*Розроблено спосіб визначення коефіцієнта згасання коливань колони насосних штанг на основі отриманих у ході досліджень штангових свердловинних установок динамограм. Обґрунтовано основні принципи реалізації способу. На гирлових та глибинних динамограмах виділено ділянки періодичної зміни навантаження та проведено їх апроксимацію. Встановлено вплив зміни амплітуди та періоду коливань навантаження у часі на коефіцієнт згасання по всій довжині колони насосних штанг*

*Ключові слова: колона насосних штанг, динамограма, коефіцієнт згасання, навантаження, коливання, осцилограма, апроксимація*

*Разработан способ определения коэффициента затухания колебаний колонны насосных штанг на основе полученных в ходе исследований штанговых скважинных установок динамограмм. Обоснованы основные принципы реализации способа. На устьевых и глубинных динамограммах выделены участки периодического изменения нагрузки и проведена их аппроксимация. Установлено влияние изменения амплитуды и периода колебаний нагрузки во времени на коэффициент затухания по всей длине колонны насосных штанг.*

*Ключевые слова: колонна насосных штанг, динамограмма, коэффициент затухания, нагрузка, колебания, осциллограмма, аппроксимация*

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# AN EXPERIMENTAL AND THEORETICAL METHOD OF CALCULATING THE DAMPING RATIO OF THE SUCKER ROD COLUMN OSCILLATION

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## 1. Introduction

In the process of oil pumping with a downhole sucker rod pump (DSRP) unit, a sucker rod (SR) column is affected by a system of static and dynamic forces [1]. The static forces include the weights of rods, the pump plunger, and the reservoir fluid column above the plunger. The dynamic forces result from uneven oscillations of a rod column and the fluid. Furthermore, the SR column is affected by the forces of a mechanical friction between the rods and the pump compressor pipes (PCPs), a mechanical friction between the plunger and the cylinder, a viscous hydrodynamic friction between the SR column and the fluid, as well as hydrodynamic resistance to the liquid flowing in the pump valves. Currently, the main way to control the loading and the state of the DSRP is to measure its dynamics. A dynamogram analysis reveals probable malfunctions, deviations from the optimum pumping mode, and accurately determines the load and the nature of the SR column oscillation. The oscillation processes require further studying: they substantially affect the SR column durability, so further research in this direction is important.

## 2. Analysis of the previous studies and statement of the problem

Some studies [2, 3] devoted to the load in the SR column and some parameters of its oscillation used estuarine and abyssal measurements. Numerous experimental studies have proved that outside the area of static and dynamic stability of the SR column its constant oscillations occur with a frequency of the external load. There has been further research in this direction [4]. A team of authors [5] performed similar work on assembling a combined column of fiberglass and steel rods. One more study [6] focuses on the parameters of a nonstationary oscillation of the SR column and uses a mathematical model. Studies [7] and [8] are focused on the law of motion of the SR column in a directed well and a numerical modelling of its operation in a roughly vertical well, respectively. Dynamic loads for one-stage and two-stage SR columns were assessed in [9]. The research findings show that with the average resonance the friction force that is proportional to the velocity leads to restriction in the oscillation amplitude, and the parameter resonance can develop in the presence of friction.

The DSRP dynamogram is a graphic model that reflects the real-time mode for the loading of the upper part of the SR column within a single operation cycle. The dynamic characteristics in the real-time mode allows assessing the resistability of the mechanic system "SR column – fluid – PCP column" to external loads, carries information about the structure of the system – its non-linearity and the mechanism of the oscillation energy dissipation (damping) – and provides an estimate of its stability and capacity for self-excitation of oscillations [10].

An important feature of the dynamic behaviour of the SR column is its ability to absorb irreversibly some oscillation energy. The damping properties of the SR column, such as mechanical oscillation of the system, are caused mainly by three groups of dissipative forces: the forces of internal friction in the material of rods, the SR column friction against the inner walls of the PSP column in a viscous medium (resistance of the environment), and friction in the seals and threaded joints (structural damping).

In the case of external friction, dissipative forces in the system "SR column – fluid – PCP column" can be considered viscous and adopted as proportionate to the velocity of the SR column relative motion in a relatively fixed PCP column [10 and 11]:

$$F_{оп} = -\mu V = -\mu \dot{x}, \tag{1}$$

where $\mu$ is a coefficient of viscous resistance (friction), $V = \dot{x}$ is a PCP-relative velocity of the SR motion, the sign "–" in formula (1) indicates that the resistance force is directed opposite the velocity of relative motion.

