797. Research of lateral vibrations of a passenger wagon running along the curved path

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Abstract. The objective of this work is to study transverse vibration of a passenger car body running at various speeds over the track irregularities, which are usually encountered in practice. The tasks that are addressed in this research work: perform tests at track irregularities of symmetrical sinusoidal shape running both along straight and curved paths, as well as driving over the junctions along the straight and curved paths, and compare the results.

Keywords: passenger wagon, horizontal vibration, irregularities of sinusoidal shape, passing track irregularities at the junction, vibration acceleration, vibration velocity, displacement.

Introduction

With the development of traction means and increasing movement speed when higher safety requirements are continuously raised, significant attention is given to the study of dynamic processes of rolling stock and to investigation of interaction forces between wheel and rail. This allows to identify the main design parameters of railway and rolling stocks, to select the proper materials, to ensure the strength, durability and reliability of mechanisms, and to achieve maximum movement uniformity and comfort level.

This work considers a problem of wagon dynamics - horizontal dynamic processes, occurring while a wagon is moving the railway irregularities.

Horizontal dynamic processes have a significant impact on the uniformity of movement, i.e., on the ability of elastic suspension of rolling-stocks to maintain vibrations of the body within the limits of comfort. One of the key indicators that determine the uniformity of movement is the amplitude of irregularities and the speed of driving.

With increasing the driving velocity of wagons some parameters of interaction process of rolling-stocks with track are changed, the level of impact forces exerted by rolling-stock on the track are increased.

Reduction of dynamic interaction forces between the wheel and the rail, especially in the horizontal (transverse) plane remains an important problem. Movement of a wagon in the track section in the horizontal plane is directed by rails. Because of this effect the limit values of directing forces increase, and their values limit further increase of car speed, causing intense wear of the lateral rail profile [1].

The train running speed on the railway plan, while moving along the curved path, is limited by radii of lying curves [1, 2, 6], cant, lengths of the inserts of transition curves and straights, as well, there results centrifugal and centripetal forces [5]. They cause extra pressure of the wheels on the external and internal rail. This results in faster rail wearout, generation of distortion in rail structure, stress in rails and ties increases, and they can induce track defects, such as rails canting, splicing defects and therefore the risk for safe railway traffic appears.

In general forces acting on a train running on curved track section are presented in Fig. 2 [2].

Due to the centrifugal force there appears centrifugal transverse acceleration a_n, m/s^2. High values of this acceleration can cause discomfort to passengers. Unsuppressed lateral centrifugal acceleration determines levels of dynamic forces of wheel acting on rail, as well as the forces acting on passengers transported by train moving on the curved path (passengers comfort). According to the expertise and studies of railway experts, it was found that high unsuppressed lateral acceleration values are uncomfortable to passengers. Passengers evaluate satisfactorily prolonged and repeated unsuppressed lateral acceleration of 0.4-0.8 m/s^2. When its value is equal to 1.0 m/s^2, passengers evaluate this centrifugal acceleration satisfactorily under the condition that it is often short-lived and not repeated frequently. For railway trains with good dynamic properties values of $a_{n,kel}$ can be taken 0.9–1.0 m/s^2. To ensure the comfort of passengers according to studies carried out by Russian railway experts normal lateral unsuppressed acceleration values have been determined, with assessment of the maximum achievable speeds of passenger trains $[a_{n,kel}] = 0.7$ m/s^2, when $v_{max} \leq 160$ km/h, and $[a_{n,kel}] = 0.6$ m/s^2, when $160 < v_{max} \leq 200$ km/h [1, 2].

