Structures active suspension for stabilizing vertical reactions of the road to the car wheels when driving over irregularities

V I Ryazantsev* and Li Heng-Xu
Bauman Moscow state technical University (BMSTU)

Abstract. The development of automotive technology is clearly characterized by the mass introduction of numerous active safety systems in the design of cars, such as anti-lock brakes, stability control systems, etc. In the conditions of a significantly increased number of motor transport, which is operated on roads of relatively low quality, the question of increasing the stability of the car when driving on uneven roads naturally arises. There are quite a lot of such roads in countries with large territories. There are numerous cases of the formation of sections with regular profiles on improved roads. Movement in such areas can cause resonant vibrations of unsprung masses, which, in turn, leads to a loss of stability of the vehicle. This article discusses the effectiveness of various structures of controlled suspensions that can be used in the stabilization system of vertical reactions of the road to the car wheels when driving on an uneven surface.

1. Introduction
In all countries that produce automotive equipment, much attention is paid to the issues of vehicle safety, in particular, the problems of improving traffic stability and manageability. A significant influence on the solution of these problems is provided by the properties of used car suspensions, which determine the character of oscillations that occur in them. Since the used unmanaged suspensions do not allow you to get acceptable performance of the car, which is important for safe driving in some road conditions, designers of automotive technology have been working on the creation of controlled suspensions for a long time. One of the directions of this work is the development of suspensions to reduce vibrations of the car body, which to a certain extent allows you to increase the stability of movement and handling of the car. Vehicle safety, in particular, the stability of its movement, is provided by numerous active safety systems. The system analysis of the problem of active vehicle safety is presented in the article [1]. The use of active suspensions to ensure dynamic driving of a vehicle while improving safety and comfort is considered in [2]. In [3], we discuss the characteristics of modern designs of active suspensions that allow their regulation when driving a vehicle. For such suspensions, in particular, adaptive shock absorbers, elastic elements with nonlinear characteristics have been developed. Often the surface of the road to the places of accidents, where you need to move at high speed, is damaged for various reasons (natural disasters, landslides, incorrect operation of the road, etc.) [4]. Traffic with high speeds of special rescue services vehicles is difficult.

Such circumstances call for the use of active safety systems that can help speed up the movement of vehicles of these services. The article [5] discusses the issue of transporting seriously ill patients, which is desirable to perform at high speeds. The problem of controlling the active suspension for a
car experiencing shock road disturbances is discussed in the article [6]. In [7, 8, 9, 10, 11, 12] the issues of active suspension control are considered, in particular, adaptive control is considered, which allows the system to be automatically adjusted, adapting to external conditions. The interaction of the wheel with the road in curved motion, its interaction with the irregularities of the relief surface, are presented in [13, 14]. In [15, 16], the magnetorheological damper of the rear semi-active suspension is controlled based on the signals of sensors located in the front of the vehicle. The relationship between the sliding angle of the tire and the stability of the car is presented in [17]. In [18], methods for converting statistical data of the road micro-profile are considered.

2. Stabilization system of the vertical reaction of the road to the wheel when the car is moving over irregularities

When a car is moving over irregulars a result of vertical vibrations of the wheels, especially in the mode of wheel resonance and at frequencies close to it, at certain moments, the vertical reactions of the road to the wheels may take small values or even zero. In this case, as shown by the practice of car operation and calculations, the lateral stability of the car when driving is sharply reduced. The stability of the car can be improved by applying a system for stabilizing the vertical reactions of the road to the wheels. Such a system can be considered as a new active safety system that increases the stability of the vehicle on uneven roads.

The scheme of the stabilization system for the vertical reaction of the road to the wheel (SSVRR), when the car is moving over irregularities made on the basis of a traditional car suspension is shown in Fig.1. The actuator is placed parallel to the spring and the shock absorber. An electric drive or hydraulic cylinder can be used as an actuator. The actuator force is controlled by the control unit based on a signal corresponding to the vertical reaction of the road to the wheel. The vertical response can be obtained either by corresponding measurements directly in the wheel ("smart tire") or by measurements of a number of parameters in the suspension and virtual processing of this data.

