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Design and Experimental Validation of Dump Truck Active Safety System Algorithms

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***Abstract*— As a result of experimental tests and operating experience of BELAZ mining dump trucks, it has been established that the active safety system in difficult driving conditions on haul roads is in great demand. Loss of control on a slippery road as a result of driver error can lead to a serious accident and costly mining equipment repairs. The article proposes control algorithms that use additional information from the front wheel sensors. This made it possible to significantly improve the dump truck controllability in driving conditions of poor wheel adhesion, preventing the dump truck from yaw and wheels block, reduce mechanical impacts on the transmission and structural elements of the vehicle. Adapt the dump truck active safety system characteristics to changes in driving conditions. The test results are shown on a BELAZ dump truck with a carrying capacity of 90 tons. They confirm the effectiveness of the developed control system in comparison with that currently used in serial products.**

Keywords*— *road vehicles, control systems, wheels, process control, vehicle safety, advanced driver assistance systems, motor drives.

I. INTRODUCTION

Mining (off-road) dump trucks are used in open-pit mining and work mainly in difficult road and climatic conditions. The maximum load capacity of such dump trucks, today, is 450 tons, and the speed of movement on a horizontal surface exceeds 60 km/h [1]. Under such operating conditions, the dump truck control system must be adaptive, ensure driving stability and controllability.

Modern vehicles are equipped with many different traffic safety systems. These are the anti-lock brake system (ABS), the acceleration slip regulation (ASR), the electronic differential lock system (EDS), as well as electronic stability program (ESP), which was named ESC, DSC, VDC, etc. in dependence to the vehicle manufacturer. The main task of the ABS and ASR systems is to maintain controllability on a slippery road by maintaining slip in the optimal range corresponding to the maximum coefficient of longitudinal grip of the wheels with the road surface [2]. The width of this range is a criterion for the quality of systems operation. The effective operation of ABS allows you to shorten the braking distance, ASR together with EDS - to increase the cross-country ability, and ESP - to prevent truck yaw [3,4].

In conditions of driving on dry asphaltic concrete surface, ABS increases the braking distance, but retains controllability and reduces wear on the expensive wheel rubber of a mining truck. A modern ABS system should provide [2,5]: minimum braking distance, maintaining control, adaptability to external conditions (changes in slip coefficient), smooth braking (jerk-free).

The use of ASR allows you to increase the traction force, maintain driving stability and reduce the load on the transmission [6]. ESP, combining and developing the advantages of ABS and ASR, prevents skidding and side slip, helps to stabilize the car's position during extreme maneuvering on slippery road surfaces [7,8].

The development of traffic safety systems for mining dump trucks with electromechanical transmission (EMT) is an important task. Difficult road conditions (mud, wet clay, ice) and dump truck operation modes (descents and ascents uphill) place increased demands on such systems [9].

The set of traction electrical equipment (TEES) of the mining dump truck EMT includes [10]: two traction induction motors (TIM), a synchronous traction generator (STG), a control system converter cabinet (CSCC) and a high level controller unit (HLC). Traction motors installed in the rear axle on the left and right sides of the dump truck set the wheels in motion. The diesel engine rotates the STG shaft, depending on the power required for traction. Electric machines are controlled by CSCC, which includes blocks of controllers for power converters (PCC), traction generator excitation system unit (TGES), microclimate control system unit (MCCS), as well as a cooling system power inverter unit (CSPI) for liquid-cooled version. The HLC unit controls the dump truck movement. With the control system signals and generates task for the lower-level controllers that are part of the CSCC and the diesel engine controller unit (ICE).

In general terms, the control formation procedure involves: the TIM torque is calculated depending on the pedal depression (Accelerator or Brake) and the power that the internal combustion engine develops in the traction mode or the controlled ventilated braking resistor unit (VBRU) is able to dissipate in the braking mode, limiting the acceleration dynamics and controlling wheel slip. Separate torque control of the dump truck wheels improves handling and traffic safety in difficult road conditions [11,12].

II. STANDART ABS SYSTEM

Here and below, under ABS we mean the independent operation of two systems: ABS and ASR, their aim is to ensure optimal sliding, respectively, in traction and braking modes.

The standard ABS system works independently on the sides of the dump truck, controlling the acceleration of the drive wheel, and, in case of exceeding the maximum value, reduces the electromagnetic torque of the TIM, restoring wheel adhesion to the road.

