IMPROVEMENT OF THE FOREST TRACKED VEHICLES' CONTROL BY USING IMPULSE CONTROL TECHNOLOGY FOR THE STEERING MECHANISM

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Abstract: This paper proposes an impulse control technology for the steering mechanism to improve forest tracked vehicles' control. The steering control system for the tracked vehicle employs a "diagonal" steering control scheme in combination with the principle of low-frequency (5-15 Hz) pulse-width modulation of pressure in the hydraulic system. The study offers several modulator and control system designs. The main parameters of the steering control system were selected. Based on the results, an experimental control system was manufactured. The results of the experiment showed that the use of the proposed methodology allows creating conditions suitable for applying the impulse steering technology with minimal changes in the transmission design. Furthermore, the use of low-frequency modulation allowed direct control of disc slipping. This advantage may be useful in designing steering control systems for tracked vehicles. The future study can focus on developing and testing the control system for a modernized skidder chassis.

Keywords: tracked vehicles, steering mechanism, closed-loop control systems, pulse-width modulation.

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INTRODUCTION

Forest management heavily leans on the use of the full tracked chassis machines. In addition to traditional skidders (skidders) and forwarders, typical for the timber industry in Russia, the prospect of introducing small-sized machines has emerged. The small-sized machines are designed, for example, to collect non-timber materials, but they are also potentially capable of solving many other problems that are not directly related to logging. Studies of the working tracked skidders show that the machine is in the steer mode for more than 40% of the operating time. Therefore, one of the key problems is to ensure the quality of the tracked vehicle steering control (a smooth change in the turning radius, a one-to-one correspondence of the controlled body position to the radius of the turn. It is desirable to implement the spot turn operation) (Kováč et al., 2020).

The modern approach to the increase of the tracked vehicle control is based on three modes: the well-proven principle of using hydrostatic transmission as part of a multi-thread steering mechanism, (solutions typical for tanks, for example, for the Abrams, Leopard, Leclerc, Armata and armored personnel carriers "Marder", etc.); the use of the multi-radius steering mechanisms with a large number of fixed radii (for example, a 32-speed transmission described in the work (Claus et al., 2020)); application of electromechanical transmissions (for example, new solutions proposed in the works (Wu et al., 2019; Gen et al., 2020)). In relation to heavy machines with the on-board gearboxes, an alternative way was proposed - the use of closed (tracking) steering control systems (Yi et al., 2018; Dobretsov et al., 2020).

The use of hydrostatic gears as part of the double-flow transmission allows solution of the problem in complex.

However, this type of gear is difficult to manufacture and expensive to purchase. Similar results are achievable in the transmission with the closed steering control system (Yi et al., 2018), in particular, in the double-flow transmission with the friction controlled steering mechanism (Dobretsov et al., 2020). Prior to the occurrence of technologies creating reliable, compact, and fairly inexpensive high-power electric traction motors in serial production, the approaches described in the articles (Yi et al., 2018; Dobretsov et al., 2020) were practically unrivaled. Their advancement was restrained mainly by the fact that they were developed for military tracked vehicles.

The emerging trend towards development of tracked vehicles with hybrid power systems allows us to assume that similar technologies can be applied to forest tracked vehicles serving various purposes. The article (Oh et al., 2017) discusses a new approach to the development of the parallel-type hybrid propulsion system based on the double-flow transmission. Such approach can both solve the problem of steering control quality and realize the main advantages of the parallel hybrid propulsion system - economy and reliability.

In all cases, we are talking about development of the double-flow transmission with summation of power flows before delivery to the final drive and then to the drive wheel. In all cases, provision for the placement of additional components and assemblies is required. Component density of the transmission layout needs to be also significantly increased.

Development of the double-flow transmission, which allows combination of power flows directly on the caterpillar band, is another alternative (Lozin et al., 2019a).

Based on the concepts (Lozin et al., 2019a), the principle of “diagonal” steering control has been proposed for the application in heavy and high-speed tracked vehicles (Ni et al., 2019). These concepts can be applied in transmission modernization for skidders and forwarders, but, as in previous cases, this type of modernization will be too radical. It is more reasonable to employ such technical solutions in the design of new machines. When upgrading the serial chassis of the third drawbar category, it seems reasonable to consider improvement of the steering control by using closed (servo) steering control system based on the principle of the impulse control of slipping of the friction unit, which acts as a steering mechanism.