![Figure 1. Scheme of system of stabilization of vertical reaction of the road to the wheel when the car is moving over irregularities.](image)

The result of applying the system of stabilization of vertical reactions of the road to the car's wheels when driving on a road with a periodic profile that causes resonant vibrations of the wheels can be seen in the diagram (Fig. 2).

A diagram shows that SSVRR can dramatically change the character of the course of the vertical reactions of the road on the wheel when driving on the periodic profile, significantly stabilizing this
reaction. Below are the structures of controlled suspensions that can be applied to the SSVRR system on the car. Cars that use controlled suspensions with a structure containing an elastic element do not lose the ability to move if the control system is damaged. Reducing the number of structural elements in the controlled suspension creates better conditions for the layout of the car structure.

![Figure 2](image2.png)

**Figure 2.** Vertical reaction of the road to the wheel of a car with a system in the form of A without control (0-5 s), a controlled P-regulator (5-10 s) and PD controller (10-15 s) when moving along a sinusoidal profile \( z_d = 0.01 \sin(61.8t) \).

3. **Structures of controlled suspensions that can be applied to the SSVRR system on the car**

As the first variant A of the controlled suspension structure suitable for use in the vertical reaction stabilization system, we will consider a suspension with a parallel spring, shock absorber and actuator (Fig. 3).

![Figure 3](image3.png)

**Figure 3.** Dynamic suspension scheme with structure A of the stabilization system of vertical reaction of the road to the wheel

Differential equations of such a system:

\[
m_1 \ddot{z}_1 = k_{tire}(\dot{z}_2 \dot{z}_1) + c_{tire}(z_2 - z_1 + R_{tire}) - k_{sd}(\dot{z}_2 - z_2)
- c_{ress}(z_1 - z_2 + L_{ress}) - m_1 g - F_a
\] (1)
\[ m_2 \ddot{z}_2 = k_{sd}(\ddot{z}_1 - \ddot{z}_2) + c_{res}(\dot{z}_1 - \dot{z}_2 + L_{res}) - m_2 g + F_a \]  

\( F_a = k_p(F_{ztire} - F_{ztirestat}) \)  

where \( F_a \) is the actuator force, \( R_{tire} \) is the free radius of the wheel, \( L_p \) is the free length of the elastic suspension element, and \( g \) is the acceleration of gravity. The second option is to consider the structure B, which consists of a parallel spring and an actuator. Of course, this structure gives the layout advantages, reducing the number of elements of the structure, its simplification and, from this point of view, cheaper. Variant of structure C is a parallel actuator and shock absorber. The fourth variant D is characterized by the absence of an elastic element and a shock absorber. In the design of this suspension, only the actuator remains. The peculiarity of the structure E is that the spring and the actuator are placed in series. In this suspension, the actuator serves as the main spring. Thus, this spring is virtual, its function is performed by the electronic part of the control system. The real spring serves as a bump in the suspension. In variant F, \( \text{Fig. 4} \), the spring performs the usual function. The actuator also creates a force in the function of the position of the body and the vertical reaction of the wheel.

\[ m_1 \ddot{z}_1 = k_{tire}(\ddot{z}_1 - \ddot{z}_1) + c_{tire}(\dot{z}_1 - \dot{z}_1 + R_{tire}) - k_{sd}(\dot{z}_1 - \dot{z}_2) - m_1 g - F_a \]  

\[ m_2 \ddot{z}_2 = k_{sd}(\ddot{z}_1 - \ddot{z}_2) - m_2 g + F_a \]  

\[ F_a = c_{resv} (z_1 - z_2 + L_p) + k_p(F_{ztire} - F_{ztirestat}) \]  

here \( c_{resv} \) is a rigidity of the virtual elastic element.

Most of the above structures of suspension were implemented on serial or experimental samples of automotive equipment as devices that provide body positioning. In this study, we will consider the use of these structures of controlled suspensions, the purpose of which is to stabilize the vertical reactions of the road to the wheels of a car moving on an uneven road.

