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Vilnius Gediminas Technical University Transport Engineering Faculty, J. Basanavičiaus g. 28, LT-03224, Vilnius, Lithuania

EXPERIMENTAL TEST RESULTS OF THE INFLUENCE OF ADAPTIVE DAMPING LEVEL ON PASSENGER CAR DYNAMICS DURING DOUBLE-LANE-CHANGE MANEUVER

Grzegorz Ślaski

Poznan University of Technology, Institute of Motor Vehicles and Machines, ul. Piotrowo 360-965 Poznań, Poland,+48 61 66 52 222, Fax: ,+48 61 66 52 736. E-mail: Grzegorz.Slaski@put.poznan.pl

Abstract. The paper presents the results of some experimental tests conducted on a passenger car equipped with changeable damping level shock absorbers in order to investigate the influence of adaptive damping level controller on vehicle dynamics during double lane change maneuver. The shock absorbers were semi-active dampers with a by-pass proportional valve. The dampers were controlled by a prototype controller developed and programmed with Matlab/Simulink system and implemented on the controller rapid prototyping platform dSpace. The car was equipped with some sensors used by the controller and some used just to measure vehicle dynamics. Optical vehicle velocity sensors, vehicle roll and pitch rate gyroscopic sensors, vehicle lateral and longitudinal acceleration sensors, sprung and unsprung mass accelerations and suspensions deflection sensors were used. The steering angle and brake pedal travel sensors were also used. The prototyping board was the source of additional signals connected with control algorithm and calculated on-line by a real time computer during controller functioning. Several tests of double-lane-change maneuver were performed with various constant sets of damping level within the limits of available damper characteristic and some with adaptive controller actively changing damping level due to some chosen signals predicting vehicle dynamics. The results of some exemplary tests were presented to show the behavior of the car during this maneuver. A statistical analysis was performed to investigate the influence of various constant damping levels and adaptive damping level on vehicle dynamics before formulating conclusions at the end of the article. The obtained results show the level of improvement of vehicle dynamics with semi-active dampers controlled with adaptive controller taking into account some lateral vehicle dynamics aspects.

Keywords: vehicle dynamics, changeable damping, vehicle dynamics, changeable damping, safety, road test, adjustable shock absorber controller

1. Introduction

One of two main tasks that vehicle suspension has to manage is vibration comfort and the other is to ensure good handling. Good handling depends on tractive force potential and small roll and pitch angles causing wheel-ground contact angle changes. For this reason finding a balance between comfort and handling is the goal of suspension optimization process (Rajamani 2006; Wong 2001).

When the type of road excitation is always the same, and the masses of the vehicle are constant it is possible to find the best combination of stiffness and damping parameters to get the best possible vibration comfort.

But designers of the suspension system also have to take into account the other suspension task, namely a road-holding ability influencing vehicle handling. The problem is that when damping parameter is chosen to maximize road-holding ability it does not provide the best possible comfort. Designers have to make a trade-off between comfort and road-holding ability by choosing a compromise value off suspension damping (Williams, 1997).

This problem is the aim of many studies, but most of them concern only vertical vehicle dynamics (for example Savaresi, S. M. *et al.* 2010).

Kinematic excitations from road irregularities are not the only problem; another are mass forces caused by rapid changes of lateral and longitudinal accelerations resulting from a maneuver such as rapid steering or braking. Those forces cause excessive roll or pitch angles disturbing the steering process and making car handling more complicated. This happens because of the roll steer effect defined as undesirable and uncontrollable changes in the steering angle of the steered wheels during the rolling action of the vehicle body due to cornering maneuver or asymmetric bumps (Habibi, Shirazi and Shishesaz 2007). One way to minimize this effect is optimization of suspension mechanism, another is improving roll damping. It can be achieved using high damping shock absorbers, but it will influence vehicle vibration comfort. Therefore a system of adjustable dampers should be used which would allow to increase their demanding to a high level only in specific situation demanding high roll damping.

The author of this paper has performed some tests of possible changes in vehicle dynamics while driving through double lane change track with various damping settings of adjustable dampers. Dampers were set to be continuously “soft”, “middle” or “hard” or their damping settings were changed actively by a prototype controller.