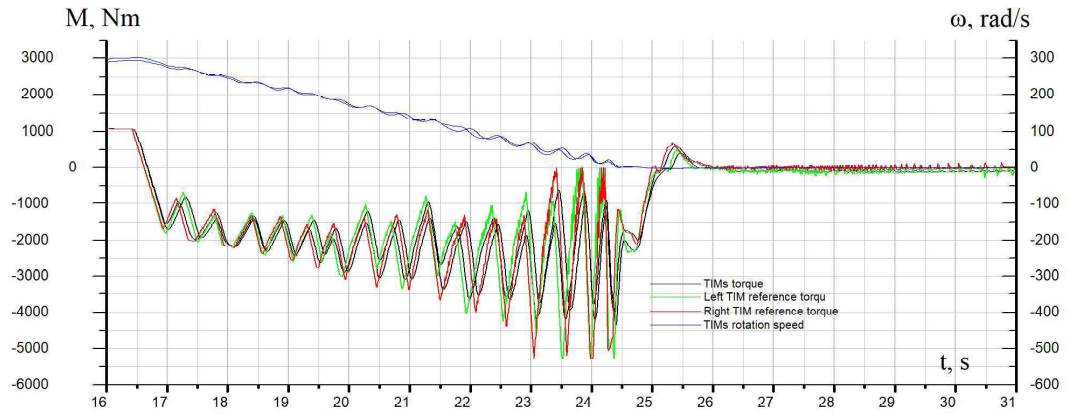
Fixing the transition to the anti-lock or anti-slip mode, the ABS system generates torque switching (in the cycle: reset to zero and reverse recovery according to the master).

As a result of limiting the dynamics in terms of torque and power, the period of torque pulsations ranges from 0.5 to 1 sec. ABS mode exit is performed under the condition that the current wheel speed reaches the speed value calculated from the expected acceleration (deceleration), at which slippage does not occur at this speed [13].

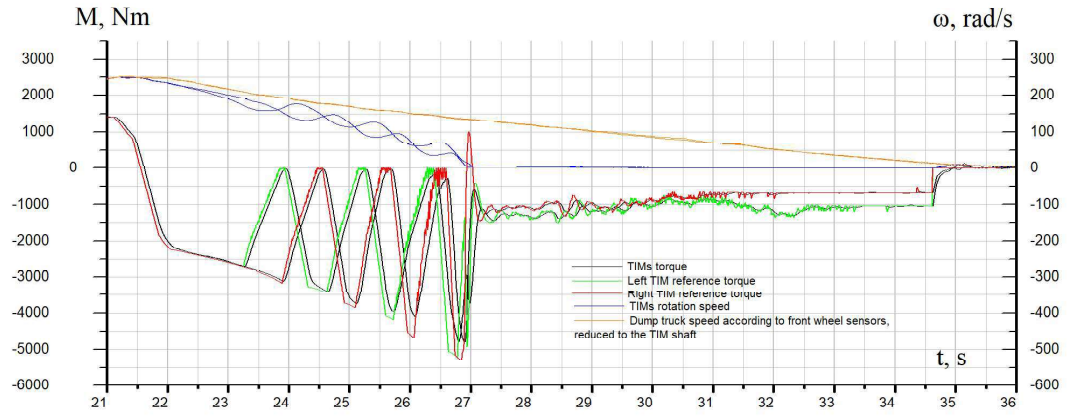
The operation of the ABS system during emergency braking in various road conditions is shown in Fig. 1, where the green and red colors show the values of the torque set by the HLC for the left and right sides, the black and blue colors show the values of the electromagnetic torque and TIMs speed.

Operation in real conditions revealed the shortcomings of the standard ABS system [14]:

- The pulsations of the electromagnetic torque (from the limit value in the braking mode to zero with a frequency of 1-2 Hz, Fig. 1) impose increased requirements on the traction drive, increase losses, and affect the service life of the motor-wheel mechanical transmission.
- The condition for transition to the ABS mode is determined by the characteristic of the maximum acceleration at which the wheel does not lose traction, due to the speed of rotation. It should be mentioned that this characteristic is calculated for certain driving conditions and road surface. Figure 1a illustrates the operation of the standard ABS system, the setting of which was carried out on an empty dump truck during driving on a flat section of a dry gravel road. Changing road conditions (ice covered with packed snow) while maintaining the system settings leads to non-optimal ABS operation (Fig. 1b) - the wheels are blocked, sliding on the snow, and only an experienced driver can maintain controllability of the dump truck in this case. The speed of the dump truck (reduced to the TIMs shaft) is highlighted in orange color.
- The system does not provide optimal sliding and adaptability to changes in wheel grip on the road. A possible solution in this case may be a set of different settings optimized for specific operating (road) conditions (for example, soil, snow, ice, clay, etc.).
- The difference in the conditions of the driving wheels' grip of the left and right dump truck sides leads to a mismatch in their speeds (a wheel with a lower coefficient of adhesion slows down or accelerates faster). In this case, it is necessary to determine the maximum possible speed mismatch, based on the maximum turning radius of the dump truck, and remove the traction moment from the wheel, the speed of which is higher, or the braking torque from the wheel, the speed of which is lower. This task is performed by the wheel differential lock subsystem, which generates the ABS mode activation signals.



