Loreta LEVULYTĖ
Vidas ŽURAULIS
Edgar SOKOLOVSKIJ

THE RESEARCH OF DYNAMIC CHARACTERISTICS OF AVEHICLE DRIVING OVER ROAD ROUGHNESS

BADANIA DYNAMICZNYCH CHARAKTERYSTYK RUCHU POJAZDU NA NIERÓWNOŚCIACH DROGI

The paper analyses the effect of road roughness on the variation of the vertical oscillations' frequency of the sprung and unsprung masses of a vehicle driving at varying speed. The research aims to determine the regularity with which the wheel of a vehicle moving at varying speed reproduces the roughness of road pavement texture. The theory of mathematical statistics is used to define the distribution law of road defects measured during the experiment. In the present investigation, the displacements of the wheel and suspension of the vehicle, driving at varying speed over the defects of the selected road section pavement, have been evaluated. Based on the frequency characteristic obtained from the measured data, the frequency variation of the displacements of the sprung and unsprung masses in a vehicle moving on a rough road has been determined. The vertical acceleration of the wheel and the body of a vehicle has been measured, and the frequency characteristic of vertical acceleration of the sprung and unsprung vehicles' masses has been analysed. The schematic view of the wheel's axis displacement model is presented.

Keywords: *vibrations, frequency, frequency characteristics, road roughness, dynamics, suspension displacement, wheel displacement, contact.*

Artykuł analizuje wpływ nierówności drogi na zmiany częstotliwości dynamiki pionowej resorowanych i nieresorowanych mas samochodu przy różnych prędkościach. Celem jest określenie wzoru nierówności drogi przy różnych prędkościach, za pomoca analizy zmian częstotliwości drgań kół pojazdu. Podczas przeprowadzonego eksperymentu zmierzono nierówności drogi i za pomocą teorii analizy matematycznej określono charakterystykę nierówności nawierzchni. Podczas prób jazdy po nierównościach wybranego odcinka drogi przy różnych prędkościach zmierzono przesunięcia pionowe koła i zawieszenia samochodu. Na podstawie charakterystyki częstotliwościowej oceniono zmiany częstotliwości przebiegów pionowych resorowanych i nieresorowanych mas pojazdu jadącego po nierównościach drogi. Zmierzono przyspieszenia pionowe koła oraz nadwozia i przeprowadzono analizę częstotliwości przyspieszeń pionowych resorowanych i nieresorowanych mas. Przedstawiony jest schematyczny model przesunięć osi koła.

Słowa kluczowe: *wibracje, częstotliwość, charakterystyka częstotliwościowa, nierówności drogi, dynamika, przebieg zawieszenia, przebieg koła, kontakt.*

Symbols

L_h – the length of the test road section, m;

v – the vehicle's motion speed, m/s;

$\dot{q}_1, \dot{q}_2$ – the vertical movement speed of sprung and unsprung masses,

t_1, t_2 – time,

L_h – the length of the test road section, m;

$a(t)$ – linear acceleration,

k_s – a coefficient evaluating the properties of tyres and shock-absorbers,

l_d – the length of road section of road pavement,

g – acceleration of gravity,

h – depth of pothole,

z_f – the vertical displacement (bounce) of front suspension,

z_r – the vertical displacement (bounce) of the rear suspension,

Δz – a oscillation limits of the rear suspension displacement

l – the vehicle's base,

θ – pitch angle,

m_a – a vehicle's mass,

ω – angular oscillation along the vertical axis according to the Fourier analysis,

z_i – the vertical displacement of the wheels,

φ – the displacement angle of the curve,

$\Delta \dot{z}_i$ – the speed of suspension movement,

Δz_i – the amplitude of suspension's vertical displacement,

L_k – the length of the contact zone of the wheel with the road defect,

h – a vertical coordinate (the depth of road pavement depression),

ω – angular oscillation along the vertical axis according to the Fourier analysis,

z_i – the vertical displacement of the wheels,

l – the vehicle's base,

θ – pitch angle.

1. Introduction

It can be observed that the development of the transport system and increase in traffic volume are accompanied by the development and improvement of road infrastructure. More effective road traffic safety systems are also designed and implemented, and new technologies, materials and equipment are used in road construction. The automobile design is being constantly improved to increase traffic safety, ride comfort, automobile control and road grip of a tyre. However, a significant problem associated with the need for increasing ride comfort and road grip of a tyre of vehicle moving on a rough road still remains unsolved. The forces acting on the wheels of vehicle moving on a rough road, are transmitted to a vehicle's suspension and, then, to a vehicle's body. The vehicle's suspension transforms random impacts experienced by a vehicle moving on a rough road into the vibrations of its body. Modern technologies allow us to evaluate the vehicle-road interaction from various perspectives. A vehicle moving on a road is under the influence of various internal and external factors, which, to a great extent, determine its stability and safety. The efficient performance of a transport system depends on the interaction between its elements [13].

