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ABOUT THE HALF-WAVE LENGTH OF THE BOTTOM-HOLE CORE-DRILL COMPOSED OF STRUCTURAL ELEMENTS OF DIFFERENT STIFFNESS

In the formation of the well under the influence of axial load and rotation speed, the core drilling shell is curved, while its lower bottom-hole part consists of elements of different stiffness: core retrieving barrel and drilling pipe. To determine the half-wave length in this part of the process tools, the energy method was used, according to which, all external forces on the said length changes into potential energy of the curved drill string. The solution of the corresponding equation helped to obtain a formula for determining the length of the half-wave of the string bottom-hole area. The obtained relationship is different from the well-known formula of B.I. Vozdvizhensky and M.G. Vasilyev in that it additionally takes into consideration the ratio of the core retrieving barrel and half-wave, ratio of moments of inertia of the core retrieving barrel and drilling pipes, and the mass ratio of core barrel and drilling pipes per unit length. To reduce the well deviation, it is recommended to install rib stiffeners in the "half-wave crests" of the bottom-hole part of the drilling string.

Keywords: deviation, drilling line, rib stiffeners, half wave length, half-wave crests.

It is common knowledge that during well drilling the tool string under the influence of axial load and torsion torque becomes unstable and assumes a wave shape. As a consequence, additional conditions are created promoting deviation of the well and its departure from the design direction.

Any half-wave length in the compressed part of the tool string is calculated according to G.M. Sarkisov's formula [1, 2]:

$$l = \frac{9500}{n}\sqrt{\pm z + \sqrt{0.25z^2 + \frac{1.1jn^2}{100q}}}, \qquad (1)$$

where l – is the half-wave length, cm

n – is the string rotation speed, rpm;

z – is the distance from the zero section, where the compression of the lower part of the tool string conditional on the bottom-hole reaction proceeds to tensile, cm;

j – is the axial moment of inertia of the tool string cross-section; cm^4;

q – is the weight of 1 cm of drill pipes that form the tool string, kg/cm.

Equation (1) is valid if the length of the tool string half-wave, first from the bottom-hole, consists of the same rigidity element (for example, the drill collars for rotary drilling).

When core drilling, the said half-wave consists in general of two structural elements: core retrieving barrel and drilling pipe (Fig. 1).

In *A*, *B*, *C* points and other points the drill string touches the wellbore walls. The direction of the well is greatly influenced by first contact point of the drill guide on the borehole wall (point *A* in Fig. 1). The closer point *A* is to the bottom-hole, the more the well route will deviate from the projected route (along arrow *B* in Fig. 1). To move point *A* away from the bottom-hole to a greater distance, the stiffness of the tool string needs to be increased, which will contribute to a smaller wellbore deviation.

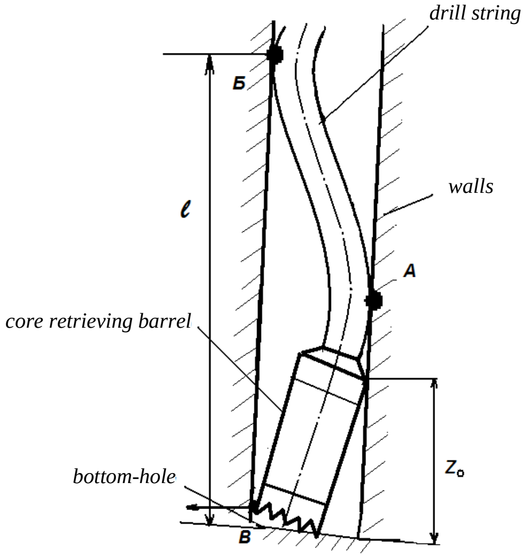

Fig. 1. Deviation of the bottom-hole part of the tool string under the influence of external loads.

A radical solution for increasing the stiffness of the tool string is to install centralizers at points *A* and *B* whose diameter will be close to the well diameter.

The diameters of drill pipes and core barrels, which the bottom-hole section of tool string consists of, are standardized. The following diameters are used in the coring process, mm: 42, 50, 63 (drill pipes), 46, 57, 73, 89, 108, 127 (core barrels). Therefore, the length of the half-wave of the tool string, located first from the bottom-hole, is generally equal to the sum of the lengths of two components with different diameters: core retrieving barrel and drilling pipe. The model of the bottom-hole part of the tool string represents a shaft with two stiffened areas (Fig. 2), where the bottom area shapes the core retrieving barrel, and the top one shapes the drill string.

The task of calculating the said length l (see Fig. 1) is solved using the energy method, according to which the whole work of external forces at the half-wave length (centrifugal and axial load) transforms into potential energy of the curved shaft (of the tool string) at the same length:

$V = A_C + A_1$ (V – potential energy of the curved shaft; A_C, A_1 – work of centrifugal and longitudinal (axial load) forces respectively).

