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The Influence of Operating Factors on the Ram-type Steering Gear Elements Force Interaction

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ABSTRACT

Article deals with ram-type ship steering gear load capacity, rigidity and parts force interaction. It is shown that mechanism of perception and transmission of lateral force by the parts of a ram-type steering gear can contain three stages depending on gaps between elements. Presented mathematical model of load distribution considers the size of the gaps between the ram and the sleeve, as well as the ram and the guide beam. At the example of R-18 steering gear using the developed model it is shown that the guide beam works inefficiently. In case of minimal gaps in linkings, the guide beam can take 74% of the lateral load, and when the gaps are increased to the maximum allowable values in operation, the guide beam will take only 56% of the lateral load overloading the ram which leads the intensity of wear on their sleeves and system oil leakage increases, which leads to an increased fire hazard in the tiller room.

1. Introduction.

The perfection of the design of any machine depends on the ability to maintain the stability of technical characteristics and operating parameters throughout the entire period of operation (maintainability is one of the reliability criteria) [1]. In machines, the mechanisms contain redundant constraints, and during operation, loads are redistributed between parts, which leads to overloading some and unloading of others [2 – 4].

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2. Problem statement.

In some cases, this causes a change in the technical characteristics of the machine and an increase in mechanical losses, which contradicts modern trends in energy saving [5, 6]. This is especially important for ship steering gears, the safety of which depends in particular on the safety of navigation [7, 8].

Work [2] devoted to analyzing the design of ram-type ship steering gears, which show the presence of a significant number of redundant constraints, most of which arise from the connection of rams with a guide beam, creating conditions for further research.

The work aims to analyze the influence of operating factors, particularly gaps in kinematic pairs of ram-type steering gear, on the load distribution between the ram and the guide beam, and evaluate the guide beam efficiency.

Study tasks:

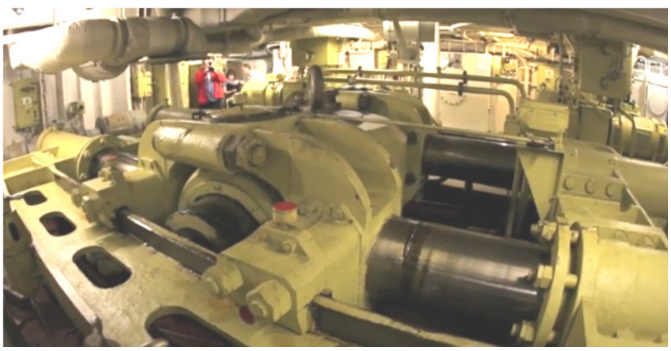
- to develop a mathematical model of load distribution between the ram and the guide beam;
- to establish the influence of operational factors, particularly the gaps between the ram and the guide beam;
- evaluate the efficiency of the guide beam and establish

reserves for improving the design of ram-type steering gears.

3. Materials and Methods.

We will evaluate the efficiency of the guide beam as an unloading element in the ram-type steering gear, taking into account the influence of operational factors, by analyzing the load distribution between the ram and the guide beam during gear operation, taking into account possible gaps that arise due to the wear of its parts. We will perform the calculation using the example of the R-18 steering gear (Fig. 1).

Figure 1: General view of the steering gear R-18 mechanism.



Source: Authors.

To do this, consider the calculation scheme shown in Fig. 2. The lateral force F_l acting on the ram and guide beam from the tiller operation is determined by the ratio:

$$F_l = F_t \sin\alpha = \frac{M_t}{2}\sin\alpha\cos\alpha = \sum_{i=1}^{n} F_{ri} + F_{gb}, \qquad (1)$$