The prototype controller was designed and implemented on a real time control computer by the author to perform the tests.

2. Test vehicle and suspension control system

The test vehicle was Opel Astra with CDC dampers controlled by author’s prototype damper controller implemented on dSpace controller prototype platform.

Beside the sensors used by the control system, the car was also equipped with a special sensor to measure vehicle dynamics in order to verify the controller effectiveness.

The dampers were typical CDC dampers with a by-pass valve. The whole control and measurement system was autonomous from the other vehicle control systems. It allowed a full control over prototyped semiactive suspension controller to perform the necessary tests.

Fig. 1. The view of some hardware used to implement the prototype suspension controller inside test vehicle

The range of possible damping adjustment allowed to obtain various damping ratio for the shock absorbers between 0.2 and 0.4. The shock absorber characteristics is asymmetric and nonlinear. Mean values of damping forces for various control current levels are presented in Figure 2. The influence of control signal (electric current) on damping ratios changes is almost linear in limit values of this signal (from 0 to 1,6 A).

A nonlinearity of damper’s characteristics occurs in higher values of the damping coefficient and the damping ratio for low values of damper speed and lower values for higher velocities. The values for low velocities are almost two times higher than for higher velocities.

Although the shock absorber has adjustable damping force, the force changes are situated within the limits of usual values of damping ratios in vehicle suspensions (0.2 – 0.4) with 0.2 value possibly optimal for comfort and 0.4 possibly optimal for handling (depends on particular car and situation).

The proportional valve of shock absorber is controlled by electric current of a valve coil obtained with Pulse Width Modulation (PWM) control technique. With this technique, the output transistor is used as an on/off switch, feeding the solenoid coil with a series of on/off pulses at a constant voltage.

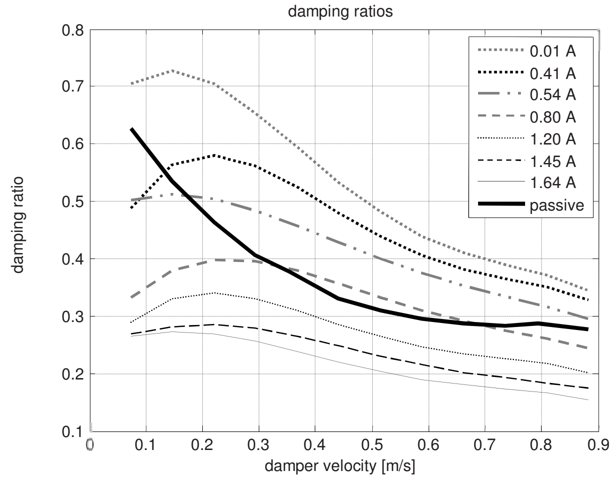

Fig. 2. Damping ratios of the passive and semi-active suspension of investigated vehicle with sprung mass corresponding to curb vehicle weight

The real time computer dSpace with input/output board and power amplifier was used to produce the PWM signal. The computer was a prototyping platform allowing to measure signals from the set of sensors and to control electric current adjusting the damping force of dampers (Ślaski, 2007). The suspension controller had multilayer and hierarchical structure shown in Figure 3.

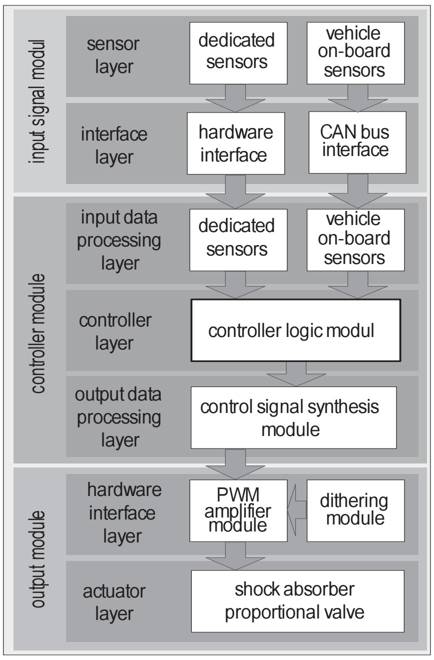

Fig. 3. Suspension controller architecture diagram

The controller architecture assumed three principal modules:

1. input signal module – a hardware signal conditioning module, and an interface to software part on input side of the system,
2. controller module – a module responsible for executing control algorithms; it consisted of software signal conditioning layer, a control logic layer and software control signal synthesis layer,
3. output module – a second part of the system hardware, a software-hardware interface for output signals with a power stage (PWM amplifiers) for shock absorbers proportional by-pass valves.

