UDK 531.395:519.6:629.331:625.746.53

NUMERIČKA SIMULACIJA PROLASKA VOZILA PREKO PREPREKA NA CESTI
NUMERICAL SIMULATION OF VEHICLE PASSAGE OVER OBSTACLES ON THE ROAD

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Sažetak: *U radu su prikazani rezultati numeričke simulacije prolaska različitih klasa vozila preko cestovnih prepreka, provedene u SIMULINKU. Od prepreka modelirane su vibracijske trake i umjetne izbočine, tzv. ležeći policajci. Kod modeliranja pasivnog ovjesa korišteni su četvrtinski i puni model vozila. U slučaju poluaktivnog modela ovjesa korišten je Skyhook kontroler.*

Ključne riječi: - dinamika vozila
- cestovne prepreke
- numerička simulacija

Summary: *In the paper the results of the numerical simulation of the passage of different classes of vehicle over obstacles on the road, carried out in SIMULINK, are shown. Road obstacles in the form of vibrating strips and bumps are chosen. For passive suspension modeling, a quarter-sized as well as full-sized vehicle model is used. In the case of semi-active suspension modeling, the Skyhook controller is used.*

Key words: - vehicle dynamics
- road obstacles
- numerical simulation

1. UVOD

Odgovarajući na pitanje: *Koja je najvažnija osobina automobila?*, većina će vozača na prvo mjesto staviti sigurnost, a na sljedeće udobnost. Ako se zanemari dio udobnosti putnika povezan s unutarnjim dizajnom vozila, konstruktorima automobila preostaje za rješavanje teži dio problema vezan uz ovjes. Zbog širokog spektra različitih uzbuda nemoguće je jednim karakteristikama ovjesa zadovoljiti ukuse svih vozača [1]. Različitost namjene automobila, od malih gradskih automobila, preko lakih komercijalnih vozila pa do sportskih automobila razlog je velikom broju različitih pristupa projektiranju ovjesa.

S ciljem omogućavanja vozaču da sam tijekom vožnje odabire konfiguraciju svojega ovjesa, automobilska industrija radi na razvoju različitih tipova poluaktivnog i aktivnog ovjesa [2],[3],[4]. Vrhunski ovjes za sada je rezerviran za skupe, ekskluzivne automobile. Razlog je tome što klasičan pasivni ovjes sudjeluje u cijeni izrade automobila s manje od 1%, dok udio poluaktivnih i aktivnih ovjesa raste i do 20%.

Odgovarajući na drugo pitanje: *Što vas najviše čini nervoznim na prometnicama?* većina će vozača visoko

1. INTRODUCTION

In answer to the question: "*Which is the most important behavior of the car?*" drivers will mostly answer by placing safety in the first place and comfort in the second place. If the comfort aspect surrounding the interior design of the vehicle is neglected, then constructors have to solve the most difficult part of the problem connected with suspension. Due to the wide range of different types of appeal, it is not possible to satisfy the dissimilar tastes of all drivers with the characteristics of one suspension system [1]. The variety of vehicle categories, from small city cars and light commercial vehicles to racing cars is the reason for the large number of varying approaches to suspension design.

With the aim of enabling the driver, while driving, to choose the suspension configuration, the automobile industry is developing different types of semi-active and active suspension systems [2],[3],[4]. The best suspensions are nowadays reserved for the expensive, exclusive cars. The reason for this is that the classic passive suspension represents less than 1 % of car production costs, while semi-active and active suspensions represent about 20% of car production costs.

rangirati različite umjetno stvorene prepreke kojima službe zadužene za sigurnost na cestama pokušavaju rješiti problem prebrze vožnje. Pri tome se donose razni propisi [5] koji su temeljeni na iskustvenim spoznajama a koje su često puta daleko od rezultata koje pokazuju proračuni. Rezultat toga je da neadekvatno dimenzionirane i postavljene prepreke na prometnicama mogu izazvati i negativne posljedice za ovjes automobila a kroz duže vrijeme eventualno i za zdravlje vozača vozila. U ovom su radu iznijeti rezultati numeričke simulacije [6] prolaska vozila preko cestovnih prepreka pasivnog i poluaktivnog modela ovjesa dobiveni u [7].