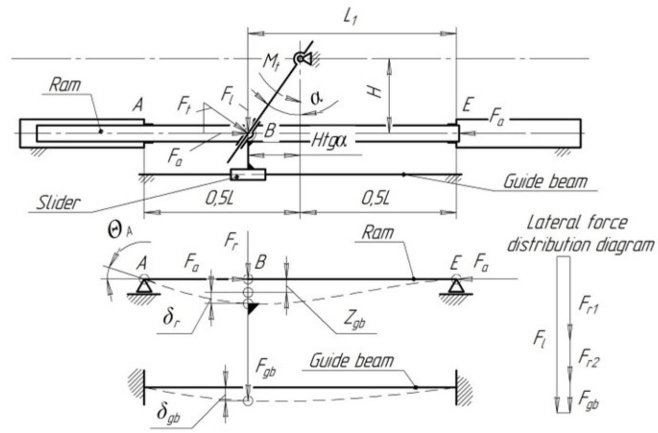
where:
F_t – tiller tangential load;
α – stern transfer angle;
M_t – tiller torque;
H – the distance between the axes of the baller and the ram;
F_{ri} – part of the lateral force perceived by the ram at the i-th stage of its loading;
F_{gb} – part of the lateral force perceived by the guide beam.

The ram will work under the conditions of longitudinal and transverse bending, its deflection in the absence of pinching in both supports will be [9]

$$\delta_r = \frac{\delta_{r0}}{1 - \frac{F_a}{F_{Eu}}}, \qquad (2)$$

where:
δ_{r0} – deflection of the ram as a two-support beam during transverse bending due to the action of only the transverse force F_r;
F_a – axial force compressing the ram;
F_{Eu} – Euler force for the ram.

Figure 2: Steering gear R-18 mechanism calculation scheme.



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$$F_a = F_t\cos\alpha = \frac{M_t\cos^2\alpha}{2H}; \qquad (3)$$

$$F_8 = \frac{\pi^2 J_r}{L_1^2}; \qquad (4)$$

$$L_1 = 0,5L + Htg\alpha, \qquad (5)$$

where:
J_r – the ram cross-section moment of inertia;
E – elasticity modulus of the ram and guide beam material (predominately steel);
L – distance between hydraulic cylinders.

For the R-18 gear, the maximum torque is M_t = 1000 kN•m, the main dimensions of the gear are the following: H = 600 mm, L = 1600 mm. The guide beam and ram are made of steel (E = 2.1×105 MPa). The ram has an annular section with outer and inner diameters d_r = 240 mm, d_{r1} = 160 mm, and moment of inertia J_r = 130690254 mm^4. Under such parameters (for α = 35°, where the maximum length of the ram and the value of the axial force), taking into account the longitudinal bending gives an increase in deflection of only 0.31% ($\delta_r = 1.0031\delta_{r0}$). Because of this, we further consider only the transverse bending of the ram.

If there are gaps, 2Z between the ram and the sleeve of the hydraulic cylinder, as well as Z_{gb} in the connection of the ram (slider equipped) with the guide beam, the perception by the ram and the guide beam will take place in n stages. The number of these stages cannot be determined directly, as the gap ratio, the stiffness of the ram, and the position of the point of application of the lateral force determine them.

In the absence of exhaust of the gap Z_{gb} in the connection of the ram with the guide beam, an elementary double-beam system (EDBS) is formed (Fig. 4, III), where the ram is a beam with radial flexibility λ_{rn}, and the guide beam is rigidly clamped at both ends with radial flexibility λ_{gb}. For such a system, the ratio between forces and deformations is valid:

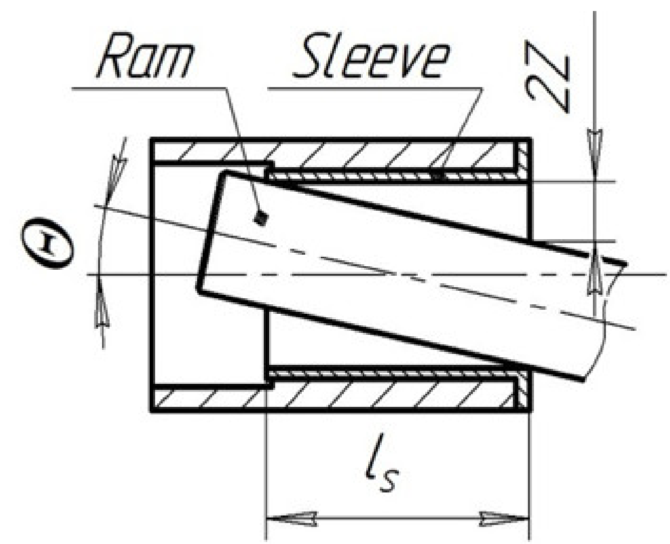
$$\begin{cases} F_{rn} + F_{gb} = F_l - \sum_{i=1}^{n-1} F_{ri}; \\ \delta_{rn} = \delta_{gb}; \\ \delta_{rn} = F_{rn}\lambda_{rn}; \\ \delta_{gb} = F_{gb}\lambda_{gb}; \end{cases} \Rightarrow \begin{cases} F_{rn} = \left[F_l - \sum_{i=1}^{n-1} F_{ri}\right] \frac{\lambda_{rn}}{\lambda_{rn}+\lambda_{gb}}; \\ F_{gb} = \left[F_l - \sum_{i=1}^{n-1} F_{ri}\right] \frac{\lambda_{gb}}{\lambda_{rn}+\lambda_{gb}}; \end{cases} \quad (6)$$