The input signal module consisted of a sensor layer and interface layer – both for special dedicated sensors for controlled suspension and for vehicle dynamics measurement sensors. Some of them were the type used for other control systems in today's cars. Such on-board sensors provide their information using CAN communication, so the tested controller had a CAN bus interface. Other dedicated sensors had their own hardware interfaces.

The controller module was the main module for the suspension controller functioning, responsible for its available functions.

The input data processing layer was a software interface to hardware sensor interface. Its main task was to convert the electric signal value into a measured physical parameter value. It also consisted of digital filter or detrend procedures.

The most important layer was the controller layer (Fig. 4) responsible for executing control algorithms of the controlled suspension. It had to execute complicated strategies of ride comfort and handling.

Next layer was the one shaping output data – control signals based on the results of logic operation. The functioning of this layer depends on the type of actuator, which imposes the type and shape of control signal – in this case it was PWM signal with specific parameters – signal frequency and signal pulse width.

The last output stage module of suspension control system consisted of a hardware interface layer and actuator layer.

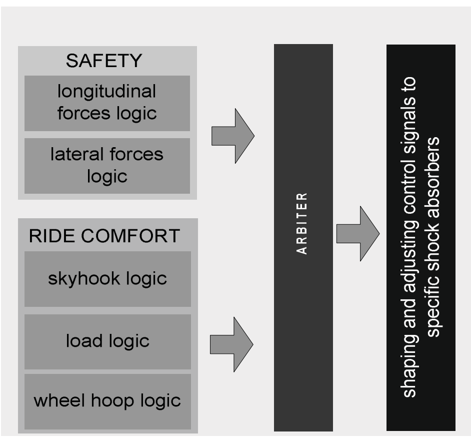

Fig. 4. Suspension controller module architecture diagram

The hardware interface layer is hardware part that can be called a power stage. It has to be an interface to the software output data processing layer and simultaneously it has to be able to produce stronger power signals. Therefore it contains some amplifier elements.

From the point of view of executing control algorithm the most important of all controller layers was the controller module. Its overall form is shown in Figure 4.

The core of the system was an "arbiter" block, which coordinated the control and chose a more important strategy at the moment. It could choose between comfort and safety strategies, so two other very important blocks were just a comfort strategy block and a safety strategy one.

Both the blocks were constantly making calculations and decisions. Only the arbiter block decided which of the two control signals should be used at a given moment and used one of them.

The last block was control signal synthesis and adjusting block shaping and also adjusting control signals to specific shock absorbers.

The safety strategy block executed control algorithm responsible for good vehicle handling. It was assumed that unsafe situations occur during sudden driver's operations with the brake, accelerator pedal or steering wheel movement. For that reason two blocks inside "safety" block were "steer_logic" and "brake_logic".

"Steer_logic" block detected sudden and fast steering wheel operations and higher than trigger value of side accelerations. Taking into account also vehicle velocity this block took decisions on increasing the damping ratio. Steering wheel angle signal and its time derivative were used to watch over driver's intentions and lateral acceleration signal was used to confirm dynamic state of the vehicle.

The "brake_logic" block was built in a similar way, but it detected sudden and very fast movements of the brake pedal. It detected not only brake pedal travel over adjusted threshold but also, after calculations of brake pedal velocity, it could better recognize an unsafe situation.

Next module "comfort block" in the tests was set to minimal damping and was not switched to active control. That setting for frequencies over body resonance range provides very good vertical vibration isolation, so the comfort is good (Savaresi, S. M. et al., 2010).

3. Test methodology

The test where performed using ISO 3888-1 "Passenger cars – Test track for a severe lane-change manoeuvre – Part 1: double lane-change" methodology. This test is generally used for subjective evaluation of vehicle dynamics.

The dimensions of the test track for a double lane-change are presented in Figure 5. The vehicle was driven along the track at various speeds – 80, 90 and 100 km/h.