First, we calculate the potential energy of the shaft:

$$V = V_1 + V_2\,. \qquad (2)$$

Potential energy of the upper I (V_1) and lower II (V_2) shafts equals:

$$V_1 = \frac{EJ_1}{2}\int_{\pounds}^{l}\left(y^{\mathrm{II}}\right)^2 \mathrm{d}x;\; V_2 = \frac{EJ_2}{2}\int_{0}^{\pounds}\left(y^{\mathrm{II}}\right)^2 \mathrm{d}x, \qquad (3)$$

where E – is the elasticity modulus of the shaft (tool string), for steel E=$2\cdot10^5$ MPa;

J_1, J_2 – is the moment of inertia of the drill pipe and the core barrel cross sections,

y – is the curve function along which the tool string bent, $y = e\sin\frac{\pi x}{l}$ (see fig. 2) (e – is the deflection of the core retrieving barrel, equal to the clearance between the well and core barrel, l – is the half-wave length of the tool string).

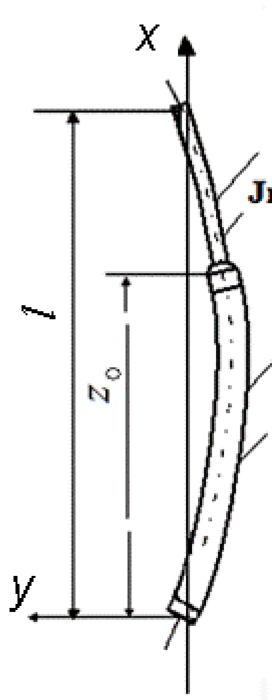

Fig. 2. Model of the bottom-hole part of the tool string:
I – *drill string;* II – *core retrieving barrel.*

Having calculated the second derivative of the function (y) and applying it to the formula V_1 and V_2, denoting by $z_0 / l = \varphi$, we obtain

$$\begin{aligned} V_1 &= \frac{EJ_1 e^2\pi^4}{4l}\left(1-\varphi+\frac{\sin 2\pi\varphi}{2\pi}\right), \\ V_2 &= \frac{EJ_2 e^2\pi^4}{4l}\left(\varphi-\frac{\sin 2\pi\varphi}{2\pi}\right). \end{aligned} \qquad (4)$$

Applying (4) to (2), we will obtain the full value of the potential energy of the shaft:

$$V = \frac{EJ_1 e^2\pi^4}{4l^3}\left[1+\left(K-1\right)\left(\varphi-\frac{\sin 2\pi 4}{2\pi}\right)\right], \qquad (5)$$

where $K = J_2 + J_1$.

We calculate the work of external transverse (centrifugal) forces, whose value is equal to

$$A_c = A_1 + A_2 \qquad (6)$$

The value of works of the centrifugal forces on upper A_1 and lower A_2 sections of the shaft is equal to:

$$A_1 = \frac{q_1\omega^2}{2g}\int_{\pounds}^{l} y^2 \mathrm{d}x = \frac{q_1\omega^2}{2g}\int_{\pounds}^{l} e^2 \sin^2\frac{\pi x}{l}\mathrm{d}x =$$

$$=\frac{q_1\omega^2e^2l}{4g}\left(1-\varphi+\frac{\sin 2\pi\varphi}{2\pi}\right), \quad (7)$$

$$A_2=\frac{q_2\omega^2}{2g}\int_0^{\pounds} y^2\mathrm{d}x=\frac{q_2\omega^2}{2g}\int_0^{\pounds} e^2\sin^2\frac{\pi x}{l}\mathrm{d}x=,$$

$$=\frac{q_2\omega^2e^2l}{4g}\left(\varphi-\frac{\sin 2\pi\varphi}{2\pi}\right). \quad (8)$$

where q_1, q_2 is the mass per 1 m of drill pipes and core barrels respectively:

ω is the angular spin rate of the tool string;

g is the gravity acceleration equal to 9.81m/s^2.

The total work of the centrifugal forces accounting for (7) and (8) is equal to

$$A_C=A_1+A_2=\frac{q_1\omega^2e^2l}{4g}\times$$

$$\times\left[1+(m-1)\left(\varphi-\frac{\sin 2\pi\varphi}{2\pi}\right)\right], \quad (9)$$

where $m=q_2/q_1$.