2. DEFINIRANJE CESTOVNIH PREPREKA

Dimenzije standardnih cestovnih prepreka za smanjenje brzine vožnje definirane su u [5]. Prema tom pravilniku prepreke se dijele na vibracijske trake i umjetne izbočine.
Vibracijske trake su prepreke koje pri prijelazu vozila proizvode veće vibracijske i zvučne efekte te time upozoravaju vozača da smanji brzinu. Postavljaju se preko cijele širine kolnika na međusobnom razmaku od 8 do 22 metra ovisno o ograničenju brzine vožnje (od 30 do 80 km/h). Njihova širina u pravilu je od 20 do 40 cm a visina 18 do 25 mm. Umjetne izbočine definirane su kao građevinski elementi čije su dimenzije također definirane u ovisnosti o ograničenju brzine (npr. za ograničenje brzinu vožnje na 50 km/h širina umjetne izbočine ne smije biti manja od 60 cm a visina ne smije prelaziti 3 cm).
Za modeliranje vibracijske trake korišten je u Simulinku [6] blok *signal generator* koji proizvodi impulsnu uzbudu amplitude koja odgovara visini trake te trajanja impulsa jednakog vremenu potrebnom da automobil prijeđe preko trake. Umjetna je izbočina u istom matematičkom programu modelirana u sklopu bloka *from workspace*.

3. MODELIRANJE PASIVNOG OVJESA VOZILA

Numerička simulacija prolaska vozila preko cestovnih prepreka izvršena je na dvama fizikalnim modelima i to na četvrtinskom i punom modelu.

3.1. Model s 2 stupnja slobode, «četvrtinski model»

Najjednostavniji model pasivnog sustava ovjesa je tzv. četvrtinski model. Sastoji se od dviju masa, mase kotača i ¼ mase vozila, krutosti gume kotača, krutosti opruge, prigušenja amortizera i pobude uzrokovane konfiguracijom ceste po kojoj se vozilo kreće.
Sustav je shematski prikazan na slici 1, dok je na slici 2 prikazana shema modela u programu Simulink.

In answer to the second question, with regard to anxiety on the roads, the majority of drivers will highly rank different artificially made obstacles by means of which the roads safety services are trying to solve the problem of speeding. Different regulations, based on empirical evidence, which are often far replaced from the results of the calculations, are prescribed [5]. The result of this can be seen in inadequate dimensioning and setting of road obstacles that can cause negative consequences on car suspension, and over a longer period, eventually on the drivers' health. In this paper the results of numerical simulation [6] for vehicle passage (of both vehicles of the active and semi-active suspension model types) over the road obstacles obtained in [7], are carried out.

2. ROAD OBSTACLES DEFINITION

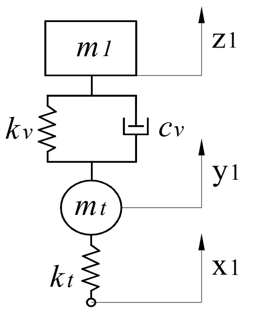
Dimensions of standard road obstacles for reduction of driving speed are defined in [5]. Due to these guidelines, obstacles are separated into two classes, vibrating strips and artificial bumps.
Vibrating strips are obstacles which generate higher vibrations and sound effects in order to warn drivers to decrease driving speed. They are set over the whole width of the road at distances of 8 to 22 meters, depending on the limitation of the driving speed (from 30 to 80 km/h). The width of vibrating strips is generally 20 to 40 cm with a height of 18 to 25 mm. Artificial bumps are defined as constructive elements whose dimensions are also defined with respect to speed limitation (for example for a driving speed limitation of 50 km/h, artificial bump width cannot be shorter than 60 cm with a height of no more than 3 cm).
In the case of vibrating strip modeling, the block *signal generator* in Simulink [6] is used. This block generates impulse excitation corresponding to the strips height and with an impulse duration equal to the time necessary for the car to pass over the stripe. An artificial bump is, in the same mathematical program, modeled in accordance to the block *from workspace*.

3. VEHICLE PASSIVE SUSPENSION MODELLING

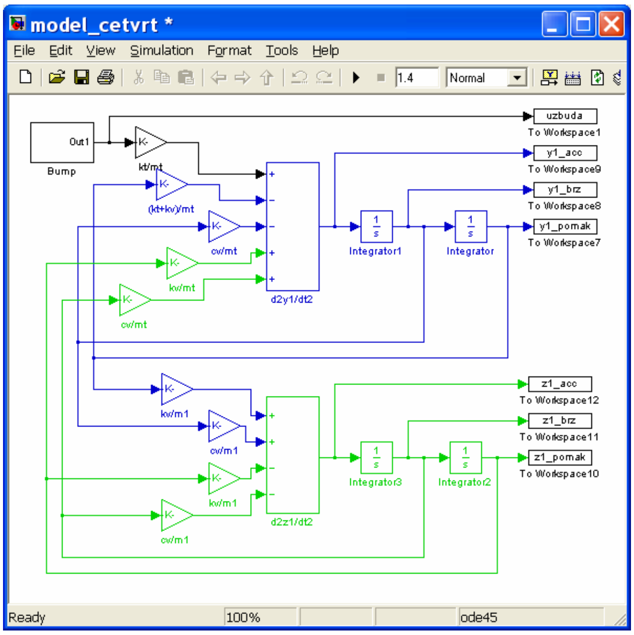
Numerical simulation of vehicle passage over obstacles on the road was made on two models, the quarter model and the full model.