The conditions for fixing the ram as a beam may vary depending on the following. If there is a gap of *2Z* between the ram and the sleeve of the hydraulic cylinder (Fig. 3), it is possible to turn its end in support *A* by the amount:

$$\theta_{max} = \frac{2Z}{l_s} \quad (7)$$

where:
l_s – ram sleeve length.

Figure 3: Ram in sleeve disposition scheme.



Source: Authors.

If there is a sufficient angular gap ($\Delta\theta_A = (\theta_{max} - \theta_A) \geq 0$) in support A, the ram will be able to deform as a beam on two hinged supports (Fig. 4, I), the deflection at point B, the application of force and compliance in this case will be calculated as (8), and angle of rotation in support A – according to expression (9) [10]. In the absence of an angular gap, support A should be considered a rigid pinch (Fig. 4, II), and deflection and yielding will be calculated according to expression (10). Deflection and flexibility of the guide beam – according to expression (11).

$$\delta_{r1} = F_{r1}\frac{L_1^2(L-L_1)^2}{3EJ_rL} = F_{r1}\lambda_{r1}; \quad (8)$$

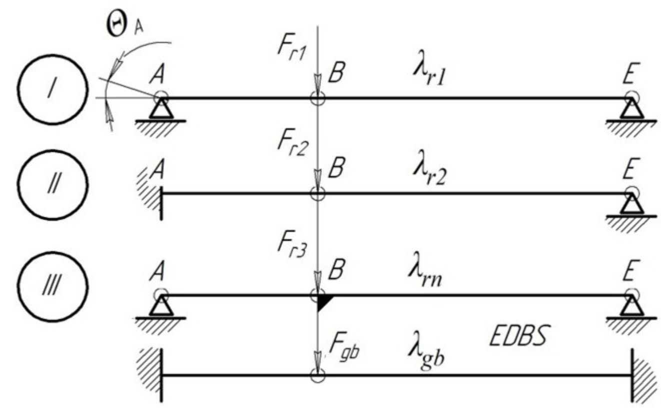
$$\theta = F_{r1}\frac{L^2(L_1/L - \left[L_1/L\right]^3)}{6EJ_r}; \quad (9)$$

$$\delta_{r2} = F_{r2}\frac{L_1(L-L_1)^3\left[6L^2 + 3LL_1 - L_1^2\right]}{12EJ_rL^3} = F_{r2}\lambda_{r2}; \quad (10)$$

$$\delta_{gb} = F_{gb}\frac{L_1^3(L-L_1)^3}{3EJ_gL^3} = F_{gb}\lambda_{gb}, \quad (11)$$

where:
J_{gb} – the guide beam cross section moment of inertia.

Figure 4: Scheme for determining the stages of load perception.



Source: Authors.

At the same time, the radial force required to completely remove the angular gap in support A will be calculated by expression (12), the deflection of the ram corresponding to this gap is calculated by expression (13), and the force required for the deflection of the ram (hinged) by the amount the Z_{gb} gap between the ram and the guide beam is according to expression (14).

$$F_\theta = \frac{6EJ_r\theta_{\max}}{L^2(L_1/L - \left[L_1/L\right]^3)}; \quad (12)$$

$$\delta_\theta = \frac{2\theta_{\max}(L-L_1)^2L_1^2}{L^3(L_1/L - \left[L_1/L\right]^3)}; \quad (13)$$

$$F_Z = \frac{Z_{gb}}{\lambda_{r1}}. \quad (14)$$

The ratio between forcesF_θ, F_Z, and F_l determines the number of stages of load perception, its possible cases (their number is 3! = 6) are given below.

