Selecting the design parameters of hydrostatic control system for a long-base truck train

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Abstract. For the delivery of long and bulky goods today long trailer trucks are used. In order to comply with the regulated maneuverability indicators, the semi-trailer of the truck train must be equipped with swiveling axles and an appropriate control system. Analysis of control systems for long-base truck trains showed that the most common today are hydro-volume control systems. The article describes the hydro volume control system of the pivot axles of the long-base truck train. The kinematic schemes and the description of the method for calculating the design parameters of the hydrostatic control system of a long-base truck are given.

1. Introduction
At present, up to 68% of all freight traffic is carried out using long-base truck trains. But such vehicles make up only 12% of all trucks on secondary roads [1]. In the EU countries, there are legislative acts strictly regulating the external and internal radii of vehicle rotation, which limits the use of truck trains with uncontrolled axles, both in cities and on secondary roads.

In addition, at present there is a great need for the transportation of long, heavy and oversized cargo. For these purposes, multi-axle semi-trailers with a telescopic sliding drawbar, the length of which can reach 36 m, have become widely used. It is physically impossible for such vehicles to move on public roads without control systems of a trailing link [2].

It is also necessary to note the economic aspect, for example, according to calculations made by TRIDEC, the use of a control system with swiveling axles or wheels on a semi-trailer allows reducing tire wear by up to 66% [3].

For a long time in Russia, priority was given to mechanical control systems. Analysis of the control systems of the trailed links of long-base truck trains showed that the most common today are hydrostatic control systems (HCS) [4].

This article describes the methodology for selecting and calculating the design parameters of the hydrostatic control system of the pivot axes of a long-base truck train.

The use of the hydrostatic control system of the pivot axles of a long-base truck train significantly improves the controllability and maneuverability of a long-base truck train, as well as significantly improves traffic safety, especially in conditions of intensive traffic flows.

2. Rated parameters of truck train maneuverability
Today, the main regulatory document in force on the territory of the Russian Federation that regulates the requirements for the design of the vehicle is Technical Regulations of the Customs Union on the
safety of wheeled vehicles, which in its turn is based on the requirements of the UNECE Regulations [5].

The regulated maneuverability indicators adopted in the UNECE Regulations are the dimensional outer turning radius \( R_a < 12.5 \text{ m} \) and the dimensional inside turning radius \( R_i > 5.3 \text{ m} \), the turning width of the track wheels \( B_R < 5.5 \text{ m} \) (Germany) [6].

The Russian Federation regulates the minimum turning radius \( R_{\text{min}} \leq 12 \text{ m} \).

As a criterion for optimizing maneuverability, researchers often use \( B_T \) which is an overall lane, \( B_R \) is the swivel width of the track of the wheels, and \( C_d \) is the shift in the trajectory of the trailer link relative to the main trajectory of the tractor [7, 8].

Figure 1 presents the estimated indicators of maneuverability of the truck train.

**Figure 1.** Estimated indicators of maneuverability of the truck train. \( R_a \) – outer radius, \( R_i \) – internal radius; \( R_{\text{min}} \) – minimum turning radius; \( B_T \) – overall lane; \( B_R \) – the swivel width of the track of the wheels; \( C_d \) – trailer link trajectory shift; 1 – base point of the tractor; 2 – base point of a semitrailer.

3. **Selection of HCS design parameters**

3.1. **Selecting the type of axles to be driven**

On modern semi-trailers, both individual wheels and axles of the semi-trailer can be controlled.

HCS are “passive”, i.e. without amplification. The force required to turn the steering wheels or axles is created by the master device (hydraulic cylinders), and the necessary forces or moments are realized due to the lateral reactions of the front steering wheels of the tractor.

The use of pivot axles allows using them at high axial loads, while at the same time less driving forces are required to rotate the axis. As a disadvantage, it is noted that the use of rotary axes requires large axle distances. An example of a control system with rotary axes is shown in figure 2.
Figure 2. Kinematic scheme of a truck train with controlled axes of the company Tridec. 1 – master cylinders; 2 – pivot points; 3 – executive cylinders.

