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Simulacija bočnega nihanja potniških vagonov

Simulating the Lateral Vibrations of Passenger Wagons

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V tej raziskavi sva se posvetila dinamiki železniških potniških vagonov, metodam za reševanje problemov s tega področja in dinamičnim pojavom v vagonu. S programskim paketom ADAMS/Rail sva ustvarila matematični model, ki omogoča izračun prečno vsiljenega nihanja vagona. V postopku izdelave tega modela sva ocenila geometrijske in mahanske značilnosti vagona. Poleg tega sva predstavila funkcije, ki opisujejo sinusoidne nepravilnosti železniške proge v ravnini, in sicer za primere, ko sinusoidna valovna dolžina znaša 10 m, 20 m, 30 m in 40 m in je valovna amplituda 0,0025 m, 0,0035 m, 0,0050 m in 0,0065 m. Z uporabo teh funkcij sva opisala vpliv vzbujanja na dinamični sistem.

(Ključne besede: vagoni potniški, dinamika, nihanja bočna, modeli matematični)

In this investigation we look at the dynamics of railway passenger wagons, the methods of providing solutions and the dynamic processes of a carriage. Using the program package ADAMS/Rail, a mathematical model is created to calculate the transversally forced oscillations of the carriage. During the creation of this model the geometrical and mechanical characteristics of the carriage are estimated. In addition, the functions describing the sinusoidal irregularities of the road in the plane are presented for cases when the sinusoidal wavelength is 10 m, 20 m, 30 m and 40 m, and the wave amplitude is 0.0025 m, 0.0035 m, 0.0050 m and 0.0065 m. With the help of these functions the excitation influence on the dynamic system is described.

(Keywords: railway passenger cars, dynamics, lateral vibrations, mathematical models)

0 UVOD

Zaradi izboljšav na lokomotivah, povečanih hitrosti in strožjih zahtevah prometne varnosti postajajo raziskave dinamike pojavov celotne vlakovne kompozicije ter analize medsebojnega delovanja sil koles in tirnic vse bolj pomembne. Mnogi znanstveniki na različnih koncih sveta so delovali, in v mnogih primerih še vedno delujejo, na področju raziskovanj vlakovnih kompozicij. Mednje spadajo Rao V. Dukkipati, S. Narayana Swamy ([1] in [2]), C. Andersson, P. Carlbom, J. Forstberg [3], M.F .Verigo, A.J. Kogan [4], V.F. Uskalov [5], W.O. Shiehlen [6], Veršinskij [7]. Veliko število držav, v katerih potekajo raziskave vlakovnih kompozicij, dokazuje, da problemi vezani na dinamiko vlakovne kompozicije ostajajo nerešeni in pomenijo izziv za posamezne države. Ti problemi so zelo pomembni tudi za Litvo, saj se je tu stanje

0 INTRODUCTION

With the improvements in traction devices, the increased speeds and the stricter traffic-safety requirements, research into the dynamic processes of rolling stock as well as analyses of the interaction forces between the wheel and the rail becomes more and more important. A lot of scientists from all around the world have worked, and in many cases continue to work, in the area of rolling stock. These include Rao V. Dukkipati, S. Narayana Swamy ([1] and [2]), C. Andersson, P. Carlbom, J. Forstberg [3], M.F. Verigo, A.J. Kogan [4], V.F. Uskalov [5], W.O. Shiehlen [6], Vershinsky [7]. The large number of countries where the dynamics of rolling stock is being investigated shows that the problems related to rollingstock dynamics remain unsolved and represent a challenge on the national level. These problems are also very important in Lithuania because the condition of the trains and the railways has vlakov in železnic poslabšalo in je zato potnikom težko ponuditi udobno vožnjo.

Prispevek obravnava problem dinamike vodoravnih dinamičnih procesov, ki se pojavlja ob gibanju vagona po progi z bočnimi nepravilnostmi.

Vodoravni dinamični pojavi močno vplivajo na stabilnost gibanja, tj. na zmožnost elastične zveze vlakovne kompozicije, da ohrani prečno nihanje v mejah, potrebnih za zagotavljanje udobja in varnosti potnikov. Eden glavnih kazalnikov, ki določa enakomernost gibanja, upošteva amplitudo in pospešek nihanja. Prispevek predstavlja odvisnosti teh kazalnikov od hitrosti gibanja in nepravilnosti tira.

worsened, making it difficult to provide passengers with acceptable levels of comfort.

This paper discusses one of the problems of the dynamics of wagons' horizontal dynamic processes that occurs while a wagon moves along lateral road irregularities.

Horizontal dynamic processes have a great impact on the stability of movement, i.e., on the capability of the elastic lug of the rolling stock to maintain transversal oscillations within the limits of the requirements for providing comfort and safety for passengers. One of the main indicators that determines the evenness of movement involves the amplitudes and accelerations of oscillations. This paper discusses the dependences of these indicators on movement speed and road irregularities.