Cases 1-2. If $F_l < F_\theta < F_Z$ or $F_l < F_Z < F_\theta$ the lateral force F_l is not enough to exhaust the angular gap between the ram and the sleeve ($\Delta\theta_A \geq 0$) and the linear gap between the ram and the guide beam Z_{gb}. Accordingly, the ram will perceive all the load as a beam on two hinged supports. In this case, the number of load perception stages will be $n = 1$, and the calculation scheme will have the form I in Fig. 4. The loads and deformations of the ram and the guide beam will be:

$$\begin{gathered} F_r = F_l; \\ F_{gb} = 0; \\ \delta_r = F_l\lambda_{r1} \\ \delta_{gb} = 0. \end{gathered} \quad (15)$$

Case 3. With $F_\theta < F_l < F_Z$ the lateral force F_l, it is not enough to exhaust the linear gap Z_{gb} between the ram and the guide beam, but it is enough to select the angular gap between the ram and the sleeve ($\Delta\theta_A < 0$). Accordingly, the perception of the load will occur in two stages ($n = 2$): deformation of the ram will occur first as beams on both hinge supports, and then - with one pinched and the other hinged, and the guide beam will not work. The calculation scheme will have the form I + II in Fig. 4. The loads and deformations of the ram and the guide beam will be:

$$\begin{gathered} F_r = F_l = F_{r1} + F_{r2} = F_\theta + F_{r2}; \\ F_{gb} = 0; \\ \delta_r = \delta_\theta + F_{r2}\lambda_{r2} = \delta_\theta + (F_l - F_\theta)\,\lambda_{r2}; \\ \delta_{gb} = 0. \end{gathered} \tag{16}$$

Case 4. With $F_Z < F_l < F_\theta$ a lateral force F_l is not enough to exhaust the angular gap between the ram and the sleeve ($\Delta\theta_A \geq 0$), but it is sufficient to select the linear gap Z_{gb} between the ram and the guide beam. Accordingly, the perception of the load will take place in two stages ($n = 2$): first, the ram will bend by the amount Z_{gb}, then the operation of the elementary two-beam system described above takes place. The calculation scheme will have the form I + III in Fig. 4. The loads and deformations of the ram and guide beam will be:

$$\begin{gathered} F_r = F_{r1} + F_{r2} = F_Z + F_{r2}; \\ F_{r2} = [F_l - F_Z]\,\tfrac{\lambda_{r1}}{\lambda_{r1}+\lambda_{gb}}; \\ F_{gb} = [F_l - F_Z]\,\tfrac{\lambda_{gb}}{\lambda_{r1}+\lambda_{gb}}; \\ \delta_r = Z_{gb} + F_{r2}\lambda_{r1}; \\ \delta_{gb} = F_{gb}\lambda_{gb}. \end{gathered} \tag{17}$$

Cases 5-6. The options for$F_\theta < F_Z < F_l$ or $F_Z < F_\theta < F_l$ which are the most difficult, are valid for small gaps $2Z$ between the ram and the sleeve (steering gear after repair or adjustment). We assume that the angular gap between the ram and the sleeve ($\Delta\theta_A < 0$) is immediately exhausted, and the support A of the ram becomes pinched, and the linear gap remains unexhausted ($\delta_\theta < Z_{gb}$). At the same time, the residual lateral force and deflection of the ram as a pinched beam will be:

$$\begin{gathered} \Delta F = F_l - F_\theta; \\ \Delta\delta = (F_l - F_\theta)\,\lambda_{r2}. \end{gathered} \tag{18}$$

