DESIGN SOLUTIONS AND ACTIVE SAFETY INCREASING FOR "VZN" SHOCK ABSORBERS

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Abstract

The paper presents the principle, some design solutions and last theoretical and by simulation results, for the suspension realized with the self-adjustable shock absorber, called shortly VZN, relative to the standard one. The self-adjustable shock absorber VZN, an intelligent shock absorber, realized without electronics or mechanisms, grant with European Patent EP1190184B and Romanian Patent 118546, is much better than standard ones because confers possibilities of stepwise adjustment of damping force as function as the instantaneous piston position. That means lower damping coefficients at the stroke beginning, for easier medium position arriving for a well adherence, damping coefficients for well correspondence between comfort and adherence, in the medium area, high damping coefficients both adjacent parts at the medium area for better adherence and well axle movement brake, and very high damping coefficients at the ends, for better body and axles protection. This concept is realized with planar or circular valves, a new patent request presenting specific solution. The cheaper and compact solution uses metering holes like damping valves, some of these being presented in the paper. The theory shows its great damping coefficient evolution with the stroke, give progressive anti-gyration effect and regressive redressing gyration effect along vehicle body transversal and longitudinal axes, increasing pitch and roll stability. Simulation tests denote high performances for VZN shock absorbers, relative to standard one, its great adaptation capacity relative to load, road condition, and efficiency, better body stability-skyhook behaviour, better protection at the stroke ends, lower RMS body acceleration, improving pitch and roll stability at and so active safety increasing. So the automotive self-adjustable shock absorber VZN, confers high performances, nearly semi-active suspensions at low costs, nearly standard shock absorbers being an important option for the future.

Keywords: *self-adjustable shock absorber, metering hole, skyhook, pitch, roll, anti-gyration effect, redressing effect*

1. Introduction

The self-adjustable shock absorber is called VZN, this acronym being abbreviation for VARIABLE ZETA NECESSARY for well NAVIGATION, where ZETA represents the relative damping, which is stepwise changed automatically, according to the piston position.

The smart shock absorber VZN, realized without electronics or mechanisms, grant with European Patent EP 1190184 B1, and Romanian Patent 118546 B1, gives the general organization solution, without practical solution for specific elements, like valves, sealing and guiding elements.

For cost and technology reasons, a new request of patent, presenting specific solutions for planar and cylindrical filling valves, sealing-guiding elements and alignment of cinematic elements was done, some of this elements being presented in the papers [1], [2].

The VZN dynamic shock absorber model was theoretically optimized, considering the piston position on full load and unload and for end stroke movement very high breaking [1].

The theoretical pitch and roll stability evaluations were made for identical sprung masses on each body position (front left, front right, rear left and rear right), and for identical metering holes on both unbalancing and redressing senses.

The simulations were made for three harmonic signals, representatives for the real hard road conditions, at full load situation, and at 100% and 50% shock absorber damping efficiency.

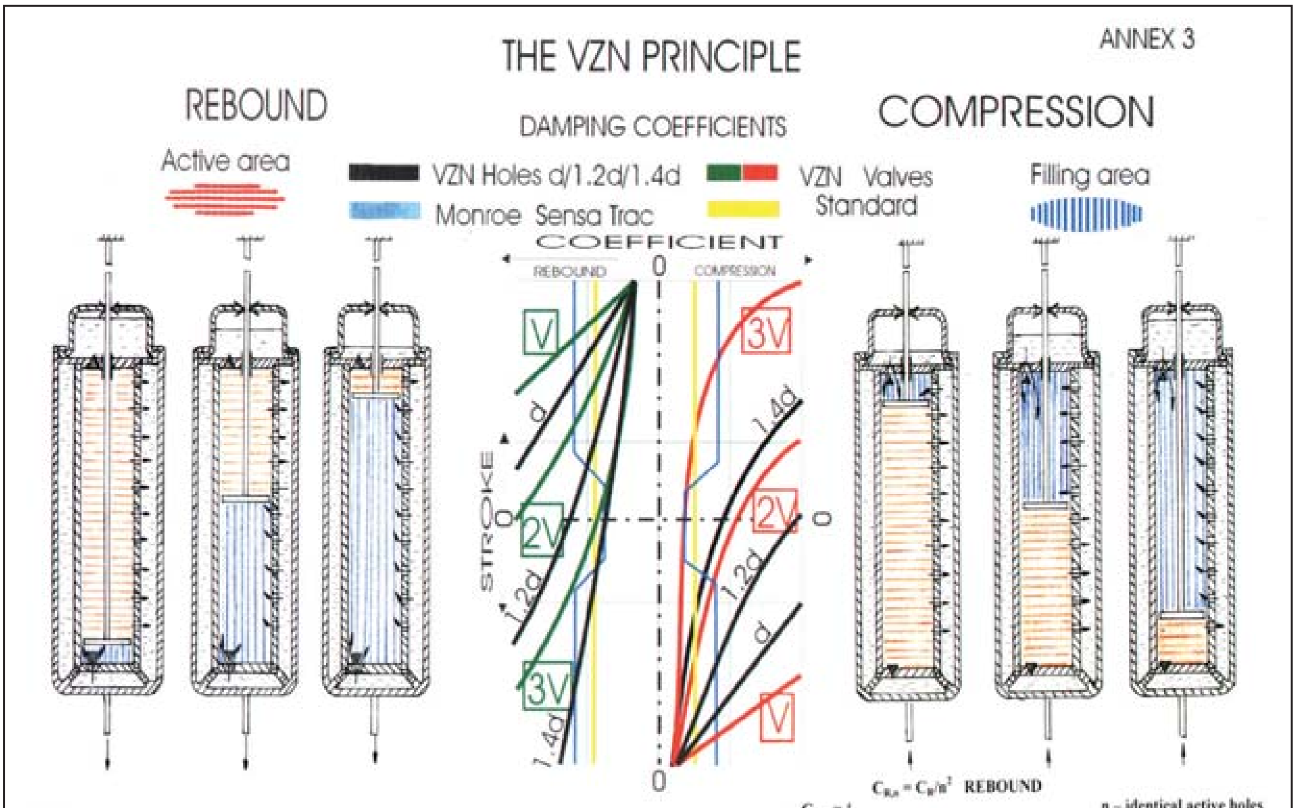
The theoretical an by simulation results show high performances for VZN shock absorbers, relative to standard one, its great adaptive capacity relative to road condition, even at low hydraulic efficiency.

2. The principle of the self-adaptive shock absorber – "VZN"

The energy dissipation system of the self-adjustable shock absorber consists of an inner cylinder having sideways damping valves, placed optimally between to the ends. The inner cylinder is closed at ends with inner head and valve body, either containing or no filling valves. The piston slidably mounted within the inner cylinder, without filling and damping valves.