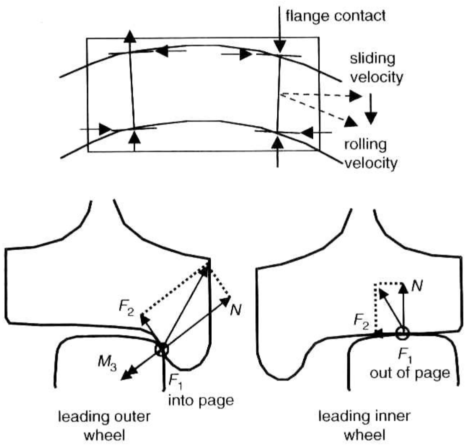


Fig. 1. Schematic view of forces acting on wheels of a bogie moving on the curved path. N is normal load, F_2 is lateral creep force, F_1 longitudinal creep force, and M_3 is spin moment [1]

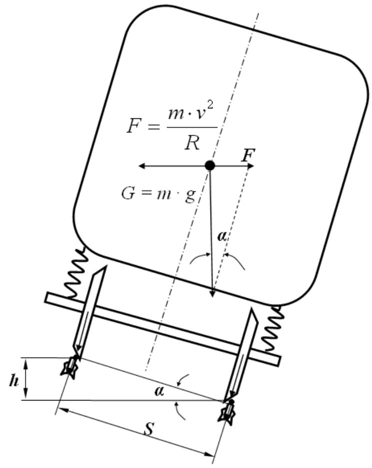


Fig. 2. Forces, acting on a train running on the curved track section [2]: F – centrifugal force, kN; F_h – centripetal force, kN; h – cant of outer rail, mm; G – train weight, kN; S – distance between the axis of rails heads, mm; α – wagon tilt angle to the horizon, in degrees

There is the necessity for such the movement of wagons that values of forces of contact and deflection between the wheel and the rail profiles were as low as possible. At the same time there will be a possibility to increase railway traffic speed, ensuring sufficient ride comfort.

Lateral vibrations of passenger wagon arising from driving along curved trajectory through symmetric irregularities of sinusoidal shape and passing track irregularities at rails junctions are investigated. Analytic, experimental and numerical research methods have been used in this work.

Exterior experiments have been carried out by help of wagon-measurer registering actual rail track irregularities. Vibrations measurement equipment VAS-21 was used to measure vibrations of wagon body. The data were processed using VAS Editor, MS Excel software packages.

For theoretical study MSC.ADAMS/View and MSC.ADAMS/Rail software packages were used. A dynamic model of a typical passenger wagon [4], exploited in Lithuania, was developed and numerical simulation of interaction of passenger wagon with track was performed.

2. Experimental investigation

Objective of the experimental measurement was to measure dynamic characteristics of wagon vibrations (Fig. 3), while running on the curved path, to define possible relation with characteristics of track irregularities of this section (Fig. 4) in the same section.

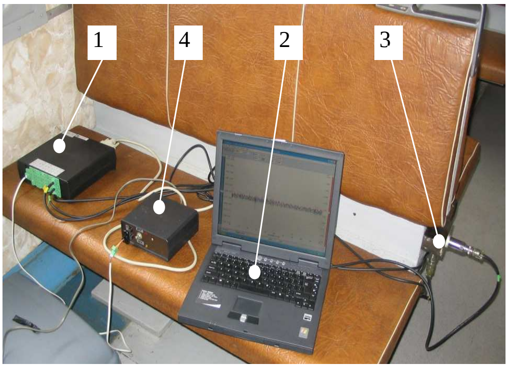


Fig. 3. Setup for measurement of wagon vibrations: 1 – measurement system VAS-21; 2 – personal computer; 3 – vibrations measuring sensors; 4 – power supply

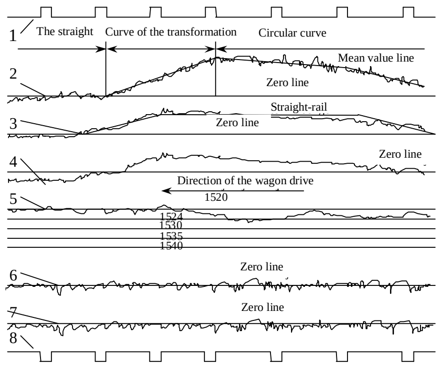


Fig. 4. Sample of the corrugations prophilograms of the wagon – measurer: 1 – notation of the speed; 2 – rails level; 3 – the right rail position in the horizontal plane; 4 – the left rail position in the horizontal plane; 5 – track width; 6 – the right rail corrugations in the vertical plane; 7 – the left rail corrugations in the vertical plane; 8 – notation of the kilometers

Comparison of the data of characteristics of transverse wagon vibrations measured during experimental studies with simultaneously recorded irregularities of the railway section track in plan is presented in Fig. 5.

