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# Basic principles of vehicle suspension control

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**Abstract.** The paper is devoted to the description of the basic operation principles of control systems over suspension (cushioning) system elements of a vehicle. The basic operation algorithms, as well as the basic principles of change of properties of suspension or cushioning components under different vehicle driving conditions, are presented. The list of sensors and signals, which shall be present in the system to ensure its effective operation, is proposed. The results of experimental analysis of the pneumatic elastic element (air bellows) stiffness and the results of computer simulation of the vehicle behavior when turning are additionally presented.

## 1. Current state of adjustable vehicle suspension systems

Advanced computer-aided design systems are used in designing of modern vehicles [1]. This allows ensuring comfortable driving under normal conditions, however, this does not ensure efficient operation of the suspension under the conditions difficult or unusual for the vehicle. Moreover, change of component properties during operation and their wear may cause inefficient operation of the chassis during normal driving as well. To solve these issues, the adjustable elements of the suspension (cushioning) system are used. The vast majority of modern comfortable vehicles are currently equipped with such systems, however, they all have different component base and control algorithm operation principles. Nevertheless, a number of specific elements and their control methods can be distinguished for all these systems, which will be discussed below.

The standard adjustable suspension has one or two systems:

- adjustable elastic (spring) elements (usually air suspension) [2];
- adjustable shock absorbers.

Besides, a roll (pitch) stabilization system is sometimes applied.

Regardless of which of these three systems is installed, a suspension control system consisting of the following elements is necessary for their operation:

- suspension control unit;
- acceleration and suspension position sensors;
- control interface.

Special signals are required for the suspension control system (the set of which changes depending on the system complexity):

- vehicle speed;
- steering wheel angle / turning speed;
- brake pedal pressing speed;
- accelerator pedal pressing speed;
- transmission gear engagement;
- signal from the interface (driving mode);
- position of each wheel;

- body acceleration (at the centre of gravity and above each outer corner of the vehicle);
- current rate in the control elements of the shock absorbers;
- road surface profile (from cameras or lidars)
- data on the road friction coefficient.

The information on the wheels position and body accelerations is converted to the information necessary for the system operation, such as body roll or vibration values in individual points.

## 2. Suspension control principles

When developing a suspension control system, it is necessary to take into account three important aspects:

*1) The control system operates depending on the driving conditions.*

It is the information on the vehicle driving parameters that shall determine the suspension behavior. There is no general logic able to select the component properties correctly without the information on driving speed, vibrations or environment condition.

*2) The control system is designed on the basis of the suspension components.*

The control logic is based on the suspension technology and the possibilities of its control which depend on the subsystems, components and quality of their interaction.

*3) The control system shall be determined by parameters and target requirements.*

Whatever the algorithm, it is the actual control system adjustment and parameterization that will determine the final system response (reaction) and vehicle driving behavior. Generally, the algorithms do not ensure the desired level of the vehicle parameters without adjustment. The system shall be regulated by a certain set of the coefficients, the impact of which is connected to the physical parameters of the vehicle driving.

Vehicles with a suspension control system often feature several driving modes, such as: Auto (Main), Sport or Comfort. Each of the modes has its own set of coefficients, which changes the driver's experience under certain conditions. The additional modes use the signals of pedals pressing and steering wheel turning preceding the longitudinal and lateral roll.

In the modern civil vehicles equipped with the control system, the basic setting is preferred to be based on the condition of the maximum comfort at low and medium speeds. For this purpose, the shock absorbers resistance for the low frequencies of oscillations is decreased to the minimum. As the driving speed or body oscillations increase, the shock absorbers resistance increases, which leads to a decrease in oscillations and increase in stability of the vehicle driving. The control system interference leads to an increase of the shock absorbers resistance and the average level of vibrations in the passenger compartment, therefore, the chassis basic setting is important, as it will allow decreasing the level of involvement of the control system and increasing the driving comfort. During operation, the system changes the suspension components characteristics, therefore, their properties shall be balanced not only within the basic setting, but also within the changed settings, so that the increase of suspension damping or stiffness (rigidity) does not lead to unbalance or re-distribution of operation frequency of the front and rear axles. During suspension operation, it is important to ensure smooth body motion in relation to the centre of gravity without the unbalanced sagging (subsidence) of the right and left sides. For the comfortable vehicles, a big vertical body movement is not unpleasant for the passengers, however, frequent and significant body roll causes discomfort.