1 NEPRAVILNOSTI ŽELEZNIŠKEGA TIRA

Najpogostejša je skoraj sinusoidna nagubanost tirnic, obravnavana v virih [1] do [3] in prikazana na sliki 1,

1 RAILWAY-TRACK IRREGULARITIES

Nearly sinusoidal rail corrugations, like those described in [1] to [3], (Fig. 1) are the most commonly encountered

$$\eta(t) = a \cdot \sin\left(\frac{2\pi}{l}x\right) = a \cdot \sin\left(\frac{2\pi}{l}vt\right) \quad (1),$$

kjer je l valovna dolžina sinusoidnih nepravilnosti, a amplituda sinusoidnih nepravilnosti, v hitrost in t čas.

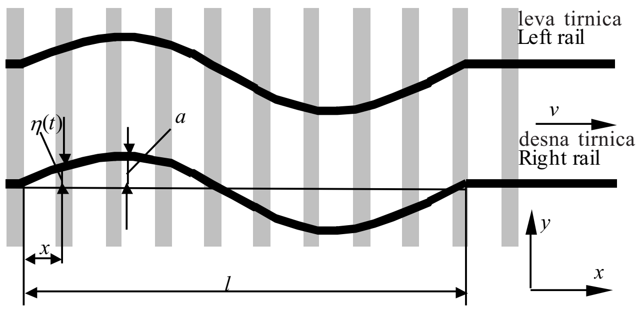
Analiza dolgoročnih opazovanj železniške proge [7] je pokazala, da je imelo 55 do 65 odstotkov odsekov železnice, narejene iz železobetonskih tirov, nepravilnosti v vodoravni smeri in v obliki pravilne sinusoide. Poleg tega je imelo 20 do 30 odstotkov teh tirov še nepravilnosti v obliki nepravilne sinusoide, ki pa jo v dobrem približku lahko vpišemo s pravilno sinusoido.

Glavne povprečne vrednosti vodoravnih nepravilnosti so podane v preglednici 1 [5].

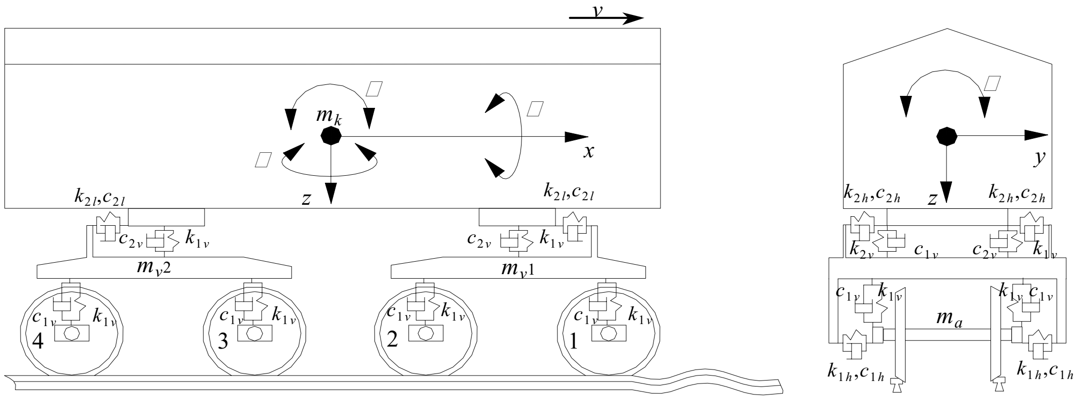
where l is the wavelength of the sinusoidal irregularities, a is the amplitude of the sinusoidal irregularities, v is the velocity and t is the time.

In an analysis of the long-term conditions of a railway [7], 55 to 65 % of the pieces of the railway track with ferro-concrete rails were found to have irregularities in the horizontal direction in the form of a correct sine wave. In addition, 20 to 30 % of these pieces were found to have irregularities in the form of an incorrect sine-wave form that would not be difficult to approximate to a correct sine wave.

The major average values of the horizontal irregularities are given in Table 1 [5].



Sl. 1. *Osnovna shema sinusoidnih nepravilnosti železniške proge*
Fig. 1. *Principal scheme of the sinusoidal irregularities of the railway*



Sl. 2. *Poenostavljeni, dinamični model potniškega vagona*
Fig. 2. *Simplified, dynamical model of a passenger wagon*

Preglednica 1. *Nepravilnosti približno sinusoidne oblike*
Table 1. *Characteristics of practically sinusoidal irregularities*

Oblika bočnih nepravilnosti Shape form of the lateral irregularities	***Parametri bočnih sinusoidnih nepravilnosti η(t) Parameters of lateral sinusoidal irregularities η(t)***	
	a [m]	*l [m]*
pravilna sinusoida correct sine wave	*0,001 do/to 0,003*	*10 do/to 25*
nepravilna sinusoida incorrect sine wave	*0,002 do/to 0,004*	*10 do/to 20*

2 OPIS MODELA POTNIŠKEGA VAGONA

Raziskave različnih vrst železniškega prevoza vključujejo:
- analize sil, ki se pojavljajo med kolesom in tirom;
- vpliv koles, podvozja in drugih delov konstrukcije na dinamiko vagona;
- analize gibanja vagona po nepravilnem tiru;
- analize občutljivosti železniškega vagona;
- določitev amplitudno-frekvenčnih značilnosti elementov vagona.

