Comparative analysis of the operation efficiency of the continuous and relay control systems of a multi-axle wheeled vehicle suspension

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Abstract. In order to improve the efficiency of the multi-axle wheeled vehicles (MWV) automotive engineers are increasing their cruising speed. One of the promising ways to improve ride comfort of the MWV is the development of the dynamic active suspension systems and control laws for such systems. Here, by the dynamic control systems we mean the systems operating in real time mode and using current (instantaneous) values of the state variables. The aim of the work is to develop the MWV suspension optimal control laws that would reduce vibrations on the driver’s seat at kinematic excitation. The authors have developed the optimal control laws for damping the oscillations of the MWV body. The developed laws allow reduction of the vibrations on the driver’s seat and increase in the maximum speed of the vehicle. The laws are characterized in that they allow generating the control inputs in real time mode. The authors have demonstrated the efficiency of the proposed control laws by means of mathematical simulation of the MWV driving over unpaved road with kinematic excitation. The proposed optimal control laws can be used in the MWV suspension control systems with magnetorheological shock absorbers or controlled hydropneumatic springs. Further evolution of the research line can be the development of the energy-efficient MWV suspension control systems with continuous control input on the vehicle body.

1. Introduction
Currently, with the use of pneumatic and hydropneumatic suspensions and increase in operational speeds, controlled suspension systems are becoming more and more popular in the global automotive industry.

There are two large groups of controlled suspensions categorized by their control rate: statically controlled and dynamically controlled suspensions.

By the static control (control by the averaged parameters) we mean the process of changing the parameters of the suspension passive elements during the change of the vehicle motion parameters in order to adapt the suspension system of the multiaxle wheeled vehicle (MWV) to these new motion conditions. The motion conditions include the vehicle speed, load, road surface quality, etc. In a steady state, i.e. when the motion conditions are constant, no control occurs. Thus, the objective of the static control is to provide the optimal values of the parameters of the suspension passive elements for each of the steady states of motion.
In this paper, by the dynamic control (control by the instantaneous value of a parameter) we mean the control of the sprung mass oscillations by changing the force applied to the vehicle body from the suspension unit over time. The specific value of this compensating force is defined by the oscillations damping algorithm. This force can be created either by the suspension special active elements using an external power source or by changing the parameters of the suspension passive elements. The systems with dynamic control using external source of energy are known as active suspensions, and the systems with control of the current values of the parameters are called semi-active suspensions. Review of the works in the field of the active suspensions is provided in [1, 2]. Theoretical aspects of the active vibration isolation systems for general cases of the rigid body vibration isolation as well as for special cases like driver’s seat suspension engineering have been studied by many researchers: Balagula V. Ya., Gaytsgori M.M., Genkin M.D., Yablonskiy V.V., Eliseev S.A, Inosov S. V., Sinev A. V., Furman F.A. and others [3 – 11]. Automobile active suspensions have been studied in the works of Kol'tsov V.I., Furunzhiev R.I., Ostanin A.N., Sharapov V.D., Sutton H.B., Thompson A.G. and others [12 – 16]. The researchers note that the active suspensions is the most effective choice in terms of ride comfort.

There are two different types of active suspensions. Active suspensions of the first type have no passive springing and damping elements, the body of the vehicle being connected to the wheels by means of non-elastic links capable of changing the force in the suspension according to the control system signal [4, 12]. In the systems of this kind it is preferable to use the disturbance control principle [16].

Active suspension of the second type has passive springing and damping elements generating variable forces in the suspension unit. Active elements of the suspension (for instance, hydraulic actuators) generate forces for body oscillations damping. Active suspensions of this type are of particular interest for practical use due to the following reasons:

1) less energy consumption for active elements actuation due to lower requirements of the control signal processing speed needed to provide the necessary efficiency;
2) lower response speed requirements of the control system;
3) high reliability, firstly, due to simplicity of the control system, secondly, due to ability to sustain vehicle operation in case of the control system failure.

Dynamic control systems can be divided into continuous control systems and discrete (relay) control systems. In the systems of the first type, the control input is defined as additional force to the suspension forces. Work [17] describes an example of this type control system. The relay control can be implemented as a two-level suspension damping control system [18] that provides either high or low damping according to the motion conditions.

Suspension control system (SCS) efficiency and quality depend on many factors: control rate, i.e. the time from parameter registration to the moment of the control input generation; accuracy of the measurement and transfer of the parameters used for the control input generation; accuracy of the control input generation by the actuators. Performance degradation of the SCS parameters in terms of any of the above mentioned factors may lead not only to the lower efficiency of the system but to the full loss of its functional capability.

In real life, there are no control systems with instantaneous response. Signal delay time $\Delta t$ is determined by the time required for the needed parameters registration, their transfer to the on-board computer, and computation and generation of the control input by the actuators. Increase of the signal delay time can deteriorate the performance of the control system.

