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Optimization of parameters of boom lifting mechanism of equipment for repair and development of oil and gas wells

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Abstract. The paper discusses the procedure for calculating the optimal parameters of the boom lifting mechanism for the repair and development of oil and gas wells. Based on the results of the calculation method, graphs were built. A graph of the force developed by the drive versus the boom elevation angle and a graph of the force versus the boom attachment angle is plotted. The results are presented to determine the optimal parameters of the boom lifting mechanism using this method.

1 Introduction

The problem of optimizing the parameters of lifting mechanisms was dealt with by such well-known scientists as A.S. Lunev, who is engaged in optimizing the parameters of hydraulic systems of lifting mechanisms. Georgy Litvak is a specialist in the field of dynamics and control of lifting and transport mechanisms. He developed techniques for optimizing the parameters of lifting mechanisms, such as cranes and elevators. Yuri Sytner - conducted research on optimizing the parameters of lifting mechanisms and proposed effective methods for managing them. Vladimir Maleshko is the creator of new approaches to the design and optimization of lifting mechanisms. He was engaged in research in the field of mathematical modeling and optimization of lifting and transport mechanisms.

From the point of view of applied physics, optimization of the parameters of the boom lifting mechanism solves several problems at once. The boom of the lifting mechanism is subject to mechanical loads during lifting. Optimization of lifting parameters should consider the maximum mechanical stresses that may arise in the boom [1-2].

It is also necessary to consider the dynamics of lifting. During boom lifting, dynamic loads arise, which must be considered when optimizing lifting parameters. The most critical is the control of boom oscillations to prevent its strong oscillations or even destruction. In this case, it is necessary to consider the masses of the boom, its length and degree of stiffness in order to achieve maximum stability and reduce dynamic loads.

Optimization of lift parameters should consider energy efficiency to ensure minimum energy consumption and maximum performance. For example, it is possible to optimize the hydraulic drive system to reduce energy losses, thereby increasing its efficiency.

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In addition, optimization of boom lifting parameters helps to improve system safety. Selection of correct fasteners, use of reliable control, monitoring, and emergency shutdown systems, as well as taking into account operating conditions, can significantly reduce the risk of emergency situations and ensure the safety of employees.

All these problems require consideration of fundamental laws of physics, such as Newton's laws, mechanics of deformable bodies, and control principles. Optimization of boom lifting parameters from the point of view of applied physics will help to ensure the safety, efficiency and reliability of the mechanism.

In lifting machines, hydraulic drives with reciprocating movement of the output link are widely used. Minimizing the maximum force Fmax generated by the drive at different positions of the output link reduces the drive cost, which can be a significant cost for the entire machine [3].

Let us consider the influence of the structural parameters of the boom lifting mechanism (Figure 1) on the maximum value of the force *F* developed by the hydraulic drive.

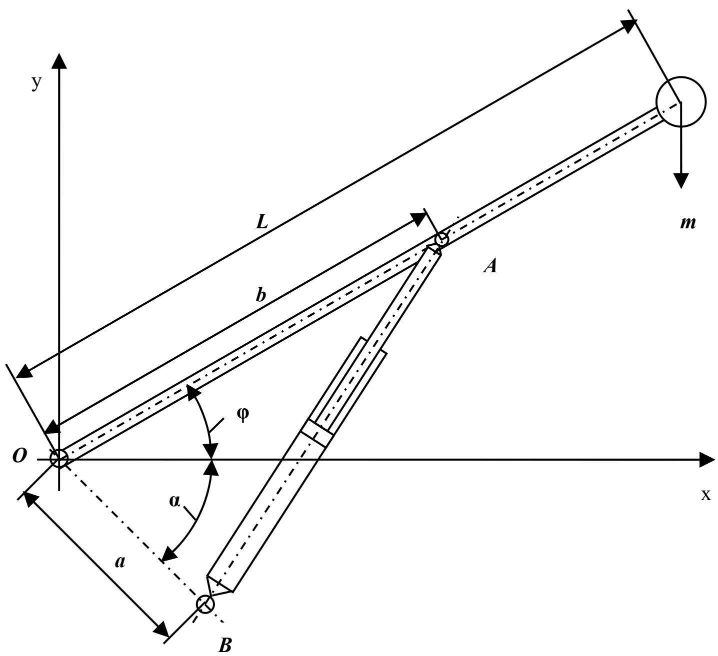

Fig. 1. Influence of design parameters of boom lifting mechanism.