3.1. Model with 2 d.o.f., «quarter model»

The simplest model of the system of passive suspension is the quarter model. It consists of two masses (the wheel mass and ¼ of the vehicle mass), stiffness of the tire, damping of the damper and excitation caused by the road configuration on which the vehicle is driving.
The scheme of the system is shown in Figure 1. and the model scheme in Simulink is shown in the Figure 2.



Slika 1. Model s dva stupnja slobode gibanja, četvrtinski model
Figure 1. Model with two degrees of freedom of movement – quarter model



Slika 2. Shema modela u Simulinku
Figure 2. Model scheme in the Simulink

Model opisuju jednadžbe gibanja sustava

The model is described by the following equations of motion

$$
\begin{aligned}
&m_1\,\ddot{z}_1 + c_v(\dot{z}_1 - \dot{y}_1) + k_v(z_1 - y_1) = 0 \\
&m_t\,\ddot{y}_1 + c_v(\dot{y}_1 - \dot{z}_1) + k_v(y_1 - z_1) + k_t(y_1 - x_1) = 0
\end{aligned}
\tag{1}
$$

za potrebe izravne integracije jednadžbe su svedene na sljedeći oblik:

for the purpose of direct integration, the equations are transformed to the following shape:

$$
\begin{aligned}
&\ddot{z}_1 = y_1\frac{k_t}{m_1} + \dot{y}_1\frac{c_v}{m_1} - z_1\frac{k_v}{m_1} - \dot{z}_1\frac{c_v}{m_1} \\
&\ddot{y}_1 = x_1\frac{k_t}{m_t} - y_1\frac{k_t + k_v}{m_t} - \dot{y}_1\frac{c_v}{m_t} + z1\frac{k_v}{m_t} + \dot{z}_1\frac{c_v}{m_t}
\end{aligned}
\tag{2}
$$

3.2. Model sa 7 stupnjeva slobode, «puni model»

Osim prije opisanog modela s 2 stupnja slobode gibanja uobičajeno se koriste i dva modela s 4 stupnja slobode gibanja (tzv. ½ modeli) i to *pitch* (naginjanje vozila oko poprečne osi) i *roll* (naginjanje vozila oko uzdužne osi) model. U ovom radu korišten je model ovjesa vozila sa 7 stupnjeva slobode gibanja, tzv. puni model, koji predstavlja svojevrsnu kombinaciju ranije spomenutih modela. Puni je model shematski prikazan na slici 3, a pripadne su jednadžbe gibanja dane u [7].

3.2. Model with 7 d.o.f., «full model»

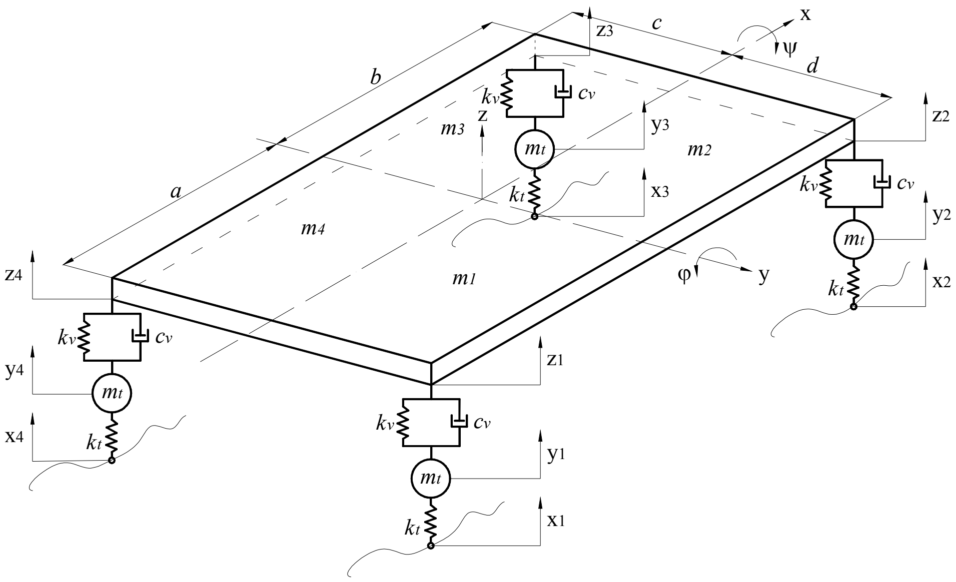
In addition to the earlier mentioned model with 2 d.o.f., there are two models with 4 d.o.f. in frequent usage (the so-called half models); the *pitch* model (inclination about the transversal axis) and the *roll* model (inclination about the longitudinal axis). In this paper the model with 7 d.o.f., the so-called full model, is used. This model represents a special combination of the aforementioned models. The full model is schematically described in the Figure 3, with the associated equations of motion given in [7].