Raziskovalna simulacija, ki je bila del programa ADAMS/Rail, je potekala na potniškem vagonu s podvozjem tipa KVZ CNII ([8] in [9]).

Slika 2 prikazuje dinamični model preučevanega vagona.

Vagon je oblikovan kot toga karoserija, vezana na okvir z vzmetjo in dušilniki (k_2 in c_2), ki imajo linearne značilnosti. Okvir je prav tako oblikovan kot togo telo, povezano s dvojicama koles (k_1 in c_2) prek vzmetno-dušilne enote.

2 DESCRIPTION OF THE PASSENGER-WAGON MODEL

Research into various types of railway transport includes:
- analyses of the forces that appear between the wheel and the rail;
- the influence of the wheels, bogies and other parts of the construction on the dynamics of the carriage;
- analyses of the carriage's movement along an irregular track;
- analyses of the railway carriage's sensitivity;
- the determination of the amplitude/frequency characteristics for the elements of a carriage.

In this work a passenger wagon with the KVZ CNII-type bogies ([8] and [9]) was used in the simulation research as part of the ADAMS/Rail program.

The dynamical model of the research wagon is shown in Figure 2.

The wagon is modelled as a rigid body, which is connected via a spring and truck dampers (k_2 and c_2) that have linear characteristics. The bogie frame is also modelled as a rigid body, which is connected to the wheel sets (k_1 and c_2) by the

Preglednica 2. *Tehnični podatki potniškega vagona s podvozjem tipa KVZ CNII*
Table 2. *Technical data of the passenger wagon with the KVZ CNII-type bogies*

Parameter	***Vrednost / Value***
masa karoserije, kg *Mass of a wagon body, kg*	*43 400*
masa okvirja, kg *Mass of a bogie frame, kg*	*2 615*
masa podvozja, kg *Mass of a wagon bogie, kg*	*7 100*
masa kolesne dvojice, kg *Mass of a wheelset, kg*	*1 500*
masa ležajnika osi, kg *Mass of an axle box, kg*	*155*
premer koles, m *Diameter of the wheels, m*	*0,92*
nosilo medosne razdalje, mm *Tape circle distance, mm*	*1 520*
nosilo kolesne dvojice, m *Wheelset base, m*	*2,4*
razdalja med dvema podvozjema, m *Distance between two bogies, m*	*17*
primarna bočna togost vzmetenja, kN/m *Primary lateral suspension stiffness, kN/m*	*860*
sekundarna bočna togost vzmetenja, kN/m *Secondary lateral suspension stiffness, kN/m*	*385*
sekundarno bočno dušenje vzmetenja, kNs/m *Secondary lateral suspension damping, kNs/m*	*100*

Povezava je linearna. Izbrani parametri modelnega vagona in njegovo gibanje so predstavljeni v preglednici 2.

Da bi povzeli značilnosti modela, moramo vse linearne enačbe, ki določajo vsiljeno nihanje modela, ki ga povzročajo motnje, povezane z neenakomernostjo proge, izraziti z matrikami [7]:

spring–damper unit. The connection is a linear type. The parameters chosen for the modelled wagon and its movement are presented in Table 2.

In order to summarize the model, all the linear equations defining the forced oscillations of the model, and which are caused by disturbances due to the road roughness, should be expressed by matrices [7]:

$$[M]\{\ddot{y}\}+[C]\{\dot{y}\}+[K]\{y\}=[B]\{u\} \quad (2),$$

kjer so $\{y\}$ krajevni vektor, $\{u\}$ vektor motenj, $[M]$ matrika vztrajnosti, $[C]$ matrika dušenja, $[K]$ matrika togosti in $[B]$ matrika porazdelitve motenj.

Ko izberemo način izračuna, lahko dinamične enačbe nihanja opišemo z Lagrangevimi enačbami drugega reda, ali z D'Alembertovim načelom (če silam, ki delujejo na točke sistema, dodamo sile vztrajnosti, dobimo uravnotežen sistem sil) [4]. Diferencialne enačbe morajo upoštevati geometrijske, fizikalne in statične odvisnosti.

Na temelju geometrijskih razmerij lahko določimo odvisnosti sprememb (tj. deformacij)

where $\{y\}$ is a position vector, $\{u\}$ is a vector of disturbances, $[M]$ is inertial matrix, $[C]$ is a damping matrix, $[K]$ is a rigidity matrix, and $[B]$ is matrix representing the distribution of disturbances.

After selecting the calculation scheme, the dynamic equations of the oscillations can be described by Lagrange's type-II equations or by D'Alembert's principle (by adding the inertial forces to the forces acting on the system points, a balanced system of forces is obtained) [4]. The differential equations should take into account geometric, physical and static dependencies.

