Improvement of the active safety of the vehicle for driving on the irregularities by the method of control of vertical reactions on wheels

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Abstract. Countries with large territories have numerous roads of relatively nobody's quality, characterized by the presence of large irregularities. There are improved roads, but they are badly damaged by inappropriate exploitation or by geophysical and climatic hazards. Such roads are characterized by unevenness, periodic or randomness. The speedy movement of medical transport, rescue vehicles and special services can be difficult because of the possible loss of vehicle stability, which leads to accidents. Often, the loss of stability in such situations is associated with the appearance of resonance vibrations of the vehicle's wheels, which leads to a deterioration of the wheel to the road, reducing the transverse stability of the axle and thus allowing it to slide transversely. There are many active safety systems, such as ABS, directional stability system and others, which lose their effectiveness in these circumstances. This inconvenience can be avoided by applying the stabilization system for vertical reactions to the vehicle's wheels (SVRDK).

Introduction

The control of the suspension has been one of the priority tasks in the field of car construction for a long time. The widely used uncontrolled suspension vehicle does not provide sufficient running quality in the required driving conditions. This defect has been corrected by using a controlled suspension. Another quality that can be related to the vehicle's body vibrations is the stability of the vehicle. Many works are devoted to the study of the vehicle's stability and the active safety systems. The problem of vehicle stability can be reflected in different aspects. Thus, for special vehicle designers, the question of the stability of the vehicle in the event of a tire breakage can be asked [1]. Traffic safety, including driving stability, is ensured by the numerous active safety systems. System analysis of the active vehicle safety problem is presented in the article [2]. The active suspension is used among the active safety features in cars. The active suspension systems can minimize or completely reduce the vehicle's roll to ensure dynamic ride while improving safety and comfort [3]. The characteristics of modern active suspension designs allow their adjustment directly when the vehicle is in motion, depending on the road conditions, both in automatic and manual mode [4]. In particular, adaptive shock absorbers, elastic elements with non-linear characteristics and improved running quality have been developed. Often the road surface is seriously damaged for many reasons, such as natural disasters, landslides, landslides, improper operation of the road, etc. [5].
with high speeds of emergency vehicles is difficult. Traffic with high speeds of emergency vehicles is difficult. This problem requires the use of active safety systems that can help to accelerate the progress of special service vehicles. This paper [6] discusses the strategy for using a particular turning trajectory, the strategy for emergency braking in order to ensure that the vehicle moves sustainably. The article [7] discusses the issue of transporting seriously sick patients, which is desirable to perform at higher speeds. The problem of active suspension control for a vehicle experiencing impact perturbations is appropriately formulated as a mixed control problem FTS/H∞ [8]. This paper [9] studies the control for the model of an active vehicle suspension system with input time delay in the presence of an external disturbance. The control under consideration allows trade-offs between energy consumption, processing performance, and smooth running. The estimation of the tire's slip angle to control the vehicle's stability is presented in [10]. In work [11], the magnetorheological damper of the rear semi-active suspension is controlled on the basis of sensor signals located in the front of the vehicle. The paper [12] presents the method of adaptive control of the active suspension of the vehicle. This method allows the active suspension of the vehicle to be automatically adjusted so that external disturbances do not affect the dynamic characteristics of the system. The article [13] is devoted to the design of the antilock braking system (ABS) regulator to adjust the slip of the wheel to its preferred value by controlling the slip mode of the wheel. ABS should be resistant to external influences, such as changes in friction between the tire and the road caused by changes in road conditions, loads, etc. The paper [14] considers methods of converting statistical data of road microprofile. The interaction of wheel elements with the ground at curvilinear motion is investigated in the paper [15]. The operation of the antilock brake control system, the structure of the system is shown in the work [16]. The mathematical model of a straight-line rolling tire, which allows studying its interaction with the roughness of the relief surface, is presented in [17]. The paper [18] presents the research within the framework of synthesis of the adaptive suspension system used for damping vibrations in multiaxle wheeled vehicles. A review of existing methods of friction assessment with the development of a new method, which is used to develop an effective ABS control system, is presented in [19]. The main attention in the article [20] is given to the control of braking torque of electric vehicles. The recommendations concerning the topology of hierarchical system with the distribution of torque between electric and hydraulic brakes and accurate accounting of hybrid energy storage are given.

