Ensuring the safety of animals and agricultural products by increasing the stability of the tractor semi-trailer

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Abstract. The article considers the stability of transportation and technological machines considering design features and operating conditions. The study highlights the importance of establishing scientifically based requirements for parameters and application of design solutions, which ensure comfortable conditions for transporting animal and vegetable cargoes of the agro-industrial complex. The authors present a mathematical model for assessing the stability of a multilink machine with the allocation of inertia forces as key parameters. The authors propose to use the calculated model when studying the stability of technological machines in the process of transportation of animal and vegetable cargoes of agro-industrial complex in semi-trailers and assessing the critical ratio of the angle of rotation, and speed of inertial forces. This is necessary to exclude abnormal situations, such as the folding of the semi-trailer and overturning of the machine. The authors propose reducing the width of the overall corridor during curvilinear movement by controlling the parameters of the steering angle of the steering wheels of the semi-trailer, depending on the folding angle, and reducing the sliding of the semi-trailer wheels. A crucial element in the design is the inclusion of a parallelogram-type setting mechanism fixed on the fifth wheel. The proposed control system for turning the multilink machine has a simplified design, turns the steerable wheels of the semi-trailer depending on the folding angle, and increases the characteristics of maneuverability, passability, and stability of movement with steerable wheels of the semi-trailer. Development of the design solution involves the inclusion of a digital control unit with an adaptive change module considering the type of transported cargo, such as animals, as objects forming the effect of the floating value of the center of mass and vector of inertial forces.

1 Introduction

For the agro-industrial complex, transport and technological machines are of great importance in solving the tasks of moving agricultural cargoes and cargoes of special conditions of placement, such as oversized baskets with plants, cattle, pigs, poultry, sheep, and others.

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Crossable relief, many turns, and slopes characterize the area of the agro-industrial complex. The control of technological machines becomes more complex because of this, and it is worth mentioning that hard surfaces are scarce in most places. The agro-industrial cargo regulations require that certain rules are followed to ensure safety. For oversized plants, shrubs, and trees, it is necessary to ensure immobility and minimum oscillating loads to avoid branch breakage and leaf fall. More stringent are the requirements for animal transportation: the smooth running of the machine and the gentle mode of loads (inertial forces) when driving on winding roads [1].

The analysis of applied models of technological machines shows the wide use of the basic tractor with a semi-trailer for special conditions for AIC cargo transportation. For road trains, designers rely on the accepted typical characteristics of stability, maneuverability, and smoothness [2]. We must apply additional, scientifically based requirements to the parameters of stability and smoothness, and also design solutions that guarantee comfortable conditions of animal transportation without stress.

The purpose of this work is a theoretical and practical substantiation of the simplification of the design of steering control of the technological machine to improve the stability characteristics of maneuvering with guaranteed smoothness of motion.

2 Materials and methods

Mathematical model for stability assessment of a multilink machine.

The author [3] singled out the problem of determining the parameters of a wheeled machine that provides stability and controllability in curvilinear motion as the key problem in the article. The article singles out overturning as the most dangerous in terms of severity of consequences types of loss of stability of a wheeled machine. The article contains analytical research and justification of the developments identified in terms of accuracy, novelty, and universality in establishing the criteria of static and dynamic stability of the machine against transverse overturning. These studies are relevant for both vehicles and wheeled low-clearance tractors. The authors propose the use of mathematical models as fundamental [4]. The work [5] proposed for heavy-duty road trains the design of a maneuverability enhancement device, changed the basic model of a fifth-wheel truck considering the misalignment of semi-trailer axles, which leads to the deterioration of rectilinear motion stability caused by the oscillations of the trailer link [6].

The study [7] considers the key factors that cause loss of stability, the overturning of a wheeled machine when driving on a turn and wheel striking a stationary obstacle.

The theory of wheeled technological machines emphasizes transverse and longitudinal stability [8-11].

The transverse stability of the machine provides control of lateral sliding of wheels and exclusion of overturning in the plane perpendicular to the longitudinal axis. Longitudinal stability requires the elimination of wheel slip caused by sliding when overcoming a steep hill. Since technological machines do not have a high-speed mode of movement when operating in the conditions of the agro-industrial complex, it is reasonable to select the following parameters as indicators of transverse stability: the turning radius and the angle of the transverse slope of the road [12-15].

To exclude the effect of folding of the tractor and semi-trailer, controllability control of a multi-link machine reduces as a special case of controllability violation and rolling of the machine into a skid. I.e. creation of a constructive effect of steerable semi-trailer wheels. Here, not the axles, but only the trunnions of all trailer wheels are pivotable (Fig. 1).