Due to this structure the shock absorber assures on both rebound respectively compression strokes small damping coefficients at the beginnings of strokes due to the fact that the liquid is discharged through a high number of damping valves, medium damping coefficients at the medium position due to the fact that the liquid is discharged through a medium number of damping valves, while when the piston approaches by strokes ends the damping coefficients increase due to the reduction of the active damping valves numbers.

Fig. 1 presents the VZN principle, relative to the standard and Monroe Sensa Trac variants. It shows the damping coefficient evolution for compression and rebound stroke.



n	1	2	3	4	5	6	7	8	9	10
$C_{R,n}$	$C_R/1$	$C_R/4$	$C_R/9$	$C_R/16$	$C_R/25$	$C_R/36$	$C_R/49$	$C_R/64$	$C_R/81$	$C_R/100$
$C_{C,n}$	$C_C/1$	$C_C/4$	$C_C/9$	$C_C/16$	$C_C/25$	$C_C/36$	$C_C/49$	$C_C/64$	$C_C/81$	$C_C/100$

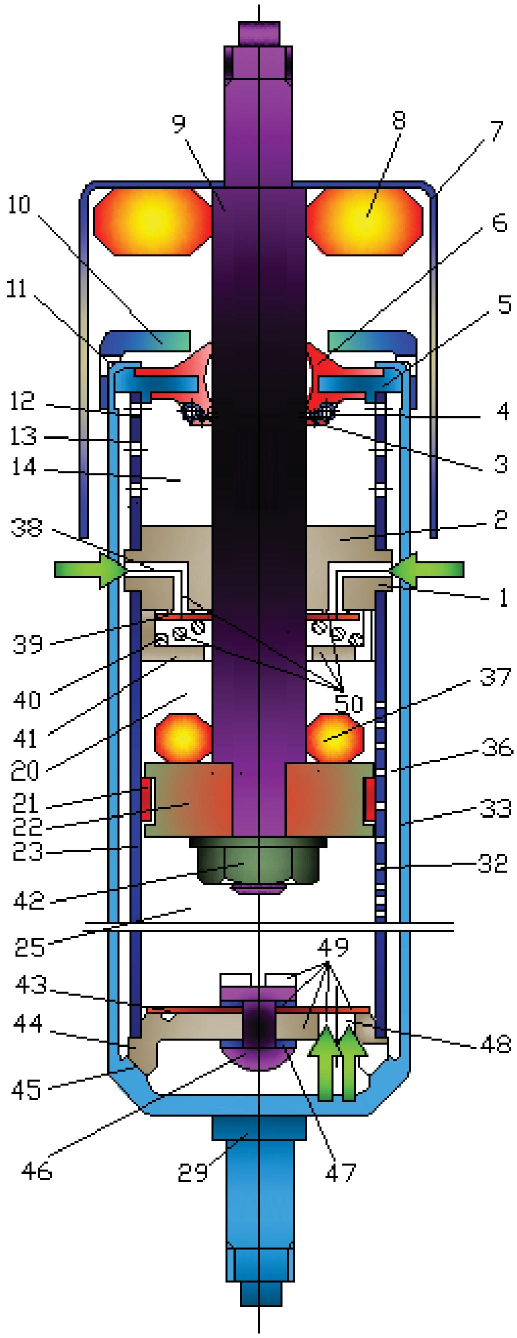
Fig. 1. The "VZN" principle

At the standard solution, they are constant along the stroke. At the Monroe Sensa Trac solution the damping coefficients have decreased values on rebound and compression in the medium position, in order to confer high comfort at the little unevenness. At the VZN concept, for identical damping valves, or metering holes the damping coefficients decrease with the square number of active valves or metering holes. "d" represents the metering hole diameter, and "V" the damping valve tuning at low, medium and high fluid debit.

3. Main "VZN" shock absorber constructive solutions

The European [1] and Rumanian [2] patents give the principle solutions for VZN concept.
The Patent request [3] gives the principle solutions for the filling valves.
The paper will present the main solutions for planar and cylindrical filling valves.

3.1. VZN- shock absorber planar filling valves solution

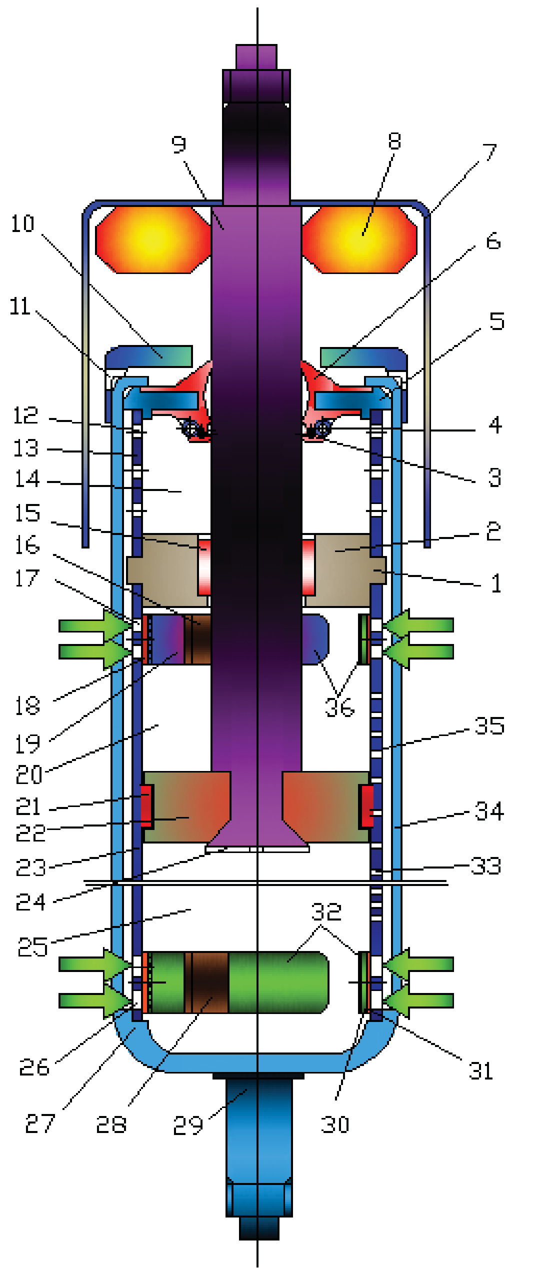


1. Annular shoulder
2. Inner (upper) lid
3. Annular spring
4. Annular spring
5. Outer lid
6. Seal system
7. Protector
8. Compression stopper bumper
9. Rod
10. Bumper hanger
11. Orifices
12. Communication holes
13. Balance chamber cylinder
14. Balance chamber
20. Compression chamber
21. Segment
22. Piston
23. Inner cylinder
25. Compression chamber
29. Catch bar
32. Metering holes
33. Outer cylinder
35. Rebound stopper bumper
38. Filling duct
39. Annular plate valve
40. Cylindrical/conical spring
41. Glass Shape Cage
42. Self blocking nut
43. Circular plate valve
44. Inner inferior lid
45. Conical annular shape
46. Rivet
47. Washer
48. Filling holes
49. Rebound filling valve
50. Compression filling valve