## 3. Basic modes of suspension control

Modern suspension control algorithms are developed on the basis of the equations describing the vehicle body movement. However, the equation parameters ensuring a high level of comfort, as a rule, do not ensure the required steerability/controllability, therefore, additional modules increasing individual consumer properties of the vehicle are applied on top of the basic algorithm. Meanwhile, even without the key algorithm, a set of modules for various driving conditions can ensure a high level of comfort and steerability/controllability of the vehicle. A set of basic modules defining the behaviour of the suspension control system in various driving conditions is presented according to Table 1. A condition is imposed for these modules that adjustable shock absorbers, antiroll bars (adjustable ARB) and pneumatic elastic elements with four variants of stiffness each are installed in the vehicle (Variant 1 – the "softest" parameter, Variants 2, 3, 4 – increase in stiffness by 30, 70 and 100% respectively). The proposed recommendations on algorithms are based on the FSUE "NAMI" expertise in the development of passenger vehicles and on the results of the computer simulation, part of which is presented below.

A change in stiffness occurs due to a change in the internal volume of the pneumatic element [3]. The condition is imposed that there are 3 suspension modes in the vehicle: Main, Comfort, Sport.

**Table 1**. List of modules under examination.

| Section | Condition | Event |
|---|---|---|
| 4.1 | Suspension mode switch | Main mode<br>Additional mode - Comfort<br>Additional mode - Sport |
| 4.2 | Roughness (bump/pothole) under one of the wheels | Unexpected change of the road profile under one of the wheels |
| 4.3 | Wavy (undulant) road | Great roughnesses (undulation) with low frequency of impact/influence (wave effect) |
| 4.4 | Braking | Pressing the brake pedal<br>Keeping the brake pedal pressed |
| 4.5 | Turning movement | Beginning and ending of the turning movement<br>Long cornering<br>Braking/acceleration during the turning movement |

The principle of changing the resistance of shock absorbers in the modern automotive industry is based mainly on changing the valves section by a forward electric motor. The change in the stiffness of antiroll bars is achieved by way of opening the central clutch and by way of installing an electric motor, which turns the stabilizer creating additional torque of resistance to the lateral roll. The change of the stiffness of a pneumatic element is achieved by way of step change of the internal volume. However, the peculiarity of pneumatic systems operation consists in the inertness of the operation environment being used; therefore, a quick change of the internal volume seems hard to attain. Therefore, a system of opening several air volumes is applied [4].

In order to check the feasibility of considerable change in the stiffness of a pneumatic element by way of reducing its internal volume, an experiment was carried out where its stiffness was measured with various internal volumes. The layout of the experimental unit is shown in Figure 1.