Therefore, the range of forces affecting the SR column has components of mechanical and hydrodynamic origin. However, it is noteworthy that the "SR column – fluid – PCP column" is a resilient system whose oscillation intensity grows when the pump is lowered deeper and the balancer oscillations are more frequent. The suggested system shows a ratio of amplitudes of the disturbing and decaying components of oscillations as a constant value, independent of time [12]. This regularity is even as the force of dominant resistance is proportional to the velocity of the column motion. Meanwhile, the vast majority of such oscillatory systems, which are dealt with in practice, are devoid of this proportionality. The forces of viscous resistance prove to have a more complex dependence on the velocity of relative motion. This leads to serious difficulties in the mathematical analysis of oscillatory processes. Therefore, if a simple apparatus for linear differential equations is used for solving engineering problems, in many cases, the process of damping is linearized despite the fact that the resistance is not exactly proportional to the velocity. The value of the damping ratio is experimentally determined on the basis of evaluating the energy scattered during oscillation. The damping ratios of the SR column oscillation can be determined on the basis of studying real dynamograms.

## 3. The objective and tasks of the study

The objective of the study is to develop a method for determining the damping ratio of the SR column oscillations on the basis of the dynamograms obtained from the DSRP research.

To achieve the objective, it is necessary to solve the following problems:

(1) to prove the basic principles of implementing the method for determining the damping ratio,

(2) to determine the value of the damping ratio of the SR column oscillations by specifying in dynamograms the sections of periodic load changes in the form of oscillograms and their approximation.

## 4. The rationale for the basic principles of implementation of the method for determining the damping ratio

It is expedient to consider the SR column as a spring-suspended load (Fig. 1, *a*) whose oscillation in a viscous medium is described by means of the following equation [11]:

$$\ddot{x} + 2n\dot{x} + k^2 x = 0, \tag{2}$$

where $x$, $\dot{x}$, and $\ddot{x}$ are, respectively, the shift, velocity, and acceleration of the load, $n = \mu/2m$ is an oscillation damping ratio, $m$ is a load mass, $k = \sqrt{c/m}$ is the frequency of the load oscillation, and $c$ is the tightness of the spring.

The equation (2) is solved as follows:

$$x = e^{-nt}\left[x_0 \cos k^* t + \left(\dot{x}_0 + nx_0\right)/k^* \sin k^* t\right]$$

or

$$x = ae^{-nt}\sin\left(k^* t + \alpha\right), \tag{3}$$

where

$$k^* = \sqrt{k^2 - n^2};$$

$$a = \sqrt{x_0^2 + \left(\left(\dot{x}_0 + nx_0\right)/k^*\right)^2};$$

$$\alpha = \mathrm{arctg}\left(\frac{x_0 k^*}{\dot{x}_0 + nx_0}\right).$$

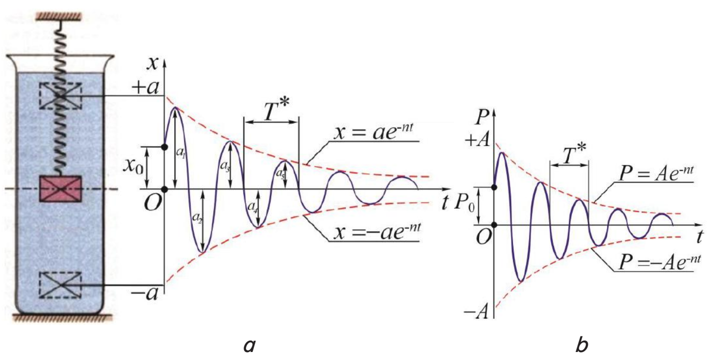


Fig. 1. Characteristics of the damped oscillations: *a* describes the law of the coordinate change; *b* describes the law of the force change

When there is the multiplier $e^{-nt}$, oscillations that are described by equation (3) are damped. Typically, function diagram (3) is restricted by decrement curves of the type:

$$x = \pm ae^{-nt}. \tag{4}$$

Damped oscillations that are described by function (3) are conditionally periodic. The conditional period $T^*$ (Fig. 1, *b*) is a period of time between two successive passages of the load through the state of static balance in one direction:

$$T^* = 2\pi/k^* = 2\pi/\sqrt{k^2 - n^2}. \tag{5}$$

If at the moment of the transition process of damping the time of the load attachment is equal to the conditional period of natural oscillations $T^*$ of the SR column, further research on the intensiveness of oscillation damping can employ instead of the coordinate $x$ in equation (4) the value of the current load $P$ taken from the dynamogram:

$$P = \pm A e^{-nt}, \qquad (6)$$

where A is an amplitude value of the load.