Fig. 2. The VZN shock absorber planar filling valves solution

3.2. VZN- shock absorber cylindrical filling valves solutions

Using cylindrical filling valves, from cylindrical plates fixed on the inner cylinder, cheapest solutions of Self-Adjustable Shock Absorber-VZN have been realized. The 3rd Figure shows the longitudinal section, where the elements are:



1. Annular shoulder
2. Inner (upper) lid
3. Annular spring
4. Annular spring
5. Outer lid
6. Seal system
7. Protector
8. Compression stopper bumper
9. Rod
10. Bumper hanger
11. Orifices
12. Communication holes
13. Balance chamber cylinder
14. Balance chamber
15. Guide
16. Shaped rivet filling compression
17. Compression filling holes
18. Cylindrical plate valve, f. c.
19. Plus cylindrical plate/s, f. c.
20. Rebound chamber
21. Segment
22. Piston
23. Inner cylinder
24. Riveting
25. Compression chamber
26. Rebound filling holes
27. Annular shoulder
28. Shaped rivet filling rebound
29. Catch bar
30. Plus cylindrical plate/s, f. rebound
31. Cylindrical plate valve, f. rebound
32. Rebound filling valves
33. Metering holes
34. Outer cylinder
35. Oil tank
36. Compression filling valves

Fig. 3. The VZN –shock absorber cylindrical filling valves solution

In both figures 2 and 3 the filling is showed as: FILLING

Both solution shoved in 2 and 3 Figures are equipped with compression stopper bumper.

The solution with planar filling valves is presented with rebound stopper bumper.

Both situations, between the balance chamber and the inner cylinder, the inner upper lid (2) are fitted with the annular shoulder (1).

At the VZN shock absorbers the compression and rebound stopper bumpers are reduced more 70% or missing, due to the hydraulic high-energy dissipation at the stroke ends.

The positions, numbers, shape and dimensions of the metering holes are in correlation with the car weight, road and ride conditions.

4. On pitch theoretical consideration

The suspension reaction forces equilibrate the movements given by the longitudinal forces, us the aerodynamic forces acting in the side pressure centre, or inertial forces, acting in the gravity centre. They can be considered like a resultant longitudinal force F_L, acting at „h" distance relative to the line of the suspension element on body attachments.

Under the longitudinal forces $\pm F_L$ the body rotates due to the spring deformation, the system being equilibrated by the spring reaction R_{FR}, R_{RR}, which increase/decrease relative to the initial situation with ΔR.

The viscous forces D_{FR}, D_{RR} given by the front and rear shock absorbers stabilize the movement.

Fig. 4 represents the planar pitch model, in initial situation, without longitudinal forces and in the equilibrium position in situation with longitudinal forces.

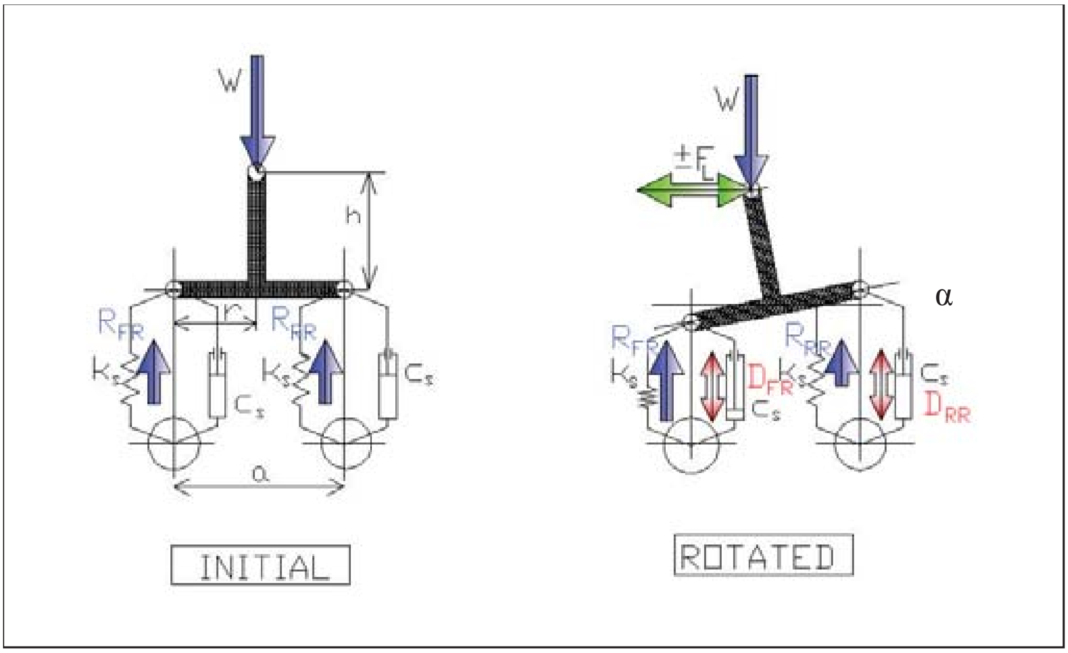


Fig. 4. The planar pitch model

where:

W – body weight,

F_L	– longitudinal force,	R_{FR}	– front springs reaction,
R_R	– rear springs reaction,	k_S	– spring rigidity,
δ	– spring deformation,	α	– pitch angle,
a	– wheel base,	$r = \frac{a}{2}$.	

Considering VZN shock absorbers having 10 identically metering holes, so damping coefficients have variation of 100 times, along the stroke, at system unbalanced/redressing, the shock absorbers acts with anti-gyration/anti-redressing torques, the active metering holes according roll angle being indicated in the Fig. 5, for both states.

