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THE INFLUENCE OF ADAPTIVE DAMPING LEVEL ON VEHICLE VIBRATION COMFORT – PASSENGER CAR EXPERIMENTAL TESTS RESULTS

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Abstract. The paper presents the results of experimental tests conducted on a passenger car equipped with changeable damping level shock absorbers in order to investigate the influence of damping level on vehicle vibration comfort. The shock absorbers were semiactive dampers with a by-pass proportional valve. The dampers were controlled by prototype controller developed and programmed with the use of Matlab/Simulink system and implemented on controller rapid prototyping platform dSpace. The tests took place on the roads around Poznan city with various surfaces (city asphalt and Belgian block, and highway asphalt surface) and with various vehicle speed levels.

The test data collected during road test were processed to find rms values of vertical accelerations and to compare the obtained results with the International Standard Organization ISO 2631 standard limits. Some charts of rms accelerations values for various damping levels over frequency ranges are presented in the paper. The obtained results show the level of improvement in vehicle vibration comfort and can be used in developing semiactive suspension controller process.

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

1. Introduction

The vibration comfort of a passenger vehicle is one of two main tasks that vehicle suspension has to manage. For this reason maximizing comfort is one of suspension optimization process goals (Rajamani 2006; Wong 2001).

When the type of road excitation remains always the same, and the masses of the vehicle are constant, it is possible to find the optimal 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 second suspension task – a road-holding ability influencing vehicle handling. Problems arise when the damping parameter chosen to maximize road-holding ability does not provide the best possible comfort. Designers have to balance the comfort and road-holding ability choosing compromise value of suspension damping.

It is much more complicated when they have to define operating conditions for the designed vehicle. They can change because of variable vehicle loads (e.g. numbers of passengers, mass of load), variable road excitations (various road surfaces), variable road excitation frequency (variable vehicle speed).

Using passive damping elements (it is still a common type of dampers used in modern vehicles) which have only one characteristics of the damping forces the designer are able to choose damping characteristics optimal only to one set of all the factors mentioned above.

One way to overcome this limitation is to use changeable damping in vehicle suspension and adjust its value adequately to current vehicle operation conditions (Savaresi *et al*. 2010).

Many researchers conducted a vast amount of theoretical investigations on possible comfort or safety improvement in some specific vehicle operation conditions – very often in some assumed simple cases. They often use simple linear quarter car models and sinusoidal excitations models, as they are easy to use and to interpret the obtained results. Transmissibility functions are often used to analyze obtained results.

There are also some more complicated models of cars used, namely nonlinear suspension and random excitation models (Verros *et al.* 2005). But few test results of a real vehicle with adjustable dampers are presented.

The author of this paper has performed some tests of possible changes in vertical comfort level when using the possibilities given by changes of suspension damping with the use of adjustable dampers.

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.

The dampers where typical CDC dampers used in this car model with IDS suspension system, but the whole control and measurement system was autonomic and configured by the author for the necessary tests.

The dampers allowed to get various damping ratio values between 0,2 and 0,4.

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

The shock absorber characteristics is asymmetric and nonlinear. It is possible to find a mean value of damping forces for a symmetric model of shock absorber characteristic as illustrated in figure 2 (Ślaski 2010).

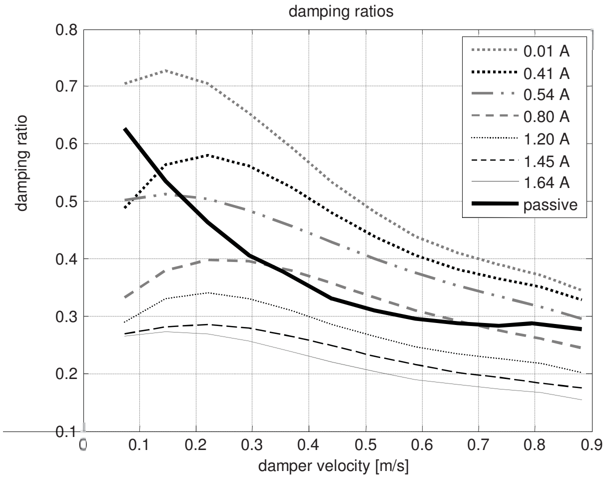

Fig. 2. Damping ratios of a passive and semi-active suspension of the investigated vehicle with sprung mass corresponding to curb vehicle weight

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. The influence of the control signal - electric current - is almost linear in limit values for this signal (from 0 to 1.6 A).

