Algorithm for Automatic Differential Locking System of a Heavy Truck

V. Anchukov, A. Alyukov

Abstract— **The article presents an algorithm for the automatic differentials locking system of a six-wheel drive heavy truck. For the fully differential transmission, a control law for the 2 inter-axle and 3 inter-wheels locks of the differentials has been developed. The process of control is realized by multi-criterion analysis of the current mode of operation of the vehicle. The algorithm for controlling differential locks is approved by means of simulation using the model of the three-axis six-wheel drive vehicle with a detailed transmission. The obtained results testify to the adequacy and efficiency of the developed control algorithm with the possibility of further equipping the automatic locking system for the differentials of commercially produced vehicles with the proposed control system.**

***Index Terms*— automatic differential locking, differential control, heavy vehicle transmission,**

I. Introduction

TRUCKS are one of the most common modes of transport and, therefore, are operated under different conditions. The most important property that determines the efficiency of a truck is mobility.

Problems of mobility and patency of cars have a wide development in modern scientific and engineering practice. To ensure the normal functioning of vehicles in difficult and extreme road conditions, further search for optimal means and methods of power distribution is necessary. One of the most effective and common ways to increase the patency is to introduce rigid kinematic links.

Lockable differentials significantly increase the patency of wheeled vehicles. Constructions of this kind are widely used in multi-purpose vehicles, construction and agricultural machinery [9]. However, there are a number of barriers that limit the distribution and regular application of lockable differentials in practice. First of all, this includes increased fuel consumption, as well as reduced stability and controllability of the vehicle while driving with blocked differential connections in the transmission. Accordingly, there is a need to apply technical solutions to avoid these negative aspects and to ensure the maximum efficiency of introducing rigid kinematic links. This can be achieved by means of automating the process of enabling / disabling the differential locks.

World automakers widely use so-called "active" differentials [4, 5, 6], functioning as part of "intelligent" all-wheel drive systems. The main advantage of the use of power distribution mechanisms of this kind is adaptation to current road conditions and vehicle operation mode, which positively affects the energy efficiency, safety and controllability of the vehicle. It should be noted that the "active" differentials have proven themselves in the transmission of passenger cars, and the use of such structures in the truck industry is a further prospect for the development of the automotive industry.

The development and implementation of a fundamentally new technical device always requires serious financial costs. The necessary and most expensive stage of design are experimental studies. However, at the present time, methods of simulation modeling [2, 3, 7, 10] and digital prototyping are increasingly being developed. With the help of adequate mathematical models and digital counterparts, it is possible to determine the majority of the main characteristics of the developed product without resorting to numerous experiments, which has a positive economic effect and substantially reduces the overall design costs. The methods of simulation and PLM modeling have been successfully used for many years by leading world automotive companies [8,10].

II. Description of the mathematical model

The object of the study is a three-axle all-wheel drive truck of increased terrain - KAMAZ 65222. The car has a fully differential transmission with 2 inter-axis and 3 inter-wheels differentials, all differentials equipped with cam lock clutches. The main task is to develop an algorithm for controlling differential locks, which can be adapted to the operating mode and road conditions, as well as integrated into the standard ABS / ASR system.

The mathematical model of the process of vehicle movement should include all the main vehicle subsystems together with the actual characteristics of the particular research object, only in this case it becomes possible to obtain reliable results and their further use in the design of the product. The coordinate frames assignment of a 6WD truck is shown in Figure 1.

Using the LMS Amesim 1D modeling package, a mathematical model of the spatial motion of a 6x6 wheeled truck was developed. The developed mathematical model displays the process of the truck's movement at the required

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design modes taking into account the specific dynamics of specific units and assemblies.

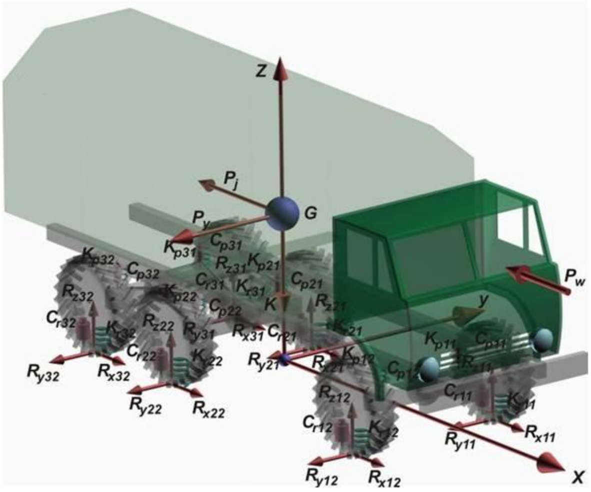

Figure 1 – Coordinate frames assignment of a 6WD truck.