It is evident that the accuracy of the control system cannot be higher than the accuracy of the measurements. Control system measurement errors are determined by the following factors: sensor errors; analog-to-digital signal transformation errors; computational errors; feedback errors of the control system actuators.

However, no scientifically grounded criteria has been proposed to assess the performance of a suspension control system so far. As a result, firstly, it is impossible to perform efficiency analysis of new control laws in real-life operational conditions, and, secondly, it is impossible to compare different control laws. The object of this work is to develop criteria for assessment of the efficiency of the
suspension control laws at different values of the delay time and input signal measurement errors, another object of this work is to compare efficiency of the continuous and relay MWV suspension control laws by mathematical simulation methods described in [17] and [18].

2. Efficiency criteria for multi-axle wheeled vehicle suspension control system performance

Let’s define requirements for the control system efficiency criteria. These criteria must be dimensionless to provide comparison of the control system efficiency in different operation conditions. Besides, efficiency criteria must be based on the overall vibration level measure (GOST 12.1.012-2004), i.e. standard dispersion of the vertical accelerations on the driver’s seat.

Control system efficiency criterion taking into account only system elements response delay as a function of the vehicle speed \( V \) is then

\[
K_{\Delta t}(V) = \frac{D_{\Delta t}(V) - D_0(V)}{D_{\Delta t_0}(V) - D_0(V)} \times 100\%
\] (1)

where \( D_{\Delta t}(V) \) – standard dispersion of the vertical accelerations on the driver’s seat for active or semi-active suspension with total response delay \( \Delta t \); \( D_0(V) \) – standard dispersion of the vertical accelerations on the driver’s seat for passive suspension; \( D_{\Delta t_0}(V) \) – standard dispersion of the vertical accelerations on the driver’s seat for the active suspension with response delay \( \Delta t = 0 \) (a perfect system).

Criterion (1) shows relative decrease in control efficiency when the system has non-zero response delay. It is evident that for a perfect system \( K_{\Delta t}(V) = 100\% \).

SCS efficiency criterion taking into account only total relative error of measurement as a function of the vehicle speed \( V \) can be expressed as

\[
K_{\Delta \alpha}(V) = \frac{D_{\Delta \alpha}(V) - D_0(V)}{D_{\Delta \alpha_0}(V) - D_0(V)} \times 100\%
\] (2)

where \( D_{\Delta \alpha}(V) \) – standard dispersion of the vertical accelerations on the driver’s seat for active or semi-active suspension with total measurement error \( \Delta \alpha \); \( D_{\Delta \alpha_0}(V) \) – standard dispersion of the vertical accelerations on the driver’s seat for the active suspension with total measurement error \( \Delta \alpha = 0 \) (a perfect system).

Criterion (2) shows relative decrease in control efficiency when the system has a non-zero measurement error. It is evident that for a perfect system \( K_{\Delta \alpha}(V) = 100\% \).

To compare different SCSs, let us introduce criterion \( K \), describing the difference between the performance of a suspension with a perfect suspension control system (for the case of zero response delay) and the performance of a passive suspension.

\[
K(V) = \frac{D_i(V) - D_0(V)}{D_0(V)} \times 100\%
\] (3)

where \( D_i(V) \) – standard dispersion of the vertical accelerations on the driver’s seat for the case of the active suspension.

Criterion (3) shows the relative decrease in standard dispersion of the vertical accelerations on the driver’s seat for the case of the active suspension in comparison with the case of the passive suspension.

3. Response delay effect on the control system efficiency

Works [17] and [18] analyze relay and continuous suspension control systems by the computer simulation of a MWV straight-line motion with speeds from 10 to 70 km/h over an unpaved road. The vehicle motion over the terrain was simulated by the mathematical model developed at the Department of Wheeled Vehicles of the BMSTU [2]. In the MWV mathematical model the speed of the vehicle is not a preset value but is determined by the forces of the interaction between the rolling wheels and the terrain. This provides higher accuracy of the MWV motion simulation. The model is built in MATLAB/Simulink. The model includes a member providing a constant delay of the control signal.
The delay simulates the resultant delay of all control paths of the system. Figure 1 shows the efficiency criterion $K_{\Delta t}(V)$ calculated according to formula (1) for a continuous control system at different vehicle speeds and the signal delay time varying from 0 to 0.3 s.

![Figure 1. Efficiency criterion $K_{\Delta t}(V)$ for a continuous control system at different vehicle speeds $V$ and different signal delay time $\Delta t$.](image)

The dependencies in Figure 1 show that the continuous control system is sensitive to the response delay time of its components. The response delay time range from 0.1 to 0.3 s is characteristic for the most control systems. A continuous control system with such a delay time becomes considerably less effective. Therefore, the continuous control systems require higher speeds of response. It is fair to say that the system will remain effective if the response delay time does not exceed 0.1 s.

Similar research has been performed for the relay control system with the response delay time varying from 0 to 0.5 s. The simulation showed that within the said delay time range the relay system kept its efficiency, the criterion $K_{\Delta t}(V)$ value being equal to 100%.