**4. Results of the study of energy efficiency of various active suspension structures for the system of stabilization of vertical reactions of roads to car wheels**

Investigating the processes of stabilization of the vertical reaction of the road to the wheel of a car moving on an uneven road, consider the fluctuations in the suspension of one wheel. It is important for
designers to have information about the energy efficiency of different suspension structures in the system for stabilizing vertical reactions to the wheel. In order to compare energy efficiency when using different structures, the dependence of the average power realized in the actuator during the stabilization of vertical reactions on regular profiles with different amplitudes was studied. For a reasonable comparison of results in different test modes, the simulation provided stabilization of a level at which the amplitude of vibrations of the vertical reaction of the road is reduced to 100N. This stabilization is almost marginal. Reducing the amplitude from 1000N to 100 N may be desirable in some driving conditions, but more often you can do with a lower level of stabilization of the vertical reaction. The road profile provides excitation of the studied model at a frequency of 8 Hertz. The table 1 shows the results of calculations of the average power of the control drive with different structures of suspension when driving a car along a sinusoidal profile with amplitude of 0.01 m.

**Table 1.** The average power of the actuator in various structures of the controlled suspension when driving a car along a sinusoidal profile with amplitude of 0.03 m

| The structure of the suspension | Average power (W) |
|---------------------------------|-------------------|
| A: Parallel spring, shock absorber and actuator | 1241 |
| B: The actuator and the parallel spring | 759.9 |
| C: parallel actuator and shock absorber | 1384 |
| D: The actuator | 1767 |
| E: An actuator and a spring of increased rigidity (bump stop), placed in series, and a shock absorber parallel to them | 1239 |
| F: An actuator and spring placed in series, and a shock absorber parallel to them | 5086 |

The relative distribution of the average power of the actuator in suspensions with different structures in accordance with table 1 can be represented using the following expression: B<E<A<C<D<F. Similar calculations are made for a number of other values of the road profile amplitudes. As a result, based on the obtained data, the diagram shown in Fig.5.

**Figure 5.** Average actuator power for different structures active suspension A,B,C,D,E,F in the function of the sinusoidal profile amplitude
In general, the realized average actuator power in structure B is less than the average actuator power in structure A. The same power in structure B is less than the power in structure D. When the amplitude of the road surface is small, the power in structures A is less than the power in structures C and E. As the amplitudes of the road profile increase, the power difference gradually decreases, and the power of structure A even exceeds the power of structures C and E.

Fig. 6 shows a decrease in power consumption in the suspension structure A with an increase in the value of the proportional coefficient of the regulator, and then its subsequent slow increase, i.e. the average power curve has a minimum.

![Figure 6](image)

**Figure 6.** A relationship between actuator’s average power and the coefficient of P-controller in the suspension with structure A when moving in the resonant mode of the wheel

A next, we will consider the effectiveness of the stabilization system for vertical reactions of the road to the wheels when driving a car on a random road. In fig. 7, you can see oscillations of the vertical reaction from the road to the wheel when driving a car with a conventional passive suspension on a road with a random profile, and in fig. 8, oscillation of the same vertical reaction when the wheel's vertical reaction stabilization system is operating.

![Figure 7](image)

**Figure 7.** Vertical reaction of a road to a car wheel without stabilization system of vertical reaction on a random road.
Figure 8. Vertical reaction of a road to a car wheel with stabilization system of a vertical reaction on a random road

Evaluation of the effectiveness of the stabilization system of vertical reactions of the road to the wheels when driving a car on a random road can be given by calculating the dispersion of the vertical reaction and its standard deviation. The dispersion and standard deviations of the vertical response when modeling the movement of a car with controlled suspensions of various structures are presented in table 2.

| The structure of the suspension | The dispersion of the vertical reaction ($N^2$) | Standard deviation of the vertical reaction ($N$) |
|---------------------------------|-----------------------------------------------|-----------------------------------------------|
| Parallel spring and shock absorber | 746496                                       | 864                                           |
| A: Parallel spring, shock absorber and actuator | 10000                                        | 100                                           |

It is important to note another property of the considered system of stabilization of vertical reactions of the road to the car wheels. It has a certain stabilizing effect on the car body, reducing its resonant vibrations by 20-30%.

5. Conclusion

The presented materials allow us to conclude that various suspension structures can be used in suspensions with active control in order to stabilize the vertical reactions of the road to the car wheels. The use of various suspension structures depends on the desire of the designer to get advantages in layout, in energy savings, or even in comfort.

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