4. REZULTATI NUMERIČKIH SIMULACIJA

U ovom radu provedena je analiza vezana uz usporedbu ovjesa različitih tipova automobila i uz simulaciju poluaktivnog ovjesa.

4. RESULTS OF NUMERICAL SIMULATIONS

In this paper, an analysis connected with the comparison of the suspension of different types of cars and connected with the simulation of semi-active suspension, is carried out.



Slika 3. Model sa sedam stupnjeva slobode gibanja, puni model
Figure 3. Model with seven degrees of freedom of movement, full model

4.1. Usporedba različitih tipova automobila

Na punom modelu automobila (slika 3) ispitan je utjecaj veličine automobila na udobnost vožnje. Korištene su tri različite veličine automobila koje predstavljaju automobile iz različitih klasa i to mali gradski automobil, kompaktna klasa i viša srednja klasa. Za uzbudu je uzeta vibracijska traka namijenjena za ograničenje brzine od 50 km/h, koju vozilo prelazi brzinama od 30, 50, 70 i 90 km/h [5].

4.1. Comparison of different car types

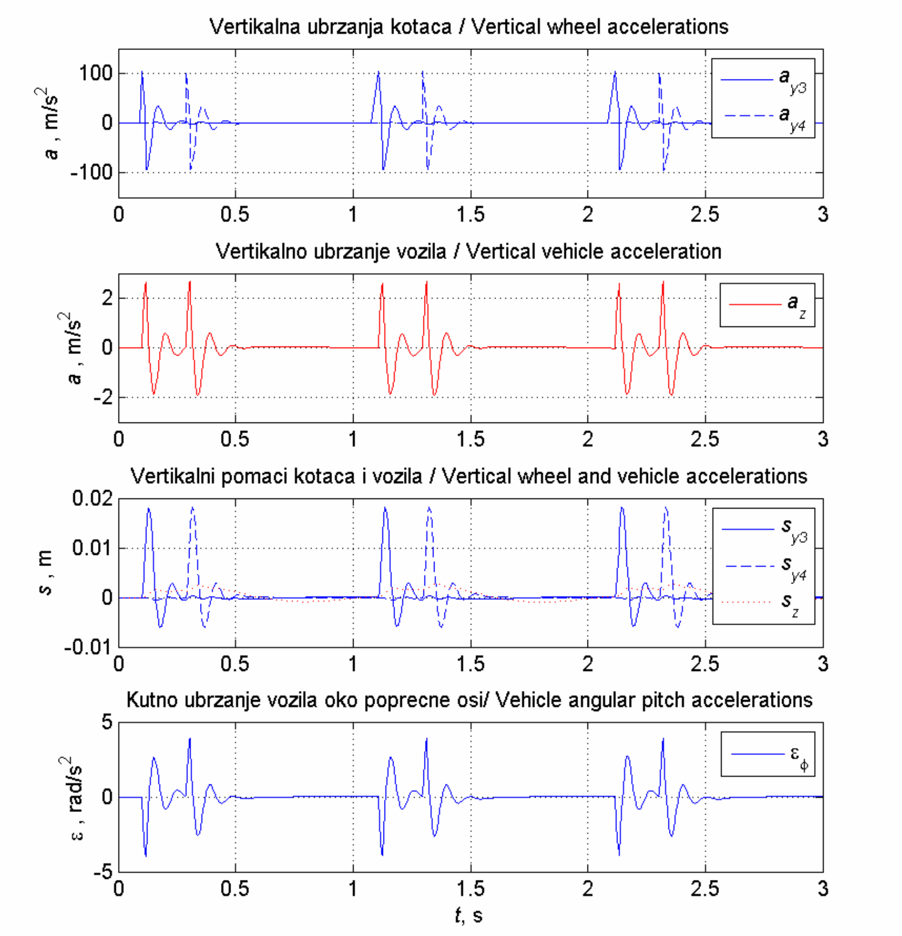
In the full model of the car, Figure 3, the influence of car size on driving comfort is investigated. Three different car sizes, representing cars from different classes (small city cars, compact class and higher midsize class) are used. As the excitation example, a vibrating stripe intended for a speed limitation of 50 km/h, which the car passes over at speeds of 30, 50, 70 and 90 km/h has been chosen [5].