When the vehicle is moving on uneven terrain as a result of vertical wheel oscillations, especially in wheel resonance and close to it frequencies, at certain moments the vertical reactions of the road to the wheels can be quite small. Sometimes, when the wheel is taken off the road, these values can become zero. In this case, as practice and calculations show, the lateral stability of the vehicle during driving is dramatically reduced. The stability of the vehicle can be improved by using a system to stabilize the vertical road to wheel response. Such a system can be considered as a new active safety system that increases the stability of the vehicle on an uneven road.

**Theoretical Background**

Figure 1 schematically shows the system for stabilizing the vertical wheel response. The dynamic model of the stabilization system under consideration includes the suspended mass simulating the car body, unsprung mass simulating the mass of the car wheel with moving parts of the suspension, bearing unit and brake mechanism. In the suspension structure, the actuator (actuator) is switched on in parallel with the elastic element and shock absorber. As an actuator, almost any linear motor can be used: hydraulic or electromagnetic. The presented model is described by the equations:

\[
\begin{align*}
    m_2 \ddot{z}_2 &= c_c \cdot (z_1 - z_2 + A_n) + k_d \cdot (\dot{z}_1 - \dot{z}_2) + c_c \cdot (z_1 - z_d - r_d) - m_2 g \\
    m_1 \ddot{z}_1 &= -c_c \cdot (z_1 - z_2 + A_n) - k_d \cdot (\dot{z}_1 - \dot{z}_2) - c_c \cdot (z_1 - z_d - r_d) - m_1 g + \\
    &+ c_t \cdot (z_d - z_1 + A_t) + k_t \cdot (\dot{z}_d - \dot{z}_1)
\end{align*}
\]
Analysis of the vertical response of the road to the wheel
The vibrational properties of the system, in particular, the resonance zone of the wheel, can be seen on the diagram of changes in the vertical response from the road in the function of time when simulating the movement of the car on the sinusoidal profile with a variable frequency of exposure of the road to the wheel (Figure 2).

Figure 1. Control diagram of the vertical reaction of the road to the car's wheel when driving on a periodic profile.

It's right here: $m_2$-sprung mass; $m_1$-unsprung mass; $c_e$ -rigidity of elastic element; $k_a$ -rigidity of shock absorber; $c_t$ -transfer coefficient, which determines the value of force created in the actor; $c_t$ - the tire radial stiffness; $k_t$ -coefficient of inelastic resistance in the tire; $z_2$, $z_1$ -vertical coordinates of the suspended and unsprung masses; $z_d$ -vertical coordinate of the road profile; $A_n$, $A_a$ -constant coefficients; A-actuator (e.g., hydraulic cylinder);DDR-sensor of dynamic radius; ID-source of pressure.

Figure 2. The vertical response of the road to the wheel in the passive linear suspension when the vehicle is moving along a periodic profile at an increasing speed.
The analysis of this graph shows that the natural frequency of the unsprung mass imitating the mass of the wheeled-steam node is approximately 8 hertz. In the real movement of the car in the resonance mode, the wheels may be detached from the road. In this case, the mathematical description of the relationship between the wheel and the road becomes non-linear. For the decision of a nonlinear problem of such plan the method of the imitation modeling realised in package Matlab Simulink is applied.

When driving with uncontrolled suspension in the wheel resonance mode, the character of the change in the value of the vertical reaction of the wheel for the given parameters of the system of suspension of the car and the road profile is represented by the diagram in Figure 3a. In these conditions of movement the value of vertical reaction of the road to one wheel varies from 0 to 15000 N. The peculiarity of the graph in Figure 3a is the presence of zones, in which the vertical reaction of the road is equal to zero. Such a change in the vertical response of the road increases the likelihood of loss of stability of the car. Figure 3b shows the same process with the vertical response stabilization system (SVRDK).

![Figure 3. The vertical response of the road to the car's wheel when driving in resonance mode on a sinusoidal profile with an amplitude of 0.02 m: a) without suspension control, b) with suspension control.](image)

The use of this control system reduces the vibration amplitude of the vertical road response as shown in Figure 3b. The vertical reactions in the system of suspension with the control of these reactions sharply decreases at the influencing of the road on the resonance frequency of unsprung masses of the passive system of suspension amplitude of, in the given case, approximately in 30 times.