Šiaudinis and Čygas [14] defined the main factors causing road pavement deformation. In their opinion, these include the increasing traffic volumes of heavy vehicles, the increased axle loads of the vehicles, exceeding those, which were earlier considered to be admissible in road design.

Evaluating the rapidly increasing heavy vehicle traffic volumes in Lithuania, Čygas et al. [3] investigated the problems of road pavement strengthening, taking into account the actual road pavement loads. The development of road rutting was investigated by applying the force law models to low-loaded road pavement analysis [5].

Road-tyre interaction is of paramount importance to vehicle's stability. Investigating this problem various mathematical models of road-pavement-vehicle interaction have been constructed and used for describing the impact of road roughness on the motion of the vehicle's sprung and unsprung masses. In this way, the authors attempted to evaluate road-tyre interaction.[10].

Park et al. [10] investigated the vibrations exited on the body of a vehicle driving on a rough road. It has been found that when a vehicle is moving at higher speed, its response to road pavement roughness is weaker. The displacement of the vehicle's body and suspension depend on the suspension damping element characteristics and structure as well as on road roughness. The severe tyre deformations occur when a vehicle drivers over road defects.

Žuraulis et al. [18] studied the vehicle's transverse dynamics and described the methodology of identifying the critical speed of a vehicle, following a circular trajectory. In all cases, the procedures of selection and evaluation of road friction parameters are extremely important, when traffic accidents are investigated, because they have a strong influence on the dynamics of the vehicle and deceleration parameters [13, 15].

Merzouki et al. [9] determined the dynamic dependences of the interaction tyre-road pavement according to the dynamic model, which enabled them to determine longitudinal forces of the tyre-road pavement contact. The wheel is exposed to the forces of inertia, rigidity and friction. When rolling, the wheel deforms in the contact zone, thereby deforming the road. The deformation of various road pavement is caused not only by the heavy vehicle's payload, but also depends on the climatic conditions. Heavy vehicles and the varying climatic conditions cause rutting, cracks and wear of road pavement, which, in turn, have a negative effect on the road pavement condition and the vehicle's dynamics.

The main areas of scientific interests, which can be observed in recent studies, include the analysis of road roughness, the interaction between tyre and road, the effect of road roughness on the ride comfort in a vehicle, etc. [1, 2, 4, 7, 17].

A vast majority of scientists analyse road roughness or vehicle's dynamics separately. However, comprehensive evaluation of the influence of road roughness on the vehicle's dynamics requires, primarily, the evaluation of the interaction between tyre and road. For automobiles driving at varying speed, the dynamic behaviour of the wheel (tyre) interacting with road defects determines the strength of the road grip of a tyre on a rough road and the bounce of the vehicle body (along the vertical axis). These dynamic parameters can be evaluated by measuring the vertical acceleration of the vehicle's wheels (unsprung masses) and the body (sprung masses) representing the as well as the suspension displacement of a vehicle driving at varying speed.

2. Theoretical description of methods used in road roughness evaluation

The *International Road Roughness Index* (IRI) has been defined by the US National Cooperative Highway Research Program (NCHRP). IRI is, essentially, a computer-based virtual response system. In order to calibrate it, an ideal system was defined for a computer – the profile index was tailored to correlate well with the output. The filter is based on a mathematical model, referred to as quarter-car. A special set of parameters for quarter car defined by NCHRP is called The Golden Car. IRI summarizes the roughness qualities that impact the vehicle response and are most appropriate, when a measure of roughness embracing the overall vehicle operating cost, ride quality, dynamic wheel loads and surface condition is required [12]. IRI allows us to assess the road quality by using the direct methods of road roughness measurement and to recalculate the obtained values by the formulas into the IRI scale, or to measure road pavement roughness by laser profilometer, analysing the road profile according to the computer algorithm created for Fourier analysis, which presents the value of IRI in a digital form. IRI may be defined as a relation between the distance covered by vertical (oscillation) movement of a calibrated vehicle and the horizontal distance travelled by a vehicle driving along the road during the test run. The profilometer – measured IRI index of road roughness is calculated by the computer algorithm according to the following formula:

$$IRI = \frac{1}{L_h} \int_0^{L_h/v} |\dot{q}_2 - \dot{q}_1| dt \tag{1}$$

The condition of a particular road (with respect to its roughness) can be determined in the comparative analysis of road roughness measurement results with the admissible roughness levels specified by international standard (ASTM E1926-08) for roads of various categories.

Road pavement defects have stochastic distribution, and, therefore, the sprung and unsprung masses of a driving vehicle are subjected to uneven (bounce) vibration. This uneven (bounce) vibration is based on the variation of the frequency amplitudes of the sprung and unsprung masses during vertical acceleration.