Tablica 3. Karakteristike različitih tipova automobila
Table 3. Characteristics of different types of the cars

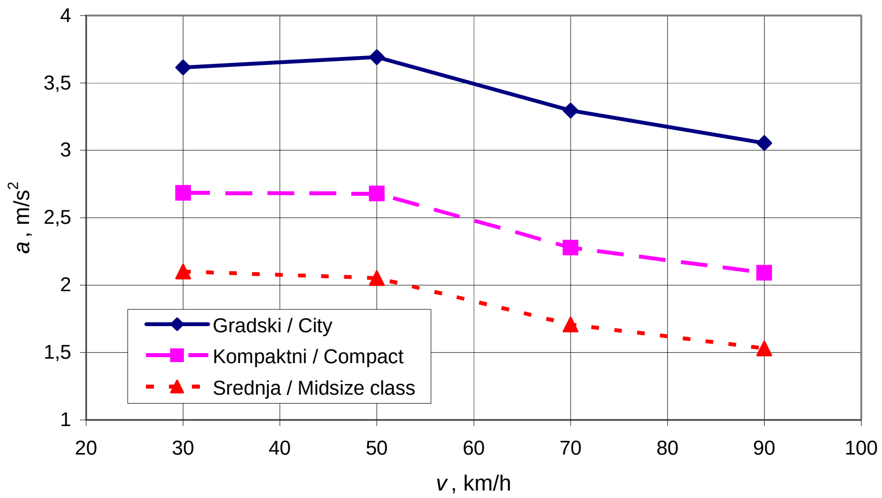
Osobine/ Characteristics	k_v	c_v	m_t	k_t	**a,b**	**c,d**	**m**	J_x	J_y
Gradski automobil/ City car	16000	1400	30	150000	1.2	0.75	920	400	700
Kompaktna klasa/ Compact class	16000	1400	36	150000	1.3	0.8	1200	560	1050
Viša srednja klasa/ Higher midsize class	16000	1400	40	150000	1.4	0.9	1500	780	1260

Rezultati simulacija prikazani su na slikama 4 do 8. Iz dijagrama je vidljivo da je veći automobil s istim postavkama ovjesa udobniji od manjeg. Manje je vertikalno ubrzanje kotača i težišta, manji su pomaci, a i nagib automobila. Takvi su rezultati očekivani jer je logično da veći, odnosno teži automobil ima veću inerciju te za istu uzbudu daje manji odziv sustava.

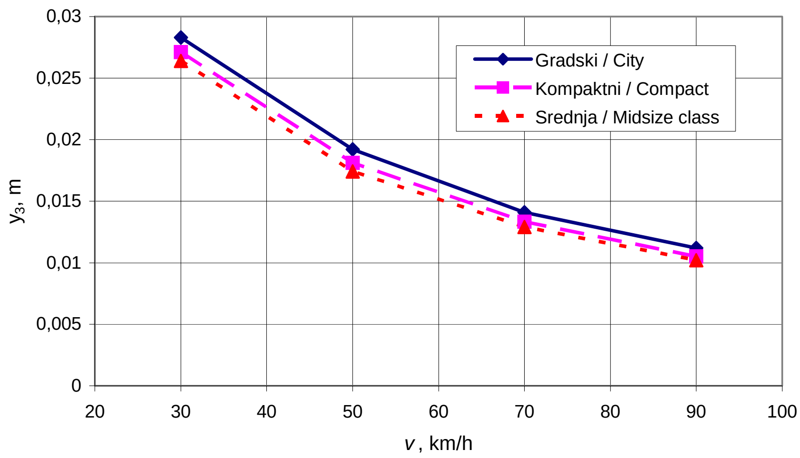
Results of simulation are shown in Figures 4 to 8. From the diagrams it is obvious that cars with larger dimensions, and with the same suspension characteristics, are more comfortable than smaller cars. The vertical acceleration of the wheel and the vehicle is smaller as well as the displacements and the pitch angles of the car. Such results are expected because it is logical that larger and respectively heavier cars have a bigger inertia and for the same excitation give a smaller response of the system.



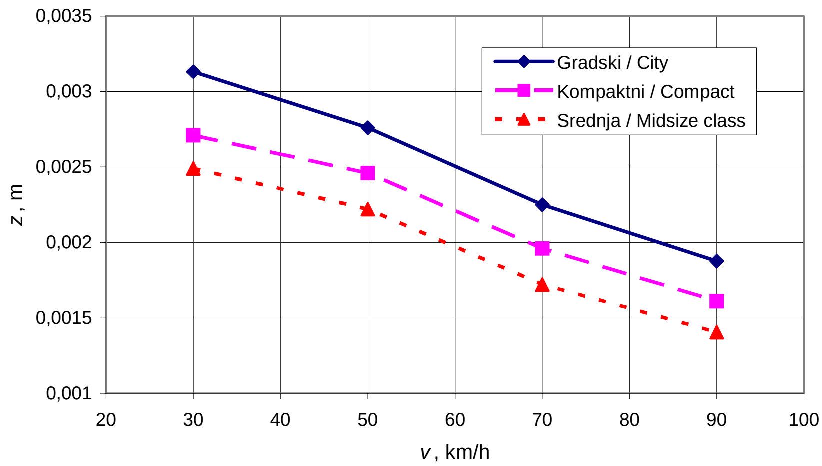
Slika 4. Dijagrami kinematičkih veličina automobila kompaktne klase pri prelasku preko vibracijske trake brzinom od 50 km/h
Figure 4. Diagrams of kinematic quantities of a compact class car during passage over vibrating stripe at the speed of 50 km/h.



