

CALCULATION OF THE MECHANISM FOR THE STRETCHING AND RETRACTING OF THE BOOM OF A TRUCK MOUNTED CRANE

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ABSTRACT. A methodology for the calculation of the mechanism for the stretching and retracting of the telescopic boom of a truck mounted crane is developed. The necessary force of the piston rod of the hydraulic cylinder for the stretching of the boom is determined using the principle of mechanics for the possible displacements of the telescopic boom with the load. Two cases are considered - at maximum and minimum angle of inclination of the boom, and at maximum angle a greater force is obtained. At first the problem is solved when the friction forces between the separate sections of the boom and the resistance in the rollers of the lifting polyspasts are ignored, and after that the obtained forces are corrected by the relevant coefficients. The necessary diameter of the piston and the necessary displacement of the hydraulic cylinder for the stretching and retracting of the boom are determined, and after that a hydraulic cylinder is chosen. The working liquid consumption of the hydraulic cylinder is determined. The maximum forces in the ropes of the polyspasts for the stretching and retracting of the upper section of the boom are determined and ropes are chosen.

On the basis of the developed methodology a concrete example is solved for the crane KC-45717, mounted on the truck chassis KamAZ.

Keywords: telescopic boom, tackle block, hydraulic cylinder, cable

ИЗЧИСЛЯВАНЕ НА МЕХАНИЗМА ЗА РАЗПЪВАНЕ И ПРИБИРАНЕ НА СТРЕЛАТА НА АВТОМОБИЛЕН КРАН

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РЕЗЮМЕ. Разработена е методика за изчисляване на механизма за разпъване и прибиране на телескопичната стрела на автомобилен кран. Определена е необходимата сила на буталния прът на хидроцилиндъра за разпъването на стрелата, като се изхожда от принципа на механиката за възможните премествания на телескопичната стрела с товара. Разгледани са два случая - при максимален и при минимален ъгъл на наклон на стрелата, като по-голяма сила се получава при максимален ъгъл на наклон. Първоначално задачата е решена като се пренебрегват силите на триене между отделните секции на стрелата и съпротивлението при въртенето на ролките от подемния полиспастр, след което получените сили се коригират чрез съответните коефициенти. Определени са необходимият диаметър на буталото и необходимият ход на хидроцилиндъра за разпъване и прибиране на стрелата, след което е избран хидроцилиндър. Определен е разходът на работна течност на хидроцилиндъра. Определени са максималните сили във въжетата на полиспастите за разпъване и прибиране на горната секция на стрелата и са избрани въжета.

На базата на разработената методика е решен конкретен пример за кран KC - 45717, монтиран на автомобилно шаси КамАЗ.

Ключови думи: телескопична стрела, полиспастр, хидроцилиндър, въже

Introduction

The methodologies for the calculation of the mechanisms for hoisting, traveling, slewing and boom inclination of the cranes are given in the textbooks, referring to the load lifting machines, but a methodology for the calculation of the mechanism for the stretching of the boom is not given.

In Reutov (2013) equations for the calculation of the forces in the hydraulic cylinder and the cables for the stretching and retracting of the boom of a truck mounted crane are obtained. Calculations with and without the regard to the friction forces between the sections and the resistances in the hoisting tackle block is done.

In Sharipov (2002) a methodology for the calculation of the hydraulic drives is given. In „Kran strelovoi avtomobilnai KS 45717K-1“ the design and the technical parameters of the calculated crane are given. In “Kanat dvoinoi svivki (GOST)”

the Russian standard for the cables, used in the truck cranes, is given.

The aim of the present work is the development of a methodology for the calculation of the mechanism for the stretching and retracting of the boom on the basis of these references. With the help of this methodology a concrete example is solved.

The boom of the crane KS-45717 (Fig.1) (Kran strelovoi avtomobilnai KS 45717K-1) is three sectional telescopic. It consists of a base section 4, a middle stretching section 2 and an upper stretching section 1. The mechanism for the stretching and retracting is mounted on the boom.

The sections of the boom have rectangular welded construction. In the front and back end of the movable sections are mounted the plastic plates 9, which guide the sections during their movement.