The work of longitudinal force (axial load C) at half-wave length is equal to:

$$A_l=\frac{C}{2}\int_0^1\left(y^{\mathrm{II}}\right)^2\mathrm{d}x=\frac{Ce^2\pi}{4l}, \quad (10)$$

The load on the bottom-hole C, exerted by the part of tool string mass, is equal to: $C=\alpha q_1 z$, (α – is the adjustment ratio to take into account the additional weight of drill pipe links; z – is the length of the compressed part of the tool string).

Since $V=A_C+A_l$, by substituting values of V, A_C, A_l, we obtain from (5), (9) and (10)

$$\frac{DEJ_1e^2\pi^4}{4l^3}=\frac{Bq_1\omega^2e^2l}{4g}+\frac{Ce^2\pi}{4l}. \quad (11)$$

where $D=1+(K-1)\left(\varphi-\frac{\sin 2\pi\varphi}{2\pi}\right);$

$$B=1+(m-1)\left(\varphi-\frac{\sin 2\pi\varphi}{2\pi}\right).$$

Consequently, to determine the half-wave length, we should solve the quadratic equation

$$Bq_1\omega^2l^4+Cg\pi^2l^2-DEJ_1\pi^4g=0. \quad (12)$$

Solving the equation (12), after algebraic transformations, we obtain

$$l=\frac{\gamma_0}{\psi_0\mathrm{n}}\sqrt{-z+\sqrt{z^2+\left(\psi_0 n\right)^2}}, \quad (13)$$

where $\gamma_0=6,28\sqrt{\frac{J_1}{\alpha q_1 D}}$;

$$\psi_0=0,0942\sqrt{\frac{J_0}{\alpha^2q_1}DB};$$

n is the toll string rotation speed, rpm.

We then analyze formula (13) depending on the value of ratio $\varphi=\frac{z_0}{l}$. If $\varphi=0$, then $D=\mathrm{I}$; $B=\mathrm{I}$. Coefficients γ_0 and ψ_0 are respectively equal to $\gamma_0=6,28\sqrt{\frac{J_1}{\alpha q_1}}$; $\psi_0=0,0942\sqrt{\frac{J_1}{\alpha^2q_1}}$. We get the first special case: formula of B.I. Vozdvizhensky and M.G. Vasilyev for determining the half-wave of the tool string, composed of drill pipes. If $\varphi=1$, then $D=K=\frac{J_2}{J_1}$; $B=m=\frac{q_2}{q_1}$. Coefficients γ_0 and ψ_0 are equal to $\gamma_0=6,28\sqrt{\frac{J_2}{\alpha^2q_1}}$; $\psi_0=0,0942\sqrt{\frac{J_2}{\alpha^2q_1}}\cdot\sqrt{\frac{q_2}{q_1}}$. In this case, formula (13) will take the following form:

$$l=\sqrt{\frac{q_1}{q_2}}\cdot\frac{\gamma_0}{\varphi_0 n}\sqrt{-z+\sqrt{z^2+\frac{q_2}{q_1}\left(\varphi_0 n\right)^2}}. \quad (14)$$

Formula (14) expresses the second special case, where the length of the core retrieving barrel is equal to or greater than the length of the first half-wave from the bottom-hole, and the load to the bottom-hole is exerted by the weight of drill pipes.

Therefore, the length of the first half-wave from the bottom-hole in general, when the drill at the site consists of different diameter components, depends not only on the drilling conditions and rigidity of drill pipes, but also on the ratio of lengths of the drill pipe and core barrel constituting the half wave ($\varphi = \frac{z_0}{l}$); the ratio of momenta of inertia of the drill pipe and core barrel cross sections ($K = \frac{J_2}{J_1}$), as well as ratio of masses of drill pipe and core barrel per unit length ($m = \frac{q_2}{q_1}$).

Generally, bending the tool string will be influenced by the axial load *C*, centrifugal forces arising due to rotational speed and weight of the tool string, as well as the pressure of flushing fluid in the well.

Fig. 3, *a*–*g* shows the dependence of the length of the first half-wave of the tool string from the bottom-hole l on the axial load C exerted onto bottom-hole n at different values of rotational speed of the drill string. Solid lines represent half-wave lengths without accounting for flushing fluid, dashed lines account for this. As it follows from the graphs, flushing fluid, which fills the well, slightly increases the half-wave of the tool string, as if straightening the latter, but this effect is negligible (half-wave length increases by 3–5 %).

The conducted studies allow us to determine the location for installing the centralizers on the body of core retrieving barrel and the drill string. The first place is located at a distance equal to ½ half-wave, the second one at a distance equal to a half-wave length (Fig. 1). In addition, information on drilling mode parameters should be obtained.