Figure 2 shows the general view of the model. The model includes all the necessary subsystems of the car: engine, transmission, suspension system and takes into account all the necessary physical characteristics of the vehicle and the external environment: mass-inertial characteristics, wheel-terrain interaction, peculiarities of road conditions and the force of aerodynamic resistance.

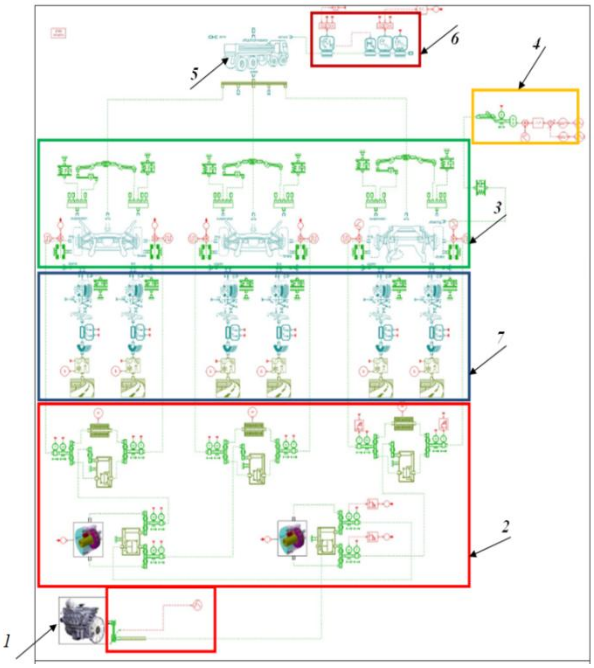

Figure 2 – LMS Amesim model of a 6WD truck.

The engine (1) operates on a partial speed characteristic: the developed torque depends on the speed of rotation of the crankshaft and the degree of fuel supply. Transmission (2) is represented by an ideal infinitely variable gearbox with variable gear ratio, the reduced drive stiffness is taken into account with the help of the driven shaft of the gearbox, the inter-axle and inter-wheel differentials of the transmission have locking clocks to which the control signal is applied. The suspension system (3) corresponds to the kinematics and elastic characteristic of the dependent suspension of the research object without taking into account the balances of the rear trolley. Steering (4) is carried out by means of the steering rack, the driving link of which is controlled by means of a signal with the value of the angle of rotation. The sprung mass of the car (5) has six degrees of freedom, and also takes into account the location of the center of gravity and the distribution of the load along the axes. The data collection system (6) includes a set of sensors for positioning the vehicle in space: roll, pitch, yaw, etc. The interaction of the wheel with the terrain (7) is implemented on the basis of the "Brixius and Dugoff" model, micro- and road macro profile, coefficient of adhesion, hardness of the ground, tire dimension (free radius and radius under load, tire width and profile height).

It is assumed that the car body is a solid body, to which the forces and displacements determined by the power plant and the external environment are transferred. Equations of motion of the body of a vehicle relative to a fixed system of coordinates in the form of Lagrange II kind have the form [4]:

$$\begin{cases} \dot{\omega} = [T_1 - G_s\, h_{COG}\, \lambda\, (\dot{V}_x - V_y\, \omega)]\, /\, J_z, \\ \dot{V}_x = V_y \omega + T_2, \\ \dot{V}_y = V_x \omega + T_3, \end{cases}$$

$$T_1 = \left[\sum_{i=1}^{2} R_{y12}^{i}\, a + \sum_{i=1}^{2} R_{y2}^{i}\, b_2 + \sum_{i=1}^{2} R_{y3}^{i}\, b_3 \right.$$
$$+ 0.5\left(R_{x1}^{right} + R_{x1}^{left}\right) B_1$$
$$\left. + 0.5 \left(\sum_{j=2}^{3} R_{xj}^{right} + \sum_{j=2}^{3} R_{xj}^{left} \right) B_2 \right] / J_z,$$