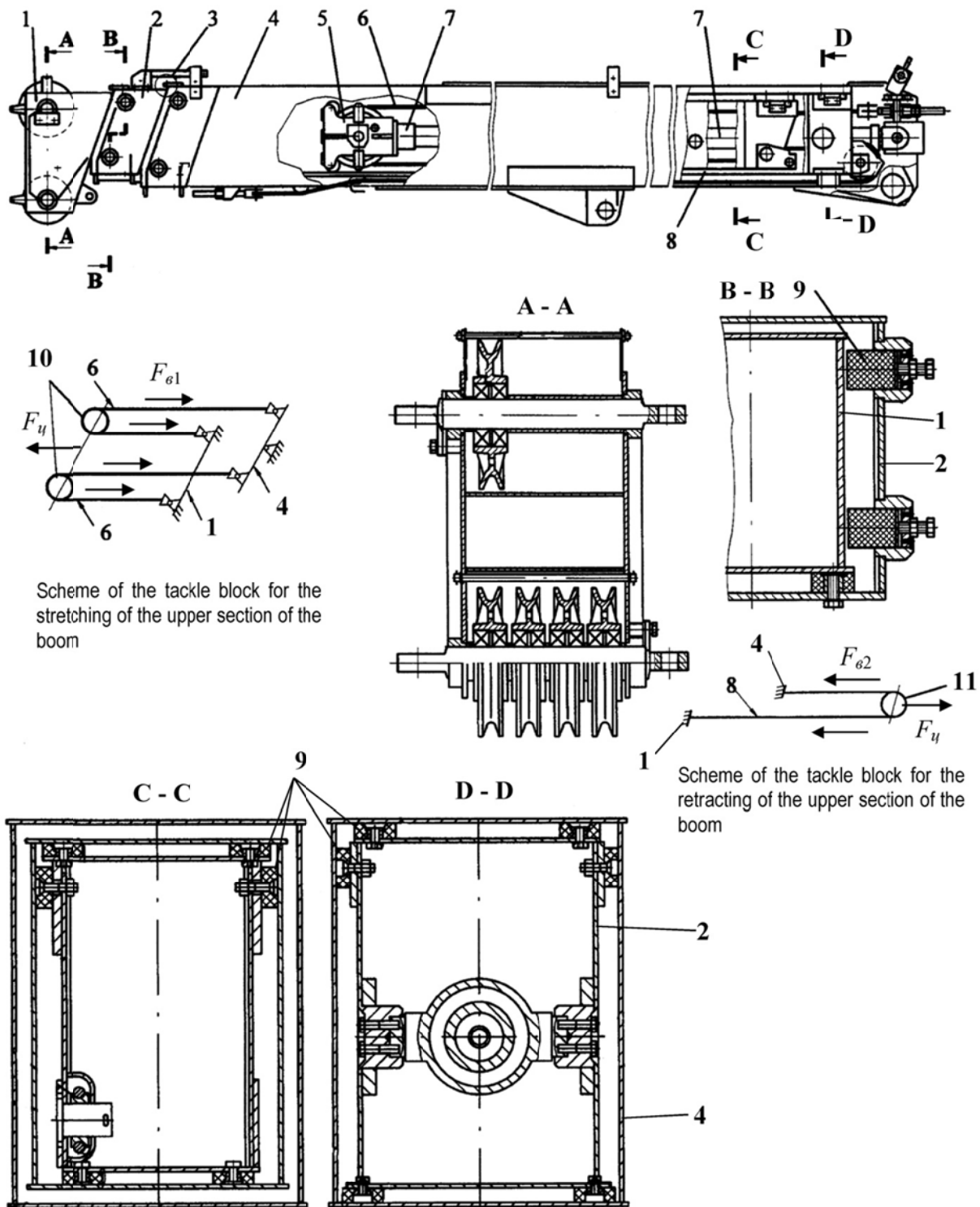


Fig. 1. Telescopic boom of the truck mounted crane KS-45717

1 - upper section; 2 - middle section; 3 - frame-restrictor of the hoisting cable; 4 - base section of the boom; 5 - bracket of the hydraulic cylinder; 6 - cables for the stretching of the upper section; 7 - hydraulic cylinder for stretching and retracting the boom; 8 - cable for the retracting of the upper section; 9 - plastic plates; 10, 11 - tackle blocks

F_{61} - tension in the cable for the stretching of the upper section of the boom; F_{62} - tension in the cable for the retracting of the upper section of the boom; F_u - force of the piston rod or the hydraulic cylinder for the stretching or retracting of the boom

The mechanism for the stretching and retracting of the sections of the boom consists of the hydraulic cylinder 7 and two cable tackle blocks. The cylinder ensures the movement of the middle section of the boom and the tackle blocks - the synchronic movement of the upper section of the boom when the middle section is moved.

