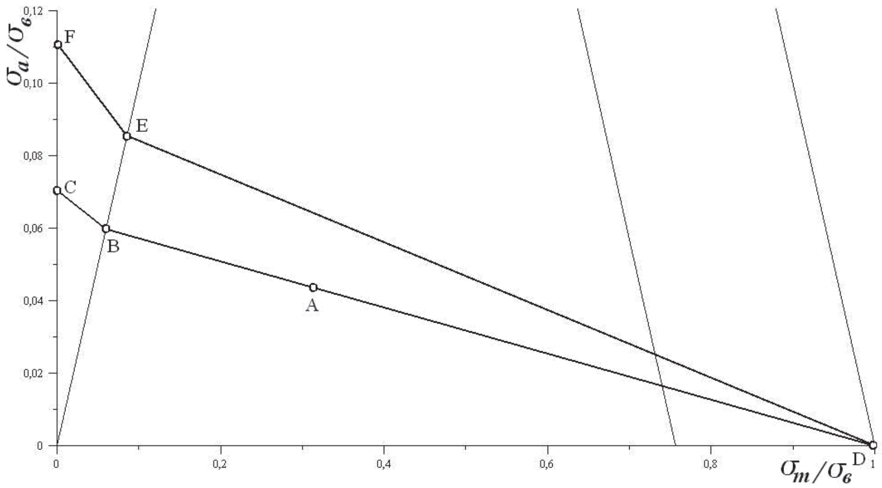

***FIGURE 6.** A chart of bringing the amplitude asymmetric cycle with a coefficient of skewness R ≥ 0*

In figure 6 FED – line the boundaries of endurance. To bring from a zero cycle using equation (9). Further enforcement conduct subject to a linear reduction of the coefficient of sensitivity to cycle asymmetry ψ_B depending on the load level.

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

Taking into account geometrical maintenance of coefficient sensitiveness to asymmetry of cycle on Hay diagram according to (9), will get equalization:

$$\psi_B = -\frac{y(C)-y(B)}{x(C)-x(B)} = \frac{\sigma_{ekv} - 0.5\sigma_{\max}(B)}{0.5\sigma_{\max}(B)} \tag{13}$$

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).

Give low amplitude asymmetric cycle with a coefficient of skewness -1 < *R* < 0 (the point *A* in figure 7) to the equivalent symmetric cycle.

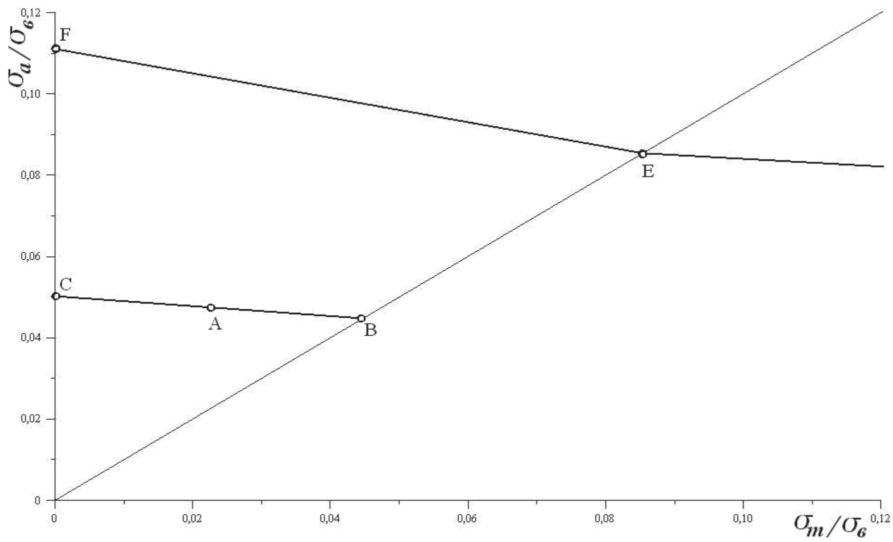

***FIGURE 7.** Scheme of bringing the small-amplitude asymmetric cycle with a coefficient of skewness -1 < R < 0*

In this case

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

Take that $\psi \frac{x(B)}{x(E)} = k \cdot x(B)$. Given that $x(B) = y(B)$, the resulting quadratic equation with unknown $x(B)$. The solution has the form

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

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

Given (13), we obtain finally

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

where:

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

$$k = \psi \frac{1 + \psi}{\sigma_{-1}}$$

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

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

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

$$\psi_B = \psi + \frac{\sigma_{\max}(B) - \sigma_m}{\sigma_B - \sigma_m}(1 - \psi) \tag{16}$$

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. Ivasiv for samples of steel 40CrNi yielded such parameters of fatigue curves [14]:

$$\sigma_{-1} = 408 \text{ MPa}, \quad V_{-1} = 29.82 \text{ MPa}, \quad \sigma_0 = 662 \text{ MPa}, \quad V_0 = 54.91 \text{ MPa}, \quad N_0 = 2 \cdot 10^6 \text{ cycles}, \quad \psi = 0.22$$

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

As you can see, the results are quite strongly correlated. This demonstrates the effectiveness of the developed method of bringing asymmetrical stress cycles to equivalent destructive actions and to determine the parameters of fatigue curves under asymmetric loads.