$$T_2 = \sum_{j=1}^{3} \sum_{i=1}^{2} R_{xj}^{i}\, / G$$

$$T_3 = \sum_{j=1}^{3} \sum_{i=1}^{2} R_{yj}^{i}\, / G$$

Where
ω - rotational speed of the body with respect to the vertical axis;
G_s – vehicle sprung mass;
G - total mass of the vehicle;
h_{COG} - height of the center of gravity;
λ - angle of body deviation in the horizontal plane;
V_X - speed of the vehicle in the longitudinal direction;
V_Y - vehicle speed in the transverse direction;
J_Z - moment of inertia of the body with respect to the vertical axis;
R_X - longitudinal reaction of the wheel;
R_Y - transverse reaction of the wheel;
a - distance from the front axle to the center of gravity;
b_2 - the distance from the center of gravity to the middle axis;
b_3 - the distance from the center of gravity to the rear axle;
B_1 - Front track;
B_2 - rear track.

III. Description of the Control Algorithm for Blocking Differentials

To increase the efficiency of the truck in mixed road conditions, the following algorithm for the operation of automatic differential locks is proposed:

1. The car is started with the transmission completely blocked. This will maximize the use of the coupling properties of the road surface and exclude the possibility of slipping the wheels during the start.

2. When the speed reaches 20 km/h, interlocking differentials are disengaged, and when the speed reaches 30 km/h, inter-axle locks are disabled. This condition is necessary to maintain the stability and controllability of the car at these speeds, because It is known that when maneuvering at high speeds, blocked differential connections can have a negative effect on these performance characteristics.

3. Regardless of the speed, the differential locks are disabled when the steering wheel is turned more than 30 degrees. The turning radius with locked differentials is less than with the unlocked ones, so this element of the control algorithm is applied.

4. When driving in settlements (GPS position analysis is used) for normal maneuvering and, consequently, ensuring the safety of all road users, all locking differentials are disabled.

5. With prolonged slipping of the wheels, accompanied by a three-time operation of the PBC system, regardless of the location of the vehicle, the corresponding differential locks are activated: when the axles are slipped, there are interaxial ones; when slipping wheels - first interaxle, and then inter-wheel.

IV. Simulation Results

To assess the functioning of the algorithm proposed above, a number of types of indicative calculation cases typical for the movement of a truck were adopted:

1. Acceleration to a speed of over 30 km/h with subsequent braking.

The most common modes of a truck's movement are acceleration and braking. The acceleration process is carried out with sequential gear shifting, braking after 25 s. movement and further continuation of the movement after 2 seconds braking. The corresponding results for vehicle speed, control signals for differentials locking and braking enabling, are shown in Figures 3-5.

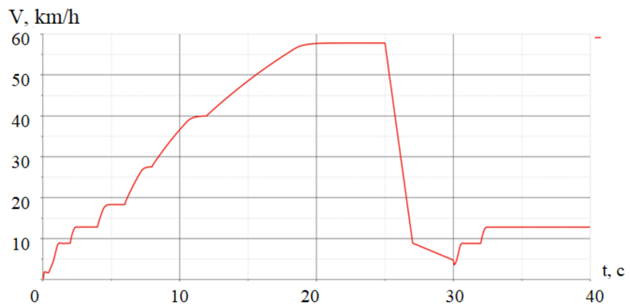

Figure 3 – Vehicle speed changing during acceleration and braking

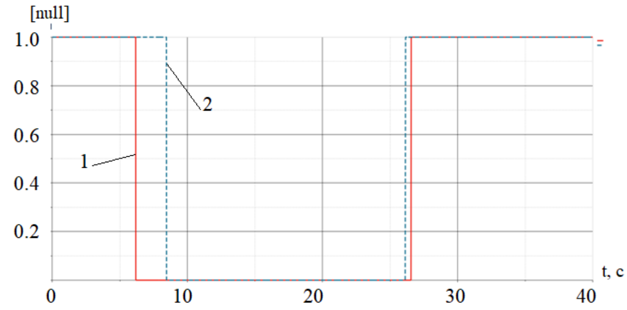

Figure 4 – Enabling/disabling differentials locking
(1 – inter-wheel; 2 – inter-axle)