It is very interesting that, although the shock absorber has adjustable damping force, this force changes in limits of normally used values of damping ratios (0.2–0.4) with 0.2 value possibly optimal for comfort and 0.4 possibly optimal for handling (depends on a particular car and situation).

The proportional valve of shock absorber is controlled by various currents of a valve coil obtained with use of Pulse Width Modulation (PWM) control technique. With PWM, 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.

To produce the PWM signal dSpace real time computer with input/output board and power amplifier was used. This real time computer was a prototyping platform allowing to control adjustable dampers and to measure signals from set of sensors.

This platform uses a real time computer with input/output board and a special developer ControlDesk programme to control, adjust and manage controller performance and data.

3. Test methodology

Test where performed to find comfort level during the test drives on roads with various surface type and conditions and with variable velocity.

Test drives were performed with the same car on the same road with various damping level sets and at different constant speeds. Tests were carried out at speeds typical of various surfaces – for example on cobblestone a road car was driven with the speeds of 20, 30 and 40 km/h and on highway asphalt it was driven with the speeds of 100 and 110 km/h.

Damping levels were the following:

- "comfort setting" – the lowest possible damping level (control current was set to be constant value 1,6A),
- "road setting" – the middle value of damping (similar to passive dampers level – control current was set to be a constant value 0.8A),
- "sport setting" – the highest possible value (control current was set to be constant value 0A – it was also the value for control switched off).

Table 1. The matrix of test drives

Road surface	Vehicle speed [km/h]								
	10	20	30	40	50	60	70	90	110
Cobblestones		+	+	+					
City asphalt					+	+	+	+	
Highway asphalt								+	+
railroad crossing	+	+	+						

During test drives the driver was sitting on a special molded rubber pad with two-axial (X and Z directions) accelerometer sensor mounted inside. Acceleration signals were recorded using controller development software.

4. Measurement data processing

The influence of vibrations on the vehicle ride comfort can be evaluated using the root mean square (rms) value of measured vertical accelerations of the vibrations.

Before these accelerations are compared for various tests, during analysis they are grouped into frequency bands before putting them together. By convention, the third order octave bands are used in comfort analyses. The amplitudes of all excitations within frequency f between f_i and f_{i+1} ($f_i < f < f_{i+1}$) are summed up, where $f_{i+1}/f_i = 2^{1/3}$.

Rms values were calculated using formula:

$$RMS(a(t)) = \sqrt{\frac{1}{T}\int_0^T a^2(t)dt}, \ [\mathrm{m/s^2}]$$

where: $a(t)$ is the time history of the vertical acceleration measured and recorded as a function of time t and expressed in m/s^2; and T is the duration of the measurement in seconds. For the acceleration $a(t)$ recorded as a stationary realization of a stochastic process, the rms value is in most cases taken as a ride comfort index (Wicher, Więckowski 2010). An example of road test acceleration data measured on a driver's seat and their rms values calculated for one-third-octave frequency bands are presented in figure 3, in linear scale.

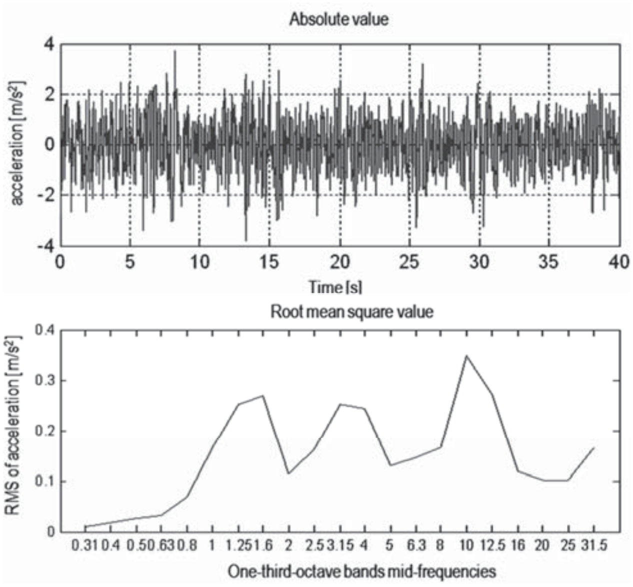

Fig. 3. Measured acceleration data and rms of accelerations obtained after data processing