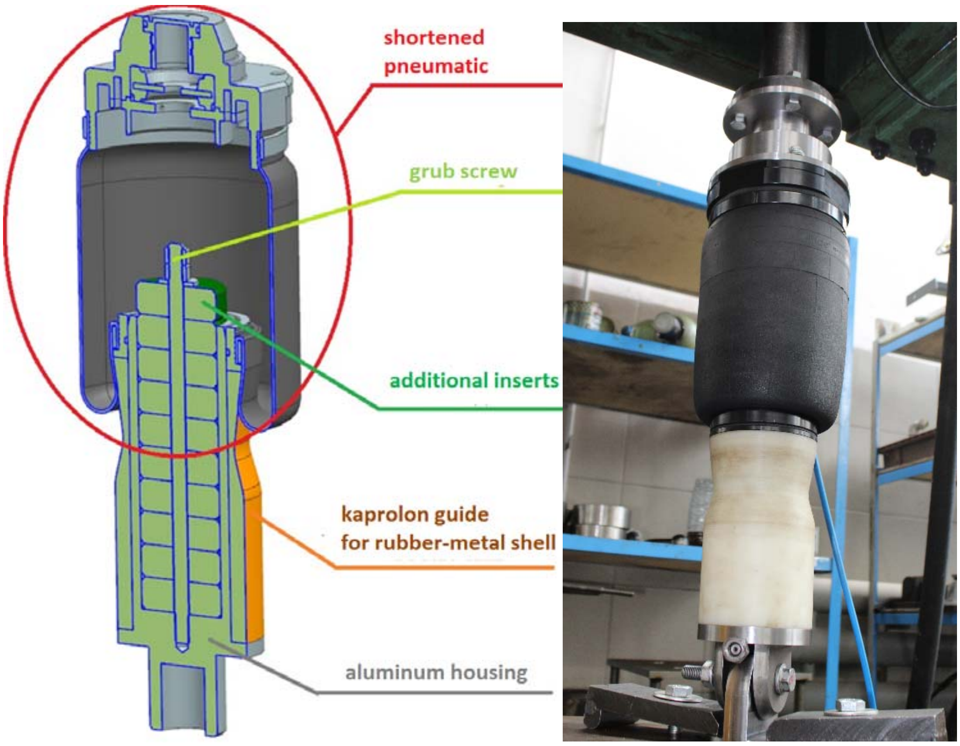


**Figure 1**. Experimental unit layout.

The test design included special washers the removal of which leads to the increase of the internal volume and reduction of the stiffness in further testing.

The tests were performed with various volumes but the same frequency – 1 Hz.

The resulting force curves for 2.9 l (dash line) and 3.7 l (solid line) are shown in Figure 2.

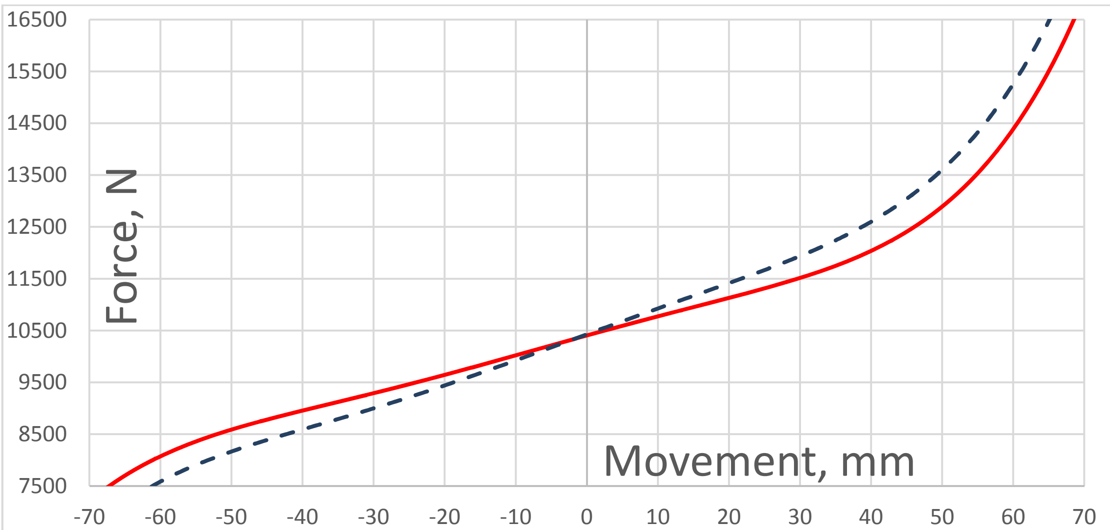


**Figure 2.** Characteristics of force developed by pneumatic element.

In Figure 3, the resulting dependence of the stiffness of the pneumatic element on the internal volume is shown.

