Calculation of the torque on the crank shaft of the low-speed balancing drive sucker rod pumps

Galeev, A.S.1, Arslanov, R.I.2, Suleymanov, R.N.1, Filimonov, O.V.1

1Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, 54a, Devonskaya St., Oktyabrsky, Republic of Bashkortostan, 452607, Russian Federation
2SBEI of HE “Almetyevsk State Oil Institute”, 2, Lenin St., Almetyevsk, Republic of Tatarstan, 423450, Russia

E-mail: ssgaleev@mail.ru

Annotation. The operation of well sucker rod pump installations is the most massive way of mechanized oil production. A significant part of the wells equipped with low-speed plants of this type have a low flow rate and high water cut. Such conditions create certain restrictions on updating and modernization of the production fund of equipment in operation. The life cycle of a rocking machine is usually significant and often exceeds 20 years. During ISPR operation, both ground and downhole equipment will inevitably wear out. A significant proportion of failures of the ground part of low-speed ISPR is associated with the reduction of the rocking machine, which is the most responsible and most expensive drive element. The resource of the gearbox directly depends on its load, which is characterized by the moment on its crank (output) shaft. Reducing the maximum torque and moment fluctuations in one full swing of the rocking machine will significantly increase the reliability of the gearbox and the entire installation. This paper describes the mathematical apparatus for calculating the moment on the crank shaft of the gearbox, based on the exact kinematics of the drive and the principle of possible movements. The proposed methodology will allow to solve the problems of designing a balancing drive of a low-speed ISPR, to determine the requirements for the engine and transmission.

1. Introduction
A significant part of the world oil well fund is operated mechanically using installations with sucker-rod pump (ISPR). Moreover, in recent years, the proportion of wells producing highly viscous products has been steadily growing. Taking into account equipping a large part of such wells with low-speed ISPR, improving their efficiency becomes one of the priority tasks [1-4]. When producing high-viscosity oil, complications arise that adversely affect the operation of downhole equipment and entail increased wear and premature failure of ISPR equipment [5]. ISPR can be divided into three parts: a downhole pump, sucker rods and ground drive. The most conservative part of the entire installation, which has been in operation for the longest time, is the conversion mechanism of the ground drive, in most cases presented in the form of a beam-pumping unit. The actual service life, based on international experience, often exceeds 20 years [6,7].
2. Methods and materials

This work was carried out in the framework of the Federal Target Program “Research and Development in Priority Directions for the Development of the Russian Science and Technology Complex for 2014-2020” under the Agreement on the provision of subsidy No. 14.610.21.0019 of 10.23.17 on the topic “Creation of a set of technological solutions for increasing oil recovery containing highly viscous oil”, a unique identifier for the work RFMEFI61017X0019.

3. Results and Discussion

The balancing drive of a borehole sucker rod pump installation is a mechanism that converts the rotational movement of an electric motor into reciprocating motion of a string of pump rods [8].

The mechanism of the rocking machine is a four-link and has one degree of freedom. The kinematic diagram of the rocking machine is shown in Figure 1. The angle of rotation of the crank O1O2 of length \(l_1\) is taken as the generalized coordinate. The axis of the crank O1 \((x_1, y_1)\) is stationary. The movement of the hinge O2 \((x_2, y_2)\) occurs in a circle:

\[
x_2 = x_1 + l_1 \cos \phi \\
y_2 = y_1 + l_1 \sin \phi
\]

Rocker (balancer) rotates around a fixed center \(O_4(x_4, y_4)\).

The hinge \(O_3(x_3, y_3)\) connecting the balancer to the connecting rod also moves along an arc of a circle of radius \(l_3\) and its motion is described by the equations:

\[
x_3 = x_4 + l_3 \cos \psi \\
y_3 = y_4 + l_3 \sin \psi
\]

where \(\psi\) is the angle between the balancer and the X axis. The distance between the hinges is equal to the length of the \(O_2O_3\) connecting rod \(l_2\):

\[
(x_3 - x_2)^2 + (y_3 - y_2)^2 = l_2^2
\]

![Figure 1. Kinematic diagram of a beam-pumping unit.](image)

and auxiliary angle \(\theta\) by the formula:

\[
\theta = \arcsin \frac{a}{\sqrt{a^2 + b^2}}
\]
we get:

$$\psi = (-1)^n \arcsin \left( \frac{l_3^2 - l_2^2 - a^2 - b^2}{2l_3 \sqrt{a^2 + b^2}} \right) - \theta + \pi n, \ n \in \mathbb{Z} \quad (7)$$

The movement of the ISPR drive is determined by the following external forces: gravity of the rod string, gravity of the liquid column, drag force of the column against the borehole wall (boundary friction), viscous friction force of the rod string against the fluid, friction forces in the gearbox and a couple of forces from the electric motor [11, 12].