The piston rod of the hydraulic cylinder 7 is attached to the back of the base section 4. The cylinder is attached to the back of the middle section 2. On the front end of the hydraulic cylinder 7 is mounted the bracket 5 with the blocks 10.

The tackle block for the stretching of the boom consists of the blocks 10 and the two cables 6. One of the ends of the cables 6 is attached to the back of the upper section 1 and the other - to the back of the base section 4.

The tackle block for the retracting of the boom consists of the block 11, mounted on the back of the middle section 2, and the cable 8. One of the ends of the cable 8 is attached to the back of the upper section 1 and the other - to the front end of the base section 4.

The length of the boom in unstretched position is 9m. When the middle section is moved toward the base section at a distance of 6m, which is equal to the stroke of the hydraulic cylinder, the upper section is moved toward the base section at a distance of 12m. This is, because the stretching tackle block has a ratio 2 and the upper section will move two times quicker than the middle section. In such a way the maximum stretched boom will have a length of 21m (9+12=21).

The retracting tackle block has also a ratio 2. When the cylinder retracts to the starting position the upper section will move backward 12m and the middle section - 6m.

Input data

The input data for the calculation of the mechanism is (Kran strelovoi avtomobilnii KS 45717K-):

- length of the boom $L=9+21$ m;
- angle of inclination of the boom $\beta=5+75^\circ$;
- lifting capacity of the crane at $L=21$ m and $\beta=75^\circ$ $Q_1=6.35$ t;
- lifting capacity of the crane at $L=21$ m and $\beta=5^\circ$ $Q_2=0.9$ t;
- mass of the upper section of the boom $m_e=657$ kg;
- mass of the middle section of the boom $m_c=642$ kg;
- mass of the hook block $m_{p\delta}=306$ kg;
- ratio of the tackle block of the hoisting mechanism $m=8$;
- velocity of stretching (retracting) of the boom $v_{pc}=18$ m/min;
- nominal pressure of the working liquid in the hydraulic system of the cylinder for stretching of the boom $p_H=20$ MPa;
- group of the working regime of the mechanism - 1.

Necessary force of the hydraulic cylinder for the stretching of the boom

With the purpose of simplifying the problem, the friction forces between the boom sections and the rolling resistances of the blocks of the hoisting tackle block are disregarded. We proceed with the principle from mechanics for the possible movements of the telescopic boom with the load. The work, which the piston rod of the hydraulic cylinder accomplishes, is

equal to the sum of the works, which the gravity forces of the middle and the upper sections of the boom and the hook block with the load accomplish. Then during the stretching of the boom the following equation is valid (fig.2):

$$F'_u \cdot s_u = G_c \cdot s_c \cdot \sin\beta + G_e \cdot s_e \cdot \sin\beta + (G_m + G_{p\delta}) \cdot s_m, \quad (1)$$

where: F'_u [kN] - necessary force of the piston rod of the hydraulic cylinder for overcoming the gravity forces of the middle and the upper section of the boom, the load and the hook block;

s_u [m] - stroke of the piston rod of the hydraulic cylinder;

G_c [kN] - gravity force of the middle section of the boom;

s_c [m] - stroke of stretching of the middle section of the boom;

G_e [kN] - gravity force of the upper section of the boom;

s_e [m] - stroke of stretching of the upper section of the boom;

G_m [kN] - gravity force of the load;

$G_{p\delta}$ [kN] - gravity force of the hook block;

s_m [m] - distance of the movement of the hook block with the load.

As the piston rod of the cylinder is connected with the middle section of the boom and the upper section of the boom is connected with the middle section by a velocity tackle block with ratio m' (the upper section moves quicker than the middle section during the stretching of the boom) the following equations are valid:

$$s_u = s_c; \quad s_e = m' \cdot s_c \quad (2)$$

The movement of the load during the stretching of the boom is determined by solving the equations (3+6) together:

$$s_m = H_2 - H_1 \quad (3)$$

$$H_1 = L_1 \cdot \sin\beta - h_1 \quad (4)$$

$$H_2 = (L_1 + s_e) \cdot \sin\beta - h_2 \quad (5)$$

$$h_1 - h_2 = \frac{s_e}{m} \quad (6)$$

where: H_1, H_2 [m] - heights of the load toward the axis of the hanging of the boom before and after the stretching of the boom;

L_1 [m] - length of the boom before the stretching;

h_1, h_2 [m] - distance between the top of the boom and the load before and after the stretching.