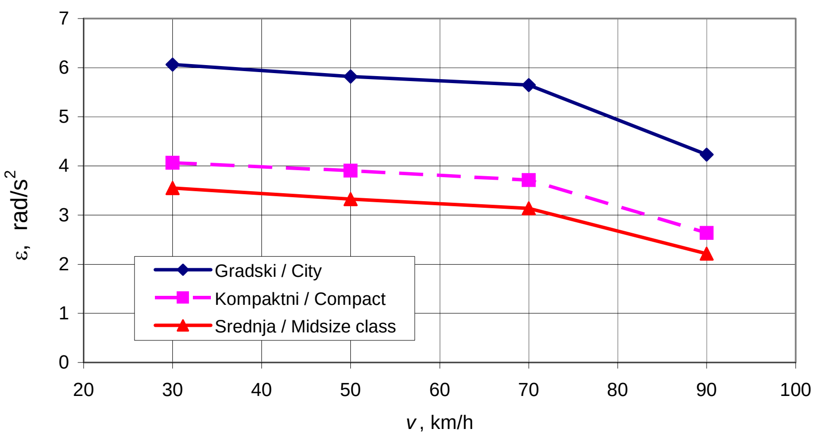
Slika 5. Vertikalno ubrzanje karoserije različitih klasa automobila pri prelasku preko vibrirajućih traka
Figure 5. Vertical acceleration of car body of different car classes during passage over the vibrating strips



Slika 6. Vertikalni pomak kotača različitih klasa automobila pri prelasku preko vibrirajućih traka
Figure 6. Vertical displacements of wheels of different car classes during passage over the vibrating strips



Slika 7. Vertikalni pomak karoserije različitih klasa automobila pri prelasku preko vibrirajućih traka
Figure 7. Vertical displacements of the car body of different car classes during passage over the vibrating strips



Slika 8. Kutno ubrzanje oko poprečne osi različitih klasa automobila pri prelasku preko vibrirajućih traka
Figure 8. Angular pitch acceleration of different car classes during passage over the vibrating strips

Veća udaljenost kotača od težišta umanjuje naginjanje jer se povećava moment inercije naginjanja automobila oko osi. Zbog simetrične uzbude (lijevi i desni kotač istodobno nailaze na prepreke) na slici 4, prikazani su samo rezultati odziva desnih kotača. Zbog pretpostavljene simetrije automobila slika 4 prikazuje da je odziv automobila prilikom prelaska prednjih odnosno zadnjih kotača gotovo jednak. Rezultati dani na slikama 6 do 8 prikazuju trend opadanja odziva modela s povećanjem brzine prelaska preko prepreka.

4.2. Rezultati simulacije poluaktivnog ovjesa

U svrhu provođenja simulacije poluaktivnog ovjesa ugrađen je u proračun unutar Simulinka tzv. Skyhook kontroler [2] koji korigira intenzitet prigušenja prigušivača u ovisnosti o vrijednosti i smjeru brzine ovješene i neovješene mase te brzine uzbude gibanjem podloge. Pri tome Skyhook kontroler mijenja silu aktuatora između ovješene i neovješene mase, koja je jednaka produktu prigušenja i brzine udaljavanja ili približavanja masa. Prigušenje aktuatora varira između minimalnog prigušenja *Csoft*, maksimalnog prigušenja *Cfirm*, ovisnog o karakteristikama aktuatora i ekvivalentnog prigušenja *Csh,* pasivnog modela koji zamjenjuje, čija se vrijednost odabire između minimalnog i maksimalnog prigušenja. U praksi ulogu aktuatora može imati hidraulički klip, kojem se prigušenje varira pomoću ventila ili poluaktivni amortizer sa zaobilaznim ventilom koji može biti otvoren ili zatvoren. Svakako je najbolji izbor tzv. magnetoreološki amortizer kojem se prigušenje može mijenjati promjenom magnetnog polja zbog kojeg se mijenja viskoznost fluida u amortizeru [2].
Rezultati primjene Skyhook kontrolera kao dijela poluaktivnog ovjesa, u simulaciji vožnje preko umjetne izbočine, prikazani su za slučaj četvrtinskog modela vozila na slika 9. Prikazani dijagrami ukazuju na poboljšanja u ubrzanjima i pomacima kotača vozila što je svakako manje štetno za samo vozilo. S druge pak strane ubrzanja i pomaci karoserije automobila, gotovo su jednaki za oba tipa ovjesa automobila.