Therefore, the novelty and significance of the conducted research for the industry is based on the application of the principle of impulse control of slipping of steering discs to a fundamentally new system of "diagonal" steering control, adapted for traction class machines demanded by timber industry.

Employment of the "diagonal" steering control scheme in combination with the principle of a servo control system and pulse-width modulation of pressure in the hydraulic system will reduce the load on the engine and transmission elements (Gen et al., 2020) and decrease energy consumption upon machine turning - mainly due to the improvement of the machine's steering response (Li and Jia, 2017). As a result, it will also lower the driver's fatigue.

The next step in the development of the proven principles of brake slip control is the implementation of a control system based on digital technologies.

Further prospects of the pulse-width modulation pressure principles' application in steering control systems of tracked vehicles are associated with the development of hyperbolic steering mechanisms based on the friction steering mechanism (Dobretsov et al., 2020) and development of various hybrid transmission systems (Zhai et al., 2017).

Friction steering elements operating under similar conditions are used in gearboxes (Claus et al., 2020) of traditional and promising unmanned transportation and traction machines (the quality of gear shifting depends on the smoothness and well-timed action of the controls); in the steering gear of tracked vehicles (the works (Qin et al., 2018; Lozin et al., 2019b) provide examples of modern and traditional steering mechanisms' design, which can be applied in forest tracked vehicles to improve controllability; high operational properties of the mechanism are ensured precisely by the smoothness of the change in transmitted rotational torque and angular velocity); in promising power distribution mechanisms of (Zhai et al., 2017; Randive et al., 2019; Dobretsov et al., 2020) and etc.

Thus, on the example of the operation of a specific braking element, provided that the load balance is distributed correctly, the problem characteristic of transport engineering as a whole can be solved.

The problem in focus can be reduced to determining the law of pressure change in the hydraulic drive and to choosing technology for monitoring pressure values in real time; that is, to determining the composition of the steering control system, parameters of its elements, and development of its operation algorithms. It should be a closed steering control system with digital character allowing the use of CAN interface. The feedback, in case of a specific brake, is conducted according to the output speed. For the machine motion control system as a whole (for example, the case of a caterpillar tractor), the feedback is conducted by the angular velocity of the tracked vehicle turning rate.

Similar control tasks can be solved with the help of amplitude and pulse-width modulation of pressure in the hydraulic actuator (Mishchuk, 2018; Gao et al., 2020). The amplitude modulation will require more sophisticated executive equipment (Fan et al., 2017; Ouyang, et al., 2019). When using pulse-width modulation, the pressure to the hydraulic system is delivered in the form of impulses (the impulse shape is close to rectangular), and the effective pressure value is formed as a naturally established average.

Control systems operating with high modulation frequencies, are widely used in foreign practices (Lv et al., 2017; Huova et al., 2018; Zhang et al., 2020). It is proposed to implement control systems working within the frequency range of 5-15 Hz. Such frequencies allow directs impact on the compression force of the disk package and control of the slipping process. The indicated frequencies will allow the mechanical part of the package to work out the control law; the operating valve has a simpler design, is cheaper and less demanding to the level of oil purification. In addition, it becomes possible to work with long hydraulic lines - that is, to upgrade existing units containing friction control elements.

The traditional motion control system of tracked vehicles is an open loop control system. The position of the control body, set by the driver, does not correspond unambiguously to the value of the turning radius. A closed-loop control system is practically devoid of disadvantage.

The closed-loop control systems for tracked vehicles' movement for the main tanks with the on-board gearboxes were developed in Russia (Lozin et al., 2019b; Volkova et al., 2019; Gen et al., 2020). The structure of the control system is shown in Fig. 1.