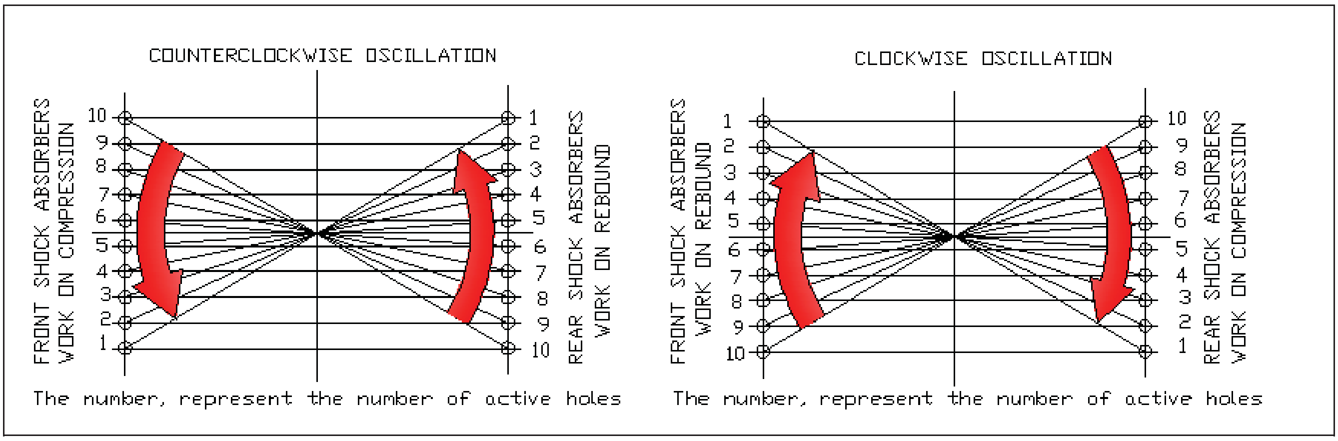


Fig. 5. The number of active holes acting on clockwise and counter clockwise

Considering the body and the pitch axle in the medium position, the front and rear sprung mass and front and rear shock absorbers identically, the number of active holes is given in Fig.6.

$$c_q = \frac{c_{0q}}{n^2} \quad q = \text{Rebound / Compression};\; n = \text{number of activ holes}. \tag{1}$$

$$c_\alpha = \frac{T_\alpha}{\varpi} = \frac{r(D_{FR_q} + D_{RR_q})}{\dfrac{V}{r}} = \frac{r^2(D_{FR_q} + D_{RR_q})}{V} = r^2(c_C + c_R) = \frac{a^2}{4}(c_C + c_R). \tag{2}$$

$$c_\alpha = \frac{a^2}{4}(c_C + c_R) = \frac{a^2}{4}\frac{(c_{0C} + c_{0R})}{n^2} = \frac{c_{\alpha 0}}{n^2}. \tag{3}$$

$$D_q = c_q V^j;\ \text{for this case}\ D_q = c_q V, \tag{4}$$

were:

c_{0q} - compression/rebound damping coefficient for one active hole,

D_{FR} - the damping force of the front shock absorbers,

D_{RR} - the damping force of the rear shock absorbers,

T_α - the pitch damping torque of the shock absorbers.

$$c_{\alpha 0} = \frac{a^2}{4}(c_{0C} + c_{0R}). \tag{5}$$

$$RAE_U^P = T_{P_U}^{VZN} \big/ T_{P_U}^S = c_{\alpha_U}^{VZN} \big/ c_{\alpha_U}^S, \text{ relative anti-unbalance effect at pitch,} \tag{6}$$

$$RAE_R^P = T_{P_R}^{VZN} \big/ T_{P_R}^S = c_{\alpha_R}^{VZN} \big/ c_{\alpha_R}^S, \text{ relative anti-redressing effect at pitch.} \tag{7}$$

The anti-gyration /anti-redressing damping coefficients and the relative torques have the values indicated in the Tab.3, for situation shown in the Fig. 6., where the number in ordinate lines represents the number of active metering holes.

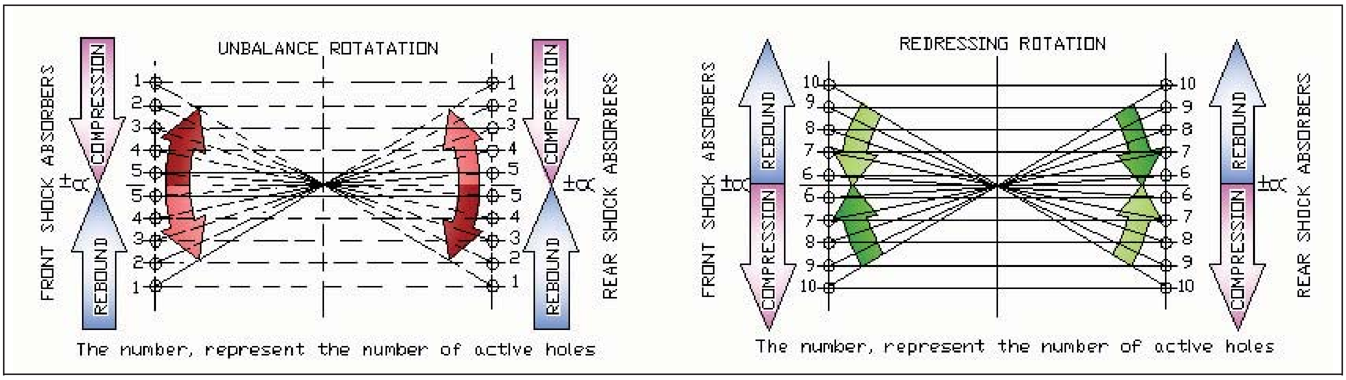


Fig. 6. The shock absorbers number of active holes acting on unbalance and redressing rotation

Tab. 1. The VZN and standard roll damping coefficients, its ratio and relative roll angle at unbalance rotation