On the basis of the geometric relations we can determine the dependencies of the changes (i.e., the povezav komponentnih vozlišč konstrukcije v določenem koordinatnem sistemu. Ob upoštevanju fizikalnih zakonov, reakcije povezav, vztrajnostne sile analiziranih komponent in momente vztrajnostnih sil izrazimo kot deformacije ter zapišemo enačbe za izračun hitrosti in pospeškov vozlišč. Dobljene odvisnosti vstavimo v sistem diferencialnih enačb dinamičnega sistema. Ko rešimo sistem, dobimo razmerje med prožilnimi silami in spremembami komponent vagona.

deformations) of the connections of the structural component nodes in the specified coordinate system. By applying physical laws, the reactions of the connections, the inertial forces of the analysed components and the moments of the inertial forces are expressed as deformations, and the equations for calculating the speeds and accelerations of the nodes are compiled. The obtained dependencies are put into the system of differential equations of the dynamic system. After the system is solved, a relation between the actuation forces and the changes of the wagon's components is obtained.

3 METODA SIMULACIJE

Simulacijo časovnega poteka smo izvedli v pogojih sinusoidne bočne nepravilnosti leve in desne tračnice (sl. 1).

Ko se vlakovna kompozicija giblje po progi z bočnimi nepravilnostmi, je karoserija izpostavljena vodoravnemu nihanju z različnimi amplitudami in frekvencami, katerih vrednosti so odvisne od naslednjih dejavnikov [10]:

- hitrosti vagona;
- mehanskih lastnosti komponent jeklene konstrukcije;
- vodoravnih odstopanj tračnic;
- porazdeljenosti nepravilnosti na obeh straneh.

Za potrebe preučevanja dinamičnih karakteristik vagona smo analizirali bočne vibracije vagona pri različnih hitrostih, od 10 km/h do 160 km/h, v območju sinusoidnih nepravilnosti in v ravnini različnih parametrov (valovna dolžina *l* je: 10 m, 20 m, 30 m in 40 m; valovna amplituda *a* je: 0,0025 m, 0,0035 m, 0,005 m in 0,0065 m).

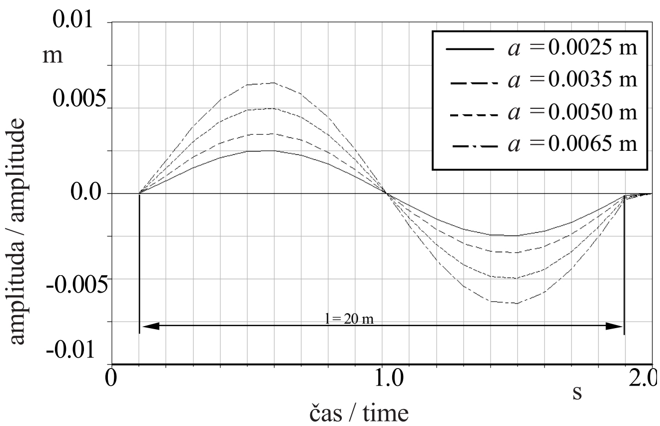
3 THE METHOD OF SIMULATION

Time-history simulations were performed under the conditions of sinusoidal lateral irregularity on both the left- and right-hand rails (Fig. 1).

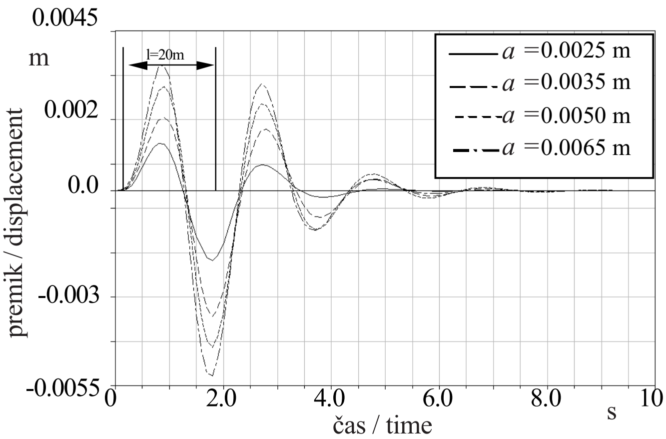
When the rolling stock moves along the lateral road irregularities, the body acquires horizontal oscillations with different amplitudes and frequencies, the values of which depend on the following factors [10]:

- the speed of the wagon;
- the mechanical properties of the structural components;
- the horizontal deviations of the rails;
- the distribution of the irregularities on both rails.

For the study of the dynamic characteristics of the truck the body's lateral vibrations were analyzed at different speeds, from 10 km/h to 160 km/h, on the sinusoidal irregularities in the plane of different parameters (the wavelength *l* is 10 m, 20 m, 30 m and 40 m; the wave amplitude *a* is 0.0025 m, 0.0035 m, 0.005 m and 0.0065 m).