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

$$\sigma_{-1} = 141.9 \text{ MPa}, \quad V_{-1} = 30.87 \text{ MPa}, \quad \sigma_0 = 247.1 \text{ MPa}, \quad V_0 = 51.83 \text{ MPa}, \quad N_0 = 5.207 \cdot 10^5, \quad \psi = 0.209$$

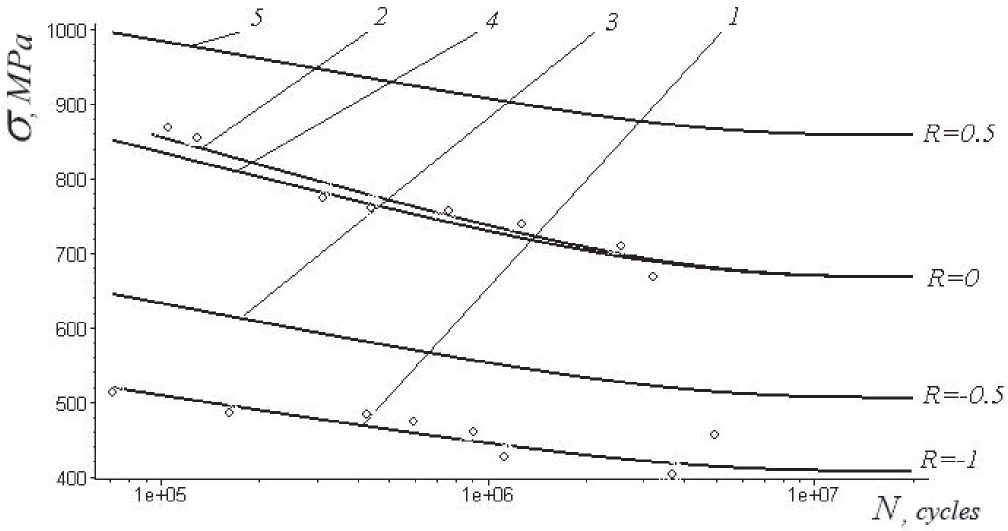

FIGURE 8. Curves for the samples on steel 40CrNi: 1 – experimental for symmetrical loading, 2 – experimental with a pulsating load, 3 – is given by equation (4) (R = 0), 4 – is given by equation (4) (R = -0.5), 5 – is given by equation (10) (R = 0.5)

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

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

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.

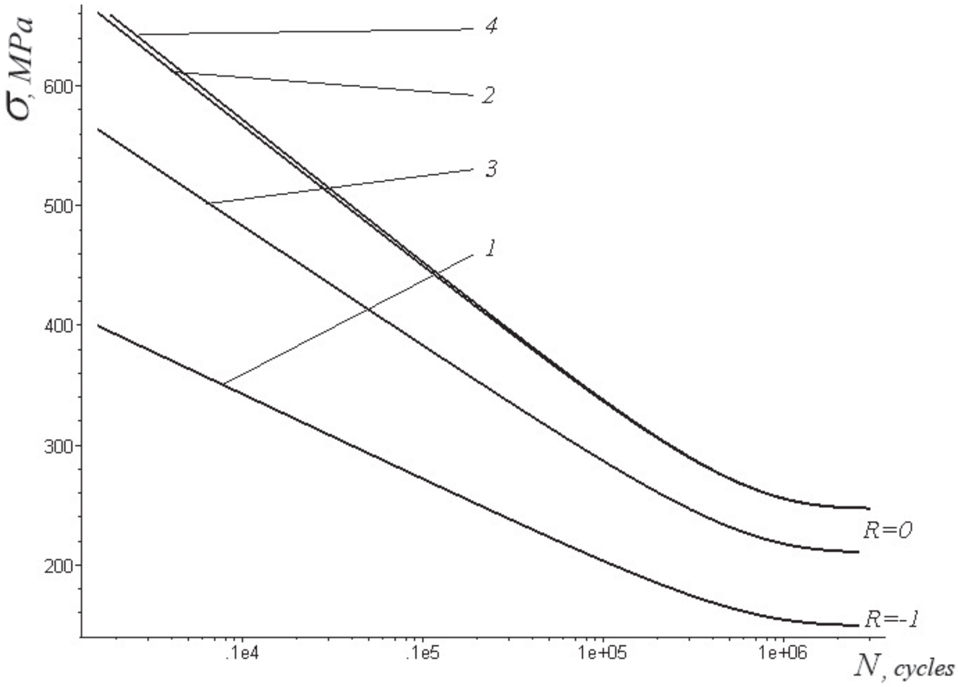

FIGURE 9. Curves for samples of steel 17G1S [7, 15]: 1 – experimental for symmetrical loading, 2 – experimental with pulsating loads, 3 – given in accordance with the Oding equation, 4 – is given by equation (4)

Special software was developed for such 'reversed' curves.

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

Conclusions

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

This greatly increases the number of costly and time-consuming experimental studies that are needed to assess the durability of the drill stem elements, which work 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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