Driving wheels can be realized both with a dependent suspension in the form of a rigid axis and with an independent suspension. At the same time, their installation requires shorter center distances. Of the minuses worth noting is the axis price increase. An example of a control system with swivel wheels is shown in figure 3.

Figure 3. Kinematic diagram of a hydrostatic control system with rotating wheels of the company Tridec. 1 – tractor; 2 – tractor saddle; 3 – master cylinders; 4 – connecting hoses; 5 – semi-trailer; 6 – executive cylinders; 7 – crank; 8 – thrust; 9 – guide.

3.2. Kinematic analysis of indicators of maneuverability of a truck train and the choice of strategy for control system

When selecting the design parameters of the control system (CS), a kinematic analysis of the drive of the controlled axles or wheels is performed. This is based on the condition of rolling all the wheels of a train, with steady curvilinear motion, with a constant turning radius, in concentric circles with a single instantaneous turning center at point O.

To ensure the minimum displacement of the trajectory of the tractor and semi-trailer $C_d$ or the minimum overall lane of traffic $B_T$ (figure 4) all axles of the semi-trailer are required to be controlled. Naturally, this mode of movement requires turning all the wheels to different angles.
The control system is characterized by the gear ratio $i_d$, which is:

$$i_d = \frac{\alpha_3}{\alpha_2};$$

where $\alpha_2$ – truck train folding angle; $\alpha_3$ – average steering angle of the semi-trailer steered wheels.

The choice of the gear ratio of the control system is determined by the design parameters of the semi-trailer: the base of the semi-trailer, the number of axles controlled and the strategy for optimizing the motion path.

The gear ratio $i_d$ can have both a constant and a variable value.

If the gear ratio in the CS is constant, i.e., $i_d = const$, then during the movement of a truck train on a turn of $90^\circ$ at the semi-trailer truck, point 3, there is a shift of the trajectory relative to point 2, to the outside when entering the turn and to the inside when leaving the turn. The shift of the trajectory negatively affects traffic safety, especially in conditions of intensive traffic flows.

Figure 5 shows a dependence graph of the angle of rotation of the steer wheels of the semi-trailer versus the folding angle of the truck train for systems with constant and variable gear ratio.
Simulation of the movement of a truck train allows us to conclude that the control system with a progressive characteristic reduces the run-on of the wheels of the semi-trailer when turning to the outside. An example of such a control system is shown in figure 2.

4. Selection of hydraulic HCS

HCS is a closed hydraulic system, where a pair of cylinders is used as master cylinders connected with a chain link mechanism by a rocker mechanism, an actuator pair of hydraulic cylinders is connected with a mechanical drive of the pivot axles and a semi-trailer frame (figure 6). To increase the reliability of the HCS, the master and actuating hydraulic cylinders are connected by two independent hydraulic circuits.

To ensure the stable operation of the system, and in order to eliminate the self-oscillations of the steered axles (wheels), an overpressure of approximately 4.0 ... 6.0 MPa is created in the hydraulic drive. Pressure is created by including a pump station in the system. To maintain a constant pressure in each hydraulic circuit, pneumatic-hydraulic accumulators are used.

The pumping station is a separate unit containing: a pump, a direct-current driving electric motor with a voltage of 24V, a power of about 4 kW and a tank for the working fluid. Since the system is autonomous, a battery is used to power the electric motor, which could be charged by the tractor.

![Figure 6. Kinematic diagram of a hydrostatic control system.](image)

- $C_1, C_2$: master cylinders; $C_3, C_4$: executive cylinders; $A_1, A_2, A_3, A_4$: pneumatic-hydraulic accumulators; $S_{P1}, S_{P2}, S_{P3}, S_{P4}$: pressure sensor in the circuit; $HB$: hydraulic unit; $MV$: manual control valve; $HP$: pumping unit; $HP$: hand pump; $F$: filter; $M$: electric motor.

A manual pressure boost is provided as an emergency circuit. Thus, it is possible by creating a pressure of 6.0 MPa to return the wheels of the semi-trailer to the initial state corresponding to a straight-line motion. In the event of a fault in the CS, it allows the train to continue moving with an unmanaged semi-trailer.
HCS is equipped with a self-diagnostic system, including axle position sensors, sensors and lamps for controlling the pressure of the working fluid.