ROTATION SENSE	The holes position [$\pm i$]	± 1	± 2	± 3	± 4	± 5
	Relative pitch angle $\alpha = f(u)$ $u = f(i,\delta)$	$\alpha = \arcsin(\frac{2u}{a}) = \arcsin(\frac{\mp\frac{\delta}{2} \pm i\delta}{\frac{a}{2}})$				
		u				
		$\pm\frac{\delta}{2}$	$\pm\frac{3\delta}{2}$	$\pm\frac{5\delta}{2}$	$\pm\frac{7\delta}{2}$	$\pm\frac{9\delta}{2}$
UNBALANCEING ROTATION	n_U	5	4	3	2	1
	n_U^2	25	16	9	4	1
	$c_{\alpha_U}^{VZN}$	$c_{\theta 0}/25$	$c_{\theta 0}/16$	$c_{\theta 0}/9$	$c_{\theta 0}/4$	$c_{\theta 0}$
	$c_{\alpha_U}^{S}$	$c_{\theta 0}/36$	$c_{\theta 0}/36$	$c_{\theta 0}/36$	$c_{\theta 0}/36$	$c_{\theta 0}/36$
	$c_{\alpha_U}^{VZN} / c_{\alpha_U}^{S}$	1.44	2.25	4	9	36
	$RAE_U^P = T_{P_U}^{VZN} / T_{P_U}^{S}$	1.44	2.25	4	9	36
REDRESSING ROTATION	n_R	6	7	8	9	10
	n_R^2	36	49	64	81	100
	$c_{\alpha_R}^{VZN}$	$c_{\theta 0}/36$	$c_{\theta 0}/49$	$c_{\theta 0}/64$	$c_{\theta 0}/81$	$c_{\theta 0}/100$
	$c_{\alpha_R}^{S}$	$c_{\theta 0}/36$	$c_{\theta 0}/36$	$c_{\theta 0}/36$	$c_{\theta 0}/36$	$c_{\theta 0}/36$
	$c_{\alpha_R}^{VZN} / c_{\alpha_R}^{S}$	1	0.73	0.56	0.44	0.36
	$RAE_R^P = T_{P_R}^{VZN} / T_{P_R}^{S}$	1	0.73	0.56	0.44	0.36

The theoretical analyses show the VZN shock absorbers confer better behaviour at the pitch, relative to the standard ones, because for identically metering holes, the anti-roll torque decrease with the square of the number of active metering holes, vary usually more 30 times.

The progressive damping coefficients give by the VZN solution confers:

- An anti-unbalance torque, progressive with the pitch angle, so giving pitch stability at unbalancing,

- An anti-redressing torque, regressive with the pitch angle, so favouring pitch stability at redressing.

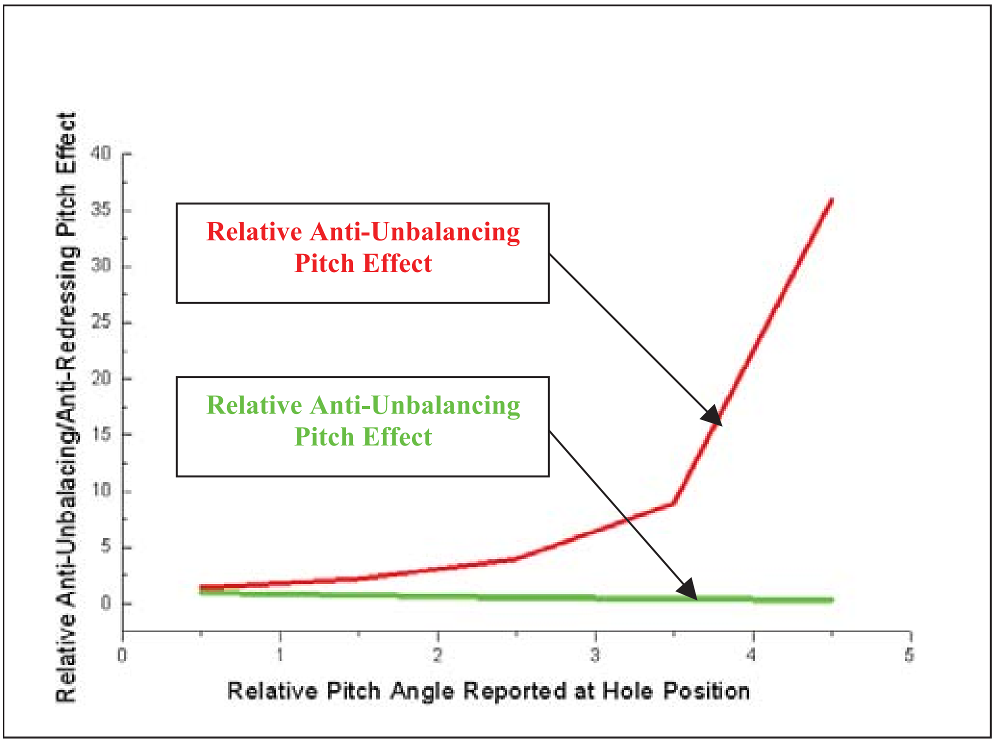


Fig. 7. The VZN shock absorber anti-pitch behaviour, relative to the standard one

4. On roll theoretical consideration

The suspension reaction forces equilibrate the lateral forces, us the wind forces acting in the side pressure centre, or centrifugal forces, acting in the gravity centre.

Considering VZN shock absorbers having 10 identically metering holes, damping coefficients have variation of 100 times, along the stroke, at system unbalancing/redressing, the shock absorbers acts with progressive anti-gyration torques and regressive anti-redressing torques.

A theoretical consideration about VZN shock absorbers roll behaviour, relative to the standard one were made in the paper [2], the conclusion being:

The progressive damping coefficients give by the VZN solution confers, relative to the standard shock absorber solution, higher roll stability, consisting of:

- An anti-roll torque progressive with the roll angle, giving anti-roll relative effect,
- An anti-redressing torque regressive with the roll angle, favouring redressing.

5. The matlab/simulink simulation

The quarter car model, used to study the vertical interaction between car vehicle and road [2] is shown in Fig. 8. The numerical simulation in this section concerns only the vertical interaction for a rear wheel, neglecting the rolling and the pitch motion of the car. The model has 2 degrees of freedom, i.e., the vertical displacement x_1 of the car body (bounce) and the vertical displacement x_2 of the wheel centre (wheel hop). At time t, the vertical profile of the road is denoted by $x_0(t)$. The model contains two levels of elastic and damping elements: one level between the wheel and the road, characterized by the stiffness coefficient k_2 of the tire and its damping coefficient c_2; the second level between the wheel and the body (vehicle suspension), including a spring with stiffness coefficient k_1 and a VZN shock absorber (or a standard shock absorber, as comparison variant) with damping coefficient c_1.

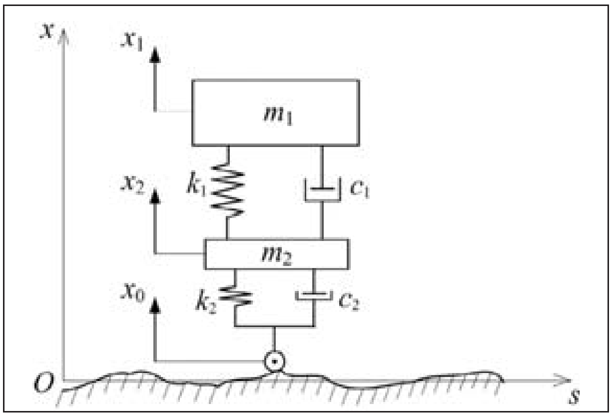


Fig. 8. The quarter car model

Fig. 8 presents the car/road vertical interaction model, where:

m_2 - the mass of one wheel –unsprung mass,
m_1 - reduced car body mass corresponding to one rear wheel -sprung mass,
$m_{1\ empty}$ - the reduced mass of the unloaded car body including driver and fuel masses,
$m_{1\ full}$ - the reduced mass of the car body for the case of maximum admissible car loading.