Oscillations are best described by their amplitude, frequency, speed and acceleration. When a vehicle drives on the road, its structural elements oscillate within the frequency range up to 500 Hz oscillations. Low frequencies up to 11 Hz are caused by vehicle-road interaction, with their value depending on the road pavement roughness and the vehicle's suspension parameters. High frequency oscillations are caused by non-smooth running of the vehicle's engine and the transmission parts. The displacement of the vehicle's sprung masses are analysed within the frequency range up to 15 Hz, whereas the displacements of the wheel's and other unsprung masses are within the range of 15–500 Hz. The impact of variable acceleration on the hu-

man body depends on frequency. People respond to mechanical oscillations, depending on their physical and mental properties, oscillation parameters and the direction of oscillation impacting the human body. The vertical acceleration impact on the vehicle's sprung masses may be estimated by the mean acceleration value as follows:

$$a_{vkr} = \sqrt{\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a^2(t) dt} \qquad (2)$$

When the wheel (tyre) hits against the road surface with a defect, the vibrations (oscillations) of the vehicle's sprung and unsprung masses may be damped until a new road defect is passed, or may continue incessantly if there are a large number of typical/stochastic road pavement defects. When the wheel makes contact with the road pavement defect (e. g. pothole), the distribution of vertical displacements of the wheels is proportional to the road force exerted by the road pavement roughness. If a rough (uneven) section of the road is long, the wheel of a vehicle driving at certain speed gets into the pothole and receives the strongest bounce impact. The critical speed of a vehicle creates unfavourable traffic conditions due to road roughness and may cause oscillation resonance, with depends on a vehicle's speed, the road pavement roughness and the depth of a depression (pothole). It is calculated from the formula:

$$v_{kr} = k_s l_d \sqrt{\frac{g}{8h}} \qquad (3)$$

When a vehicle is driving over the road defect, the front and rear suspensions move differently along the vertical axis and this causes oscillations along the lateral axis. First, the defects on the road pavement negatively affect the front and the rear suspensions, as shown in Fig. 1. When the front suspension passes a road defect and a vehicle continues its motion, the excitation from road pavement defect is instantaneously transmitted to the rear suspension. As a result, the rear suspension is impacted not only by the road pavement defects (e. g. ruts, depressions, potholes, etc.), but also by the moving front suspension. This directly impacts the wheel base of a vehicle. The rate of vertical displacement of the rear suspension at varying speed of a vehicle depends on the vertical movements of the front suspension and the amplitude of its vertical displacement, which may be higher or lower as shown in Fig. 1. In such cases, the position of the rotating axis varies. Fig. 1 shows the dependence of the rear suspension's displacement on the wheel base. In fact, the amplitude of the rear suspension's displacement also depends on the character of the front suspension's displacement along the vertical axis at the time, when
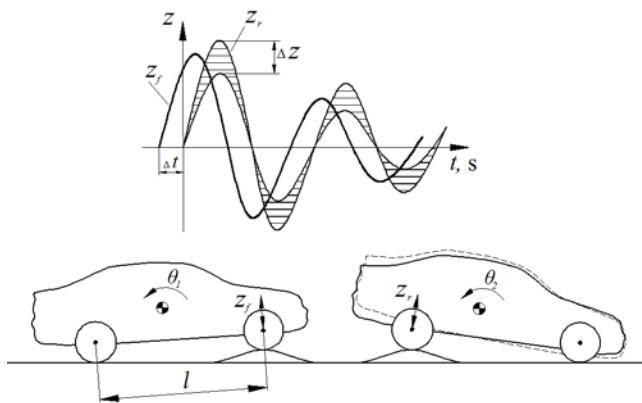

Fig. 1. The displacements of the front and rear suspension

the front part of the vehicle has already passed a road defect while the rear suspension is passing it.

When the frequencies of oscillations caused by driving on a rough road match the vehicle's own natural frequency, resonance occurs. The driving speed at which resonance occurs is calculated by the following equation:

$$v_r = \frac{l_d}{2\pi} \sqrt{\frac{k_p g}{m_a}} \qquad (4)$$

In fact, when road pavement defects are distributed over a long distance, the vehicle's dynamic characteristics are better, while when the depressions (potholes) on the road pavement are getting deeper, the vehicle's dynamics is getting worse because the critical speed decreases (Eq. 4). A part of a negative impact of a road on vehicle is absorbed by the tyre due to its elasticity. In contact with a road defect, a tyre deforms instantaneously, but when it passes the road defect, it can recover so that the displacement is not transmitted to the vehicle's suspension and body. When a vehicle moves at the velocity v, the depth of the road depression, whose impacts are absorbed by the tyre, is calculated as follows:

$$z(x) = \frac{1}{L_k} \int_{h_{min}}^{h_{max}} h(x) dt \qquad (5)$$

When the wheel (tyre) of a vehicle drives over the road pavement defect, the suspension's displacement along the vertical axis varies by size Δz, and this variation determines the excitation transmitted to the vehicle's body. Since road defects are stochastically random values, which can be approximated by the sine function, the amplitude of suspension displacement the along the vertical axis can be described by the formula:

$$\Delta \dot{z} = A \sin \omega t + B \cos \omega t \qquad (6)$$

The values A and B are follows:

$$A = z_i \cos \varphi, \ B = z_i \sin \varphi$$

If the characteristics of suspension's displacements of a vehicle along the vertical axis are known (measured), the variation of oscillation frequency may be calculated by:

$$f = \frac{\Delta \dot{z}}{2\pi \cdot \Delta z_i} \qquad (7)$$

3. Methodology of the experimental investigation and the equipment used

The experimental investigation was performed under the following conditions:
- driver: a 26-year old male, not a professional test driver; driving experience: B category – 10 years, C, CE categories – 4 years;
- during the experiment vehicle was driven by the same person (driver);
- technically neat car "Toyota Avensis" made in 1999 was used in the experiment;

- the experiment was conducted on dry asphalt pavement;
- the vehicle was fitted with summer 195/60R15 H88 tyres and the depth of the tyre protector was about 3 mm;
- according to the manufacturers' specifications, air pressure in the tyres was 2.2 bar;
- during the experiment, the driving speed was 20, 40, 60 and 80 km/h.

A test road section of experimental pavement naturally trafficked by passengers cars and heavy vehicles was for a long time, and, therefore, road defects naturally occurred due to traffic loads, climatic impacts, etc.

A mobile road surface testing laboratory RST 28 (a laser profilometer) (Fig. 2) was used to measure road pavement roughness. This laboratory is made onto the chassis of „Mercedes-Benz Sprinter". Road surface testing laboratory RST 28 is a testing system that can measure and collect data on various road surface properties at normal traffic speed and, to a large extent, is independent of speed variation (20–90 km/h) of the tested vehicle.

Fig. 2. Road surface testing laboratory RST 28

Due to a high quality of road surface testing laboratory, there is no disruption or effect on either the test quality or other road traffic. This modern multi-component road quality measurement equipment guarantees not only high accuracy of measurement results, but also allows us to identify road pavement properties. Road surface measuring devices are installed in the front vehicle's supporting structure (beam) and a pavement defect detection device is installed in the rear part of the vehicle (Fig. 2).

The following equipment was used in the experiment to measure the vehicle's dynamic parameters (Fig. 3.):
- the acceleration of the vehicle's sprung and unsprung masses and oscillation rate were measured by a sensor of the triaxle accelometer–giroscope Multi-Axial Navigation System. Technical specification (data): full scale sensitivity – ±3g; 666 mV/g; frequency response – to 10 Hz, −3dB, −6dB/octave roll-off;
- suspension's displacement along the vertical axis was measured by the wire potentiometer sensor Kuebler D8 (Fig. 3), which registers linear suspension's displacements of each wheel between the shock absorber fixing points. Technical specification (data) of the potentiometer: measurement range – 500 mm; extension force – min. 5.2 kN, max.– 7.3 kN, speed max. – 8 m/s; acceleration max. – 85 m/s^2;
- the acceleration of the wheel along the vertical axis was measured by the wheel acceleration sensor Kistler 8395A based on the principle of capacitance variation (Fig. 3). The sensing element of each axis consists of a very small inertial mass and a flexure element cantilever positioned between two plates. As the mass deflects under acceleration, the capacitance between these plates changes. Excitation and synchronous amplitude demodulation circuitry contained in the accelerometer's internal signal conditioner provides an analog output signal proportional to the applied acceleration. This output signal is scaled as a voltage which is proportional to the applied acceleration. Technical specification of Kistler 8395A: Measuring range: 200 g;
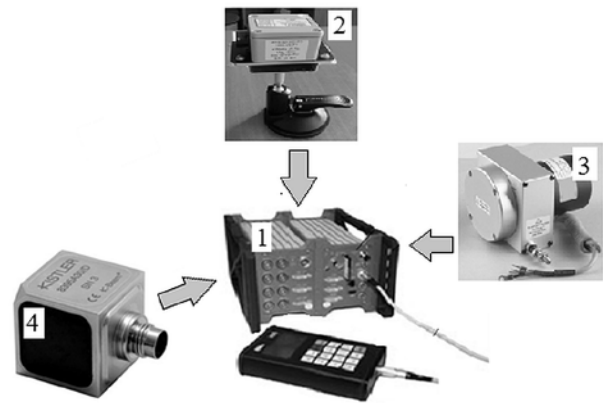

Fig. 3. The testing equipment of vehicle's dynamic:1 – Corrsys-Datron DAS3 data acquisition system; 2 – body acceleration sensor Multi-Axial Navigation Systems; 3 – a potentiometer sensor for measuring linear displacements Kuebler D8; 4 – wheel acceleration sensor Kistler 8395A

frequency response: 0–1000 Hz (5%) (except ±2 g); damping ratio, typical – 0.7; sensitivity, ±5% (ref. 100 Hz).