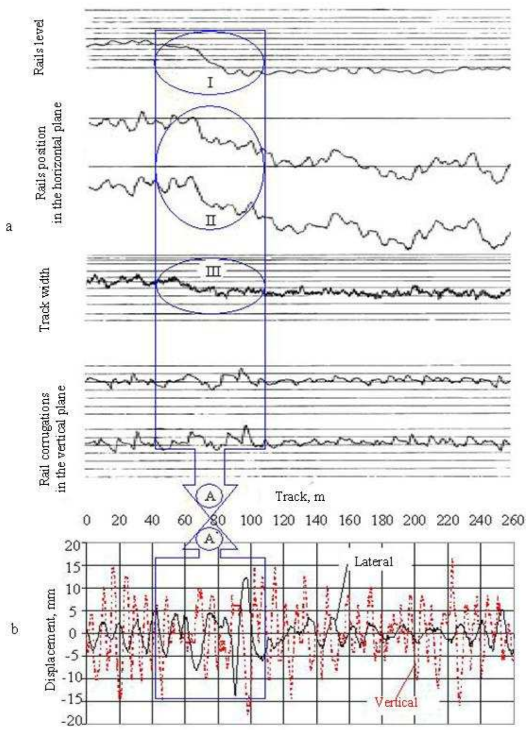


Fig. 5. Curves of condition of the measurer's tape rail track (a) and displacements of lateral and vertical vibrations of the wagon body (b), measured at the same time moment at the track section Mauručiai – Pabališkiai 61-62 km, when the wagon moves at speed 40 km/h

Track control and measurements of wagon body vibrations (Fig. 5a) were carried out in the section „Kaunas – Šeštokai" (Mauručiai – Pabališkiai 61-62 km) when the wagon was moving on curved path (radius of the curve 2 km). The wagon vibrations were measured for various rail track structures: butt-joints (track length 25 m) and jointless (longspan) rails. During the test the wagon was moving at speed from 25 to 60 km/h.

From diagrams presented in Fig. 5 one can observe that amplitudes of lateral vibrations displacements suddenly increase and the peak is observed (Fig. 5b marked area A') when the track is making a turn. From measurer wagon tape record (Fig. 5a marked area A) we can observe that impact on lateral vibrations is complex: here the change of the track level (mark I), and the situation in the plan (mark II), and track width (mark III), as well, have influence. Later, when change of the track width and the track level has stopped, amplitudes of lateral vibrations decrease. Meanwhile from the curve of displacements of vertical vibrations, given in Fig. 5b one can notice that in this case the displacements of vertical vibrations (unlike than in Fig. 5a) are significantly higher than the displacements of lateral vibrations. This is explained by the fact that the track in this stretch is worse and the vertical track irregularities in both rails are much larger (exceed 10 mm).

Lateral track stretch rails corrugation records were analyzed through calculation of different statistical parameters: medium height of rail corrugations, dispersion and correlative function.

Another statistical parameter, describing track profile, is the correlative function which is intended to determine periodicity of track corrugations. Fig. 6 presents a diagram of correlative function of track corrugations profile where periodic waves exist.