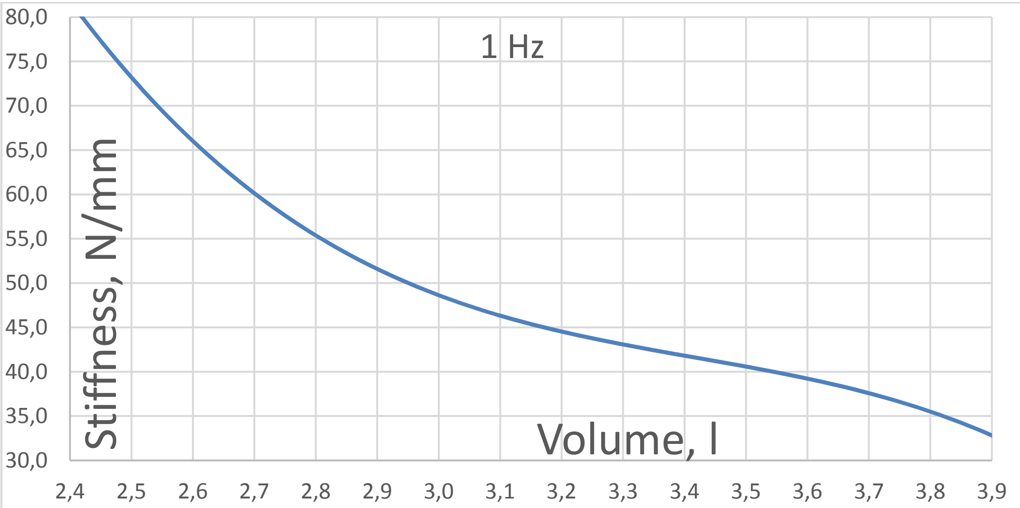


**Figure 3.** Characteristics of stiffness of pneumatic element in case of internal volume change.

One can see from the shown graph that if a pneumatic element is of the standard 3 l volume, then its volume change by +/- 0.5 l will result in the stiffness change by -17/+52% respectively. Thus, the internal volume change by 0.5 l, which is technically entirely feasible, will lead to the stiffness change by considerable 35%.

Thus, a conclusion may be drawn that the dynamic regulation of stiffness of an elastic element by way of changing the internal volume of the pneumatic element is feasible.

### *3.1. Suspension operation mode switch*

Table 3.1 presents the description for these modules based on the design of the vehicle intended for comfortable city driving. Upon that, comfort is "sacrificed" to stability at high speeds. During suspension development, the most comfortable suspension characteristic is often set for the main mode, then the Sport mode is created deliberately transferring more vibrations to the passengers to create the feeling of dynamic driving. The Comfort mode is created in a similar way allowing greater body pitches than in the main mode, which creates the feeling of smoother driving, which is considered as more comfortable one by nonprofessional drivers.

**Table 2.** Suspension mode switch module.

| **System** | **Wheel under examination** | | | | **Additional suspension mode** | |
|---|---|---|---|---|---|---|
| | **Front axle** | | **Rear axle** | | | |
| | **Left (FL)** | **Right (FR)** | **Left (RL)** | **Right (RR)** | **Sport** | **Comfort** |
| **Suspension height** | The suspension height decreases at high speeds | | | | Height decreased | as at the main mode |
| **Elastic elements stiffness** | **FL**<br>Variant 1 or 2 is equally prespecified | **FR** | **RL** | **RR** | Variant 2 or 3 is prespecified | Variant 1 is prespecified, variant 4 is prohibited |
| **Adjustable ARB** | No specific operation is required | | | | | |
| **Dampers resistance** | **FL**<br><30%<br>Shock absorbers resistance is kept at the low level except for the cases of significant body pitch or high driving speed | **FR**<br><30% | **RL**<br><30% | **RR**<br><30% | >60%<br>Limitation of the minimum damping is applied | Max < 80%<br>Shock absorbers resistance never reaches the maximum values |

Further, the suspension behavior in different driving modes is nearly identical for all modules: there are basic settings for the Auto mode, the decreased prespecified stiffness of the elastic elements and shock absorbers resistance are set for the Comfort mode, the one step "stiffer" characteristics are used for the Sport mode. A softer characteristic of the components stiffness rise is used for the Comfort mode and, on the contrary, more spur increase in stiffness and suspension elements resistance along with the increase of external impact parameters for the Sport mode.

### *3.2. Roughness (irregularity) under one wheel*

Single roughnesses are supposed to cause high-frequency oscillations with a small Z-axis travel. No direct response from the elastic elements of the air suspension, shock absorbers or adjustable ARB is required. Generally, the passive suspension part is adjusted so that these vibrations are transferred to the body minimally [5]. The exceptions can show in the Comfort mode, when the decreased shock absorbers resistance is applied. To solve this problem, the vehicle should be equipped with the wheel position sensors, which would register these oscillations and allow a timely and short-term increase in damping.

### *3.3. Wavy (undulant) road*

The wavy road causes the low-frequency body oscillations: vertical motion, lateral and longitudinal roll.