Lateral accelerations during test drives were about 4…5 m/s^2.

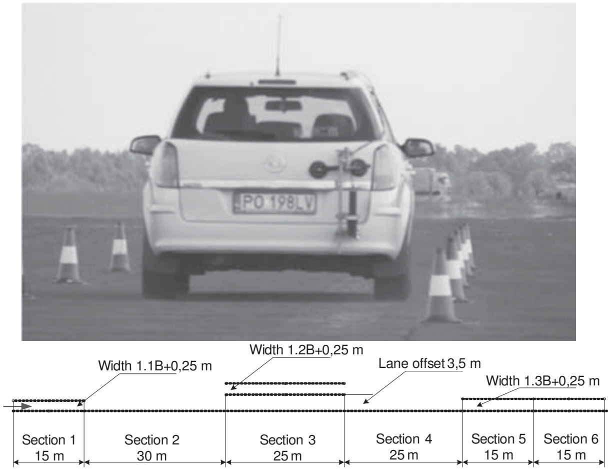

Fig. 5. Test vehicle during ISO 3888 test and track of this test (B – width of the vehicle)

During test drives the following damper settings were used:

- "comfort" (K) setting – minimum damping setting – control current was set to 1.6 A,
- "road" (R) setting – damping comparable with passive shock absorbers – it was middle damping setting – control current was set to 1.6 A,
- "sport" (S) setting – maximum damping setting – control current was set to 0 A,
- "auto" setting – the controller automatically changed damping setting from minimum to maximum damping in accordance with vehicle dynamics.

The variables analyzed after tests were time histories of:

- driver inputs: steering wheel angle $\Delta H(t)$, braking pedal travel,
- vehicle dynamics: lateral acceleration $a_y(t)$, longitudinal acceleration $a_x(t)$, yaw velocity (rate) $\dot{\psi}(t)$, roll rate $\dot{\theta}(t)$, longitudinal velocity (vehicle speed) V_X, lateral velocities of front and rear points of vehicle body V_{y_rear} and V_{y_front} (according to sensors placement)
- vehicle suspension variables: each wheel suspension deflections, each wheel suspension deflection rate,
- controller variables: "safety logic" output state, control current level.

4. Measurement results

Some measurement results are presented in Figure 6. The presented result are for the setting "auto"; it can be seen that "safety logic" output state changed from 0 state to one state at the beginning of test and was kept until the end of the test.