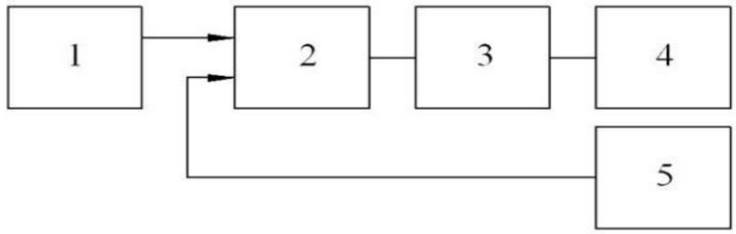

Figure 1. The structure of the servo steering control system with the pulse-width modulation of pressure: 1 – master controller; 2 - differential amplifier; 3 – pulse-width modulator; 4 - control object (friction control element); 5 - feedback sensor

The main elements are: 1. master controller (connected to the control system), 2. differential amplifier, 3. pressure modulator, 4. actuator (solenoid valve in the friction control line); 5.feedback sensor.

In straight line motion, the signals of the master controller 1 and the feedback sensor 5 are equal. The differential amplifier generates zero voltage at the output and a signal with a zero duty ratio is sent to the pressure modulator 3. The electromagnet of the modulator 3 is deenergized, the converter inlet valve is in the "drain" position, the control element 4 is turned off.

The movement of the control member leads to the appearance of an error signal at the output of the differential amplifier 2. The duty ratio of the signal at the input of the modulator 3 becomes close or equal to 1 unit. The modulator electromagnet is turned on and puts the converter inlet valve in the "discharge" position. The hydraulic cylinder of the control member is turned on.

The machine enters a turn. The error signal from the amplifier 2 decreases, and the pulse duty ratio at the input of the modulator 3 decreases too. The modulator 3 starts working in the modulation mode and alternately connects the hydraulic cylinder to the drain or discharge lines. The system is in the dynamic equilibrium, and the controlled element will slip at a constant speed, making a turn with the preselected radius.

The control system of the described structure was used at St. Petersburg Polytechnic University when working on the problem of the turn steering for military tracked vehicles. The purpose of the research is to improve controllability of tracked vehicles (and as a result, transport performance of the forest tracked vehicles) by controlling slipping discs of the friction control element.

METHODS AND CALCULATIONS

In the course of the study the following research was conducted: a design experiment (the stages of selecting the main mass-dimensional and energy parameters of the test bench, research work of control algorithms for the test object); an engineering experiment (launching, debugging and tuning of the stand; debugging of the operation of the control system components in test bench conditions and etc.).Theoretical methods (synthesis, abstraction, generalization, deduction, analogy, computer modeling) and empirical methods (description, comparison) were employed at various stages of the study.

The kinematic diagram of the test bench, developed at St. Petersburg Polytechnic University for the study of controlled slipping of disk clutches, (Yi et al., 2018) is shown in Fig. 2.

The gear system is started from a three-phase asynchronous electric motor 1 with the capacity of 125 kW at 1450 r/pm. The object of the test is the disk brake 5. When the brake is engaged, the oil from the tested pressure control system enters its booster.

To simulate the inertial mass of the chassis unit a flywheel 3 with a variable moment of inertia is provided. Rotation onto the flywheel 3 is transmitted from the electric motor 1 through a permanently closed friction clutch 2. The reduction gear 4 is installed behind the flywheel 3 and serves to obtain specified slipping speeds. The frequency of the shaft rotation 6, of the brakes 5 can be adjusted in the range from 0 to 400 r/pm due to slipping of the clutch 2.

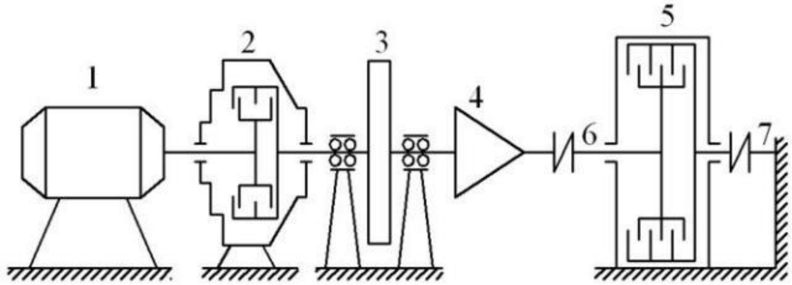

Figure 2. The kinematic diagram of the test bench for disk control and steering control system testing: 1 - electric motor; 2 - friction clutch for test bench loading; 3 - flywheel; 4 - reduction gear; 5 - tested disk control; 6 – reducer input clutch shaft 5; 7 - strain gauge shaft

The imitation of the change in the turning radius is reduced to the regulation of frequency of the shaft rotation 6 of the controlled brake 5. The instance, simulating the moment of resistance to the turn of the machine is created by the slipping clutch 2 through adjusted pilot pressure.