The analysis of the measured vehicle's dynamic parameters was performed by the software of the data acquisition system Corrsys-Datron DAS3 system (Fig. 3.). The basic module of Corrsys-Datron DAS3 is made of two components, including the data collection module (sensors) and the processor's module (information storage and processing). Operation, parameterization and online data display are achieved via the proven DAS control – display unit. Used with TurboLab Analysis 6.0 software, it is a powerful and easy-to-usen tool for professional data acquisition and evaluation.

Table 1. The main road data on the investigated road

Parameter	Results	
	Right rut	Left rut
IRI, m/km	2.618	3.277
Standard deviation	16.433	10.976
Minimum depth of road roughness (depressions) , mm	−63	−37
Maximum height of road roughness (bumps) , mm	54	26

4. The analysis of the experimental investigation results

The profilogram data on road pavement roughness enable us to evaluate the impact of road roughness on vehicle's motion. We began the experimental investigation with road roughness measurement in the vicinity of wheel the right and left ruts (tracks). It has been determined that the depth of road depressions around the right and left wheel ruts varies within the interval from −63 mm to 55 mm. Based on the measurement results of road pavement defects it has been found that the investigated experimental road section of 100 m may be referred to the roads of medium roughness according to the IRI scale (see Table 1).

The mathematical–statistical analysis was used to identify the variation of road roughness as well as the ordinates and their density throughout the whole length of the test road section. According to mathematical analysis of the road measurement results, it has been found that the road profile ordinates are distributed according to the law of the Gaussian distribution. Standard deviation of data distribu-

tion for the right (σ = 16.43) and left (σ = 10.98) wheel ruts (tracks) were calculated. The graphs of the normal distribution illustrate the distribution of the values of road profile roughness indicators. The measured road distance contains approximately 39% of positive road profile ordinates (points) and 61% of the negative ones (Fig. 4 and Fig. 5).
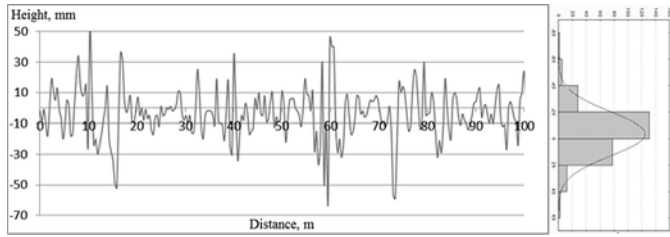

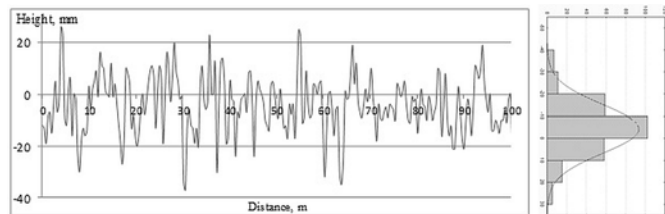*Fig. 4.   Road surface profilogram for the right wheel rut and the data histogram*

Fig. 5. Road surface profilogram for the left wheel rut and the data histogram
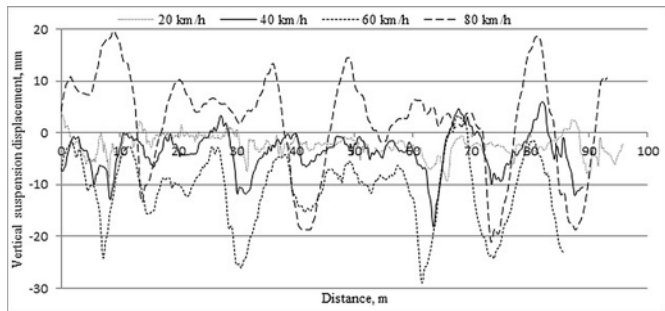
Fig. 6.   Vertical displacement of suspension, when a vehicle moves in a steady mode at varying speed
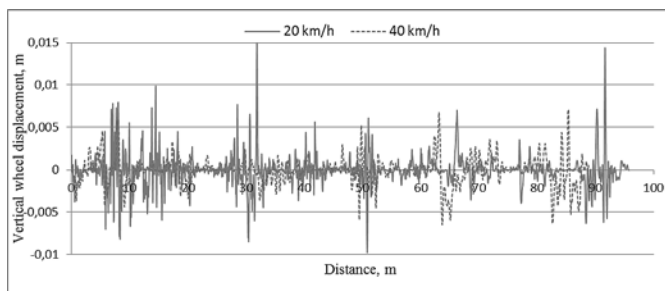

Fig. 7.   Vertical displacement of the wheel, when a vehicle drives in a steady mode at the speed of 20 or 40 km/h