If then $\Delta\delta > (Z_{gb} - \delta_\theta)$ the load will be transferred to the guide beam, and the force that the ram can additionally absorb when selecting the gap Z_{gb} will be:

$$F_{r2} = \frac{Z_{gb} - \delta_\theta}{\lambda_{r2}}. \tag{19}$$

After selecting the gap Z_{gb}, the ram and guide beam will operate as an EDBS. Thus, the load transfer will take place in three stages ($n = 3$), the calculation scheme will have the form I + II + III in Fig. 4, and the load and deformations of the ram and the guide beam will be:

$$\begin{gathered} F_r = F_{r1} + F_{r2} + F_{r3} = F_\theta + F_{r2} + F_{r3}; \\ F_{r3} = [F_l - F_\theta - F_{r2}]\,\tfrac{\lambda_{r2}}{\lambda_{r2}+\lambda_{gb}}; \\ F_{gb} = [F_l - F_\theta - F_{r2}]\,\tfrac{\lambda_{gb}}{\lambda_{r2}+\lambda_{gb}}; \\ \delta_r = \delta_\theta + Z_{gb} + F_{r3}\lambda_{r2}; \\ \delta_{gb} = F_{gb}\lambda_{gb}. \end{gathered} \tag{20}$$

Otherwise, if $\Delta\delta < (Z_{gb} - \delta_\theta)$, then the guide beam does not start working, and the ram will deform in two stages ($n = 2$), according to cases I + II in Fig. 4 and the load and deformations of the ram and the guide beam will be calculated according to (16).

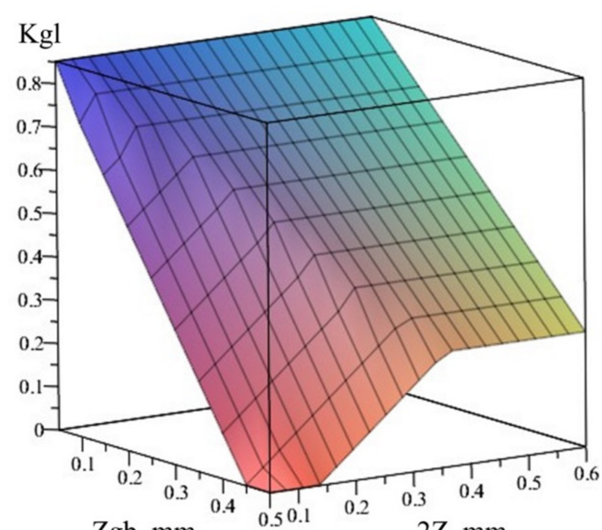
For all cases, we will estimate the efficiency of the guide beam by its load factor:

$$K_{gl} = \frac{F_{gb}}{F_l}. \tag{21}$$

4. Results.

The calculation results using the developed mathematical model are presented below in the form of graphs. When performing the calculations, it was assumed that the ram in the sleeve was installed with a gap. The fit H9/f9 provides the minimum probable gap $2Z_{min}$ = 0.084 mm, the maximum probable gap $2Z_{max}$ = 0.246 mm. Permissible in operation (limit wear) is regulated by [2Z] = 0.600 mm, and the gap between the guide beam and the ram slider is not more than [Z_{gb}] = 0.250 mm (however, in operation, of course, it can reach larger values). The minimum value of this gap is limited by the thickness of the probe Z_{gbmin} = 0.100 mm. With this in mind, 2Z = 0.005...0.600 mm and Z_{gb} = 0.005...0.500 mm were used in the calculations.

Figure 5: The graph of the influence of gaps 2Z and Z_{gb} on the load factor of the guide beam K_{gl}.



Source: Authors.

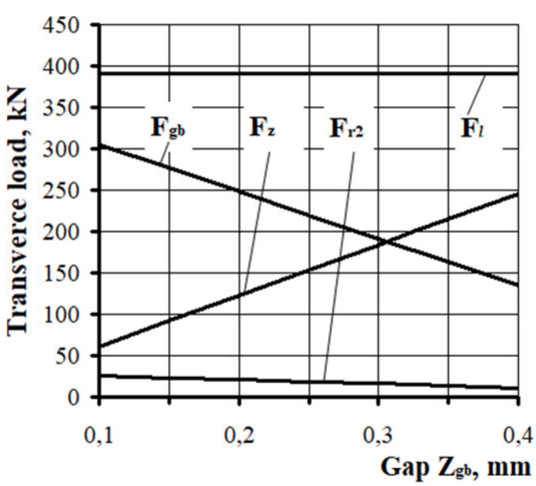
The graph of the influence of these gaps on the load factor K_{gl} of the guide beam (J_{gb} = 284981668 ??[4]) is shown in