a) on a dry road in summer



b) on an icy road in winter

Fig. 1. ABS operation when braking (pedal to the metal) of an empty dump truck with carrying capacity of 90 tons: a) on a dry road in summer; b) on an icy road in winter

The standard ABS system works by wheel acceleration, filtered to eliminate false responses when driving on uneven road surfaces. This leads to delays in the activation of the ABS mode on slippery roads and affects the quality of the system. It is possible to improve the quality if you receive information about the speed of the dump truck.

III. Adaptive ABS System

The next step in the ABS development is the development of a new system that provides sliding within the allowable range under any road conditions. To do this, the control system receives information from the speed sensors of the front (driven) wheels, which determine the linear speed of the dump truck.

The main task of the adaptive ABS system is to maintain optimal sliding of the driving wheels when the adhesion coefficient of the wheel rubber to the road surface changes. The block diagram of the adaptive system is shown in Fig.3.

In Fig. 3, the following designations are used:

- **IC –** intensity controller, which reduces the input value to the specified minimum level;
- **F –** linear filter of the first order;
- **R –** wheel slip regulator.

The adaptive ABS system reduces the torque reference module M1 generated by the control system based on the driving mode (traction or braking) without taking into account the wheel sliding, to the ΔM, the value of which is determined by the deviation of the real speed ω2 (of the drive wheel) from the calculated by the condition of no slip (ω1). The condition for switching to ABS mode is the excess slip $|\omega 2-\omega 1|$ set switching threshold $\Delta\omega 0$, the condition for exiting the ABS mode is slip reduction to the level of the switching off threshold. Thus, if ω1=ω2, the wheel does not slip and M2=M1 if $|\omega 2-\omega 1|$ exceeds $\Delta\omega 0$, ABS mode is activated and $M2=M1-\Delta M$ if $M1>0$ or $M2=M1+\Delta M$ if $M1<0$. The value of ΔM is determined by the controller P, which receives the filtered speed deviation $\Delta\omega$.

Estimated speed ω1 of the driving wheel is determined by the speed of the driven wheel based on the geometric dimensions of the dump truck and the movement trajectory. The speeds of the front and rear wheels of one side (excluding slippage) differ mostly on turns, as the exampled in Fig. 2. The example illustrates the movement of the BELAZ 75584 dump truck in a circle with a radius of 10 m. The speeds of the driven wheels are marked in black and red, the calculated speeds of the driving wheels (ω1) are green and blue for the left and right sides, respectively.

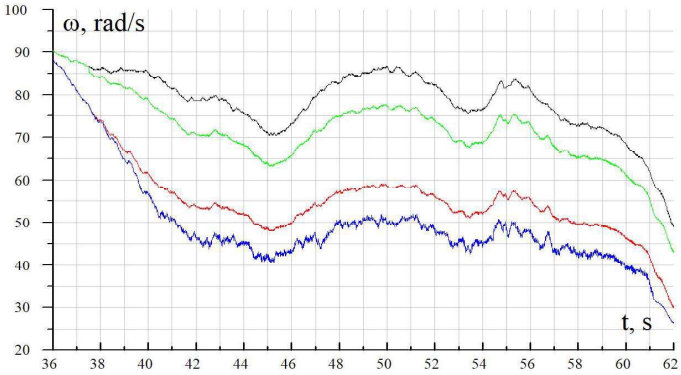


Fig. 2. The speed of the driven wheels and the estimated (slip-free) speed of the driving wheels when the dump truck circulate

IV. Experimental Results

The test of the adaptive ABS system was carried out on an empty dump truck in the winter season, driving on an icy, snow-covered road at an ambient temperature of -8 to -3°C. The dump truck was moving in a straight line, climbing 8% slope and descending 11% slope in the maximum traction and emergency braking modes (sharp braking). In these modes, a comparison was made between the operation of standard and adaptive ABS systems.