Due to road roughness, the wheel acquires displacement and certain acceleration in vertical direction, when the tyre contacts with the road pavement. The responses of the wheel to the road obstacles are transmitted to the suspension elements and, then, to the vehicle's body. The dependences of the vertical displacements of the vehicle's body, suspension and the wheel are shown in the graphs. When car is driving at the speed of 20 km/h or 40 km/h, the amplitudes of the variation of the suspension displacements are insignificant (from 5
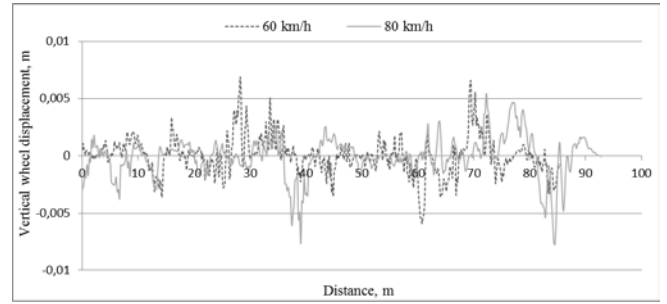

Fig. 8.   Vertical displacement of the wheel, when a vehicle drives in a steady mode at the speeds of 60 or 80 km/h

to −18 mm), however, when the speed increases, the amplitudes also increase (Fig. 6).

When a vehicle moves slowly (20 km/h or 40 km/h), the vehicle's wheel reproduces the road roughness profile at a higher frequency or rather more regularly than when it drives faster, e. g. at 80 km/h (Fig. 7 and 8).

When a vehicle is driving at the speed of 20 km/h, the frequency of the vertical displacement of the sprung and unsprung masses is similar (3.5 Hz and 5.2 Hz, respectively), while the speed is increased (40 km/h and 60 km/h) the frequency of the unsprung masse's fluctuation increases more rapidly than the frequency of sprung masses (see Fig. 9 and Table 2), since, in this case, the impact of a rough road on the vehicle's body's vibration is reduced by suspension.
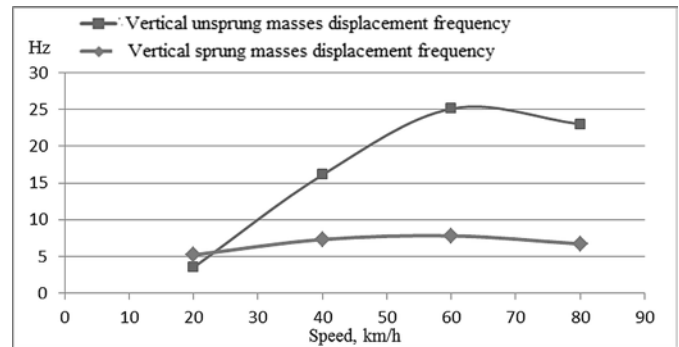

Fig. 9.   The variation of vertical displacement frequency of the suspension and unsprung masses when a vehicle drives at varying speed

Table. 2. Frequencies of vertical displacement of the wheel and suspension

Speed, km/h	Frequency of the wheel displacement, Hz	Frequency of the suspension displacement, Hz
20	3.5	5.2
40	16.1	7.3
60	25.1	7.8
80	23.0	6.7

Within the speed range of 20 to 60 km/h, the displacement frequency of the unsprung masses increases from 3.5 Hz to 25.1 Hz, i. e. by 7 times, while that of the sprung masses varies within the range of 5.2 Hz to 7.8 Hz, i.e. increases by 1.5 times. When the speed of 80 km/h is reached, the frequency of the unsprung masses decreases by 8.36%. An assumption could be made that when a car drives at the speed of 20 or 40 km/h, the wheel consistently reproduces the road roughness in both directions: at the speed of 60 km/h, stochastic road roughness recurrence occurs, while at the speed of 80 km/h, the wheel starts to reproduce positive road roughness more consistently and the wheel's vertical displacement increases (as well as at a nega-

tive roughness value). The decreasing area of the tyre-road contact increases the risk to traffic safety.

The excitation of a rough road is transmitted to the vehicle's suspension and body through vibrations, which are described by vertical acceleration. Figs. 10 and 11 present the curves of vertical acceleration of the unsprung masses (wheels) and sprung masses (vehicle's body) vertical accelerations. It could be stated that the vibration frequency falling on the body does not exceed the permitted values (35 Hz or 22 m/s²) specified in the standard *LST ISO 2631-1*.
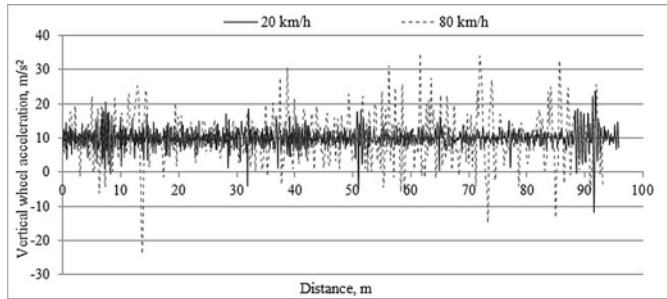