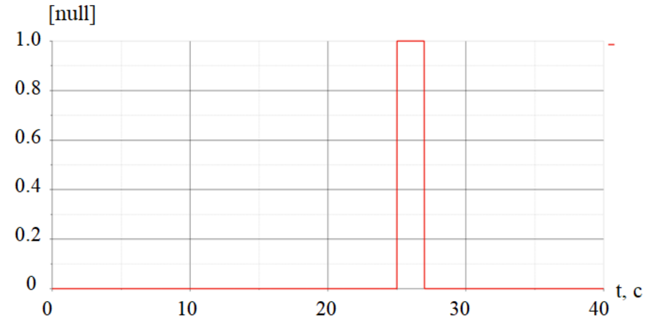

Figure 5 – Control signal for braking

According to the results obtained, in particular the data in Figure 4, it can be concluded that during the acceleration, when the speed reaches 20 km/h, the blocking of the inter-wheel differentials is disengaged, and when the speed reaches 30 km/h, the inter-axle locks are disengaged. Further, during braking and lowering the speed below the set values, inter-axle and inter-wheel lock of the differentials are successively included.

2. Curved motion with steering wheel rotation.

The movement of the truck is carried out with a gradual from the rest position to a speed of less than 20 km / h. When time reaches 5 sec, the steering control input is applied to the steering wheel for further turning the car. The results are shown in Figures 6-8.

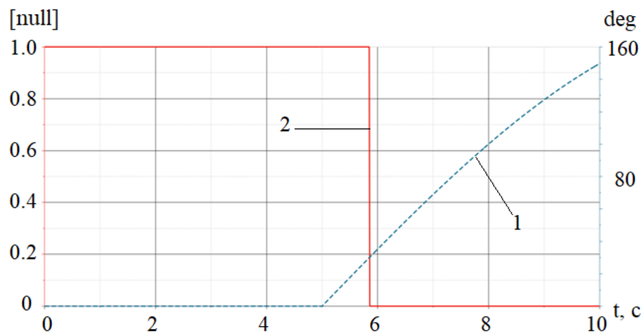

Figure 6 – Steering wheel rotation (1) and inter-axle/inter-wheel differentials locks state (2)

As shown in Figure 6, when the steering angle of 30 degrees is reached, the inter-axle and inter-wheel lock of the differentials is disengaged.

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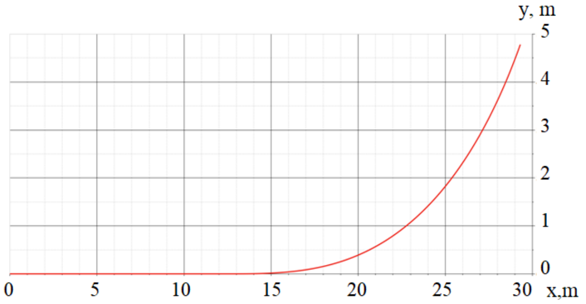

Figure 7 – Vehicle trajectory in X-Y plane

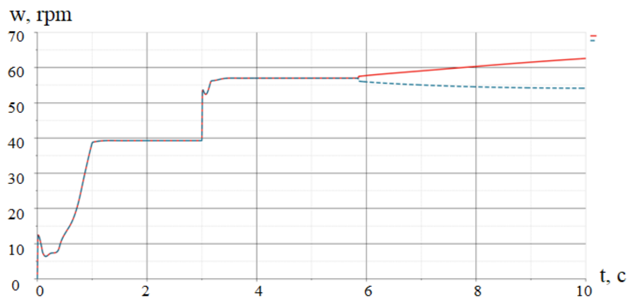

Figure 8 – Wheels rotational speed

From figures 7 and 8 it can be seen, that car turn is carried out with different speeds of rotation of wheels of the forward (operated) axis that testifies to the unlocked differential.

3. Uphill movement in city

In this case, the traffic in settlement is simulated. In accordance with the adopted algorithm, all differentials are initially unlocked, the car accelerates to a speed of more than 30 km/h, after 60 m of the path, the lift starts at an angle of 10 degrees with a semicircular entry at the beginning. The results are shown in Figures 9-13.