Sl. 3. *Funkcije, ki določajo železniške tire pri hitrosti 40 km/h*
Fig. 3. *Railway rails-defining functions when the speed is 40 km/h*



Sl. 4. *Spremembe premikov zaradi bočnih vibracij karoserije potniškega vagona, ki se giblje s hitrostjo 40 km/h na padajočem delu sinusoidne oblike, l =20 m*
Fig. 4. *Changes of lateral vibration displacements of the body of a passenger wagon that moves with a speed of 40 km/h on the slump l =20 m, of sinusoid shape*

Predpostavljali smo, da je proga popolnoma toga; v najinih izračunih nismo upoštevali deformacij tirov.

Slika 3 prikazuje funkcije sinusoidnih nepravilnosti (valovna dolžina l =20 m; valovna amplituda a je: 0,0025 m, 0,0035 m, 0,005 m in 0,0065 m), katerih časovna odvisnost ustreza proženju pri hitrosti vagona 40 km/h.

Po opisu prožilnega učinka na dinamični model, izvedenega s funkcijami, ki določajo nepravilnosti proge, je bilo mogoče analizirati vrednosti amplitude in pospeška nihanj vozlišča karoserije. Izbrana točka vozlišča je na sredini okvirja nad prvim podvozjem. Višina vozlišča je v višini človeških ramen.

Ko proga sproži gibanje preučevanega dinamičnega modela in s tem določi sinusoidno funkcijo, z upoštevanjem različnih hitrosti vagona, lahko dobimo amplitudne vrednosti sprememb in pospeške preučevane karoserije potniškega vagona.

Za določitev odvisnosti največjih amplitudnih vrednosti sprememb in pospeškov na izbranih točkah karoserije od hitrosti vagona, izraženih s sinusoidno funkcijo, ki jo določa proga, je bilo treba izdelati diagrame, ki predstavljajo te odvisnosti (gl. sliki 5 in 6).

Če analiziramo sosledje sprememb vrednosti prečnega nihanja karoserije, prikazanega na sliki 5, razumemo, da je karoserija, ki se giblje po vzdolžnih nepravilnostih v obliki sinusoide različnih amplitudnih vrednosti in valovnih dolžin, izpostavljena največjemu vzdolžnemu nihanju, ko je

We assume that the track is absolutely rigid and deformations of the rail were not taken into account in our calculations.

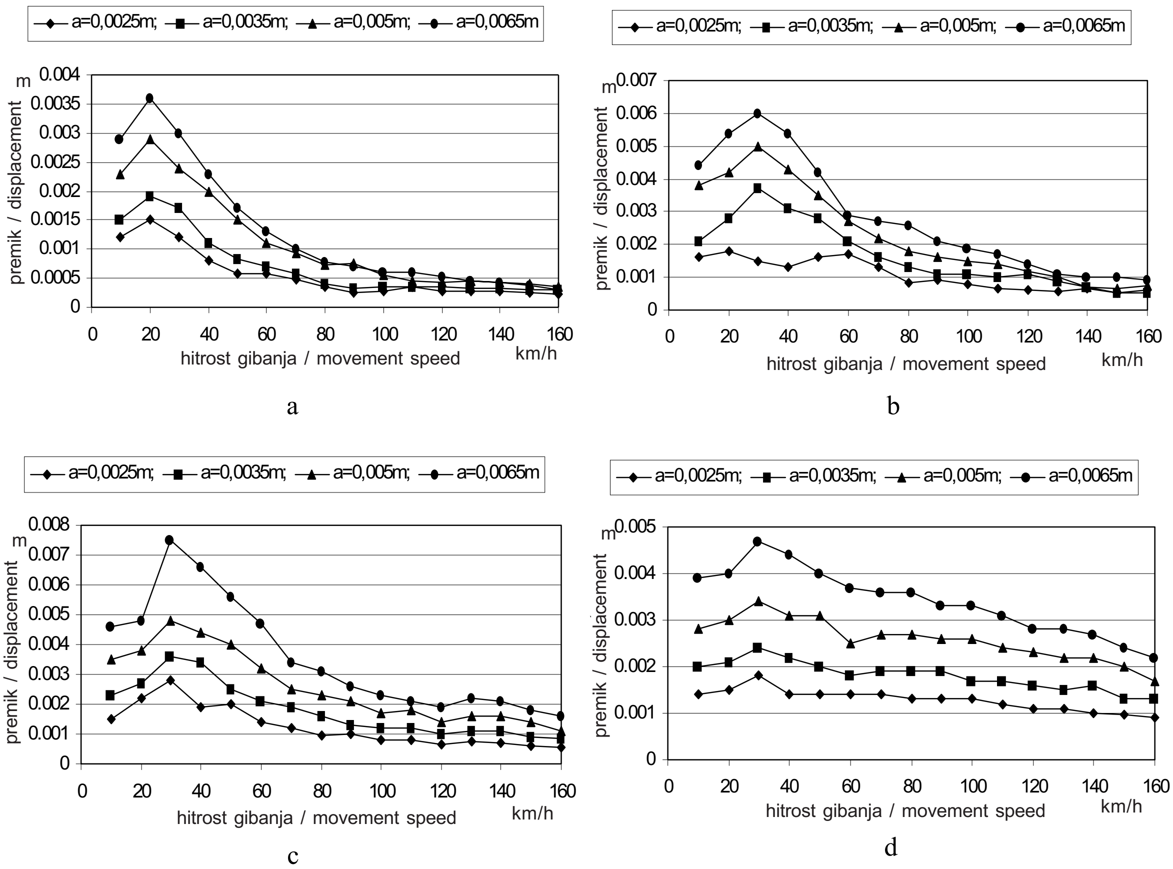
Figure 3 shows the graphs of the sinusoidal irregularity functions (wavelength l =20 m; the wave amplitude a is 0.0025 m, 0.0035 m, 0.005 m and 0.0065 m), the variation dependencies of which, with respect to time, correspond to the actuation when the speed of the wagon is 40 km/h.