The following equation is obtained for the movement of the load:

$$s_m = s_e \cdot \left(\sin\beta + \frac{1}{m} \right) \quad (7)$$

After the substitution of the equations (7) and (2) in the equation (1), the following equation is obtained for the necessary force of the piston rod of the cylinder:

$$F'_u = (G_c + m' \cdot G_e) \cdot \sin\beta + m' \cdot (G_m + G_{p\delta}) \cdot \left(\sin\beta + \frac{1}{m} \right) \quad (8)$$

The case when the boom is stretched from $L_{min}=9$ m to $L_{max}=21$ m at maximum angle of inclination ($\beta=75^\circ$)

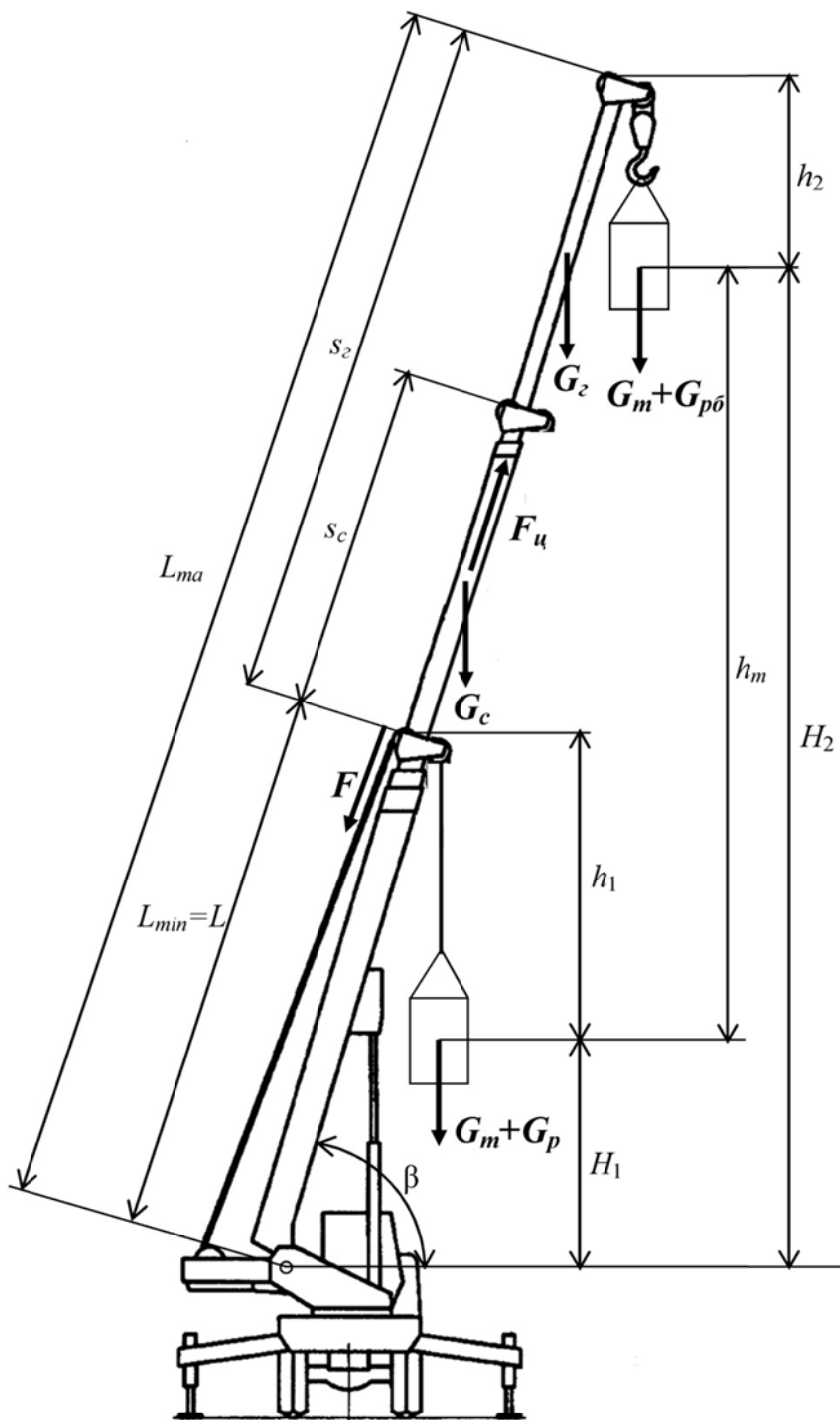


Fig. 2. Scheme for the calculation of the mechanism for the stretching and retracting of the boom