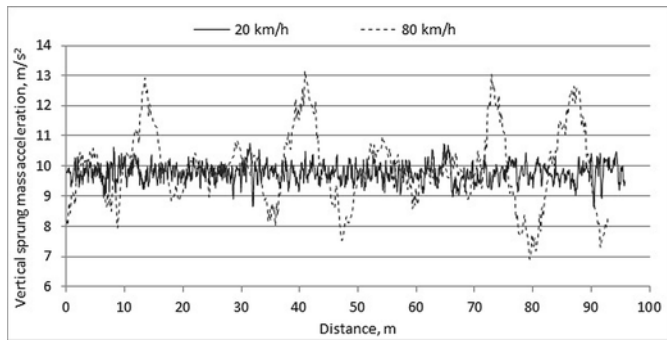*Fig. 10. Vertical wheel acceleration of a vehicle driving at the speed of 20 km/h or 80 km/h*

Fig. 11. Vertical acceleration of the vehicle body, while driving at the speed of 20 km/h and 80 km/h

When the speed increases (20, 40, 60 km/h), vertical acceleration frequency of the unsprung masses (wheels) (Fig. 12.) increases correspondingly (50.31 Hz, 87.57 Hz and 114.78 Hz), and then begins to decrease. At the speed of 80 km/h it decreases by 6% compared to the speed of 60 km/h. Under the same conditions, the acceleration frequency of the sprung masses of the (body) increases to 24.28 Hz, 32.84 Hz and 41.11 Hz, respectively, and at the speed of 80 km/h, the frequency decreases by 39% (to 25.11 Hz).
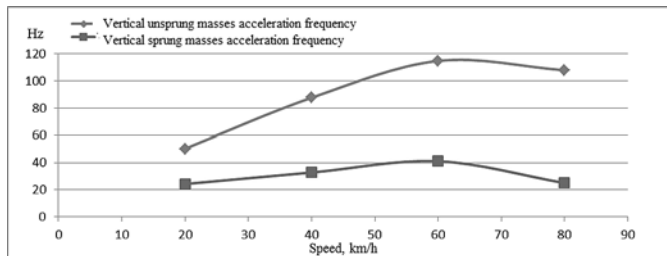

Fig. 12. Vertical acceleration frequency of sprung and unsprung masses

According to the experimental data analysis, it has been established that, at low speed, vertical wheel's displacements are distributed almost uniformly in positive and negative directions of the rough road sections because road pavement roughness is reproduced. When the speed increases from 20 km/h to 60 km/h, the wheel's displace-

ments increase due to chaotic wheel's responses to road roughness. When a vehicle drives at the speed of 80 km/h, regular extension of the wheel's displacements to a positive side of the road defects values can be observed as the wheel contacts with a positive road profile surface (it has been found that, at this speed, the wheel partially loses contact with the road surface for approximately 6.9% of the driving time, as shown in Fig. 13).

The tyre absorbs only a minor part of the road pavement texture roughness. The latter is regularly reproduced, which is shown by graphical representation of wheel displacement. Fig. 13 shows the variation of the position of the centre of momentary wheel displacement for a vehicle driving at a certain speed, which allows us to draw a conclusion about the capacity of a wheel to reproduce the roughness of a road.
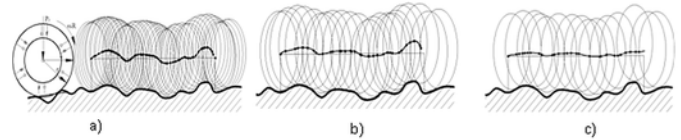

Fig. 13. A model of the wheel's axis displacement for a vehicle driving at varying speed (a schematic view): a – when the wheel regularly reproduces road pavement roughness (slow speed), b – when a wheel partially reproduces road roughness, c – when the wheel reproduces only the roughness of the upper layer of the rough road section, when a vehicle drives at higher speed, e.g. about 80 km/h

Similar regularity can be observed, when we analyse the frequencies of vertical displacement of sprung and unsprung masses and the frequencies of vertical acceleration, which increase until the vehicle speed reaches 60 km/h and then starts to decrease. At low speed (20 km/h), the vehicle's wheel transmits a bulk of road roughness through the tyre and suspension elements. At the speed of 80 km/h, when the frequency of unsprung masses' vibrations increases, the impact of road roughness on the vehicle body (causing its vibration) is reduced by suspension, which, in turn, reduces the displacement frequencies and acceleration of sprung masses (see Fig. 9 and 12).