Obviously, m_1 is a value between m_{1empty} and m_{1full}.
The equation of motion of car body is:

$$m_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{x}_2)^2 + k_1(x_1 - x_2) = F_{e,\text{stop bumper}}, \tag{8}$$

where:
$F_{e,\ stop\ bumper}$ represents the elastic striking force, being *< 0* at rebound and *> 0* on compression bumper.
The equation of motion of the wheel centre is:

$$m_2\ddot{x}_2 - c_1(\dot{x}_1 - \dot{x}_2)^2 + c_2(\dot{x}_2 - \dot{x}_0) - k_1(x_1 - x_2) + k_2(x_2 - x_0) = -F_{e,\text{stop bumper}}. \tag{9}$$

Denoting by v_1 the vertical velocity $\dot{x}_1$ of the car body and by v_2 the vertical velocity $\dot{x}_2$ of the wheel centre, the second order differential equations (8) and (9) can be transformed in the following system of four first order differential equations, ready to be numerically integrated by usual methods, e.g., the Runge-Kutta method:

$$\begin{cases} \dot{x}_1 = v_1 \\ \dot{x}_2 = v_2 \\ \dot{v}_1 = \dfrac{F_{e,\text{stopbumper}}}{m_1} - \dfrac{1}{m_1}[c_1(v_1 - v_2)^2 + k_1(x_1 - x_2)] \\ \dot{v}_2 = -\dfrac{F_{e,\text{stop bumper}}}{m_2} + \dfrac{1}{m_2}[c_1(v_1 - v_2)^2 - c_2(v_2 - \dot{x}_0) + k_1(x_1 - x_2) - k_2(x_2 - x_0)] \end{cases}. \tag{10}$$

Fig. 9 presents the shock absorber with stopper bumpers scheme, where:

- $F_{e,\ stop\ bumper}$ increases linearly from 0 to -500 daN beginning at the touch point of rebound bumper, up to the d_1 distance (stroke of the rebound stop bumper, under -500 daN), respectively decreases linearly from 0 to 1000 daN beginning at the touch point of the compression bumper, up to d_2 distance (stroke of the compression bumper stop). Otherwise, $F_{e,\ stop\ bumper}$ is null,

- "l" represents the full stroke,
- "l-(d_1+d_2)" represents the free stroke,
- "d" represents the distance between the static middle piston position and the static equilibrium position of the piston for the current value of the sprung mass m_1, is given by:

$$d = \left(\frac{m_{1-\text{empty}} + m_{1-\text{full}}}{2} - m_1 \right) \frac{g}{k_1} \, . \qquad (11)$$

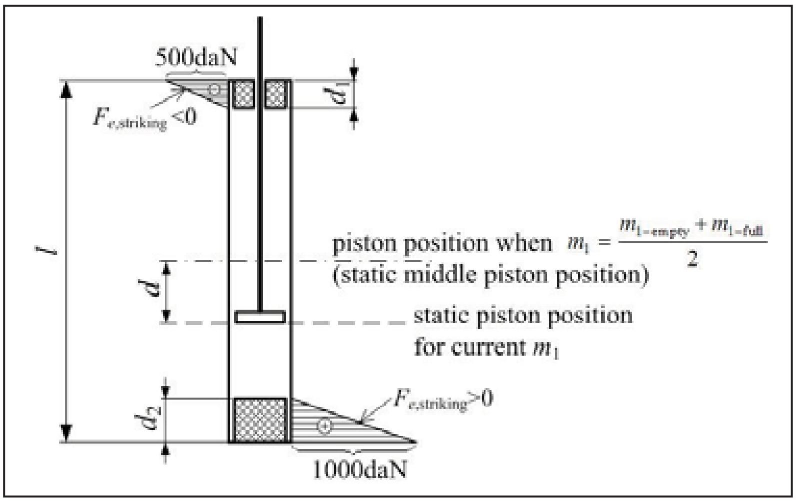


Fig. 9. The shock absorber with stopper bumpers scheme

The road/car vertical interaction has been simulated using Matlab/Simulink. The case of using a VZN shock absorber has been compared with the case of using a standard shock absorber. The considered car has the following characteristics:

- $m_{1\text{-empty}} = 240$ [kg]; $m_{1\text{-full}} = 360$[kg],
- $l = 0.236$ [m], $d_1 = 0.014$ [m], $d_2 = 0.040$ [m],
- $k_1 = 14.085$ [kN/m], $k_2 = 21.8$ [kN/m],
- $c_2 = \frac{k_2}{2\pi f} = \frac{21.8}{2\pi f}$ [kN·s/m] - Tire-damping coefficient,
- For a standard shock absorber of the considered car, the damping coefficient c_1 is given in 5 piston velocity steps [1] having values from 60.8[N] up to 51716 [N],
- For the VZN shock absorber, the damping coefficient values increases more than 3000 times between minimal and maximal values, depending of the instantaneous piston position.

To cover a large area of conditions, three strong harmonic functions (see Tab. 2) for road irregularities, and 100% and 50% shock absorbers efficiency regime were taken into account.

Tab. 2. Amplitude and frequency of the harmonic functions considered as road profile

Case	1	2	3
Road amplitude [m]	0.20	0.10	0.03
FRECVENCY [Hz]1	1	2	12

Tab. 3. Better VZN shock absorbers behaviour, relative the standard one

	100 x (Standard – VZN) / Standard [%]		
EFFICIENCY	100%	50%	AVERAGE
Root mean squares body vertical accelerations [m/s^2]	16.9; 17.6; 37	24.5; 41.3; 65.6	33.8
Forces in stop bumpers [k N]	77.8; 92.2; 100	67.9; 85.7; 100	87.2
Displacements dispersion at 3rd regime	95	96	95.5
OTHERS	Squat 4 cm reduced		SCKYHOOK