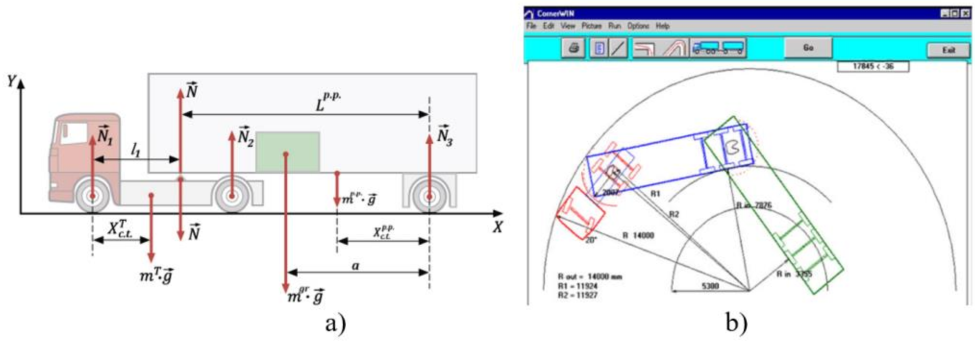

Fig. 1. Forces acting on the multilink machine (a) and rotation scheme in the Cornet WIN software emulator (b).

Considering that under special conditions of transportation of AIC cargoes, the technological machine turns at low speed, we assume that there is no lateral deformation of the tires, and the control point of the turning radius coincides geometrically with the middle of the rear axle of the semi-trailer. Turning radius formula:

$$R = \frac{L}{tg\theta} \tag{1}$$

where $\theta = \frac{\theta_{\text{В}}+\theta_{\text{Н}}}{2}$ – average steering angle of steered wheels; L - vehicle base.

According to the theoretical establishment, the rotation of a multilink machine occurs around the instantaneous pole of rotation at each moment. Non-uniformity of motion affects stability, i.e. motion with positive or negative acceleration.

The position of the instantaneous acceleration center is determined from the expression:

$$M = \left(R\frac{d\omega}{dt} - \frac{d\vartheta}{dt}\right)\frac{1}{\sqrt{\omega^4+\left(\frac{d\omega}{dt}\right)^2}} \tag{2}$$

$$\frac{d\omega}{dt} = \frac{tg\alpha}{L}\frac{d\vartheta}{dt} + \frac{\vartheta}{Lcos^2\alpha}\frac{d\alpha}{dt} \tag{3}$$

where ω - vehicle angular velocity; $\frac{d\omega}{dt}$ – angular acceleration; ϑ – vehicle speed; α – average steering angle of steering wheels.

Inertia force along the axis of the semi-trailer:

$$P_x = \frac{G_{s-t}}{g}\left(\frac{d\vartheta}{dt} - b\omega^2\right) \tag{4}$$

Inertia force perpendicular to the axis of the semi-trailer:

$$P_x = \frac{G_{s-t}}{g}\left(R\omega^2 + b\frac{d\omega}{dt}\right) \tag{5}$$

where G_{s-t} – gross trailer weight; g – gravity acceleration.

To simplify calculations and reduce to the accepted calculation units of measurement, for the ratio of the distance from the rear axle to the center of gravity (b) and the base of the semi-trailer (L) we introduce the notation $\xi = \frac{b}{L}$, and finally the calculated expression of the forces of inertia takes the form:

$$P_x = \frac{G_{s-t}}{g}\left(\frac{d\vartheta}{dt} - \xi L \frac{\vartheta^2}{13R^2}\right), P_y = \frac{G_{s-t}}{g}\left(\frac{\vartheta^2}{13R} + \xi \frac{Ld\vartheta}{Rdt} + \xi \frac{\vartheta}{3{,}6}\frac{L^2+R^2}{R^2}\frac{d\alpha}{dt}\right) \qquad (6)$$

These expressions play a role in studying the stability of technological machines in the process of cargo transportation in semi-trailers and evaluating the critical ratio of the angle of rotation and speed of inertial forces to avoid abnormal situations like the folding of the semi-trailer and the overturning of the machine.

3 Results and discussion

A prototype for upgrading the stabilization design of a semi-trailer.

The typical design of the steering system of a multi-link machine, in the example of a tractor-trailer, comprises a steering mechanism and a drive. The kinematic diagram contains steering trapezes of the base machine and the trailing link, the power drives of which comprise a copier, hydraulic cylinder, and distributors. Hydraulic systems for smooth steering and force compensators represent the drive. The presence of a hydraulic drive in the design creates risks of pipeline breakage and leaks of working fluid, which destroys the environment because of years of neutralization of harm. Changing the design to replace the hydraulic actuator with an alternative one is not always economically helpful. The design solution of transferring part of the components from the base machine to the trailer or the creation of a duplicate system complicates the design and reduces the time of coupling and uncoupling of the road train because of including additional connecting hydraulic components [16-19].

We propose to reduce the width of the overall corridor during curvilinear movement by controlling the parameters of the angle of rotation of the steering wheels of the semi-trailer depending on the angle of folding of the road train, reducing the sliding of the semi-trailer wheels.

The key to the prototype design is the inclusion of a parallelogram-type setting mechanism mounted on the fifth wheel.