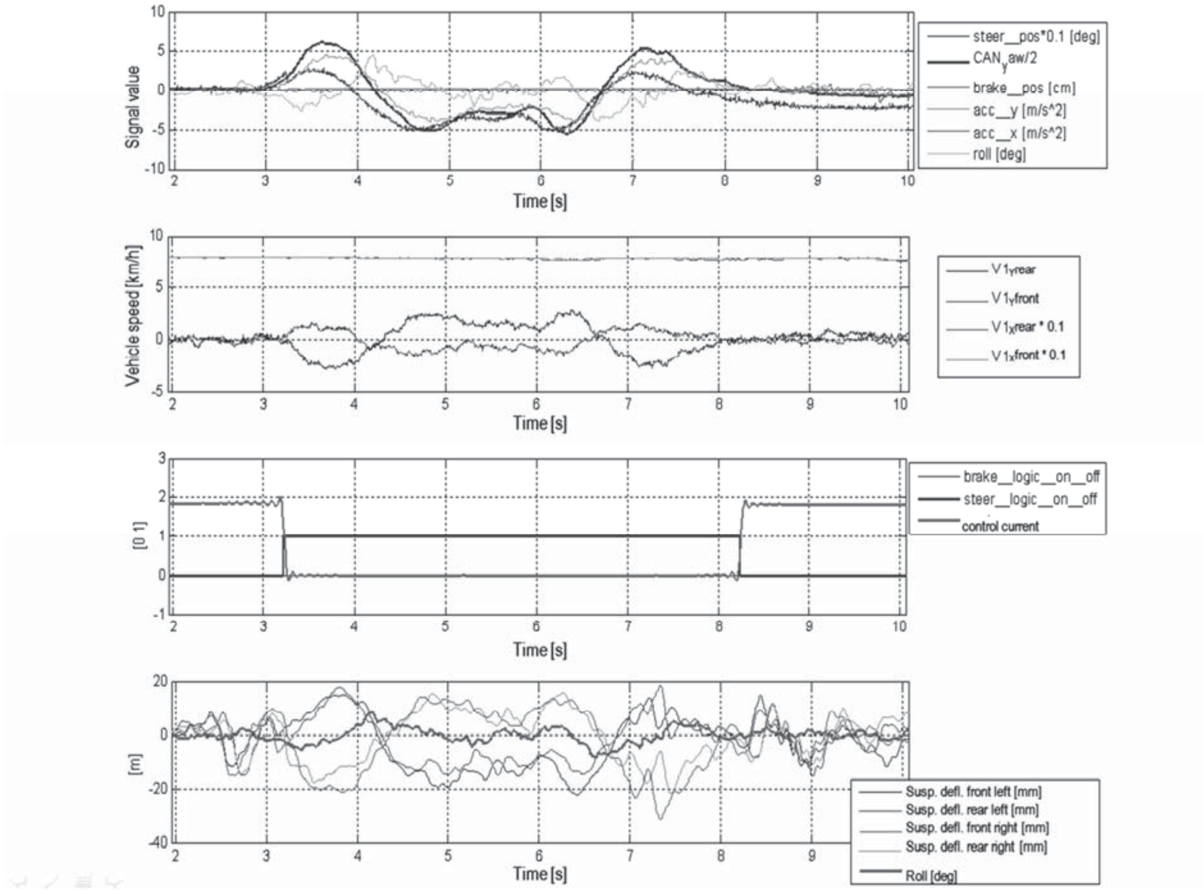

Fig. 6. Results of measurements made during drives through ISO 3888-1 track

This proves that the algorithm for the "safety logic" was effective to ensure a better safety level during all the test. At the beginning of controller developing the problem was the fact that the controller gave "0" state in the middle of test track and the delay of giving "1" state and the beginning of test.

5. Test results

All measurement results were statistically analyzed in order to evaluate the influence of damping level on vehicle dynamic behavior during the doublelane change maneuver.

The peak values of some variables recorded during drives were compared with each other for various drive speeds and damping settings. Comparison was made for three sections of test track – section 2, 4 and 5.

In Figure 7 a comparison of steering wheel angles for three constant damping levels and vehicle speed of 80 km/h and for comfort and active (auto – sport setting when "safety logic" was active) damping controlling are presented.

It can be noticed that steering wheel angles were smaller for bigger damping – for drives with the speed of 80 km/h changes are not big but for drives with the speed of 90 km/h they are clearly noticeable.

That tendency can show that it was easier to steer the car with shock absorbers set to bigger damping. This was confirmed by the test driver expressing his feelings about the ease of driving a car with various damping settings. It is probably because of the roll steering effect, which changes the steered wheel angle due to suspension kinematics during suspension deflection.

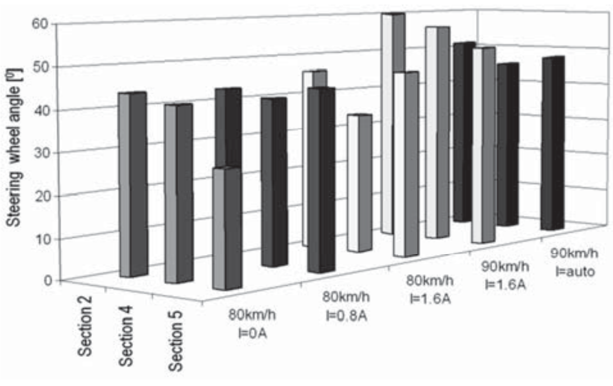

Fig. 7. Steering wheel angle peak values comparison for various test drives of ISO 3888-1 test

The peak values of yaw velocity changed with speed and damping changes similarly to steering wheel angle. This is presented in Figure 8. For "comfort" level there is no such an increase in peak values as for the steering wheel angle in the same situation. That means the driver had to turn the steering wheel more to obtain the same direction change during test drive.

The most noticeable trend is that as the damping decreases, the roll rate distinctly rises. It is presented in Figure 9.