**Table 3.** Wavy road module.

| |
|---|
| **Suspension height**: Change of height is not required. |
| **Elastic elements stiffness**: All wheels are variants 1-4.<br>The stiffness of each element is controlled separately allowing using each of 4 variants. The system stabilizes the body motion (vertical, longitudinal / lateral roll) depending on the body accelerations and wheel movements.<br>The stiffness is added to all 4 wheels equally against the vertical motion. By one or more steps, depending on the oscillations value.<br>Against the longitudinal roll, stabilization is determined by the motion direction and phase.<br>In case of the front axle running into a positive wave, the rear axle stiffness increases at the body rising stage, but both axles reduce the stiffness at the wave decrease. When the body starts to go down, the front axle stiffness increases.<br>Against the lateral roll, the stiffness decreases for the rising side and increases for the sagging one. The phases of the front and rear axles are usually considered separately. |
| **Adjustable ARB:** No specific operation is required. |
| **Shock absorbers resistance**: all shock absorbers – 0-100%.<br>In case of big lateral waves (equal under the right and left wheel), the system shall adjust the front and rear axle separately, but the approach shall be individual basing on the current vibrations level and the body pitch value. For comfortable vehicles, high amplitudes are allowed, but the generation of the bump (compression) or rebound stroke causes impacts all over the body, which is unacceptable. Therefore, when registering body acceleration and roll angle, which may lead to the suspension breakage, the shock absorbers resistance shall increase. |

### *3.4. Braking module*

There is a difference between the braking system activation time and the passive holding of the pressed pedal at slow deceleration.

**Table 4.** Braking pedal activation module.

| |
|---|
| **Suspension height**: Change of height is not required.<br>**Elastic elements stiffness**: All wheels – variants 1-4;<br>During braking, a high stiffness of the front suspension is preferable depending on the longitudinal acceleration. The rear axle stiffness shall also be increased (for the same number of steps or one step less), otherwise there may be an issue with the braking forces distribution between the axles and with the rear axle stability.<br>The system responds to the pedal pressing better than to the registration of the longitudinal dive, since the delay is reduced. |
| **Adjustable ARB:** No specific operation is required. |
| **Shock absorbers resistance**: all shock absorbers – 0-100%.<br>When activating the pedal, damping of all 4 shock absorbers increases sharply before the longitudinal acceleration or body motion occurs. Upon that, the damping value may depend on the speed of pedal pressing.<br>After the pedal pressing, the shock absorbers also become stiffer to decrease the body reverse motion. After the start of deceleration, the force on the shock absorbers decreases to avoid the body vibrations. Change of forces on the shock absorbers when braking shall be coordinated with the ABS and ESP specialists, otherwise it may affect safety. |

**Table 5**. Braking pedal holding module.

| |
|---|
| **Suspension height**: Change of height is not required. |
| **Elastic elements stiffness**: All wheels – variants 1-3.<br>After the pedal activation, the stiffness shall decrease slowly for all 4 wheels until the pedal is pressed / pressing continues again or until the longitudinal acceleration decreases below the set value. |
| **Adjustable ARB:** No specific operation is required. |
| **Shock absorbers resistance**: all shock absorbers – 0-50%.<br>The shock absorbers resistance shall be increased until the braking pedal is released. The connection with the vehicle speed is possible. |

The system behavior is similar to acceleration, but adjusted for the roll direction.

### *3.5. Turning movement module*

The turning movement module has distinctions for the Beginning of Turning Movement and Long Cornering modes and nuances for the Braking/Acceleration during Turning Movement mode.

**Table 6**. Beginning of Turning Movement module.

| |
|---|
| **Suspension height**: Change of height is prohibited and not required. |
| **Elastic elements stiffness**: All wheels – variants 1-2.<br>The stiffness level for the elastic elements depends on the steering wheel turning speed for lateral roll neutralization. At the steering wheel turning speed equal to zero, the stiffness of the elastic elements decreases. Upon that, it is not recommended to increase the stiffness by more than two steps for the comfortable mode. |
| **Adjustable ARB:** Changes from 0 to 100%.<br>The antiroll bars stiffness may increase up to 100% to decrease the roll. Upon that, the front and rear axles are controlled separately to keep the balance of roll stiffness of the suspensions and slip angles. |
| **Shock absorbers resistance**: all shock absorbers – 0-100%.<br>The stiffness of the elastic elements changes similarly, depending on the steering wheel turning speed as well as on the lateral acceleration. Upon that, in case the steering wheel speed returns to zero, they are kept in the increased state to maintain the possibility of prompt response to the lateral accelerations. |