The data processing procedure was programmed and realized with Matlab software.

5. Results

All the road test data were analyzed as described above. The charts of RMS values of vertical accelerations in frequency bands to compare the accelerations measured for drives with various damping settings with ISO 2631 exposure limits were performed. The data on these charts were presented on a logarithmic scale.

Then an analysis of the influence of damping setting was conducted in four frequency ranges:

- in body resonance peak frequency – range 1…2 Hz,
- between body and wheel resonance peaks frequency range – 5…6 Hz,
- in wheel resonance peak frequency – 10 Hz,
- over wheel resonance peak frequency – 16 Hz.

Tests were performed on city asphalt roads at low speeds (40…60 km/h) and on highway asphalt for higher speeds (90..110 km/h).

An exemplary plot of rms values of vertical accelerations of vibrations which driver was exposed to is presented on figure 4.

Results of the analysis of the all test data files to find the influence of damping ratio on ride comfort is presented in table 2.

The use of color scale for the values presented in the table helps to notice the highest and lowest values for all the range of performed road tests.

Table 2. Mean RMS values in frequency ranges: red – the highest, green the lowest (damper settings K-comfort, R – road, S – sport)

Road surface	speed	Damper setting	Frequency range			
			1…2	6…5	10	16
	km/k		Hz			
City asphalt	50	K	0.19	0.2	0.36	0.09
		R	0.12	0.15	0.16	0.06
		S	0.12	0.29	0.38	0.11
	60	K	0.16	0.09	0.13	0.06
		R	0.08	0.06	0.1	0.05
		S	0.08	0.06	0.09	0.04
	70	K	0.16	0.06	0.15	0.06
		S	0.09	0.1	0.15	0.05
	90	K	0.3	0.04	0.2	0.06
		R	0.2	0.05	0.24	0.08
		S	0.5	0.06	0.42	0.11
Highway	90	K	0.1	0.02	0.09	0.04
		R	0.05	0.03	0.09	0.04
		S	0.14	0.04	0.13	0.04
	110	K	0.11	0.03	0.07	0.05
		R	0.12	0.03	0.1	0.06
		S	0.07	0.02	0.09	0.05
cobblestone	20	K	0.33	0.13	0.25	0.08
		R	0.1	0.08	0.11	0.06
		S	0.08	0.22	0.27	0.08
	30	K	0.11	0.13	0.33	0.09
		R	0.13	0.08	0.32	0.18
		S	0.2	0.25	0.33	0.15
	40	K	0.27	0.13	0.35	0.12
		R	0.16	0.17	0.4	0.14
		S	0.12	0.26	0.38	0.16
Railway cross.	20	K	0.12	0.1	0.11	0.06
		R	0.13	0.12	0.22	0.05
		S	0.08	0.12	0.59	0.16

Some of the results show a linear and simple dependency between damper ratio value and rms values. For example driving on a city asphalt road with a damping ratio higher each time results in higher values of acceleration in the frequency range over body resonance.

Similar situation was for drives on a cobblestone road at the speed 40 km/h.

Driving on highway asphalt caused three times lower accelerations and the influence of damping ratio changes was almost imperceptible at frequencies over body resonance. It is interesting that during drives at the speed 110 km/h the sport setting of damper resulted in the lowest values of accelerations at body resonance frequency without increasing those values for all the other frequency ranges.