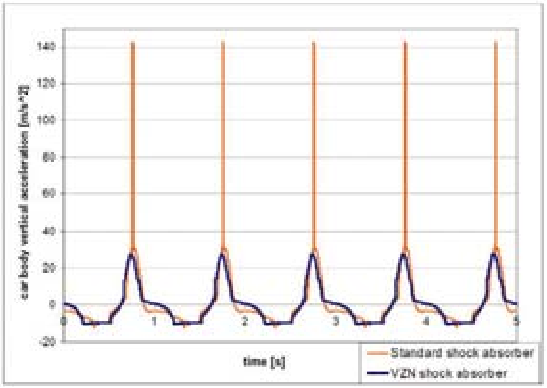
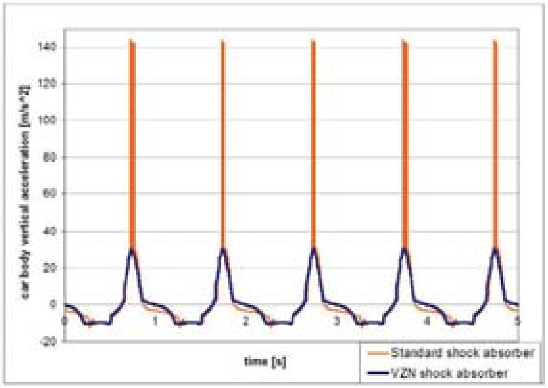
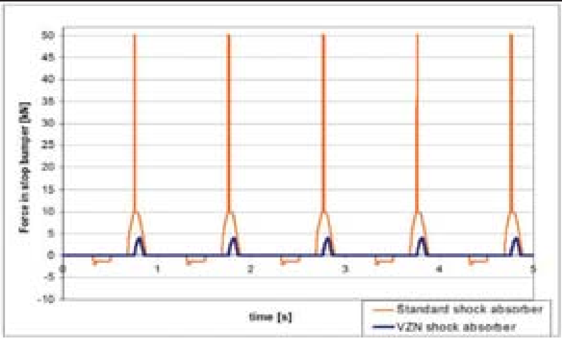
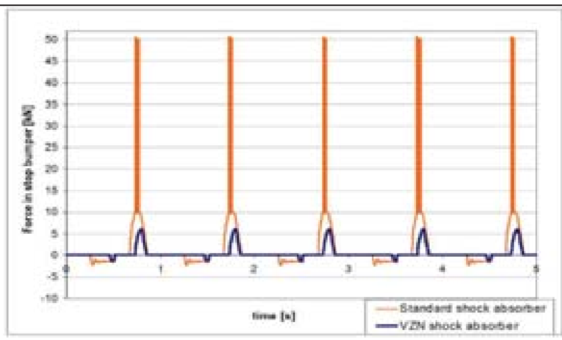
	100% efficiency	*50% VZN efficiency*
Body vertical accelerations [m/s²]	 $\ddot{x}_{1,\mathrm{RMS,VZN}} = 10.62 \,/\, \ddot{x}_{1,\mathrm{RMS,standard}} = 12.78\ \mathrm{m/s^2}$	 $\ddot{x}_{1,\mathrm{RMS,VZN}} = 11.11 \,/\, \ddot{x}_{1,\mathrm{RMS,standard}} = 14.72\ \mathrm{m/s^2}$
Forces in stop bumpers [kN]	 $\mathrm{RMS_{VZN}} = 0.86 \ / \ \mathrm{RMS_{standard}} = 3.88\ [\mathrm{kN}]$	 $\mathrm{RMS_{VZN}} = 1.49 \ / \ \mathrm{RMS_{standard}} = 4.65\ [\mathrm{kN}]$

Fig. 10. Car body behaviours for road profile with amplitude 0.2m at frequency 1Hz

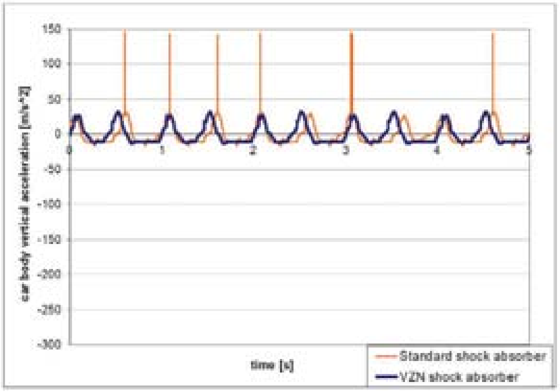
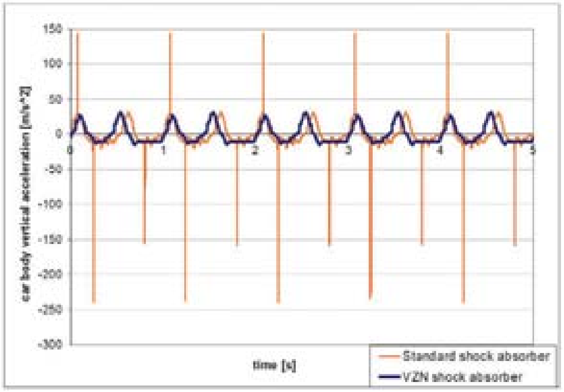
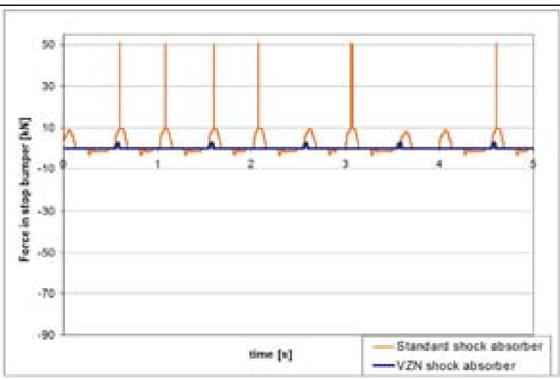
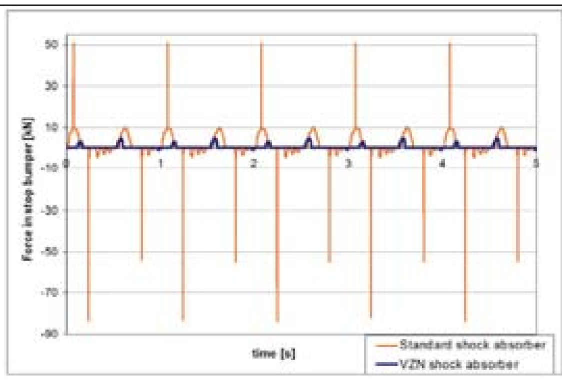
	100% efficiency	*50% VZN efficiency*
Body vertical accelerations [m/s²]	 $\ddot{x}_{1,\mathrm{RMS,VZN}} = 13.21 \,/\, \ddot{x}_{1,\mathrm{RMS,standard}} = 16.04\ \mathrm{m/s^2}$	 $\ddot{x}_{1,\mathrm{RMS,VZN}} = 12.80 \,/\, \ddot{x}_{1,\mathrm{RMS,standard}} = 21.81\ \mathrm{m/s^2}$
Forces in stop bumpers [kN]	 $\mathrm{RMS_{VZN}} = 0.38 \ / \ \mathrm{RMS_{standard}} = 4.90\ [\mathrm{kN}]$	 $\mathrm{RMS_{VZN}} = 1.03 \ / \ \mathrm{RMS_{standard}} = 7.21\ [\mathrm{kN}]$