s_2, s_c - strokes of the upper and the middle section of the boom; L_{max}, L_{min}, β - maximum length, minimum length and angle of inclination of the boom; L_1 - length of the boom before the stretching; $G_m, G_{p\delta}, G_2, G_c$ - gravity forces of the load, the hook block, upper section of the boom and the middle section of the boom; F - tension in the hoisting cable; H_1, H_2 - heights of the load toward the axis of the hanging of the boom before and after the stretching of the boom; h_1, h_2 - distances between the top of the boom and the load before and after the stretching of the boom; F_u - force of the piston rod of the hydraulic cylinder for the stretching of the boom

with load, equal to the maximum permissible for $L=21\text{m}$ and $\beta=75^\circ$, i.e. at lifting capacity $Q=Q_1=6,35\text{t}$ is considered. The ratio of the tackle block for the stretching of the upper section of the boom is assumed to be $m' = 2$. Then, the following equations are obtained:

$$F'_u = (6,3 + 2 \cdot 6,45) \cdot \sin 75^\circ + 2 \cdot (62,3 + 3) \cdot \left(\sin 75^\circ + \frac{1}{8} \right) = 160 \text{ kN} \quad (9)$$

$$\text{where: } G_c = 0,001 \cdot m_c \cdot g = 0,001 \cdot 657 \cdot 9,81 = 6,45 \text{ kN} \quad (10)$$

$$G_z = 0,001 \cdot m_z \cdot g = 0,001 \cdot 642 \cdot 9,81 = 6,3 \text{ kN} \quad (11)$$

$$G_m = Q_1 \cdot g = 6,35 \cdot 9,81 = 62,3 \text{ kN} \quad (12)$$

$$G_{p\delta} = 0,001 \cdot m_{p\delta} \cdot g = 0,001 \cdot 306 \cdot 9,81 = 3 \text{ kN} \quad (13)$$

After the calculations with the regard to the friction forces between the sections (the coefficient of friction is $f=0.15$) and the rolling resistances of the blocks of the tackle the following is found out (Reutov, 2013): the resistance from the friction forces at maximum angle of inclination of the boom ($\beta=75^\circ$) is 13% from the total resistance and at minimum angle of inclination of the boom ($\beta=5^\circ$) - 80%; the rolling resistances of the blocks are 2.7% at $\beta=75^\circ$ and 0.9% at $\beta=5^\circ$. Then, the following equation for the necessary force of the hydraulic cylinder for the stretching of the boom is obtained:

$$F_u = k_m \cdot F'_u = 1,19 \cdot 160 = 190 \text{ kN} \quad (14)$$

where: k_m - coefficient, regarding the resistance of the friction forces between the sections of the boom and the rolling resistance of the blocks of the hoisting tackle during the stretching of the boom (it is determined by equations (15) and (16));

$$k_m = \frac{100}{100 - (k_1 + k_2)} = \frac{100}{100 - (13 + 2,7)} = 1,19 \quad \text{at } \beta=75^\circ \quad (15)$$

$$k_m = \frac{100}{100 - (k_1 + k_2)} = \frac{100}{100 - (80 + 0,9)} = 5,24 \quad \text{at } \beta=5^\circ \quad (16)$$

where: k_1 [%], k_2 [%] - percentage components of the resistance of the friction forces between the sections of the boom and the rolling resistance of the blocks of the hoisting tackle from the total resistance during the boom extension.