The amplitude of the oscillations decreases within time spans $T^*$ in the geometric progression; the denominator $D$ is called the oscillation decrement:

$$D = e^{-nT^*/2}. \qquad (7)$$

The notion of the logarithmic oscillation decrement $D_1$ is often used in engineering and machine building:

$$D_1 = |\ln D| = nT^*/2. \qquad (8)$$

The aforementioned theoretical basis allows determining the damping ratio by the change of the amplitude and the period of the oscillations in time with the help of the DSRP dynamic measurement.

## 5. The results and analysis of studying dynamograms with the use of the suggested method

Further research uses the examples of estuarine and abyssal dynamograms [4]. Fig. 2 shows a estuarine dynamogram with decaying oscillations for DSRPs with a balance-type drive during the transition process. The transition process is a response of the dynamic system to the applied action after applying this action to a certain sustainable value in the time domain. Approximated curves of the change in the load of the SR column during its course up and down in the MathCAD medium were used to obtain the models of oscillograms with decrement curves (Fig. 2, *b*, *c*) whose parameters are subject to dependence (6). The SR column is steel, one-stage, and composed of rods with $d$=22 mm and its $l$=1200 m. The cyclic frequency of the column natural oscillations is $k$=6.792 rad/sec. The results of the model approximation are as follows: when the column rises, $A = 1820$ H, $n = 0{,}813$ s$^{-1}$, $T^* = 0{,}932$ sec, $D = 0{,}685$, and $D_1 = 0{,}379$; when the column lowers, $A = 9195$ H, $n = 0{,}41$ s$^{-1}$, $T^* = 0{,}927$ sec, $D$=0,827, and $D_1 = 0{,}190$.

A complex assessment of decaying longitudinal oscillations of the SR column requires similar studies both of estuary and abyssal dynamograms. The damping ratio of oscillations at different depths of the well is assessed with the use of data from experimental research of the oscillation of the SR column axial load [4] (Fig. 3). The SR column is steel and two-stage. The lengths and diameters of the column stages are as follows: the first one – $l_1$=480 m and $d_1$=25 mm; the second one – $l_2$=2330 m and $d_2$=22 mm. The cyclic frequency of the natural oscillations of the column is $k$=3.012 rad/sec. The estuarine dynamogram processing data allow asserting that the load oscillation occurs according to the periodic bioharmonic law (Fig. 3, *a*), just as it is shown in Fig. 2, *b*, *c*. Numerical processing of the dynamogram at a depth of 7654 feet (about 2330 m) indicates bioharmonic yet casual nature of oscillations (Fig. 3, *b*). The least intensive oscillation damping is registered at a depth of 9224 feet (about 2810 m) above the location of the pump (Fig. 3, *c*).