5. ZAKLJUČAK

Programski paket Matlab/Simulink pokazao se uspješnim alatom za numeričko modeliranje prolaska vozila preko cestovnih prepreka. Dobiveni rezultati na punom modelu pri prelasku preko vibrirajućih traka pokazali su trendove smanjenja kinematičkih veličina vertikalnog odziva vozila s povećanjem brzine vozila. Poluaktivna regulacija amortizera pomoću Skyhook kontrolera pokazala je također svoje prednosti u smanjenju vibracijskog opterećenja kotača i sustava ovjesa. Daljnje analize vezane uz efekte nesimetričnosti karakteristika vozila, nesimetrične uzbude te bolje matematičke definicije sustava ovjesa bit će provedene u daljnjem radu.

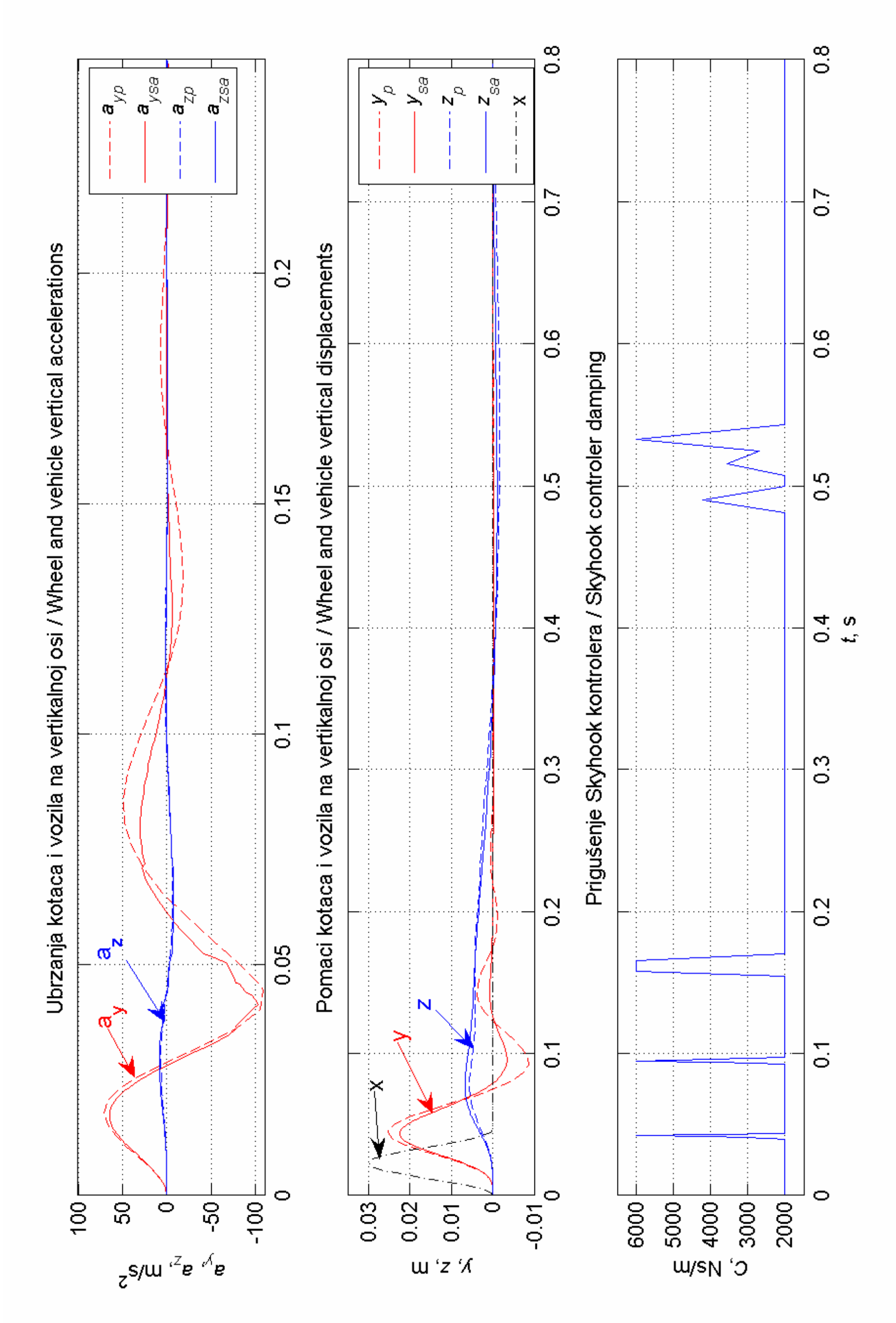
A greater distance between the wheels and the center of gravity will reduce pitch because the moment-of-inertia of the car about the pitch axis is increased. Due to symmetrical excitation (left and right wheel simultaneously reaches the obstacles), in Figure 4, only the results of the right wheel response are shown. Due to the presumed symmetry of the car, Figure 4 shows that the car response, during the passage of the front and then the back wheels over the obstacle, is almost equal. Results given in Figures 6 to 8 show the trend of decreasing of the model response with an increasing of velocity of passage over the obstacles.