Now a second case is considered when the boom is stretched from $L_{min}=9\text{m}$ to $L_{max}=21\text{m}$ at a minimum angle of inclination ($\beta=5^\circ$) with a load, equal to the maximum permissible for $L=21\text{m}$ and $\beta=5^\circ$, i.e. at lifting capacity $Q=Q_2=0.9\text{t}$. For this case the following equation is obtained:

$$F'_u = (G_c + m' \cdot G_z) \cdot \sin \beta + a' \cdot (G_m + G_{p\delta}) \cdot \left(\sin \beta + \frac{1}{8} \right) \quad (17)$$

$$F'_u = (6,3 + 2 \cdot 6,45) \cdot \sin 5^\circ + 2 \cdot (8,8 + 3) \cdot \left(\sin 5^\circ + \frac{1}{8} \right) = 6 \text{ kN}$$

$$F_u = k_m \cdot F'_u = 5,24 \cdot 6 = 31 \text{ kN} \quad (18)$$

$$\text{where: } G_m = Q_2 \cdot g = 0,9 \cdot 9,81 = 8,8 \text{ kN} \quad (19)$$

From the equations (14) and (18) is seen that force, obtained at a maximum angle of inclination of the boom is greater, i.e. $F_u=190\text{kN}$.

Necessary diameter of the piston of the hydraulic cylinder for the stretching and the retracting of the boom

$$d'_u = \sqrt{\frac{4 \cdot S'_u}{\pi}} = \sqrt{\frac{4 \cdot 11904}{3,14}} = 123 \text{ mm} \quad (20)$$

where: S'_u [mm^2] - necessary area of the cross section of the cylinder (it is determined by equation (21));

$$S'_u = \frac{1000 \cdot F_u}{\Delta p \cdot \eta_{um}} = \frac{1000 \cdot 190}{16,8 \cdot 0,95} = 11904 \text{ mm}^2 \quad (21)$$

where: Δp [MPa] - pressure drop in the hydraulic cylinder (it is determined by equation (22)); η_{um} - mechanical coefficient of efficiency of the hydraulic cylinder ($\eta_{um}=0.9 \div 0.95$);

$$\Delta p = p_{ex} - p_{usx} = 17 - 0,2 = 16,8 \text{ MPa} \quad (22)$$

where: p_{ex} [MPa] - pressure of the working liquid at the inlet of the hydraulic cylinder (it is determined by equation (23)); p_{usx} [MPa] - pressure of the working liquid at the outlet of the hydraulic cylinder (it is assumed $p_{usx}=0.2 \div 0.3\text{MPa}$);

$$p_{ex} = (0,8 \div 0,9) \cdot p_H = 0,85 \cdot 20 = 17 \text{ MPa} \quad (23)$$

Necessary stroke of the piston of the hydraulic cylinder for the stretching and the retracting of the boom

$$s'_u = \frac{L_{max} - L_{min}}{m'} = \frac{21 - 9}{2} = 6 \text{ m} \quad (24)$$

where: L_{max} u L_{min} [m] - maximum and minimum length of the boom (see fig.2).

Selection of a hydraulic cylinder for the stretching and the retracting of the boom

The hydraulic cylinder is chosen according to the necessary diameter of the piston d'_u [mm] and the necessary stroke of the piston s'_u [mm]. The conditions (25 and 26) must be fulfilled:

$$d_u = 125 \text{ mm} \geq d'_u = 123 \text{ mm} \quad (25); \quad s_u = 6 \text{ m} = s'_u = 6 \text{ m} \quad (26)$$

where: d_u [mm] - diameter of the piston of the cylinder; s_u [mm] - stroke of the piston of the cylinder.

The hydraulic cylinder KC-45717.63.900-1 is chosen with the following parameters: - diameter of the piston $d_u=125\text{mm}$; - diameter of the piston rod $d_{u1}=100\text{mm}$; - stroke or the piston rod $s_u=6000\text{mm}$; - nominal pressure $p_u=20\text{MPa}$.

Working liquid consumption of the hydraulic cylinder for the stretching and the retracting of the boom

$$Q_u = \frac{0,06 \cdot S_u \cdot v_u}{\eta_{uo}} = \frac{0,06 \cdot 12265 \cdot 0,15}{0,95} = 116 \text{ dm}^3/\text{min} , \quad (27)$$

where: S_u [mm^2] - cross section area of the hydraulic cylinder (it is determined by equation (28));

v_u [m/s] - necessary velocity of the piston rod of the hydraulic cylinder (it is determined by equation (29));

η_{uo} - volumetric coefficient of efficiency of the hydraulic cylinder ($\eta_{uo}=0,95$).