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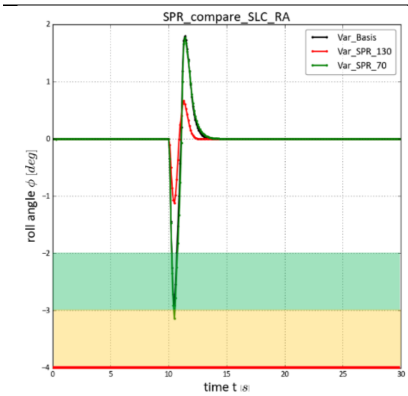
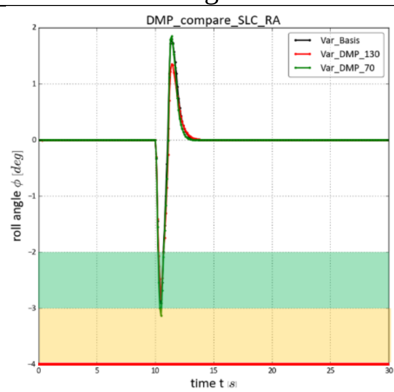
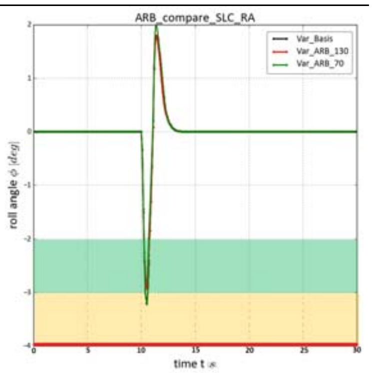
**Table 7.** Long cornering module.

| |
|---|
| **Suspension height**: Change of height is prohibited and not required. |
| **Elastic elements stiffness**: All wheels – variants 1-2.<br>At the steering wheel turning speed equal to zero, yet with the angular deviation from the neutral point (position), the stiffness of the elastic elements remains slightly increased, but lower than at the beginning / ending of the turning movement. |
| **Adjustable ARB:** Changes from 0 to 50%.<br>The antiroll bars stiffness increases, yet it is decreased in relation to the beginning of the turning movement. |
| **Shock absorbers resistance**: all shock absorbers – 0-100%.<br>The shock absorbers resistance changes in accordance with the change of stiffness of the elastic elements and antiroll bars. Upon that, the shock absorbers characteristic does not play an important role during the long cornering, as the force in the shock absorber depends on the piston speed, which is rather low at the rolls characteristic of the long cornering. |

When describing the algorithms of the suspension behavior at acceleration and braking during the turning movement, the main requirement is the safety of the vehicle behavior and, therefore, the correct operation of ABS and ESP. Therefore, keeping the suspension state established for the long cornering in the simple algorithms is preferable.

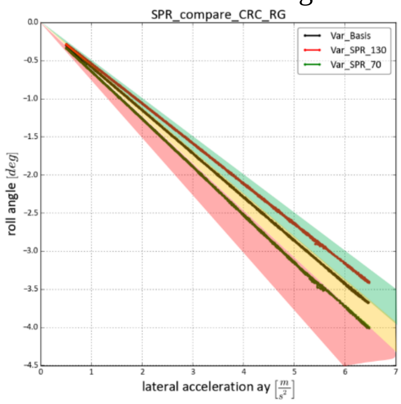
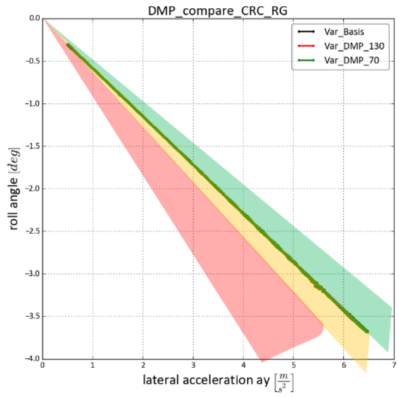
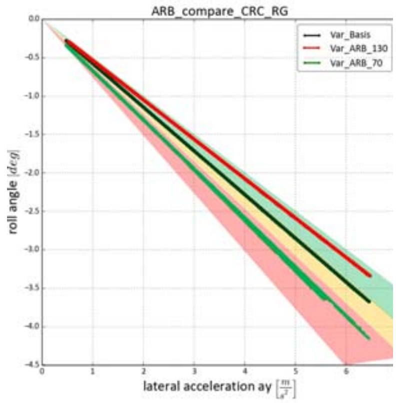
The graphs from Tables 3.5.3 and 3.5.4 can be used for analysis of the influence of springs, shock absorbers and antiroll bars characteristics on the vehicle behavior at the beginning of the turning movement and during the long cornering. The vehicle response during the lane change, which is similar to the beginning of the turning movement, is shown in Table 3.5.3. The vehicle behavior when moving at a constant radius, which is similar to the long cornering, is shown in Table 3.5.4. Each table shows the execution of these maneuvers with individual changes of the springs, shock absorbers and antiroll bars characteristics (with the stiffness increase by 30% and reduction by 30% relative to the basic value).