5. Calculation of design parameters of HCS actuators

In HCS, there are, as a rule, two master and two actuating cylinders. The location of the hydraulic cylinders depends on the chosen layout of the mechanical drive (a system of rods and levers that provides the angles of rotation of the steered wheels or axles required according to the Ackermann law).

In HCS, at first the parameters of the actuating cylinders are determined, then the parameters of the actuating cylinders are selected. Figure 7 shows the design diagram of the actuating cylinders for the controlled axle of the semi-trailer.

The force created by the executive cylinders must exceed the moment of resistance to the rotation of the steered wheels at full load of the semi-trailer, which is required primarily in the manual control mode.

\[ M_{cz} = (M_{cf} + M_{c\phi}) \cdot \eta / i_d \]  

(1)

where \( M_{cf} \) – moment of resistance to rolling of the wheels when turning the axle;  
\( M_{c\phi} \) – moment of resistance in the turntable;  
\( \eta \) – efficiency of mechanical drive;  
\( i_d \) – drive gear ratio.

\[ M_{cf} = G_{atr} \cdot n \cdot f_k \cdot r_f \cdot g \]  

(2)

where \( G_{atr} \) – load on a single axle of a semitrailer, kg;  
\( n \) – number of axles driven;  
\( f_k \) – wheel rolling resistance coefficient;  
\( r_f \) – wheel running shoulder (half track of the axle bogie), m;  
\( g \) – acceleration of gravity, m/s\(^2\).

\[ M_{c\phi} = G_{tr} \cdot f \cdot r \cdot g, \]  

(3)

where \( f \) – coefficient of friction-swing in the turntable;  
\( r \) – turntable radius, m;  
\( g \) – acceleration of gravity, m/s\(^2\).  
\( G_{tr} \) – set by semi-trailer axle manufacturer.

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**Figure 7.** The design scheme for the controlled axis of the semi-trailer.
Knowing the total moment of resistance to the rotation of the axis, we determine the driving force on the cylinder rod:

\[ P_c = \frac{M_c}{l_c}, \]  

(4)

\( l_c \) – cylinder shoulder, m;

Knowing the force on the rod and asking the maximum value of fluid pressure, we determine the area of the cylinder

\[ P_c = P_g \cdot F_c, \]  

(5)

where \( P_g \) – fluid pressure in the system, MPa;
\( F_c \) – cylinder area, m\(^2\);

The diameter of the cylinder is determined from its area, it is rounded up and selected on the basis of the standard number of hydraulic cylinders.

\[ P_g \cdot \frac{\pi D^2}{4} \cdot 2 \cdot i_d = \frac{M_c}{l_c} \]  

(6)

\( D \) – cylinder diameter, m

We express from the formula (6) the diameter of the cylinder:

\[ D = \sqrt{\frac{2 \cdot M_c}{P_g \pi \cdot i_d}} \]  

(7)

The master cylinders in HCS are taken in the same dimensions as the actuators.

6. Selection of parameters of the pumping station and control unit

6.1. Pumping station

The pumping station in the HCS serves to discharge and maintain the necessary pressure in the drive of the control system, as well as to ensure the rotation of the controlled axes in the manual control mode.

Pump performance is determined by the ability to provide the required speed of rotation of the controlled axes in the manual control mode.

If the steering speed of the wheels is strictly regulated by the UNECE and EU directives for steering and is \( \omega_{re} = 10 \, \text{rad} / \text{c} \), then, according to research literature data, for controlled axes of the semi-trailer it does not exceed 0.2 \( \text{rad} / \text{c} \) [2].

The pump capacity:

\[ Q_p = \frac{V_c}{t_{min} \cdot \eta_p} \]  

(8)

where \( V_c \) – cylinder volume;

taking into account the fact that there are two actuating cylinders, their total volume will be equal to

\[ V_c = (F_c + F_{est}) \cdot l_c \]  

(9)

\( F_c \) – borehole cylinder area, m\(^2\);
\( F_{\text{rod}} \) – rod cavity area of the cylinder, \( m^2 \);
\( l_c \) – cylinder stroke, \( m \);
\( t_{\text{min}} \) – the minimum time for the axis to turn from one extreme to the other, \( s \).