As an example, Fig. 4 shows the tool string with coring consisting of tungsten carbide drill bits with a 76-mm diameter, a core barrel with 73-mm diameter and length of 3.5 m, and a drill string of 50-mm diameter. It is proposed to drill under axial load $C = 5\,\text{kH}$ and rotation speed n = 390 rpm. While calculating according to the formula (13), the length of the tool string's first half-wave from the bottom-hole was equal to $l_1 = 5.1$ m. Therefore, centralizers will be installed at: $5.1 : 2 = 2.55$ m and 5.1 m.

At the point where first crest of the half-wave l_{c1} is located, we place four carbide welds along the circumference of the core barrel. The weld length should be taken at 20 cm to compensate for the possible displacements of half-wave crest when the drilling mode is changed. At the point of the second crest of the half-wave l_{c2} = 5.1 m, we install rubber ring-protectors with longitudinal channels for passage of the drilling fluid. The length of the second centralizer protector is taken at 30–40 cm, based on the experience of exploration drilling, when such a measure helped to prevent wear of the drill pipes.

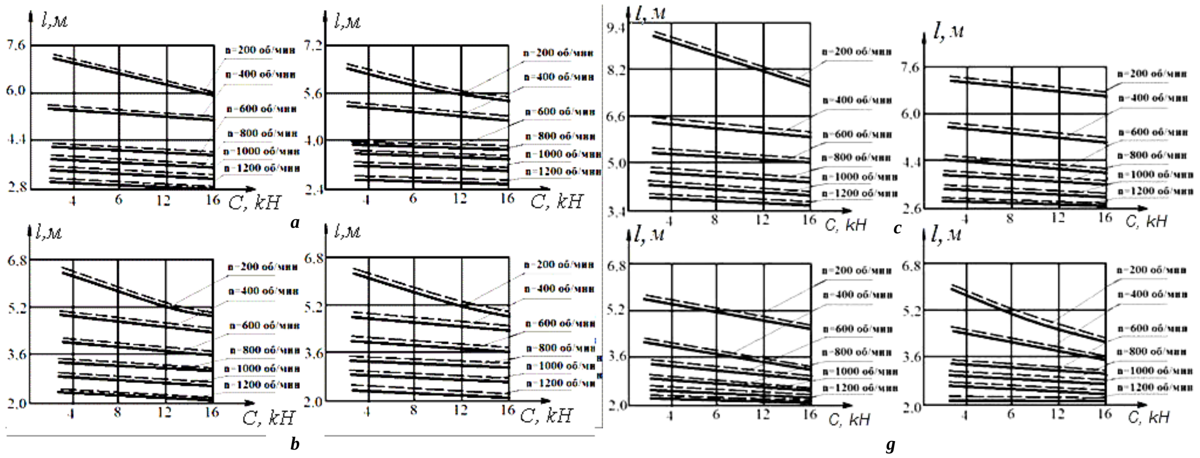

Fig. 3. Dependence of the half-wave length *l* on axial load *C* at different values of *n*.

Diameter of drill pipes: ***a***, ***c***, ***d*** – 50 mm; ***b*** – 42 mm; core barrels: ***a*** – 73 mm; ***b***, ***g*** – 57 mm; ***c*** – 89 mm; _____ – half-wave length without accounting for hydraulic forces; - - - – half-wave length accounting for hydraulic forces.

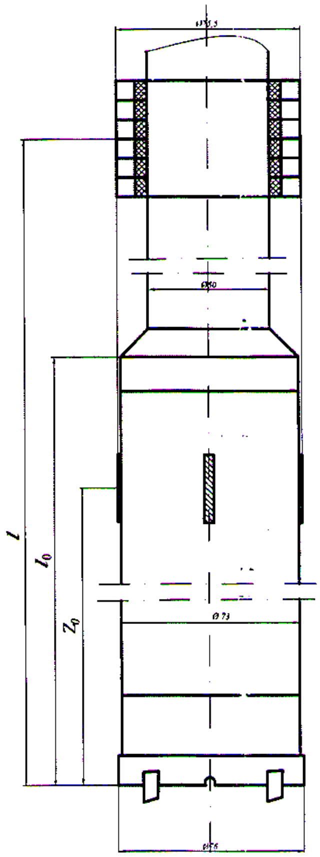

Fig. 4. Stiffened tool string.

The performed studies helped to formulate a number of conclusions.

The half-wave length *l* decreases with the increasing axial load C and decreasing drilling diameter (reduction in the rigidity of the core retrieving barrel).

For a tool string of a certain size, the half-wave length decreases with higher intensity as the number of revolutions of the drill column *n* increases than when the axial load *C* increases.

The resulting formula for determining the first half-wave length of the tool string from the bottom-hole, consisting of components of different stiffness, allows us to determine the location for installing centralizers to increase the rigidity of the bottom-hole part of the tool and contribute to smaller well deviation.

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