2 Materials and methods

To solve one-dimensional optimization problems, when you want to find a minimum or maximum function of one variable, there are several numerical methods. Here are some of them:

Dichotomy method (method of dividing a segment in half) - is based on the idea of dividing a segment into two equal parts and analyzing the values of the function on these segments. The segment is further divided into two equal parts and the process is repeated until the desired level of accuracy is reached.

The method of the golden ratio - like the method of dichotomy, however, the segment is divided not into equal parts, but in the proportion of the "golden ratio." This method converges to an optimal value faster than the dichotomy method, but requires some additional calculations [4].

Fibonacci method - based on the sequence of Fibonacci numbers and their proportions. It also divides the segment into several sub-segments, but their dimensions are determined using Fibonacci numbers. Sequential analysis of the function on subarticles allows you to approach the optimal value.

Tangent method (Newton method) - is based on decomposing the function into a Taylor series and using the derivative to approximate the minimum or maximum point. This method requires a starting point and knowledge of the derived function.

Parabolic interpolation method (Brent method) - uses the parabola approximation of the function to approximate the optimal value. It combines the dichotomy method, the golden section method, and the tangent method to achieve a more efficient and sustainable solution.

The brute force method (or full brute force method) is a simple and naive numerical method for solving an optimization problem. It consists in sequentially sorting out all possible solutions and checking their compliance with the specified conditions or criteria.

In the context of the one-dimensional optimization problem, the enumeration method involves calculating the value of the function at each of the points on a given segment, predetermined with some step. Then the point with the smallest or largest function value is selected, depending on the task setting.

The advantage of the brute-force method is its simplicity and independence from the smoothness of the function. It is used in cases where the analytic form of the function is unknown, or it is not possible to use other numerical methods [5-6].

With a large number of points on the segment, busting can be computationally costly. However, with the development of computing systems, this method can be proposed as the most promising. The brute force method can be useful in simple situations where the function is simple and the number of points for brute force is small. It can also be used as a starting point for more complex optimization methods.

3 Results and discussion

In the first approximation, the weight of the boom and hydraulic cylinders can be neglected. The dependence of the force *F(φ)* on the angle of rotation of the boom and the design parameters of the lifting mechanism can be found from the conditions of the balance of the weight *m*, at different positions of the output link of the drive:

$$\sum M_O = m \cdot g \cdot L \cdot \cos\varphi - F(\varphi) \cdot b \cdot \sin\gamma = 0 \quad (1)$$

Hence follows:

$$F(\varphi) = \frac{m \cdot g \cdot L \cdot \cos\varphi}{b \cdot \sin\gamma} \quad (2)$$

Using trigonometric relations, the γ angle can be excluded from expression (2). According to the sine theorem for the triangle ABO can be written:

$$\frac{a}{\sin\gamma} = \frac{z}{\sin(\alpha+\varphi)} \quad (3)$$

Hence follows:

$$\sin\gamma = \frac{\mathrm{a}}{\mathrm{z}} \cdot \sin(\alpha+\varphi) \quad (4)$$

According to the cosine theorem for the triangle, ABO can be written:

$$z^2 = a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(\alpha+\varphi) \quad (5)$$

Then:

$$z = \sqrt{a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(\alpha + \varphi)} \tag{6}$$

Taking into account formulas (4) and (6), expression (2) will take the form:

$$F(\varphi) = \frac{m \cdot g \cdot L \cdot \sqrt{a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(\alpha + \varphi)} \cdot \cos\varphi}{a \cdot b \cdot \sin(\alpha + \varphi)} \tag{7}$$

At specified parameters of boom lifting mechanism: minimum (φ_{min}) and maximum (φ_{max}) values of boom lifting angle and minimum (z_{min}) and maximum (z_{max}) dimensions of hydraulic cylinder, independent parameter will be one of three: linear dimensions a or b, or α angle (Figure 1) [7-8].