Fig. 5, constructed for tiller rotation angle $\alpha = 35°$ and lateral force $F_l = 392$ kN. The graph shows that the guide beam works effectively only with small gaps Z_{gb}, which is quite challenging to achieve in operation. So, with the allowable gap $[Z_{gb}] = 0.250$ mm according to the operating rules of the timing belt, the guide beam in the best case perceives 40...60% of the lateral load, larger K_{gl} values are achievable only with smaller gaps between the ram and the sleeve 2Z = 0.200...0.300 mm, which is also unlikely due to wear of rams and sleeves.

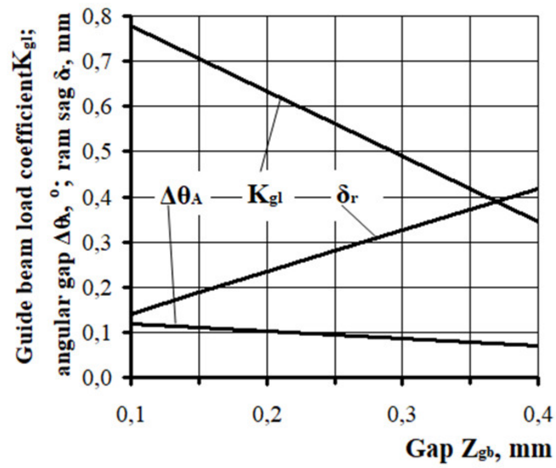
Mechanisms of perception of transverse load are illustrated in Fig. 6 and Fig. 7. Fig. 6 shows the previously described case 4 force ratio ($F_Z < F_l < F_\theta$) corresponding to the gap between the ram and the sleeve 2Z = 0.60 mm. The graph illustrates the dependence of transverse forces perceived by the ram and the guide beam. The large value of the gap 2Z between the ram and the sleeve ensures the presence of an angular gap $\Delta\theta_?$ in the support A and allows the ram to bend within the gap Z_{gb} between the ram and the guide beam, like the beams on the hinged supports, transferring the load to it. As the gap Z_{gb} between the ram and the guide beam increases, the efficiency of the latter decreases. With a gap $Z_{gb} = 0.100$ mm, the guide beam receives 305 kN of lateral force, and the ram 87 kN, or 22% ($K_{gl} = 0.78$). When the gap increases to $Z_{gb} = 0.150$ mm, the load on the ram increases to 115 kN, and the guide beam decreases to 277 kN, that is, the guide beam will take 71% of the lateral force ($K_{gl} = 0.71$). When the gap is further increased to the maximum allowable value $[Z_{gb}] = 0.250$ mm according to the rules of operation, the guide beam will take 56% of the lateral force ($K_{gl} = 0.56$) or 220 kN, and the ram, respectively, 172 kN. The gap $Z_{gb} = 0.400$ mm, which is increased beyond the allowable operating norms, unloads the guide beam up to 135 kN; accordingly, the ram is overloaded and will take 256 kN ($K_{gl} = 0.35$).

Figure 6: Graph of the dependence of transverse forces (a), the load factor of the guide beam, the angular gap in support A, and the deflection of the ram (b) on the value of the gap Z_{gb} at 2Z = 0.6 mm.

a)



b)

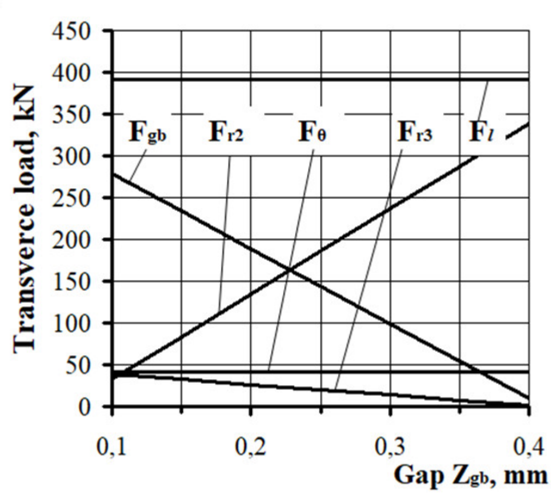


Source: Authors.