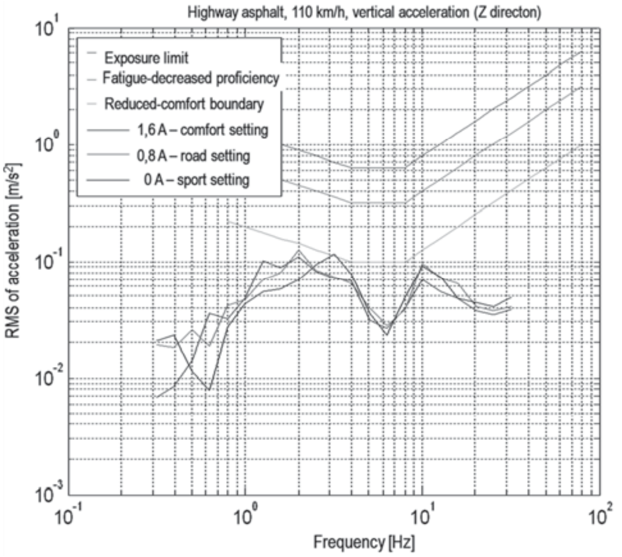

Fig. 4. Rms of vertical accelerations during road test on higway asphalt surface at speed of 110 km/h with various damper settings

Driving on city asphalt roads gave results in which it was difficult to find a simple dependency between damper setting and comfort improvement.

An analysis of the influence of speed and damping variations while driving on city asphalt roads is presented in figure 5.

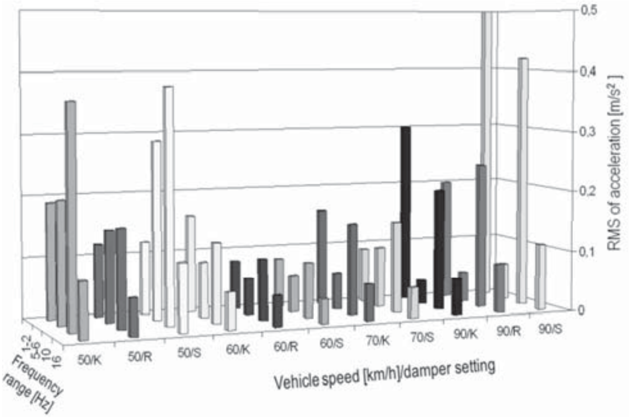

Fig. 5. Rms of vertical acceleration measured during test drives on city asphalt roads with various speed and dampers settings (K-comfort, R- road, S – sport)

Those roads are not in a good condition. It is clearly visible that acceleration values measured during city road test for the same speed as during highway test gave 2 to 3.5 times higher acceleration values.

After analyzing the results it can be inferred that the influence of damping ratio is more noticeable when the road excitation is higher. Then a higher damping ratio usually leads to higher acceleration values in all the analyzed frequency ranges apart from body resonance range.

Cobblestone road gives much higher excitations than asphalt roads. A plot of rms of accelerations measured during a test drive at the speed of 40 km/h is presented in figure 6.

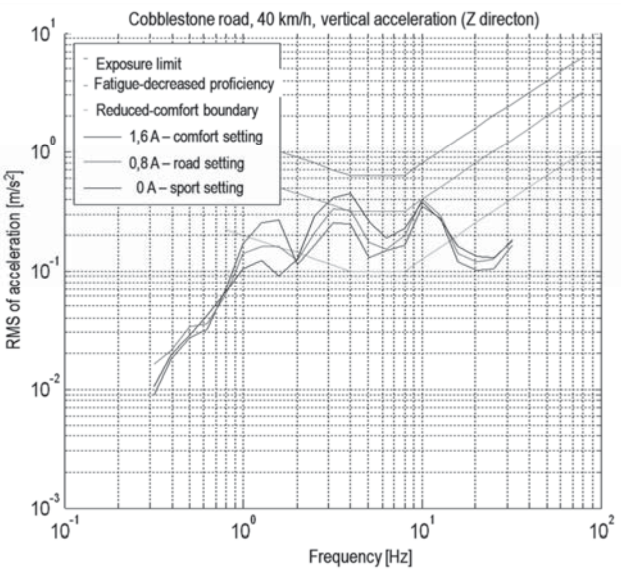

Fig. 6. Rms of vertical accelerations during road tests on cobblestone road at 40 km/h with various damper settings

Besides test drives at 30 km/h it can be found that a higher damping ratio gives smaller (even more than 3 times) accelerations in body resonance frequency range and higher accelerations in frequency ranges between body and wheel resonances and over wheel resonance frequency.