4.2. Results of simulations for semi-active suspension

For the purpose of carrying out the simulation of semi-active suspension, the so-called Skyhook controller [2] is implemented inside the Simulink. This controller corrects the magnitude of damping of the damper depending on the value and direction of the velocity of sprung and unsprung mass as well as on the velocity of excitation by the basement motion. In that case, the Skyhook controller changes the actuator force between sprung and unsprung mass which is equal to the product of damping and the velocity of the moving off and approaching of the masses. Damping of the actuator varies between minimal damping *Csoft*, maximal damping *Cfirm*, which depends on the actuator characteristics, and equivalent damping *Csh,* whose value is chosen between minimal and maximal damping. In practice, the role of the actuator must be given to a hydraulic piston, in which damping is changed by valve, and a semi-active damper. The best choice is a so-called magnetorheological damper which can change the viscosity of the fluid in the damper by changing the magnetic field [2].
The results of the usage of a Skyhook controller as a part of the semi-active suspension, in the simulation of driving over an artificial bump, for the case of the quarter vehicle model, are shown in Figure 9. Those diagrams point to improvements in the accelerations and displacements of the wheel which is surely less injurious for the car. On the other hand, accelerations and displacements of the car body are almost equal for both types of car suspensions.

5. CONCLUSION

The program package Matlab/Simulink has proven to be a successful tool for the numerical modeling of vehicle passage over obstacles on the road. Presented results of a full car model passing over the vibrating strips have shown a decreasing trend for kinematic values of the vehicle vertical response with an increase in vehicle speed. Semi-active Skyhook control of the shock absorber has proven its advantages in decreasing the vibration load on the wheel and the suspension system. Further analyses regarding unsymmetrical vehicle properties as well as unsymmetrical excitation and also a better mathematical definition of the suspension system will be carried out in future research.



Slika 9. Usporedba rezultata pasivne (indeks p) i poluaktivne (indeks sa) regulacije (Skyhook kontroler) ovjesa pri brzini vožnje v=46,8 km/h na cestovnoj izbočini projektiranoj za ograničenje brzine od 50 km/h

Figure 9. Comparison of results of passive (index p) and semi-active (index sa) regulation of suspension (Skyhook controller) for the driving speed of v=46,8 km/h on the road bump projected for the speed limitation of 50 km/h.

6. POPIS OZNAKA

6. LIST OF SIMBOLS

masa automobila	m - kg	vehicle mass
masa četvrine automobila	m_1 - kg	quarter of the vehicle mass
masa kotača	m_t - kg	mass of the wheel
uzbuda podlogom i-tog ovjesa zbog prepreke	x_i - m	road excitation of the i-th suspension due obstacles
vertikalni pomak kotača i karoserije i-tog ovjesa	y_i, z_i- m	wheel and car body vertical displac. of the i-th suspension
vertikal. brzina kotača i karos. i-tog ovjesa	$\dot{y}_i$, $\dot{z}_i$ - m/s	wheel and car body vertical speed of the i-th suspension
vertikal. ubrzanje kotača i karos. i-tog ovjesa	$\ddot{y}_i, \ddot{z}_i$ - m/s^2	wheel and car body vertical acceler. of the i-th suspension
krutost ovjesa i kotača	k_v, k_t - N/m	suspension and wheel stiffness
prigušenje ovjesa	c_v - Ns/m	suspension damping
brzina vožnje	v - m/s	driving speed
dimenzije vozila	a, b, c, d - m	vehicle dimensions
momenti tromosti vozila	J_x, J_y - kgm^2	vehicle mass moments of inertia
kutno ubrzanje	ε - rad/s^2	angular acceleration
pomak kotača pasivnog tipa ovjesa	y_p- m	displacement of wheel of passive type of suspension
pomak kotača poluaktivnog tipa ovjesa	y_{sa}- m	displacement of wheel of semi-active type of suspension

LITERATURA
REFERENCES

[1] Gillespie, T.: *Fundamentals of Vehicle Dynamics,* Society of Automotive Engineers, Inc., 1992.

[2] Reichert, B.A.: *Application of Magnetorheological Dampers for Vehicle Seat Suspensions*, Master Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia,1997.

[3] D'Amato F.J., Viassolo, D.E.: *Fuzzy control for active suspensions*, Mechatronics, 10 (2000.), pp. 897. - 920

[4] Yoshimura T. et al.: *Active suspension of passenger cars using linear and fuzzy-logic control*, Control engineering practice, 7 (1999.), pp. 41. - 47

[5] Narodne novine, NN34/2003., službeni glasnik Republike Hrvatske

[6] …, *Simulink Reference v6. pdf*, Manual, The MathWorks, Inc., 2002-2004., www.mathworks.com

[7] Radrelja, H.: *Modeliranje i regulacija sustava ovjesa osobnog automobila*, Diplomski rad, TFR, Rijeka, 2007.

Prethodno priopćenje

Preliminary note

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