After the actuation impact on the created dynamic model of the calculation was described by the functions defining the road irregularities, the amplitudes and accelerations of the oscillations of the body node were analysed. The chosen point of the node is in the middle of the frame above the first carriage. The node height is the same level as a human shoulder.

When the analysed dynamic model is actuated by the road, defining the sinusoidal function, the amplitude values of the changes and accelerations of the analysed passenger-wagon body are obtained by applying different speeds of the wagon.

In order to determine the dependencies of the maximum amplitude values of the changes and accelerations of the analysed wagon-body points on the speed of the wagon, with the road-defined sinusoidal function, some diagrams were made to represent the dependencies (see Figs. 5 and 6).

By analyzing the schedules of the changes of the values of the cross-section oscillations of the carriage body shown in Figure 5, it is clear that the car body, moving through longitudinal irregularities with a sine-wave form of different amplitudes and wavelengths, reaches the largest longitudinal fluctuations when the



Sl. 5. *Odvisnosti največjih vrednosti bočnih premikov potniškega vagona s podvozjem tipa KVZ CNII od hitrosti, ko na potniški vagon vplivajo bočne nepravilnosti sinusoidne oblike v ravnini*

Fig. 5. *Dependencies of the maximum values of lateral displacements of the passenger wagon with the KVZ CNII-type bogies on speed when a passenger wagon is affected by the lateral irregularities of the sinusoidal shape in the plane*

valovna dolžina sinusoidnega prečnega nihanja l = 10 m (sl. 5 a). Vagon se giblje s hitrostjo 20 km/h (pri različnih amplitudnih vrednostih nepravilnosti). Ko pa je dolžina l = 20 m, 30 m in 40 m (sl. 5 b do d), se vagon giblje s hitrostjo 30 km/h (pri različnih amplitudnih vrednostih nepravilnosti).

Če primerjamo največje vrednosti premikov, ki jih povzroča nihanje in so prikazane s krivuljami slike 5, z nastavljenimi zneski nepravilnosti, ki imajo amplitudne vrednosti sinusoide, lahko vidimo, da so pri valovni dolžini sinusoide l = 10 m (sl. 5 a) največje vrednosti premika povzročenega z nihanjem za 54 do 60 % manjše od vrednosti amplitude površine vzbujanja (pri hitrosti vagona 20 km/h). Kadar je valovna dolžina sinusoide l = 20 m (sl. 5 b), lahko največje vrednosti premika nihajočega vagona primerjamo z vrednostmi amplitude nepravilnosti (pri hitrosti vagona 30 km/h). Kadar je valovna dolžina

wavelength of the sine-wave cross-section oscillations is l = 10 m (Fig. 5 a). The car moves with a speed of 20 km/h (at different values of the amplitudes of irregularities). As the length is l = 20 m, 30 m and 40 m (Fig. 5 b to d), the car moves with a speed of 30 km/h (at different values of the amplitudes of irregularities).

Comparing the maximum displacement values of the oscillations shown in the curves in Figure 5 with the preset values of the irregularities with sine-wave amplitudes, we can see that at a wavelength of the sinusoid of l = 10 m (Fig. 5 a), the maximum values of the displacement of the oscillations are 54–60 % less than the values of the amplitudes of the excitation surface (when the car moves with a speed of 20 km/h). When the wavelength of the sinusoid is equal to l = 20 m (Fig. 5 b), the maximum values of the displacement of the body oscillations are comparable to the values of the irregularity amplitudes (as the car moves with a speed of 30 km/h). When the wavelength of the sinusoide l = 30 m (sl. 5 c), največje vrednosti amplitude nihanja presežejo vrednosti amplitude nepravilnosti za 12 do 15 %.