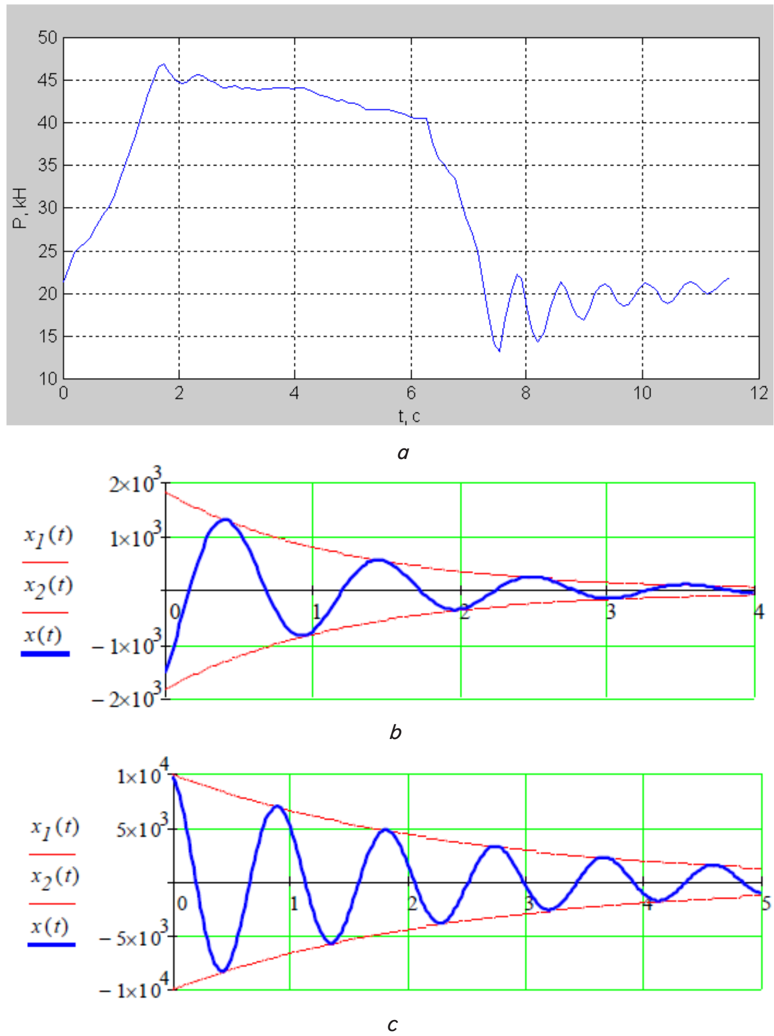


Fig. 2. A estuarine dynamogram of the DSRP with a balance-type drive: *a* is a general view; *b* is a model oscillogram with curves of the decaying oscillations when the SR column rises; *c* is a model oscillogram with curves of the damped oscillations when the SR column lowers

The research findings show that the damping of the oscillations intensifies near the estuarine part of the SR column, which is explained by a constant interaction between the polished rod and a sealing node. Therefore, damping of bioharmonic oscillations of the SR column results from mechanic friction.

Damping of bioharmonic random oscillations with a random constant that are registered at depths of 2330 and 2810 meters are less intensive. The forces of hydrodynamic friction of the SR column against the column of interstitial fluid significantly affect the damping of these oscillations. A minor share of the decaying longitudinal oscillations of the steel SR column is contributed by the forces of internal friction.