The road surface roughness, as a stochastic process, is generally described by a PSD (power spectral density) function in a frequency domain, and, in engineering practice, it is regarded as a zero-mean stationary and Gaussian process. The general expression for the relationship between the vehicle speed, the spatial frequency, and the PSD are presented in Fig. 14. During research was found, that there are some conditions show that the road roughness amplitude and the road PSD of wheel is higher than the speed is higher.
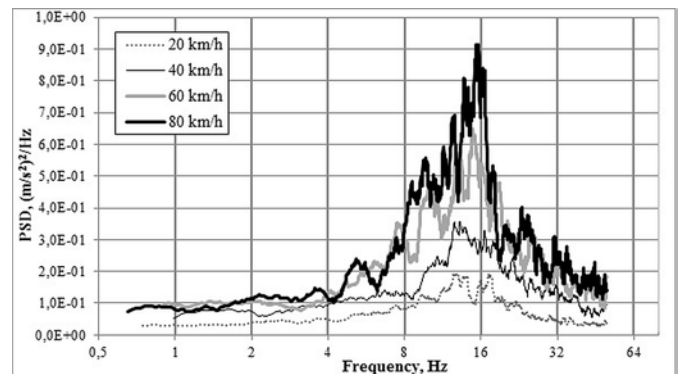

Fig.14. The typical acceleration PSD of the unsprung masses (dynamic wheel) at varying speed

The consequence analysis of the road roughness influence on the unsprung masses lets determine that, despite significantly varying speed, the maximum amplitude of the unsprung masses (wheels) vertical acceleration exhibit at 15 Hz frequency. A good agreement of this

is shown between the PSD functions (for the measured road profile) of the wheel and the suggested frequency from experimental data in Fg. 14. Taking analysis of the road surface caused wheel acceleration PSD into account, the frequency ranges from 10 to 20 Hz, at the commonly speed (20–80 km/h) increasing, it can guarantee the frequency ranges from 0.33 to 28.3 Hz, which considers the natural frequencies of the unsprung mass effectively [6].

Above natural frequency of unsprung mass, the unsprung mass has significant effect on the road holding. If this frequency, matches the frequency at which the positive value of dynamic tire deflection becomes equal to the static deflection of the tire due to the vehicle weight then, the tire is on the verge of bouncing off the ground and not able to have contact with ground. Vibrations in the vehicle body are usually considered as the vertical displacement of the vehicle body due to elevations on the rough road.

5. Conclusions

1. When a vehicle drives at the speed of about 40 km/h, the oscillations of the vehicle's sprung and unsprung masses are insignificant (reaching 5.2 Hz), which correlates with road roughness. When the speed increases, frequency of the unsprung masses', vibrations increases by 7 times. Stochastic driving of the wheel over the road defects (e. g. depressions, potholes, bumps, ruts, etc.) has a significant impact on it. When the speed of 80 km/h is reached, the frequency of the vertical motion of both sprung and an unsprung mass starts to decrease (by 14% and 8%, respectively, compared to the speed of 60 km/h). As a result, the vehicle's wheels do not regularly reproduce road roughness, and, therefore, the duration of their contact with the road surface decreases.

2. The performed statistical analysis of the data has shown that, at low speed, the intervals between the wheel's vertical displacements are almost uniformly distributed in positive and negative directions with respect to the road defects. This corresponds to the road profilogram data. When speed increases to 60 km/h and more, the range of the wheel's displacements (oscillations) increases, and vehicle movements' pitches are impacted by rough road chaotically.

3. When the driving speed reaches 80 km/h, the wheel tends to contact with positive road surface. Lower displacement zones are missed, which means a weaker wheel's response to road defects. The same tendency can be observed, when we in analyse the frequencies of vertical displacement and vertical acceleration of the sprung and unsprung masses, which increase until the driving speed of 60 km/h is reached, and then start decreasing.

4. The analysis has determined that, at the speed of 80 km/h, the wheel partially loses contact with the road surface for approximately 6.9% of the vehicle's driving time. The lack of the wheel's tyre contact with the road surface may significantly affect the total stability of the vehicle. Road surface condition should correlate with the maximum allowable driving speed and its limiting, while the performance of the vehicle's suspension and tyres should be constantly improved.

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Loreta LEVULYTĖ
Department of Automobile Transport
Vilnius Gediminas Technical University
Basanavičiaus str., 28 LT-03224 Vilnius, Lithuania
E-mail: loreta.levulyte@dok.vgtu.lt

Vidas ŽURAULIS
Department of Automobile Transport
Vilnius Gediminas Technical University
Basanavičiaus str., 28 LT-03224 Vilnius, Lithuania
E-mail: vidas.zuraulis@vgtu.lt

Edgar SOKOLOVSKIJ
Department of Automobile Transport
Vilnius Gediminas Technical University
Basanavičiaus str., 28 LT-03224 Vilnius, Lithuania
E-mail: edgar.sokolovskij@vgtu.lt