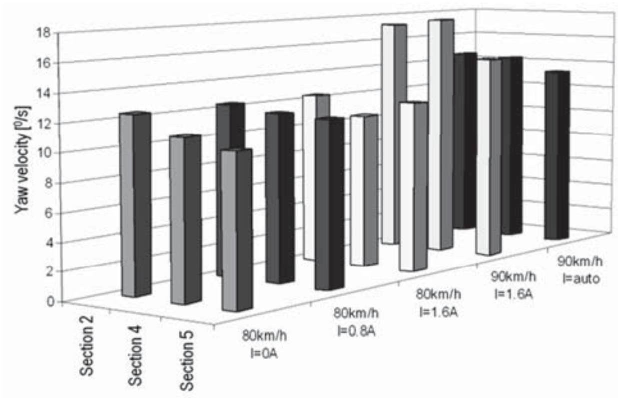

Fig. 8. Yaw velocities peak values comparison for various test drives of ISO 3888-1 test

Even for test drives at the speed of 80 km/h, when there was no distinct relation for other variables, now it can be seen that decreasing damping increases the roll rate. For this vehicle speed the highest values of the roll rate were 8 ^{0}/s for „sports" setting, 9.5 ^{0}/s for „road" and 10.5 ^{0}/s for "comfort" setting.

For the test drive at the speed of 90 km/h the increase of peak value was from 12 ^{0}/s for "sports" damping level to 15 ^{0}/s for "comfort" level. The peak value of roll rate in this case was 25 % higher for "comfort" level than for "sports" one. Similar results were presented for tests with trucks performed by other researchers (Ieluzzi *et al.* 2005).

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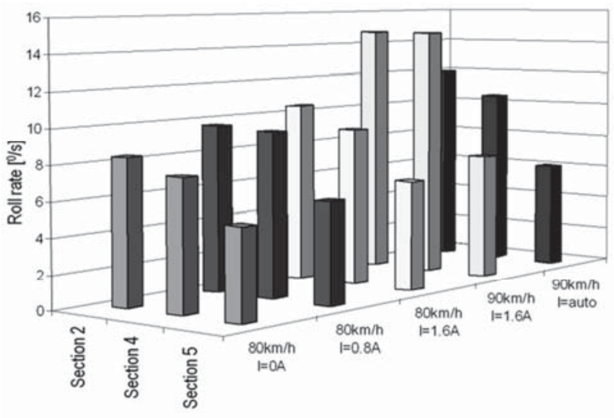

Fig. 9. Roll rate peak values comparison for various test drives of ISO 3888-1 test

6. Conclusions

A semiactive suspension prototype controller concept, its realization with a prototyping board and some test results of its functioning have been presented.

The control diagram was implemented in Simulink software and then converted into a real-time application for a dSpace ECU by means of a rapid-prototyping technique application. Afterwards, a passenger car with prototype semi-active suspension system was used in order to evaluate the real system performances during double lane change maneuver.

The presented tests and result analysis provide grounds to formulate the following conclusions concerning the tested controller functioning and damping influence on vehicle dynamics:

1. experimental results confirm the correctness of the concept and the prototype implementation of control algorithm and the whole system configuration allowing to execute the test,

2. the compared peak values of selected signals properly describe noticeable changes in vehicle behavior, because a subjective opinion of test drivers confirms an earlier conclusion on the effectiveness and usefulness of tested control algorithm for improving both the comfort and safety level,

3. decreasing the damping level increases the roll rate, which makes vehicle steering more difficult,

4. the influence of increasing the ease of vehicle steering with bigger damping is more noticeable at a higher vehicle speed (higher value of lateral acceleration).

5. the use of active damping adjusting yields similar results as using the maximum damping setting in terms of vehicle handling properties, but allows to increase vibration comfort when the handling is a secondary goal of suspension functioning.

It is important to remember that the shock absorbers have their own technical limits of changing damping ratios, so it influences the conclusions which could be formed on the basis of the shock absorbers used. Using for example a shock absorber with much higher upper limit of damping forces can have a more noticeable impact of damping changes on vehicle dynamics and handling properties.

However, the results obtained from road tests allow to include in further concepts real component limits and perform more realistic computer simulation research.

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