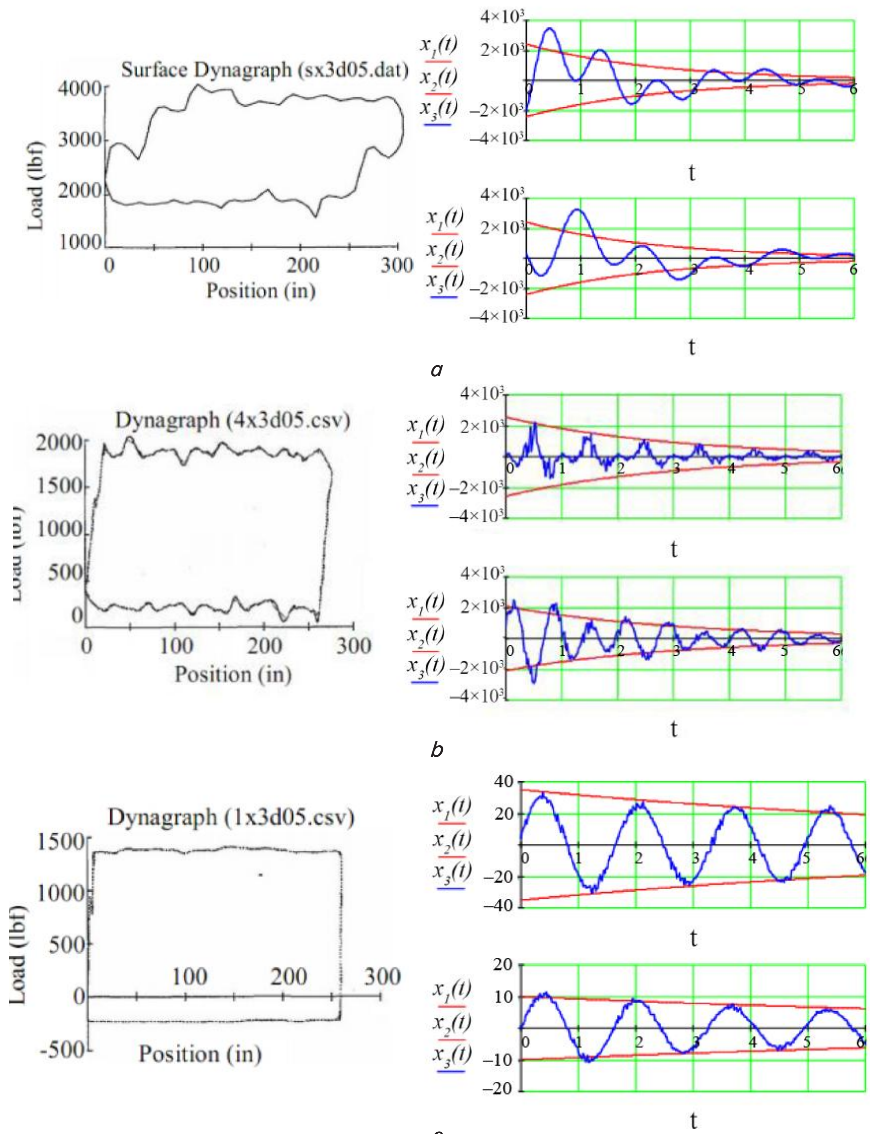


Fig. 3. A general view of the DSRP diagram with a balance-type drive and model oscillograms during the lifting and lowering of a two-stage steel SR column: *a* — at the estuary; *b* — at a depth of 2330 m; *c* — at a depth of 2810 m

The nature of oscillograms that show the lifting and lowering of a combined SR column is slightly different from those of the steel one (Fig. 4). The obtained data on the oscillations of an axial load of a two-stage combined SR column of fiberglass and steel rods have the following stage parameters: the first one: $l_1$ =1340 m and $d_1$ =22 mm; the second one: $l_2$ =980 m and $d_2$ =25 mm. The cyclic frequency of natural oscillations of this column is k=3.264 rad/sec.

Some findings of the research on a two-stage steel and a two-stage combined SR columns are shown in Tables 1 and 2.

Taking into account the obtained results (Tables 1 and 2) and the correlation (1), a conclusion can be made that the rate of damping and the amplitude of the dynamic component of the column load decrease with increasing velocity and hydrodynamic resistance forces within the range of non-damped oscillations. The forces of hydrodynamic resistance and external Coulomb friction affect the behaviour of the SR column structure with steel and fiberglass rods in different ways. In both cases, the amplitude of oscillations in the lower section of the column decreases, but the amplitude of longitudinal oscillations in the upper section of the column increases.

Table 1

Parameters of the damped oscillations of a two-stage SR column with steel rods

| Depth of the well, m | Motion of the column | Damping parameters | | | | |
|---|---|---|---|---|---|---|
| | | T, sec$^{-1}$ | A, H | n | D | $D_1$ |
| 0 (estuary) | up | 2.152 | 2420 | 0.74 | 0.451 | 0.796 |
| | down | 2.147 | 2385 | 0.71 | 0.467 | 0.762 |
| 2330 | up | 2.098 | 2085 | 0.32 | 0.715 | 0.336 |
| | down | 2.096 | 2012 | 0.30 | 0.730 | 0.314 |
| 2810 | up | 2.087 | 35 | 0.11 | 0.892 | 0.115 |
| | down | 2.087 | 11 | 0.10 | 0.901 | 0.104 |

Table 2

Parameters of the damped oscillations of a two-stage SR column of fiberglass and steel rods

| Depth of the well, m | Motion of the column | Damping parameters | | | | |
|---|---|---|---|---|---|---|
| | | T, sec$^{-1}$ | A, H | n | D | $D_1$ |
| 0 (estuary) | up | 1.942 | 2050 | 0.43 | 0.659 | 0.418 |
| | down | 1.931 | 1920 | 0.26 | 0.778 | 0.251 |
| 1340 | up | 1.929 | 1045 | 0.22 | 0.809 | 0.212 |
| | down | 1.927 | 722 | 0.14 | 0.874 | 0.135 |
| 2320 | up | 1.926 | 24 | 0.08 | 0.926 | 0.077 |
| | down | 1.925 | 12 | 0.05 | 0.953 | 0.048 |