In slow-moving rocking machines, the dynamic loads are negligible and, accordingly, the moment on the crank shaft of the gearbox is determined only by the load on the traverse and the balancing counterweight.

To calculate the moment on the crank shaft, the principle of possible movements is used, according to which the sum of the work of active forces and at any possible movement of the system is zero. The design scheme of the ISPR drive is shown in Figure 2. The active forces of the ISPR drive are:

1) Torque $M_{cr}$ applied to the crank (transmitted from the engine through the gearbox);
2) The gravity of the crank $G_{cr}$;
3) Gravity forces of counterweights $G_1$ and $G_2$;
4) The gravity of the rocker $G_3$;
5) Column weight $G_{quan}$;
6) The weight of the liquid column (only when moving up) $G_{liq}$;
7) Column resistance force $F_{re}$ (directed all the time against the movement of the column).

Consider an arbitrary position of the system (the crank is rotated through an arbitrary angle $\phi$). We give the crank an infinitesimal displacement $\delta \phi$. Then the balancer will rotate a certain angle $\delta \psi$ and the column will move a distance $\delta S$.

![Figure 2. The design scheme of the ISPR drive.](image-url)
The work of active forces on this movement will be:

\[ \delta A = M_{cr} \delta \varphi - G_{cr} \cdot r_3 \cos \varphi - G_1 (r_1 \cos \varphi - h_1 \sin \varphi) - G_2 (r_2 \cos \varphi + h_2 \sin \varphi) - G_3 \cdot r_4 \cos \psi \delta \varphi + (G_{quan} + G_{liq} - F_{re}) \delta S, \]

where \( r_3 \) is the distance from the axis of the crank to its center of gravity;
\( r_1, h_1 \) and \( r_2, h_2 \) – radial and tangential displacements of the counterweights relative to the crank;
\( r_4 \) is the distance from the axis of the balancer to its center of gravity (taking into account the traverse and connecting rods);

In accordance with the principle of possible movements, this work should be zero. Expressing the increment of the angle \( \delta \varphi \) and the small displacement of the column \( \delta S \) through the increment of the angle \( \delta \varphi \) [13-18], we obtain an equation from which we can find the moment on the crank shaft, depending on the design of the ISPR, and the position of the crank:

\[ M_{cr} = G_{cr} r_3 \cos \varphi + G_1 (r_1 \cos \varphi - h_1 \sin \varphi) + G_2 (r_2 \cos \varphi + h_2 \sin \varphi) + G_3 \cdot r_4 \cos \psi \frac{\partial \psi}{\partial \varphi} - (G_{quan} + G_{liq} - F_{re}) \frac{\partial \psi}{\partial \varphi} l_4 \]

4. Conclusion

The calculation is implemented in the form of a software product, in which, after entering the main parameters of the ISPR drive, we calculate the work performed by the acting forces, the degree of balance, and the change in the effective torque on the crank. The input window for the main parameters of the ISPR drive is shown in Figure 3.

Figure 3. The input graphical user interface for the basic parameters of the ISPR drive.

Translation (from left to right, up to bottom): ISPR drive, balancer, mass, inertia moment, length 13, length 14, X-axis coordinate, Y-axis coordinate, centre of gravity shift, save, close the window,
connecting rod, crank, mass, inertia moment, length, -axis coordinate, -axis coordinate, center of gravity position, first, second, mass, on crank position, height above crank, counterweights.

The program window with an example of the calculation is shown in Figure 4.

![Figure 4](image.png)

**Figure 4.** The output graphical user interface of the developed software.

Translation (from left to right, up to bottom): Save the results of the calculation in the table, save the graph in the graph file, close the window, engine torque, engine run up, engine run down, operating balance, power peak balance, engine run per cycle, torque swing on crank.