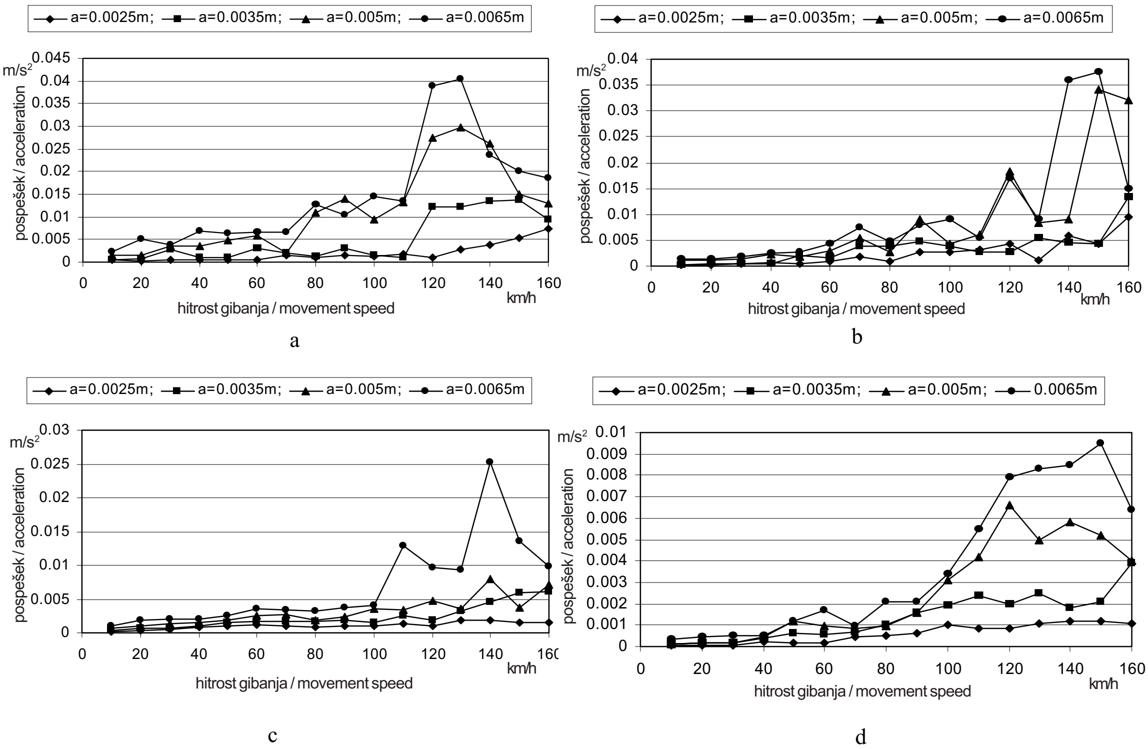
Kadar valovna dolžina sinusoide doseže l = 40 m (sl. 5 d), se vrednosti premikov prečnih nihanj vagona povečajo, nakar se te vrednosti pričnejo rahlo zniževati. Vrednost največjega premika nihanja (pri hitrosti vagona 30 km/h) doseže 71 % do 73 % nastavljenih iznosov amplitude nepravilnosti vzbujanja. To manjšo spremembo vrednosti največjega premika (v primeru, ko je hitrost vagona spremenjena zaradi nepravilnosti z nastavljenimi zneski) lahko razložimo z dejstvom, da pri prekoračitvi dolžine vzdolžne sinusoide nepravilnosti, l = 40 m, (pri nastavljenih zneskih amplitude sinusoide) sinusoida izzveni v ravno črto.

Kakor kažejo odvisnosti na sliki 5, se pri vagonu, ki se giblje s hitrostjo 10 in 50 km/h, nihanje, ki ga povzroči prožilni učinek, približa prostemu nihanju in se zato vrednosti amplitude povečujejo. Kot posledica prožilnega učinka se amplitude sprememb začnejo zmanjševati, ko je presežena hitrost 60 km/h.

sinusoid is equal to l = 30 m (Fig. 5 c), the maximum values of the oscillation amplitudes exceed the values of the irregularity amplitudes by 12 to 15 %.

When the wavelength of the sinusoid reaches l = 40 m (Fig. 5 d) the displacement values of the cross-section oscillations of the car increase, after which they start to decrease insignificantly. The value of the maximum displacement of oscillations (as the car moves with a speed of 30 km/h) reaches 71–73 % of the preset values of the amplitudes of the excitation irregularities. This minor change in the values of maximum displacement (when the speed of the wagon is different due to irregularities with the preset values) can be explained by the fact that when exceeding the length of the longitudinal sine wave of irregularities of l = 40 m (at preset values of amplitudes of the wave) the sinusoid practically turns into a straight line.

As the dependencies in Figure 5 show, when the wagon moves at speeds of 10 and 50 km/h, the oscillations caused by the actuation impact are close to the free oscillations, and therefore the amplitudes are increasing. As a result of this actuation impact, the amplitudes of the changes start to decrease when a speed of 60 km/h is exceeded.