The test-bench conditions measure: travel values of the steering unit; pressure values in the hydraulic cylinder of the controlled brake; shaft speed of the controlled brake; brake torque 5.

The test-bench contains one controlled brake; therefore, there is no possibility to continuously examine the entire range of the turning radius from infinity to fixed timing. For this reason, the test modes were divided into two parts in compliance with the turning radii: from infinity to free radius (turning when the friction clutch of the rectilinear movement is controlled by the controlled disabling); from free to fixed radius (turning when the clutch is downshift). A series of experiments was conducted to study the response of the control system to various influences induced by the steering control (stepwise movement; impulse effect; manual tracking of defined movement trajectory).

At each stage of the test modes, the influence on the quality of the carrier frequency modulation control from 1 ...

2 Hz (lower limit) to the maximum level was checked. The testing was conducted by the regulating electro hydraulic unit (at the predetermined depth of regulation).

During running tests, the comparison of static characteristics of the control system options (serial open-loop, modernized without feedback on the angular steering speed, modernized closed-loop) was made. The test runs were held along the same track. The data on the position of control elements was obtained with the help of potentiometric sensors. The slipping speed of the discs was estimated by calculations based on signals from speed sensors installed at the input and output shafts of the steering mechanism. The comparison of static characteristics of the basic and experimental control systems is shown on Fig. 3

RESULTS AND DISCUSSIONS

Results of the bench tests showed that the most accurate control of pressure in the hydraulic cylinder is made possible by the closed loop servo system employing pulse-width modulation of the pilot pressure in the hydraulic system. In practice, the upper level did not exceed 15 Hz in experiments (with the regulation depth 0.1 ... 0.9).

Stability of the system's operation in the entire range of variation of the turning radii was experimentally confirmed and the optimal range of the operating modulation frequency was revealed.

Employment of the discrete (tracking) servo steering control system improves the quality of steering control of the machine with an on-board gearbox over all variables. Moreover, the proposed steering control system, in comparison with the serial one, showed absolute stability in the entire range of the turning radii from infinity to the fixed ones; 3 ... 5 times less lag time for entering the turn; 3 ... 4 times better stability of the vehicle entering a turn; 2 ... 5 times smaller amplitude of impacts on the steering control when moving with large radii; almost full use of the steering lever stroke to control the machine. The increase in modulation frequency improves steering control (modulation frequency in conducted experiments was 8 ... 15 Hz, depending on the type of electromagnets used). Employment of faster electromagnets can increase the carrier frequency of the modulation and improve the quality of the system. Comparison of static characteristics of the basic and experimental control systems is shown in Fig. 3.

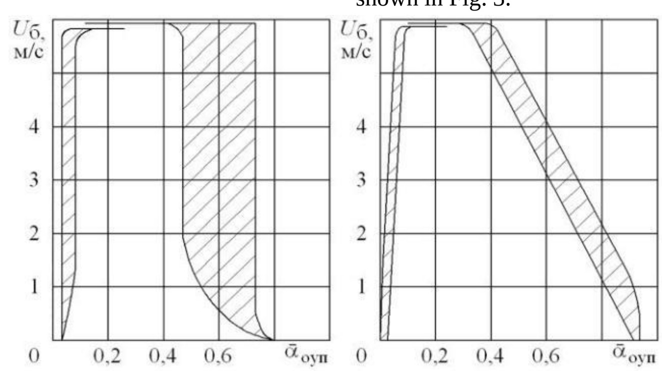

Figure 3. The static characteristic (dependence of the slipping speed of control disks in the gearbox in the position of the steering control element): for the serial steering control system (to the left) and a prototype of the closed system (to the right)

The discrete steering control system allows stable control of the disk slipping speed; its static characteristic shows that the speed of slipping monotonously changes under the steering control system movement.

The above results show that the principle of controlled slipping can significantly increase the quality of the tracked vehicle steering. Comparative tests with machines equipped with multi-stream transmissions containing hydrostatic transmissions, an electromechanical steering mechanism (for example (Wu et al., 2019)) or multistage transmissions (Claus et al., 2020) have not been carried out. However, there is no doubt that technologies competing for quality insurance in steering are rather expensive, which makes their use in forest tracked vehicles problematic.