The resulting equation for the dependence of the moment on the crank shaft of the gearbox on the mass of the drive elements, geometric parameters and the load on the cable suspension will allow us to solve direct and inverse problems of designing the balancing drive of the low-speed ISPR, to determine the requirements for the gearbox of the rocking machine, belt drive and engine.

**References**

[1] Ogarkov Y M, Tsylev P N, Korotayev A D, Burmakin A M 2005 Improving the efficiency of oil production from low-rate wells. *Bulletin of PNRPU. Geology. Oil and gas and mining* 6 pp.172-178. (in Russ.).

[2] Beliaev E F, Tashkinov A A, Tsyliov P N 2012 Improvements of the beam pumping unit electrical drive of the dripper. *Bulletin of PNRPU. Geology. Oil and gas and mining* 4. pp. 91-103. (in Russ.).

[3] Bikbulatova G I, Galeev A S, Boltneva Y A, Linar P A, Suleymanov R N, Filimonov O V 2019 Optimization of pumping fixed volume of liquid on two directions *Bulletin of the Tomsk Polytechnic University* 330(1) pp. 134-144.

[4] Khabibullin M Y 2019 Development of the design of the sucker-rod pump for sandy wells [IOP Conference Series: Materials Science and Engineering 560(1) 012065. DOI: 10.1088/1757-899X/560/1/012065.

[5] Urazakov K R, Nurgaliev R Z, Latypov B M, Bikbulatova G I and Boltneva Y A 2018 Selection of the design of the weighted bottom of the pump rod column for high-viscosity oil production *Oil industry* 10 pp. 111-113.

[6] Bikbulatova G I, Isaev A A, Boltneva Y A 2018 Investigation of the influence of complicating factors on the efficiency of screw rod pumps. *Proceedings of Tomsk Polytechnic University. Geo-resource engineering* 329(4) pp.21-29.

[7] Urazakov K R, Nurgaliev R Z, Belov A E, Bikbulatova G I, Davletshin F F 2019 Investigation of
complications in the operation of downhole rod pumps during simultaneous and separate operation Oil industry 7 pp. 114-117.

[8] Gabzalilova A K, Soloviev N N, Garifullina Z A Effect of changes in the crank radius on the kinematics of the pumping unit when regulating the dynamic level of the fluid in the well IOP Conference Series: Earth and Environmental Science 378(1) 012112. DOI: 10.1088/1755-1315/378/1/012112.

[9] Galeev A S, Filimonov O V, Suleymanov R N 2019 Development of a laser beam to the line in measuring systems IOP Conf. Series: Materials Science and Engineering 560 012125.

[10] Rahman T, Ramanathan R, Seliktar R, Harwin W 1995 A simple technique to passively gravity balance articulated mechanisms. Mech. J. Des. 117 (4) pp. 655-658.

[11] Johnson W, Laithwaite E, Slater R 1964 An experimental impact – extrusion machine driver by a linear induction motor Proc. Instrn. Mech. Engrs. 179 pp. 15–35.

[12] Williams F, Laithwaite E, Piggott L 1957 Bruchless variable – speed Induction. Motors Proceedings of IEE 14(A) pp.102–118.

[13] Jean M, Gosselin C M 1996 Static balancing of planar parallel manipulators. Proc. IEEE Int. Conf. on Robotics and Automation 1996 pp. 3732-3737. DOI: 10.1109/ROBOT.1996.509149.

[14] Van Dam P L, Herder J L 2011 Static balancing of translational parallel mechanisms. Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE DETC 2011-47525.

[15] Baradat C, Arakelian V, Briot S, Guégan S 2008 Design and prototyping of a new balancing mechanism for spatial parallel manipulators. Mech. J. Des. 130(7) pp. 072305-1-072305-13.

[16] Russo A, Sinatra R, Xi F 2005 Static balancing of parallel robots. Mech. Mach. Theory 40(2) pp. 191-202.

[17] Uicker J J, Denavit J J, Hartenberg R S 1964 An iterative method for the displacement analysis of spatial mechanisms J. Appl. Mech. Trans. ASME Ser. E 86(2) pp.309-314.

[18] Walsh G J, Streit D A, Gilmore B J 1991 Spatial spring equilibrator theory. Mech. Mach. Theory 26(2) pp.155-170.