Sl. 6. *Odvisnosti največjih vrednosti bočnih pospeškov potniškega vagona s podvozjem tipa KVZ CNII od hitrosti v primeru, ko na vagon vpliva bočna nepravilnost sinusoidne oblike v ravnini*

Fig. 6. *Dependencies of the maximum values of lateral accelerations of the passenger wagon with the KVZ CNII-type bogies on speed when a passenger wagon is affected by the lateral irregularities of the sinusoidal shape in the plane*

Če analiziramo krivulje pospeškov bočnih nihanj, prikazanih na sliki 6, vidimo, da se največji pospeški nihanja pojavijo, ko sta dolžini sinusoid vzdolžnih nepravilnosti naslednji: l = 10 m (sl. 6 a) in l = 20 m (sl. 6 b); pri tem pa je sinusna amplituda nepravilnosti: a = 0,0065 m. V obeh primerih je največja vrednost pospeška približno 0,04 m/s^2 pri hitrosti vagona 130 km/h (sl. 6 a) in 150 km/h (sl. 6 b).

Omeniti je treba, da se v vseh primerih, prikazanih na sliki 6, največja vrednost pospeškov vzdolžnega nihanja vagona z amplitudo a = 0,0025 m in s = 0,0035 m povečuje postopno. Ob povečanju amplitude a do vrednosti 0,005 m in 0,0065 m opazimo precejšnje povečanje največjih pospeškov, kadar vagon preseže hitrost 100 do 110 km/h.

Having analysed the curves of the accelerations of the longitudinal oscillations shown in Figure 6 we see that the maximum accelerations of the oscillations are reached when the lengths of the sine waves of the longitudinal irregularities are equal to l = 10 m (Fig. 6 a) and l = 20 m (Fig. 6 b), while the sine-wave amplitude of the irregularities is equal to a = 0.0065 m. In both cases the maximum values of the accelerations reach about 0.04 m/s^2 when the car moves with speeds of 130 km/h (Fig. 6 a) and 150 km/h (Fig. 6 b).

It should be mentioned that in all the cases shown in Fig. 6 the maximum values of the accelerations of the longitudinal oscillations of the carriage body at amplitudes of a = 0.0025 m and a = 0.0035 m increase gradually. With an increase in the amplitude a up to 0.005 m and 0.0065 m, a substantial growth in the maximum accelerations is observed when the car exceeds speeds of 100 to 110 km/h.

4 SKLEPI

V prispevku sva analizirala bočne dinamične pojave v vagonu, ki se giblje po tračnicah z nepravilnostmi sinusoidne oblike. Ocenila sva vpliv parametrov bočnih nepravilnosti sinusoidne oblike (valovna dolžina l je 10 m, 20 m, 30 m, in 40 m; valovna amplituda a je 0,0025 m, 0,0035 m, 0,0050 m, in 0,0065 m) in hitrosti vagona 10 do 160 km/h na bočno vibriranje karoserije. Nato sva ustvarila simulacijo interaktivne dinamike med progo in vagonom.

Po izvedbi računalniške analize je mogoče določiti optimalne hitrosti vagona in le te hitrosti smejo biti uporabljene na predelu prevladujočega gubanja posameznih segmentov.

Izsledki raziskave bodo pomagali izboljšati dinamične značilnosti vagona, tj. zmanjšati škodljivi vpliv gibanja vagona na udobje potnikov.

Med analizo železniške proge z uporabo vagonskega modela sva med naključno porazdeljenostjo nepravilnosti opazila tudi nekatere pravilnosti.

Izvedena analiza naju je vodila do naslednjih sklepov:

1. Izbrani model lahko, celo v poenostavljeni obliki, omogoči natančne rezultate in ga zato lahko uporabimo za reševanje problemov, ki nastajajo v zapletenih razmerah zunanjih vplivov.
2. Kadar hitrost vagona preseže 100 km/h, se amplituda pospeška poveča.

4 CONCLUSIONS

In this paper we have analysed the lateral dynamical processes when a wagon moves along irregularities of a sinusoidal shape on both the left- and right-hand rails. We evaluated the influence of the parameters of the lateral irregularities of the sinusoidal shape (wavelength l equal to 10 m, 20 m, 30 m, and 40 m; wave amplitude a equal to 0.0025 m, 0.0035 m, 0.0050 m, and 0.0065 m) and wagon speeds of 10 km/h to 160 km/h on the lateral vibrations of the body. Then the interaction dynamics of the road and the wagon was modelled.

After performing the computational analyses it is possible to determine the optimum speeds of the wagon movement, and only these speeds should be the allowed subject to the dominated corrugations in the particular segments.

This would allow us to improve the dynamic properties of a wagon; thereby, reducing the harmful impact of the wagon on the passenger's comfort.

When analysing lanes of road - measuring wagon, among random distribution of irregularities some regularities were noticed.

The performed analysis led to the following conclusions:

1. The used model, even in its simplified form, can provide accurate results, and therefore may be applied to solve tasks with complex conditions of external impact;
2. When the speed of a wagon exceeds 100 km/h, the amplitudes of the acceleration increase.

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