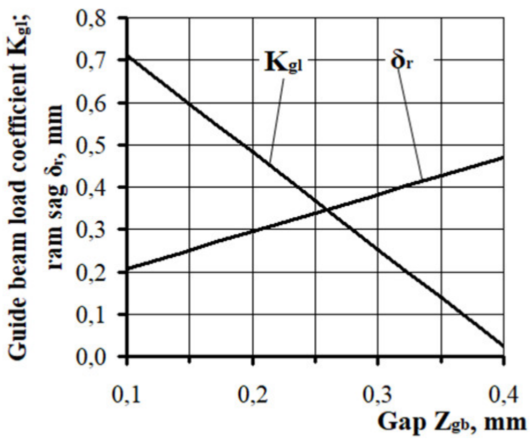
Case 5, when $F_\theta < F_Z < F_l$, illustrated in Fig. 7, where the minimum gap between the ram and the sleeve 2Z = 0.05 mm is adopted, which ensures, after closing the angular gap $\Delta\theta_A$, the ram works as a beam with a clamped support A. At a gap $Z_{gb} = 0.100$ mm, the guide beam receives 279 kN of lateral force, and the ram 113 kN, or 29% ($K_{gl} = 0.71$). When the gap increases to $Z_{gb} = 0.150$ mm, the load on the ram increases to 158 kN, and the guide beam load decreases to 234 kN, that is, the guide beam will take 60% of the load ($K_{gl} = 0.60$). When the gap is further increased to the maximum allowable value $[Z_{gb}] = 0.250$ mm according to the rules of operation, the guide beam will perceive 37% of the lateral force ($K_{gl} = 0.37$) or 144 kN, and the ram, respectively, 248 kN. The gap $Z_{gb} = 0.400$ mm, increased beyond the permissible value, will unload the guide beam down to 9 kN; accordingly, the ram will be overloaded - it will take 383 kN ($K_{gl} = 0.02$).

Figure 7: The graph of the dependence of transverse forces (a), the load factor of the guide beam and the deflection of the ram (b) on the size of the gap Z_{gb} at 2Z = 0.05 mm.

a)



b)



Source: Authors.

Thus, the performed calculations confirm that the operational efficiency of the guide beam to unload the ram from the transverse force depends on the state of the elements of the kinematic pairs of its mechanism, in particular, the values of the gaps 2Z and Z_{gb}, which confirms the structural imperfection of the R-18 mechanism due to the presence of redundant constraints. Increasing the technical level of ram-type steering gears is possible due to the use of new types of mechanisms for transferring the load from the rams to the tiller to reduce the transverse load of the rams and reduce the number of redundant constraints.

Conclusions.

1. The mechanism of perception and transmission of lateral force by the parts of a ram-type steering gear is disclosed. A mathematical model was developed that considers the size of the gaps between the ram and the sleeve, as well as the ram and the guide beam.

2. The results of calculations using the developed model demonstrate that the guide beam in the R-18 steering gear works inefficiently. The size of the gaps between lever mechanism parts significantly influences its load capacity. In a new gear, or after repair, if there are minimal gaps in linkings, the guide beam can perceive 74% of the lateral load, when the gaps are increased to the maximum allowable values in operation, the guide beam will perceive only 56% of the lateral load. When the gap between the ram and the guide beam further increases, the latter may fail altogether. With a significant load on the rams, the intensity of wear on their sleeves and the intensity of system oil leakage increases, which leads to an increased fire hazard in the tiller room.

3. Thus, the presence of a guide beam in the steering gear research design increases the number of redundant constraints in its mechanism and increases the complexity of maintenance and the danger to the crew.

4. Given the low operation efficiency and the significant complication of the gear design with the guide beam and the high loading of the rams by the transverse force, it can be argued that there is a reserve for increasing the technical level of the ram-type steering gears due to the use of new types of mechanisms for transferring the load from the rams to the tiller.

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