There are no significant differences in wheel resonance frequencies.

The last road test was performed when driving over a railroad (level) crossing at the speed of 20 km/h.

The analysis results of rms of vertical acceleration values are presented in Figure 7.

It can be found that sport setting of dampers caused much higher accelerations in wheel resonance frequency range than road setting, which in turned resulted in setting much higher than comfort setting. However, in the range of body resonance the best result was achieved with middle road setting of shock absorbers damping ratio.

This type of test should be analyzed also in the area of transient process after the end of excitation caused by railroad crossing, but this is a topic for further analysis. The analysis shows only the comfort influence of damping adjustment and of such type of single excitation on comfort.

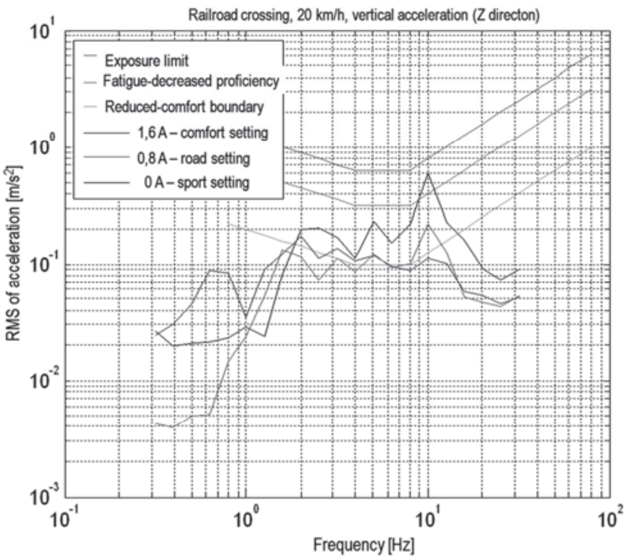

Fig. 7. Rms of vertical accelerations during road tests on cobblestone road at 40 km/h with various damper settings

6. Conclusions

The presented results are based on road tests carried out in everyday traffic. Therefore they are influenced by some other factors apart from damping changes. The road excitation was not accurately repeatable for every test drive due to changes of vehicle speed and for the stretch of road covered during the test because of traffic conditions. The traffic had a lower impact during the test on a cobblestone road and a highway because of smooth traffic on highway and low traffic on the cobblestone road. However, these limitations provide a real value of the results, as they show a practical level of possible advantages of using adjustable dampers in real operation conditions.

The presented tests and analysis results provide grounds to formulate the following conclusions concerning vehicle vertical dynamics:

1. when using a comfort setting (the lowest damping level) we get two clearly visible resonance peaks – one for sprung mass and the other for unsprung mass resonance frequency,
2. when using a sports setting (the highest damping level) the resonance peak of vehicle body moves towards higher frequencies (to 4…5 Hz); it occurs because the body and tyre become almost locked and both body and wheel vibrate as one mass suspended on the tyre only (compare Williams, 1997),
3. the sports setting reduces the acceleration values at body frequencies while the comfort setting reduces acceleration values in a range between body and wheel resonance frequencies and at frequencies over wheel resonance,
4. the weakest influence of the effect of varying the damper rate was observed for frequencies over wheel (unsprung mass) resonance (over 16 Hz).

It was also found that the influence of damping changes had a stronger influence on the observed accelerations values if the road excitations were bigger.

The above-mentioned conclusions are generally similar to vehicle and suspension dynamics theory investigated by many researches using mathematical models. But the obtained results also show that the real operation conditions – the type of road, speed of vehicle - do not always allow to predict real comfort improvement on the base of mathematical model testing.

It can be one of the reasons why the way of controlling suspension damping in a real vehicle operation condition is still a live scientific problem.

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