**Table 8.** Vehicle behavior during lane change.

<table>
<tr><th colspan="3">Roll angle change during lane change</th></tr>
<tr><th>Elastic element stiffness change</th><th>Shock absorbers resistance change</th><th>Antiroll bars stiffness change</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>The increase of the springs stiffness considerably reduces the maximum body roll. The stiffness reduction does not lead to a considerable effect due to the antiroll bars functioning.</td><td>The increase in the shock absorbers' resistance considerably reduces the maximum body roll (increase by 30% reduced the roll by 20%). The resistance reduction does not lead to a considerable effect, probably due to the antiroll bars functioning.</td><td>Change in the antiroll bars' stiffness by 30% does not lead to a significant effect. There is degradation by approximately 9% when the stiffness is reduced by 30%.</td></tr>
</table>

| | | | | | |
|---|---|---|---|---|---|
| +30% | Stability is higher (roll is less) | +30% | Stability is higher (roll is less) | +30% | No significant effect |
| Basic | meets the requirements | Basic | meets the requirements | Basic | meets the requirements |
| -30% | No effect (due to antiroll bars) | -30% | No effect (due to antiroll bars) | -30% | Minor effect |
| These graphs show that in order to increase the stability during sharp turning movements (lane changes), it is necessary to increase the stiffness of elastic elements and shock absorbers. | | | | | |

**Table 9.** Vehicle behavior when moving at constant radius.

| Dependence of the lateral roll angle on transverse acceleration, with change of components' properties | | | | | |
|---|---|---|---|---|---|
| Elastic element change | | Shock absorbers change | | Antiroll bars change | |
|   | |   | |   | |
| Considerable effect, increase of springs stiffness reduces vehicle roll | | The effect is insignificant, change of shock absorbers' properties has almost no effect on lateral roll during long cornering | | Considerable effect, increase of antiroll bar stiffness reduces vehicle roll | |
| +30% | Stability is higher (roll is lower) | +30% | No effect | +30% | Stability is higher (roll is lower) |
| Basic | At the limit of normal | Basic | At the limit of normal | Basic | At the limit of normal |
| -30% | Stability is lower (roll is higher) | -30% | No effect | -30% | Stability is lower (roll is higher) |
| These diagrams show that in order to increase vehicle stability during the long cornering, it is necessary to increase the stiffness of the antiroll bar or elastic elements. | | | | | |

## 4. Summary

The paper presents a description of the main recommendations for control of the adjustable vehicle suspension. The presented materials show the feasibility of the proposed solutions, in particular basing on the computer simulation results. The implementation of the proposed approaches can significantly increase consumer properties of a vehicle without considerable expenses for algorithms development, calibration and setup. At the same time, it is necessary to take into account three important theses:

1. *The control system operates depending on the driving conditions.*
2. *The control system is designed on the basis of the suspension components.*
3. *The control system shall be determined by parameters and target requirements.*

This means that implementation of any logic of suspension control, including the one presented in this paper, does not exclude the necessity of suspension adjustment, its adaptation to the certain vehicle and check of vehicle safety and stability.

The list of necessary sensors and equipment for the adjustable suspension operation is presented in the paper separately, but whether each of the components should be installed on-board shall be checked in terms of economic and functional feasibility of a certain vehicle.

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