The hard braking mode of a dump truck at a speed of 40 km / h with adaptive ABS on a straight section of the road is shown in Fig. 4, where the same color designation of the speed and torque graphs is used as in Fig. 1. As a result of the tests carried out at the BELAZ test site, it was established:

- The pulsations range of the electromagnetic torque and the angular velocity of the TIM is much smaller compared to the standard version of the ABS system, which increases the service life and performance of the EMT.
- The drive wheels' slip is maintained within the specified range by controlling the moment of the TIM, providing controllability during the acceleration and deceleration of the dump truck.
- The braking time (from a speed of 40 km/h to zero) for the compared variants of the ABS system differs slightly (by 2-3 seconds) in favor of the standard system, but in this mode the wheels quickly lock up, controllability is lost and the dump truck goes into a side skid.

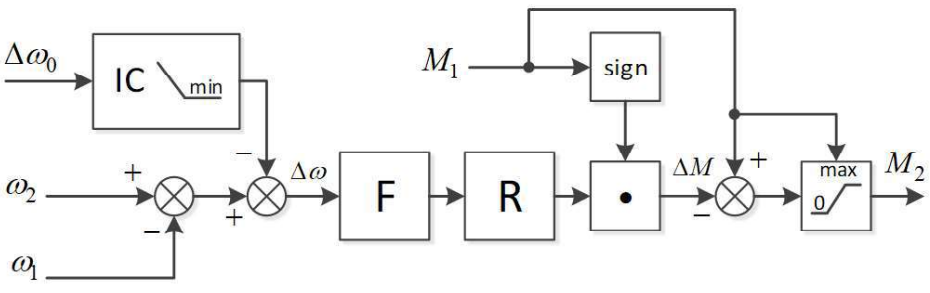


Fig. 3. Block diagram of the adaptive ABS system

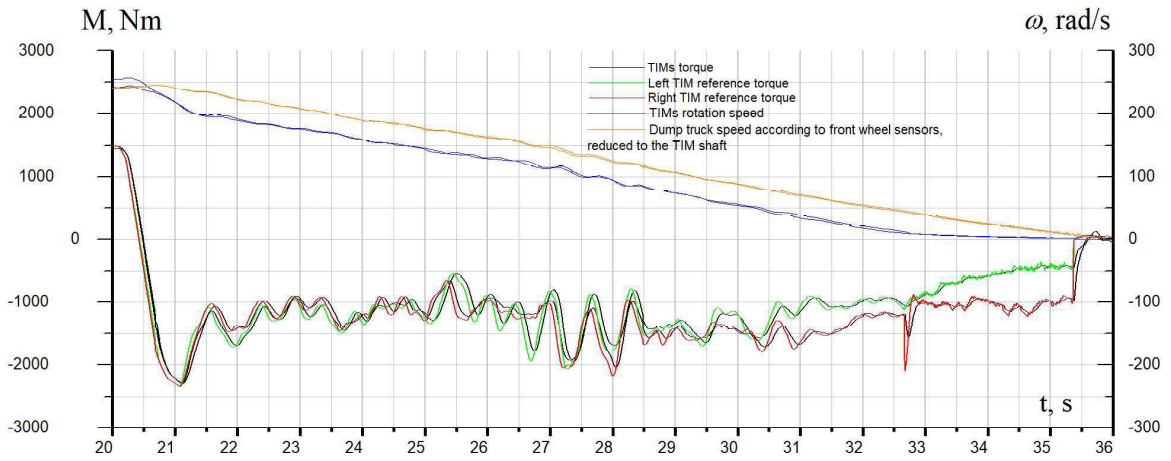


Fig. 4. The adaptive ABS system operation during braking of an empty dump truck with a carrying capacity of 90 tons on an icy road

V. CONCLUSION

The developed adaptive ABS system with speed sensors for the front wheels of a mining dump truck showed the effectiveness of braking on a slippery road in terms of maintaining controllability (no skidding and wheel locks) with a sharp and full depressing the dynamic brake pedal at a straight section and on a descent one from a slope. The adaptive system remains operational if one of the front wheel sensors fails and, compared to the standard system, works equally efficiently in various driving conditions, ensuring the driving wheels slip in a given range by controlling the torque of the traction motors.

The control algorithms discussed in the article have been tested on a BELAZ 75584 dump truck with a payload capacity of 90 tons, and it is planned to introduce them to other standard sizes of currently produced mining dump trucks. The standard ABS algorithm is left as a backup in case of undefined information from the speed sensors of both front wheels.

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