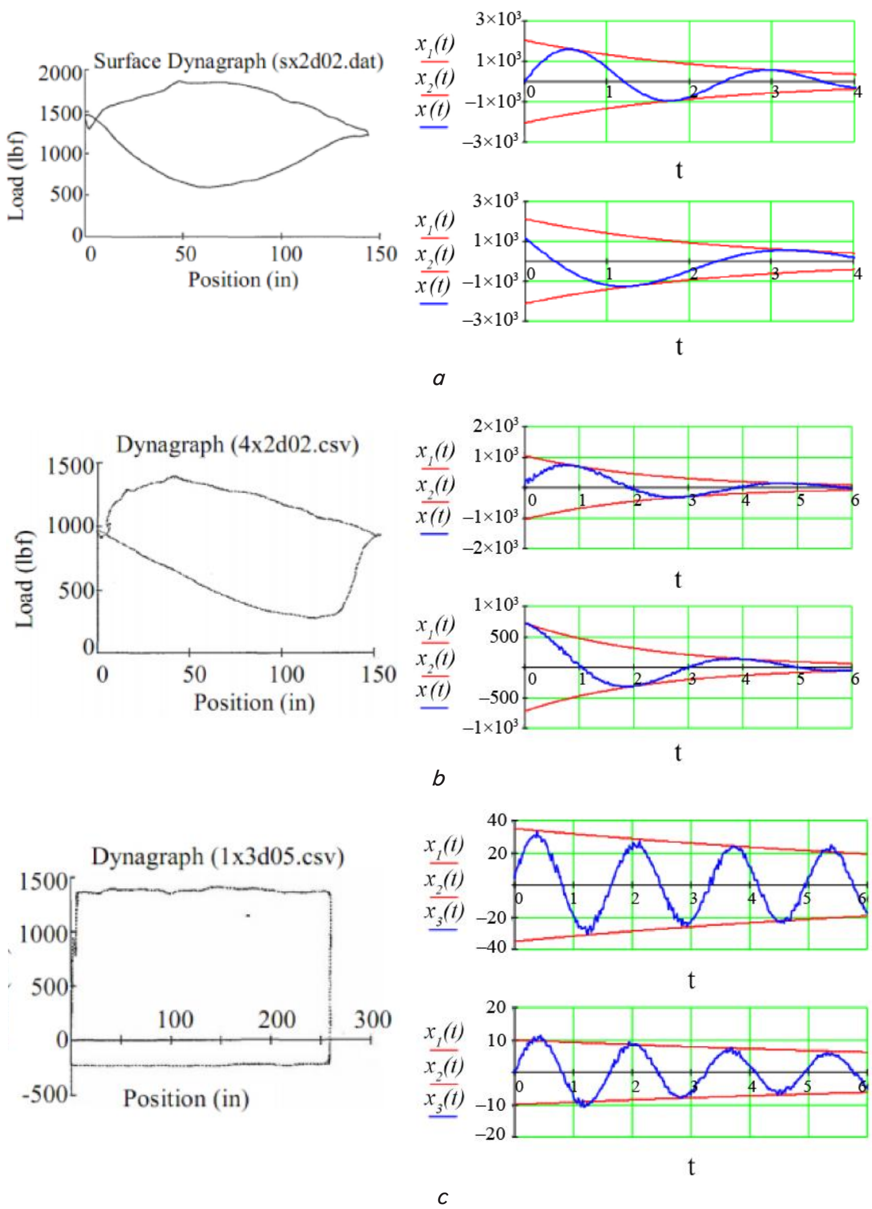


Fig. 4. A general view of the DSRP dynamogram with a balance-type drive and model oscillograms during the lifting and lowering of a two-stage combined SR column: *a* — at the estuary; *b* — at a depth of 1340 m; *c* — at a depth of 2320 m

The action of tough resistance forces of the fluid reservoir to the SR column is manifested in the rapid damping of free oscillations. Besides, there is a decrease in the amplitude of the load changes in lower sections at the time when the forces of hydrodynamic resistance are negligible. This is due to the heavy mechanical friction of the SR column against the PCP column in curved sections of the well. The action of only Coulomb friction forces in straight sections does not result in free oscillations' damping and a significant decrease of the amplitude. Unlike steel columns, columns with fiberglass rods demonstrate a noticeable damping of the load oscillation amplitude due to internal friction.

## 6. Conclusion

The undertaken set of theoretical research has resulted in developing a method of determining the oscillations' damping ratio of the SR column on the basis of the obtained dynamograms during researching the DSRP. It entailed the following:

(1) a possibility of studying the intensity of oscillations' damping in different sections of the dynamograms was proven with account for the nature of dissipative forces and their impact on the character of the SR column oscillation;

(2) real estuarine and abyssal dynamograms were analysed alongside the approximation of oscillogramed sections in the form of periodic changes in the load factor of oscillations' damping for one-stage and two-stage columns with steel rods as well as a two-stage combined column equipped with fiberglass and steel rods.

The developed method can be applied to analysing dynamograms of a particular well, whereas the determined damping ratios facilitate assessment of the SR column dynamism and establishment of the best modes of the DSRP operation to prevent resonance under actual operating conditions.

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