Since the disk type brake is the preferred object of pulse control in the tracked vehicle transmission system, the chassis upgrade will required replacement of the traditionally used "steering clutch" mechanism by the planetary steering gear.

Another example of solving the problem of "diagonal" steering control implementation is shown in Fig. 4.

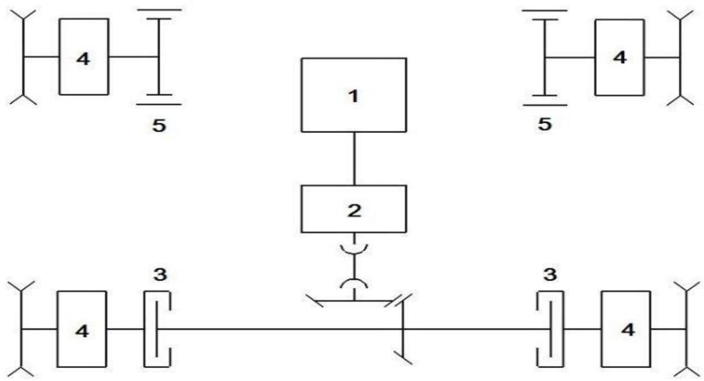

Figure 4. A simplified version of the transmission scheme of the tracked vehicle with "diagonal" steering control: 1 – engine (internal combustion engine); 2 - connecting gear and a gearbox; 3 – steering clutch; 4 - final drive (final reduction gear); 5 – brakes

The transmission runs in the following way. In case of the straight line motion, the power is transmitted from the engine 1 (internal combustion engine) through transmission containing commercially available units on to the drive wheels. The tractor steering wheels, equipped with gear rims and connected through the final drive gear 4 (or directly) with the brakes 5, rotate freely.

To enter the turn with a radius greater than a free radius it is necessary to ensure the slip of the steering clutch 3 associated with the lagging side. When the steering clutch is off, the machine enters a free turn.

To further reduce the turning radius, up to the possible (calculated) minimum, equal to a half of the track width, brake 5 is used. The brake is connected with the steering wheel of the lagging side. In this case, the turning moment is created by forces applied to the diagonal of the chassis.

With this approach it becomes possible, practically without any intrusion into the serial transmission, to install multi-disc friction brake controls with the hydraulic drive, which allows the use of pulse control technology for disc package slipping.

The front mounting of brakes provides additional advantages if compliant tracks (with rubber mount or hingeless) installed on the machine: the risk of the track slip on the rear drive wheel during braking is reduced. The possibility of power recovery is an additional advantage: apart from the brake, the steering wheel can be connected with the generator, which creates the braking force necessary to turn the machine with a radius less than a free radius.

The "diagonal" steering control scheme employment will increase the weight of the machine and complicate the chassis design. It will require development of the new track tension mechanism.

CONCLUSION

Thereby, it can be argued that the use of the closed (tracking) control system for steering of tracked vehicles will significantly increase operational characteristics of forestry and transport vehicles. It looks reasonable to extend employment of these control techniques in transmission units and special machines based on the chassis of tracked and wheeled tractors.

Therefore, Employment of the described principle of the "diagonal" control system for chassis steering of the forest tracked vehicles allows, with minimal interference into the design of the serial transmission, development of conditions suitable for implementation of the pulse control steering technology; the fundamentals of this technology have been developed for transmission disc brakes of military tracked vehicles.

Control of slipping in friction control elements of transmission units in tracked vehicles significantly increases the quality of steering in tracked vehicles. Moreover, the use of the principle of low-frequency (5-15 Hz) pulse-width modulation of pressure in the hydraulic drive allows direct control of disc slipping.

The principle of slipping control in brake control elements can be applied in steering control systems for the movement control of tracked vehicles. Further studies should consider organization of the prototype tests of the system on the upgraded skidder chassis.

Based on engineering designs, an experimental stand and a prototype of the steering control system were created. In its present form, the stand can be used for educational purposes. Without significant modifications the stand can be employed to model a steering control system for tracked vehicles.

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Availability of Data and Materials: Data will be available on request.

Competing Interests: The authors declare that they have no competing interests.

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