The calculations show that the applied control requires a power consumption of less than 2 kW per wheel for the system under consideration. Its maximum values do not exceed 3.5 kW. Maximum values of forces created by it, acting on the wheel and the body of the car, are 4500 N. The result is the stabilization of the vertical reaction of the road to the wheel with a deviation of its value from the static of less than 10%.

Analysis of the system of stabilization of vertical road reactions
The system of stabilization of vertical road reactions under consideration increases the effectiveness of a number of active safety systems when driving on uneven terrain. Let's consider the influence of the system of stabilization of vertical reactions of the road on the efficiency of such active safety system as the system of control of the car wheels convergence (SARS). Figure 4 shows the results of calculating the traffic on a circular car on a road with a profile amplitude of 0.01 m using various combinations of SVRDK and SARS. The presented trajectories show the effectiveness of the SVRDK
in the vehicle's circular motion with a periodic profile that causes oscillations at the resonance frequency of the vehicle's wheels. The efficiency of SARS in combination with SVRDK is also shown.

Similarly, the system for stabilizing vertical reactions has a positive effect on the efficiency of the anti-lock braking system. This can be judged by the results of calculations given in Table 1. The table shows the values of the braking distance of the vehicle $D$ (m) in the function of amplitude $A$ road profile and application of the SVRDK.

![Figure 4. The trajectory sections of the car's roll-on trajectory along the sinusoidal profile with an amplitude of 0.01 m with different combinations of vertical response stabilization system (SVRDK) and car wheel convergence control system (SARS). The trajectory sections and the corresponding switched on control systems are shown within the limits.](image)

| Amplitude A of the road profile $A$ (cm) | 0   | 1   | 2   | 3   |
|----------------------------------------|-----|-----|-----|-----|
| Braking distance of the vehicle $D$ (m) without SVRDK | 26.2 | 27.3 | 34  | 45  |
| Braking distance of the vehicle $D$ (m) with SVRDK | 26.2 | 26.2 | 26.2 |     |
| Increasing value $D$ (m), % | 4.5 | 24  | 42  |     |

Similarly, the system for stabilizing vertical reactions has a positive effect on the efficiency of the anti-lock braking system. This can be judged by the results of calculations given in Table 1. The table shows the values of the braking distance of the vehicle $D$ (m) in the function of the amplitude $A$ of the road profile and the application of the SVRDK.

The simulation also confirms that SVRDK under consideration stabilizes the vertical response even when driving on a random road profile. This fact extends the range of modes in which it is reasonable to use the system.
As a result of the executed researches it is received that the considered system solves problems of stabilization of vertical reaction of road on a wheel at movement of the car on roughness. In addition, the system under consideration additionally solves the problem of reducing the amplitude of vibrations of the vehicle body at its resonance frequency.

In the process of modeling the vibrations experienced by the vehicle, it has been found that at the frequency of the vehicle body's own vibrations from the action of the sinusoidal profile road with an amplitude of 0.05 m there is an impact on the suspension system of the vehicle. Figure 5 shows the calculation of the vertical position of the vehicle's centre of gravity without control (first 10 seconds) and the following 10 seconds of driving with control of vertical reactions. According to the diagram, the amplitude of vertical center of gravity vibrations of the car during the motion without using the system of vertical reaction stabilization is 0.26 m, and when using this system 0.069 m.

![Figure 5](image-url)

**Figure 5.** Changes in the vertical position of the vehicle's centre of gravity when the body vibrates at the natural frequency of the vehicle's own vibrations when driving on a sinusoidal profile with an amplitude of 0.05 m without control (0-10 s) and with control of vertical reactions (10-20 s)

Thus, the amplitude of oscillations of the center of gravity of the vehicle body when using the system of stabilization of vertical reactions to the wheels is 26% of the amplitude of oscillations of this point in the absence of control. Similar results were obtained in the calculation of angular, longitudinal and transverse body vibrations.

**Conclusion**

Our study has shown a positive effect of the work of the system of stabilization of vertical reactions of the road on the transverse stability of the car when driving on the unevenness. It is effective when the car is driven by the side wind and on bends. In the process of vehicle, movement at transition from a mode of movement on a highway in a mode of movement on rough road SVRDK allows to keep efficiency of work of some systems of active safety.

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