$$S_u = \frac{\pi \cdot d_u^2}{4} = \frac{3,14 \cdot 125^2}{4} = 12265 \text{ mm}^2 \quad (28)$$

$$v_u = \frac{v_{pc}}{60 \cdot m'} = \frac{18}{60 \cdot 2} = 0,15 \text{ m/s} \quad (29)$$

Selection of cables for the stretching of the upper section of the boom

The size of the cables is chosen according to the necessary breaking strength. The following condition must be satisfied:

$$F_{pazk} = 165 \text{ kN} \geq k \cdot F_{e1} = 3,55 \cdot 38 = 135 \text{ kN} , \quad (30)$$

where: F_{pazk} [kN] - breaking strength of the cable (it is dependent on the diameter of the cable d and the tensioning strength of the wires σ_B [N/mm^2]). At $d=16\text{mm}$ and $\sigma_B=1770\text{N/mm}^2$ $F_{pazk}=165\text{kN}$;

k - safety coefficient of the rope (it is determined from Table 1). At group of the regime of work or the mechanism 1, $k=3.55$;

F_{e1} [kN] - maximum tension in the cable (see Fig.2) (it is determined by equation (29));

Table 1.
Safety coefficient of the cables k

Group of the regime of work of the mechanism	1	2	3	4	5	6
k	3.55	4	4.5	5.6	7.1	9

$$F_{e1} = \frac{F_u' - (G_c + G_e + G_m + G_{p\delta}) \cdot \sin\beta - F}{z_e}$$

$$F_{e1} = \frac{160+30-(6,3+6,45+62,3+3) \cdot \sin 75^\circ - 8,3}{2} = 38 \text{ kN} , \quad (31)$$

where: F [kN] - tension in the hoisting cable (Fig.2) (it is determined by equation (32)); z_e - number of the cables for the stretching of the upper section of the boom ($z_e = 2$);

$$F = \frac{G_m + G_{p\delta}}{\eta_n \cdot m} = \frac{62,3 + 3}{0,933 \cdot 8} = 8,3 \text{ kN} \quad (32)$$

where: η_n - coefficient of efficiency of the tackle block (it is determined by equation (33));

$$\eta_n = \frac{1 - \eta_{po}^m}{(1 - \eta_{po}) \cdot m} = \frac{1 - 0,98^8}{(1 - 0,98) \cdot 8} = 0,933 , \quad (33)$$

where: η_{po} - coefficient of efficiency of one block ($\eta_{po} = 0.98$).

A cable type LK-RO (Kanat dvoynoi svivki LK-RO) 16-G-V-ZH-N-R-1770 GOST 2669-80 with diameter $d=16\text{mm}$, load (G), model of the wires V, with zinc-coated wires with surface density type ZH, non-twisting (N), balanced (R), with tensile strength of the wires $\sigma_B=1770\text{N/mm}^2$ and breaking strength $F_{pazk}=165 \text{ kN}$ is chosen.

Selection of a cable for the retracting of the upper section of the boom

The size of the cable is chosen according to the necessary breaking strength. The following condition must be satisfied:

$$F_{pazk} = 122 \text{ kN} \geq k \cdot F_{e2} = 3,55 \cdot 30 = 107 \text{ kN} , \quad (34)$$

where: F_{pazk} [kN] - breaking strength of the cable (at $d=16\text{mm}$ and $\sigma_B=1670\text{N/mm}^2$ $F_{pazk} = 122\text{kN}$);

F_{e2} [kN] - preliminary tension of the cable for the retracting of the upper section of the boom, necessary for the compensation of the pressure force to the cable when the boom is retracted (see Fig.2) (when the angle of inclination of the boom is large the retracting of the boom is done under its own weight) (it is assumed $F_{e2} = 30\text{kN}$).

A cable type LK-R (Kanat dvoynoi svivki LK-R) 15-G-VK-ZH-N-R-1670 GOST 2669-80 with diameter $d=16\text{mm}$, tensile strength of the wires $\sigma_B = 1670\text{N/mm}^2$ and breaking strength $F_{pazk} = 122 \text{ kN}$ is chosen.

Conclusions

A methodology for the calculation of the mechanism for the stretching of the boom is developed, which will be useful for the specialists dealing with the design and exploitation of mobile cranes.

The maximum forces in the hydraulic cylinder and the cables of the mechanism are obtained at a maximum angle of inclination of the boom with a maximum permissible load.

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