Fig. 11. Car body behaviours for road profile with amplitude 0.1m at frequency 2Hz

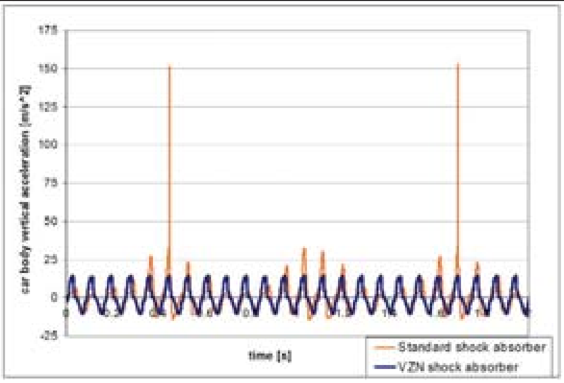
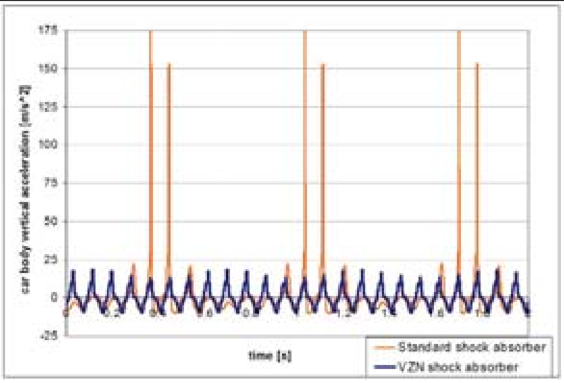
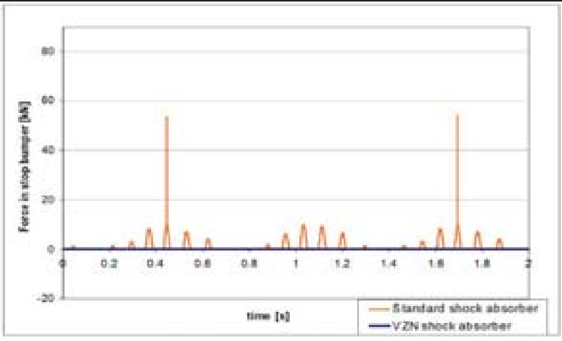
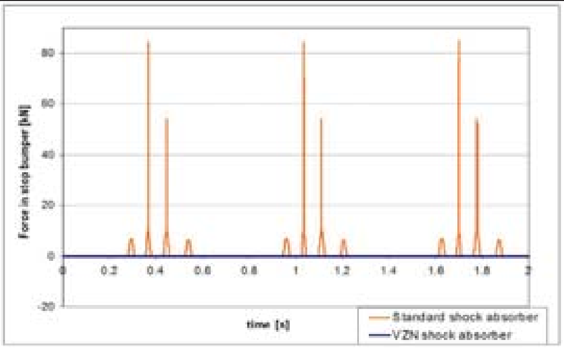
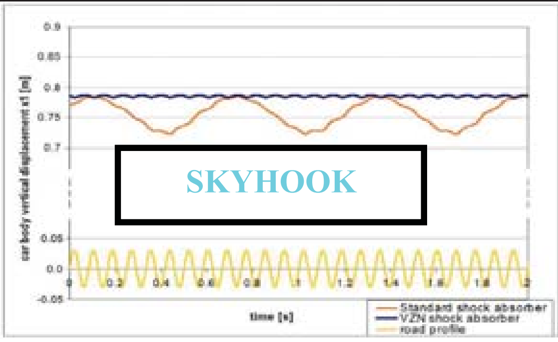
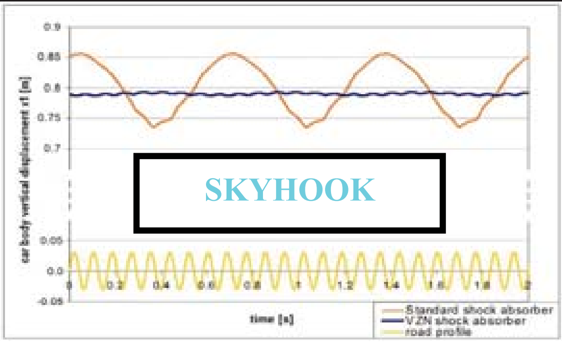
	100% efficiency	50% VZN efficiency
Body vertical accelerations [m/s²]	 $\ddot{x}_{1,\mathrm{RMS,VZN}} = 7.60 \,/\, \ddot{x}_{1,\mathrm{RMS,standard}} = 12.08\ \mathrm{m/s^2}$	 $\ddot{x}_{1,\mathrm{RMS,VZN}} = 6.36 \,/\, \ddot{x}_{1,\mathrm{RMS,standard}} = 18.53\ \mathrm{m/s^2}$
Forces in stop bumpers [kN]	 $\mathrm{RMS_{VZN}} = 0 \ / \ \mathrm{RMS_{standard}} = 3.73\ [\mathrm{kN}]$	 $\mathrm{RMS_{VZN}} = 0 \ / \ \mathrm{RMS_{standard}} = 6.37\ [\mathrm{kN}]$
Body vertical displacements [m]	 $\bar{x}_{1,\mathrm{VZN}} = 0.786 \ / \ \bar{x}_{1,\mathrm{standard}} = 0.756\ [\mathrm{m}]$ $\sigma_{x_1,\mathrm{VZN}} = 0.001 \ / \ \sigma_{x_1,\mathrm{standard}} = 0.020\ [\mathrm{m}]$	 $\bar{x}_{1,\mathrm{VZN}} = 0.790 \ / \ \bar{x}_{1,\mathrm{standard}} = 0.803\ [\mathrm{m}]$ $\sigma_{x_1,\mathrm{VZN}} = 0.0016 \ / \ \sigma_{x_1,\mathrm{standard}} = 0.04\ [\mathrm{m}]$

Fig. 12. Car body behaviours for road profile with amplitude 0.03m at frequency 12Hz

6. Conclusions

The VZN shock absorbers confer better pitch, roll, vertical bounce stability, increasing active safety, comfort, and body and axles protection relative to the standard one.

References

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