Axis rotation time from one extreme position to another
\[
t = \frac{\alpha}{\omega},
\]
where \( \alpha \) – angle of rotation of the axis from one extreme position to another, grad;
\( \omega \) – axis rotation speed, grad/s.

A DC motor is used to drive the pump.

The choice of the electric motor is carried out taking into account the power required to drive the hydraulic pump and the maximum speed of the pump. The volumetric efficiency of the pump should be taken into account as well.

Motor power of hydraulic pump drive:
\[
N_p = \frac{P_g Q_p}{1000 \eta_p},
\]
where \( P_g \) – fluid pressure, \( Pa \);
\( Q_p \) – pump capacity, \( m^3/s \);
\( \eta_p \) – volumetric efficiency of a pump.

After the capacity of the pump is determined, it is necessary to choose the volume of the tank of the pumping unit. It is selected with the calculation of 1 minute of the pump performance.

6.2. Control valve

To implement the manual control a valve is used. Its main parameters are the kinematic scheme of the distributor, the conditional flow area – the remote control, the supply voltage of the electromagnets. The control depends on the pump capacity and is selected from the table characteristics.

The hydraulic capacity of the valve is determined using the condition
\[
V_p \geq V_{TP} \text{ if } P_H = P_{H\text{max}},
\]

\[
V_{TP} \leq \frac{G_{\text{max}}}{F_{n3}} \sqrt{\frac{1}{2}(P_0 - \frac{P_H}{F_{n3}})}, \text{ whence at } X = X_{\text{max}}
\]

\[
G_m \geq \sqrt{\frac{V_{TP} F_{n3}}{\frac{1}{2}(P_0 - \frac{P_H}{F_{n3}})}}
\]

At the same time, the area of throttling windows

\[
A_0 = \frac{G_m}{\mu \sqrt{\frac{P}{\rho}}} = \frac{V_{TP} F_{n3}}{\mu \sqrt{\frac{1}{2}(P_0 - \frac{P_H}{F_{n3}})}}
\]

In practice, the choice of a hydraulic distributor can be carried out using the manufacturer’s catalog sheets or their web-sites; one should take into account the hydraulic distributor circuit, its conditional flow area, inlet pressure, control type and nominal flow rate of the working fluid. When choosing a hydraulic distributor controlled by electromagnets, it is necessary to pay attention to the technical characteristics of the electromagnet: supply voltage, type of current and operating mode of the electromagnet.

6.3. Hydropneumatic battery

Hydro accumulator (HA) in HCS serves to maintain excess pressure in the hydraulic system.
The choice of HA basically comes down to determining the constructive (full) capacity $V_k$ and the useful volume $V_e$ of the liquid (the volume of liquid displaced by gas from the HA during its discharge, when the gas pressure decreases in a given range from $P_{max}$ to $P_{min}$. $P_{max}$ is the largest working pressure in the hydraulic system. $P_{min}$ is the calculated operating pressure of the hydraulic system of the control system. To obtain the largest useful volume of liquid in HA, choose the initial air pressure $P_a$, equal to the lowest allowable pressure $P_{min}$.

In systems with automatic turning on of the pump, for maintenance of the set pressure range of working liquid the initial air pressure $P_a$ should be slightly below $P_{min}$.

$$P_{min} - P_a = 0,2\ldots0,4 \text{ MPa}$$

The useful battery capacity $V_e$ of HA in the isothermal process is determined from the following expressions:

$$V_e = V_k \left(1 - \frac{P_{min}}{P_{max}}\right)$$

where $V_k$ – capacity of HA;

$P_{min}$ – initial charging pressure of HA;

$P_{max}$ – maximum working pressure.

7. Conclusion

HCS used today on long-base road trains provide acceptable indicators of maneuverability.

The present shift of the trajectories of the tractor and trailer link on transient modes of movement can be compensated by using HCS with a variable gear ratio to reduce the offset value on transient modes of movement up to 0.2 m, which will improve the controllability and stability of the long-base truck train and significantly improve the safety of the long-base truck train, especially in the conditions of intensive traffic flows.

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