4. Measurement error effect on the suspension control system efficiency

Works [17] and [18] analyze relay and continuous suspension control systems by the computer simulation of a MWV straight-line motion with speeds from 10 to 70 km/h over an unpaved road. Measurement error is simulated as a white noise in the control signal path. The total relative error of measurement is calculated by the formulae

$$ A = \frac{\Delta C}{C} = \frac{C_{er} - C}{C}, $$

$$ D_{er} = (\Delta C)^2, $$

(4)

here $C_{er}$ – signal value measured with error; $C$ – true signal value; $D_{er}$ – total standard dispersion of the error.

$C_{er}$ can be calculated by the equation

$$ C_{er} = C + x[0; D_{er}]. $$

(5)
Here $x[0; D_{er}]$ – a white noise with zero mean value and zero standard dispersion $D_{er}$.

Figure 2 shows the efficiency criterion $K_{\Delta A}(V)$ calculated according to formula (2) for a continuous control system at different vehicle speeds and the measurement error varying from 0 to 10 %.

Figure 2 shows that the measurement errors have significant impact on the efficiency of the suspension continuous control system. Acceptable values of the total relative measurement error of all control paths lie within the range 2.5 – 5 %.

Similar research was carried out for a relay control system with the same range of the total relative error. The simulation showed that within the said range the relay system kept its efficiency, the criterion $K_{\Delta A}(V)$ value being equal to 100%.

5. Comparison of the suspension continuous and relay control system efficiency by the simulation results

Analysis of the simulation of the multi-axle wheeled vehicle motion over unpaved roads allows us to compare the two developed control laws of the suspension: a continuous control law [17] of the active suspension and a relay control law of the suspension with two levels of damping [18]. Figure 3 shows the efficiency criterion $K(V)$ according to expression (3) as a function of the vehicle speed.
Figure 3. Efficiency criterion $K(V)$ as a function of the vehicle speed for continuous and relay control systems over an unpaved road.

Figure 3 shows that the relay control system has practically constant damping level of about 50%. The continuous control system has maximum efficiency for velocities within the range 10 – 30 km/h, then its efficiency goes down and levels off at 20%. Such a behavior can be explained by the physical limits imposed on the control input.

Table 1 contains the results of the integral comparison of the efficiency of the two control systems (the relay system and the continuous system). Figure 3 shows that for the vehicle speeds in the range 10 – 70 km/h, when the main criterion of a control system efficiency is the degree of decrease in the passenger and cargo vibration levels, the efficiency of the relay control system is higher than the efficiency of the continuous control system. However, when it necessary to provide active damping of the MWV at varying external forces, the continuous control system is much more efficient for a suspension than the relay control system with two-level damping, which is shown in paper [19].

Energy consumption of the active suspension control system is orders of magnitude higher than the one of the two-level damping control system [20], since the latter spends energy only on the actuation of the suspension control elements (for instance, adjustable orifice valves) and the active suspension needs energy for generation of the compensating force in the suspension (for example, by pumping working fluid into the chambers of the hydropneumatic suspension). While the software implementation complexity of the algorithm of the both control systems is equally low, the active suspension is much more complex in design, which results in a considerably higher price and lower reliability in comparison to the relay control suspension. Table 1 shows results of the comparison of the continuous control system of the active suspension with the two-level damping relay control system.
Table 1. Comparison of the performance efficiency of the suspension control algorithms.

| Compared factor                          | Continuous control system of the active suspension | Two-level damping relay control system |
|------------------------------------------|--------------------------------------------------|----------------------------------------|
| 1 Vibration reduction                    | +                                                | +                                      |
| 2 Active damping of the MWV body at single inputs | +                                                | –                                      |
| 3 Energy consumption of the control system | –                                                | +                                      |
| 4 Software implementation simplicity     | +                                                | +                                      |
| 5 Hardware implementation simplicity     | –                                                | +                                      |
| 6 Response delay sensitivity              | –                                                | +                                      |
| 7 Measurement error sensitivity           | –                                                | +                                      |

Therefore, we can define the optimal application fields for the both control systems.

A two-level damping discrete control system should be used in the MWV suspension with relay type actuators (slide valves and pilot valves of the hydropneumatic spring units and hydraulic shock absorbers with valve actuation control system). A continuous control system should be used in the suspension with the primary function of the active damping of the MWV body.

Conclusion
The main results of the work are as follows.

The authors have obtained novel criteria for estimation of the efficiency of a suspension control system with response delay and measurement errors of the input parameters.

The authors have performed a novel analysis of the efficiency of the active continuous and semi-active relay control systems of a suspension for the case when the main control objective is the driver’s seat vibration reduction.

The paper has shown that a continuous control system of the active suspension should be used in the case when the main control objective is the active damping of the vehicle body. Discrete control system should operate in driving modes (when there is kinematic excitation of the vehicle body) and provide smooth ride at the lowest energy consumption.

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