Select the α angle as an independent parameter. Then *a* and *b* can be excluded from formula (7). To do this, write the expression (5) for the extreme positions of the boom:

$$z_{\min}{}^2 = a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(\alpha + \varphi_{\min}) \tag{8}$$

$$z_{\max}{}^2 = a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(\alpha + \varphi_{\max}) \tag{9}$$

Solving the system of equations (8) and (9) we get

$$a \cdot b = \frac{z_{\max}{}^2 - z_{\min}{}^2}{2 \cdot \left[\cos(\alpha + \varphi_{\min}) - \cos(\alpha + \varphi_{\max})\right]} \tag{10}$$

Let's substitute the expression (10) for product (a · b) in formula (8) find the expression for the sum $a^2 + b^2$

$$a^2 + b^2 = z_{\min}{}^2 - \frac{(z_{\max}{}^2 - z_{\min}{}^2) \cdot \cos(\alpha + \varphi_{\min})}{\left[\cos(\alpha + \varphi_{\min}) - \cos(\alpha + \varphi_{\max})\right]} \tag{11}$$

The right parts of equations (10) and (11) are constant. Enter symbols for them:

$$K_1 = \frac{z_{\max}{}^2 - z_{\min}{}^2}{2 \cdot \left[\cos(\alpha + \varphi_{\min}) - \cos(\alpha + \varphi_{\max})\right]} \tag{12}$$

$$K_2 = z_{\min}{}^2 - \frac{(z_{\max}{}^2 - z_{\min}{}^2) \cdot \cos(\alpha + \varphi_{\min})}{\left[\cos(\alpha + \varphi_{\min}) - \cos(\alpha + \varphi_{\max})\right]} \tag{13}$$

Then you can write:

$$a \cdot b = K_1 \tag{14}$$

$$a^2 + b^2 = K_2 \tag{15}$$

We substitute the expression (14) and (15) into formula (7) we get a dependence for force F on the angle of elevation of the boom *φ* and the angle *α*

$$F(\varphi, \alpha) = \frac{m \cdot g \cdot L \cdot \sqrt{K_2 - 2 \cdot K_1 \cdot \cos(\alpha + \varphi)} \cdot \cos\varphi}{K_1 \cdot \sin(\alpha + \varphi)} \tag{16}$$

We will find the limits for changing the *α* angle. Since the sum of the angles of *α* and *φ* forms the inner angle of the triangle ABO, it can be written:

$$0 < \alpha + \varphi < \pi \tag{17}$$

The minimum α angle is determined from the left inequality condition (17) at $\varphi = \varphi_{min}$, i.e.

$$0 < \alpha + \varphi_{min} \tag{18}$$

From here, we get:

$$-\varphi_{min} < \alpha \tag{19}$$

The maximum α angle is determined from the right inequality condition (17) at $\varphi = \varphi_{min}$, i.e.

$$\alpha + \varphi_{max} < \pi \tag{20}$$

From here, we get:

$$\alpha < \pi - \varphi_{max} \tag{21}$$

Based on constraints (19) and (21), we get the range of change in the α angle:

$$\varphi_{min} < \alpha < \pi - \varphi_{max} \tag{22}$$

For each fixed value of the α_i angle α taken from the interval (22), one can find the corresponding values of K_{1i} and K_{2i} constants K_1 and K_2 using formulas (12) and (13), and calculate the values of force F for the entire given range using formula (16)

$$\varphi_{min} < \varphi < \varphi_{max} \tag{23}$$

change the boom elevation φ angle and plot $F(\varphi, \alpha_i)$.

Using the graph $F(\varphi, \alpha_i)$, you can find the maximum value $F_{max,i}$ of the force F corresponding to the α_i value. Repeating these operations for the entire range of angle change α we get a set of values $F_{max,i}(\alpha_i)$ and choosing among them the minimum value $[F_{max,i}(\alpha_i)]_{min}$ we will find the optimal value of the α_{opt} angle corresponding to it.