Swinging rods of the setting device provide free movement along the arc slit of variable curvature and cross-section The angle of rotation of the steering wheels of the semi-trailer is changed depending on the angle of folding of the road train and stabilization of the steering wheels of the semi-trailer during the transition of the road train from curvilinear movement to rectilinear movement. The clips generate the rolling effect of the trailer wheels moving "track to track", while the aid of the spring-loaded roller in the restoration of the setting device to its neutral position.

Figure 2 is a schematic of the steering system of a single axle semitrailer tractor-trailer; Figure 3 shows the mechanical copier.

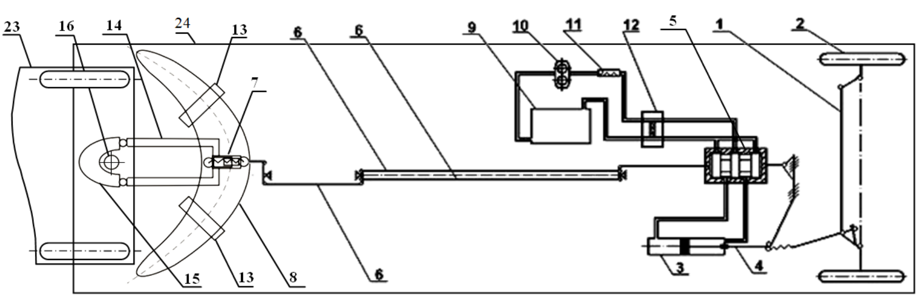

Fig. 2. Scheme of semi-trailer control system: 1 - trailer steering trapezoid; 2 - steerable wheels; 3 - executive cylinder; 4 - rod; 5 - hydraulic spool valve; 6 - rod; 7 - setting device; 8 - regulating profile of variable curvature and cross-section; 9 - oil tank; 10 - hydraulic pump; 11, 12 - control devices.

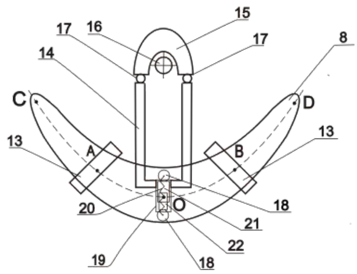

Fig. 3. Schematic diagram of a mechanical copier controlling a semi-trailer.

Setting device 7 (Fig. 3) comprises two rollers 18, body 19 connected with rods 6, spring 20, outer 21, and inner 22 pipes ensuring correct deformation of the spring. The setting device is connected to the fifth wheel coupling of the tractor 15 by a rod 14, which is attached to the fifth wheel coupling by joints 17 (joint attachment of the rod allows connection-disconnection of the coupling pin of the semi-trailer 16 with the fifth wheel coupling of the tractor and provides the required angles of flexibility of the road train in the longitudinal vertical plane).

The geometric dimensions of slot 8 set the required angles of rotation of the steering wheels of the semi-trailer depending on the angle of the folding of the road train links. When moving the setting device along sections OA and OB of the slot provides rotation of semi-trailer wheels to the angles corresponding to rolling of semi-trailer wheels inside the tractor wheel track. Mechanical locks 13 limit the movement of the setting device along the arc AOV. The ends of the slots 8 have constrictions provided. When the spring-loaded rollers roll on the surface of the slots, they compress as they enter the body of the setting device. When the road train passes from curvilinear movement to straight movement, the elastic forces of the compressed spring move the setting device from the narrow part of the slot to the middle position (point O), providing stabilization of the steering wheels of the semi-trailer.

The principle of operation of the prototype devices: rotation of the tractor 23 and semi-trailer 24 relative to each other in the longitudinal horizontal plane (in case of curvilinear movement of the road train) and movement of the setting device 7 in the slots 8 along the corresponding arc CAOVD (Fig. 5). Movement of the setting device by rods 6 of the steering drive causes displacement of the spool of the hydraulic distributor 5, accompanied by a supply of the working fluid under pressure from the oil tank 9 by the hydraulic pump 10 to the executive cylinder 3. The displacement of rod 4 of the cylinder through the steering trapezoid 1 causes steering wheels 2 to rotate by an angle proportional to the longitudinal displacement of steering rod 7, the value of which depends on the radius of curvature of slot 8.

4 Conclusions

The authors of the article proposed a mathematical model as a calculation dependence in the stability study of technological machines for cargo transportation in semi-trailers and assessment of the critical ratio of the steering angle, speed of inertial forces to exclude abnormal situations, such as the folding of the semi-trailer and overturning of the machine.

The technical solution of modernization of the design of the multilink machine semi-trailer steering allows to:

- Increase the reliability of the system,
- Reduce the force on the steering wheel of the tractor,

• Simplify the design, which sets the parameters of the steering angle of the steering wheels of the semi-trailer depending on the folding angle of the semi-trailer,
• Increases the characteristics of maneuverability and passability of the machine by reducing the width of the overall corridor in curvilinear movement and the coincidence of rolling traces of the tractor and semi-trailer wheels,
• Reduces the intensity of tire wear by reducing wheel skid when turning with a minimum radius
• Increases the stability of the semi-trailer.

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