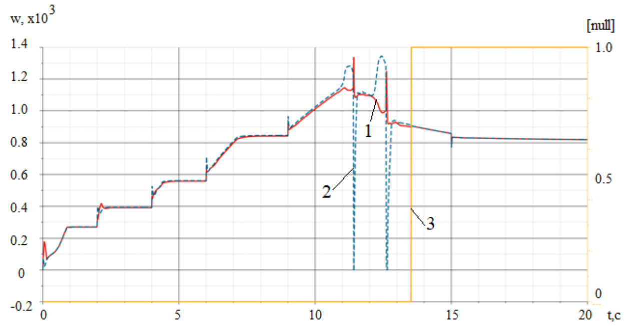

Figure 9 – Transfer case output shafts rotational speed (1 – front axle shaft; 2 – rear cart shaft) and control signal for inter-axle differentials locking (3)

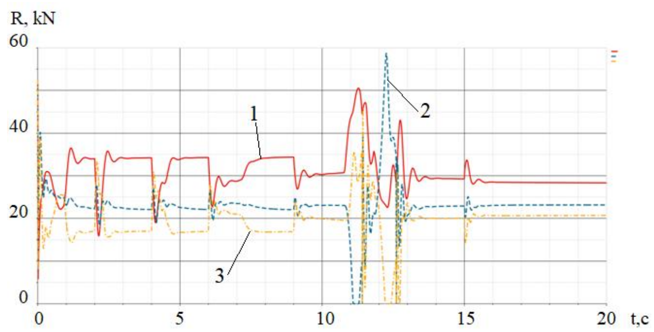

Figure 10 – Wheels vertical reactions
(1 – front axle; 2 – middle axle; 3 – rear axle)

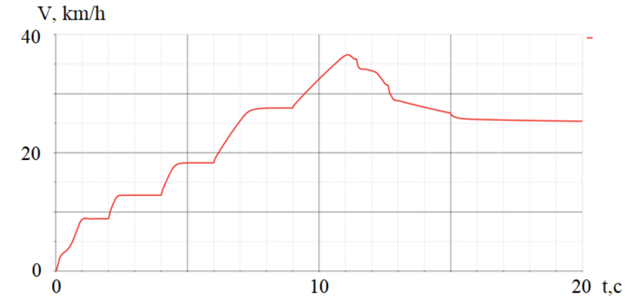

Figure 11 – Vehicle speed when moving uphill

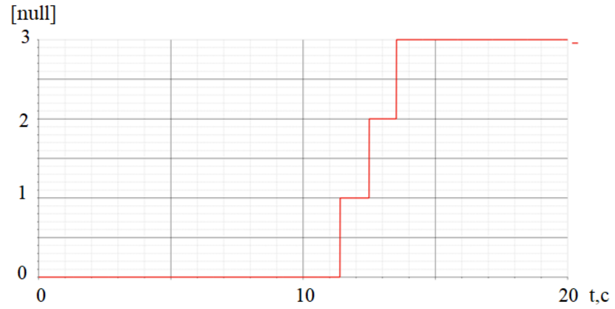

Figure 12 – ASR enabling counter

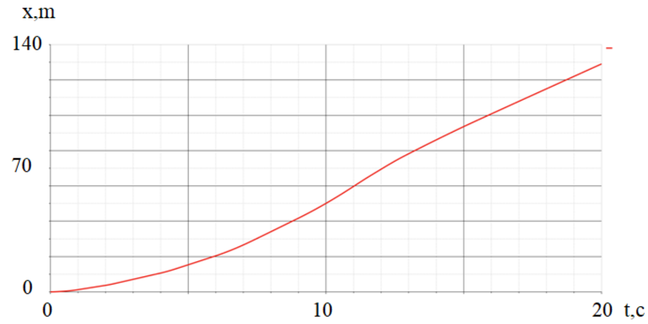

Figure 13 – Lateral coordinate changing when moving uphill

According to the change in the speed of rotation of the output shafts of the transfer box (Figure 9), it can be seen that the wheels of the rear cart are slipping, this is a consequence of the consecutive short-term hanging of the wheels of the middle and rear axles (Figure 10) when the car enters the haulage area. When the axles are slip, the ASR system is triggered, however, its work is not enough to continue the motion, therefore, after the 3rd actuation (Figure 12), a control signal is sent to enable the inter-axle locks of the differentials (Figure 9). After that, the truck continues to move upward (Figure 13) at a constant speed (Figure 11).

V. Conclusion

1. An algorithm for controlling automatic locking of differentials of a truck with a wheel formula 6x6 is developed.
2. Means of simulation mathematical modeling confirmed the overall efficiency and effectiveness of the proposed algorithm for typical modes of vehicle operation, including in conjunction with regular active safety systems (ABS and ASR).
3. Simulation results proved that the proposed strategy for controlling power distribution mechanisms does not adversely affect the stability and controllability of the vehicle when rigid kinematic constraints are introduced in the course of the motion.

4. Based on obtained results, the struckture of the software and hardware complex for automated control of truck differential locks has been formed.

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