To determine linear dimensions *a* and *b*, we solve the system of equations (14) and (15). From equation (14) one can find a:

$$a = \frac{K_1}{b} \tag{24}$$

We substitute the expression (24) for *a* into equation (15) as a result we get:

$$\left(\frac{K_1}{b}\right)^2 + b^2 = K_2 \tag{25}$$

or

$$b^4 - K_2 \cdot b^2 + K_1^2 = 0 \tag{26}$$

It is easy to find *b* from equation (26) (negative values are not considered as having no physical meaning in our problem)

$$b_1 = \sqrt{\frac{K_2 + \sqrt{K_2^2 - 4 \cdot K_1^2}}{2}} \tag{27}$$

$$b_2 = \sqrt{\frac{K_2 - \sqrt{K_2^2 - 4 \cdot K_1^2}}{2}} \tag{28}$$

For two values b_1 and b_2, we get two values for size *a*:

$$a_1 = \frac{K_1}{b_1} \tag{29}$$

$$a_2 = \frac{K_1}{b_2} \tag{30}$$

It isn't difficult to show that:

$$a_1 = b_2 \tag{31}$$

$$a_2 = b_1 \tag{32}$$

With formulas (27), (28), (31) and (32) it is easy to show that

$$b_1 > a_1 \tag{33}$$

$$b_2 < a_2 \tag{34}$$

Since size a has a greater influence on the dimensions of the base, the ratio (33) is preferable. Therefore, in the future we will use the ratio (33).

Substituting the optimal value of the angle α_{opt} in formulas (12) and (13) we get the optimal values of K_{1opt} and K_{2opt}, and substituting them in formulas (27) and (29) we get the optimal values of a_{opt} and b_{opt}.

Based on the above algorithm, a program for calculating the optimal parameters of the boom lifting mechanism was developed.

The results of calculations are shown in Figures 2 and 3 at the specified parameters of the boom lifting mechanism: minimum (φ_{min} = — 20 °) and maximum (φ_{max} = 80 °) values of the boom lifting angle and minimum (z_{min} = 1 m) and maximum (z_{max} = 1.8 m) dimensions of the hydraulic cylinder, for a load weighing m = 1500 kg, boom length L = 3 m.

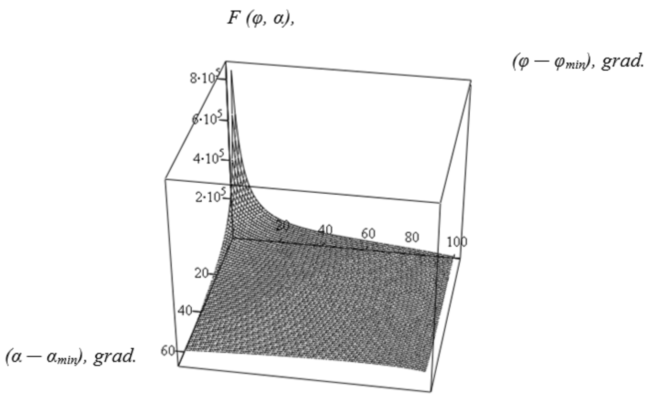

Fig. 2. Dependence of force F developed drive, from boom lifting φ angle and angle α.

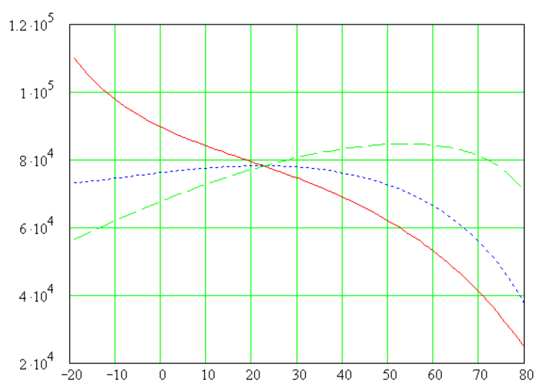

Fig. 3. Dependence of force F on φ at fixed α.

4 Conclusion

Figure 2 shows the dependence of force F (φ, α) on the boom rotation angle and the α angle. Figure 3 shows the dependence of force F (φ, α) on the boom rotation angle for several α angle values. Because of calculation, the following optimal values of parameters of the lifting mechanism were obtained for the given values of the boom mechanism parameters: the optimal value of the a_{opt} = 70.4 °, the optimal values of dimensions are a_{opt} = 0587 m and b_{opt} = 1.266 m.

Proposed method allows determining optimal parameters of boom lifting mechanism.

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