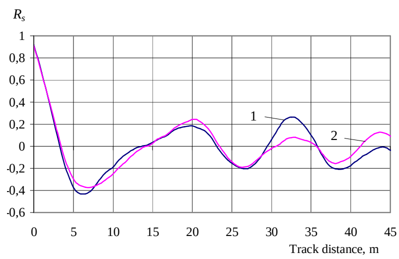


Fig. 6. Correlative function of lateral plain railway rail corrugations of: 1 – left rail; 2 – right rail

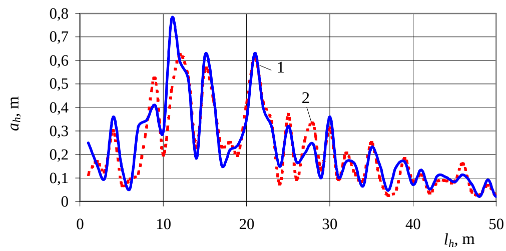


Fig. 7. Distribution amplitudes of lateral irregularities on railway rail plain with reference to wave length

After harmonic analysis of lateral track corrugations in the considered section rail, the surface roughness and their amplitudes were estimated. Fig. 7 provides distribution of amplitudes of lateral irregularities on railway rail plain with reference to wave length. The results are listed in Table 1.

Table 1. Characteristics of lateral railway rails corrugations

Rail	Medium corrugation height	Wave length derived from correlative function R_s, m	Harmonic analysis	
			Wave length l_h, m	Amplitude a_h, m
Left	0.137	15-20	4-35	0.36-0.8
Right	0.171	15-20	4-35	0.32-0.63

3. Numerical simulation

While forming dynamic model of a passenger wagon and track by means of the software ADAMS/Rail, adaptation of this system to the Lithuanian environment was one of the main objectives of this investigation. ADAMS/Rail software adaptation in this study is based on the following parameters [4]:

- bogie axle wheel profile;
- rail profile;
- railway track width (1520 mm);
- rail inclination angle.

Having formed dynamic wagon model using ADAMS/Rail software, we performed the following initial analysis of the construction:

- load analysis;
- linear analysis;
- dynamic analysis.

As the main objective of our investigation is vibrational characteristics of the wagon body, especially their influence on passengers on the basis of even movement norms, the characteristic node for our measurements was selected. It is located on longitudinal (x) wagon axis, above the bogie, at a distance of 0.7 m from body floor (at shoulder level of a sitting passenger): node "Front" (10, 0, -0.7) (coordinates are presented as a distance from wagon floor center, Fig. 9). This location was chosen aiming to compare dynamic modeling results with wagon body measurement results.

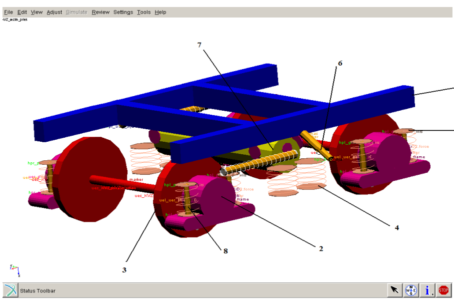


Fig. 8. Dynamic model of passenger wagon bogie

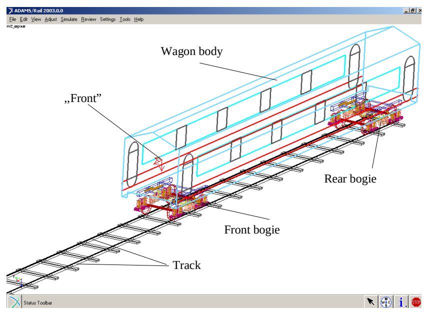


Fig. 9. Dynamic model of interaction of passenger wagon and track

Formation of the dynamic model of the wagon, moving on rails with lateral irregularities, is based on the following assumptions:

- Wheel rolling surface is perfectly smooth.
- When a wagon moves, track ground, rails and wheels are treated as rigid and tightly interconnected bodies. Thus when wagon moves through track corrugations, wheel centers reiterate trajectory of vertical rail vibrations.
- Values of track corrugations were taken from a tape made by the wagon – measurer, thus elastic rail deflection from wagon weight force has already been evaluated.
- Wagon has moved into the track section subjected to analysis at proper constant speed, before it was not affected by any forces, which could cause free vibrations.

Frequent irregularities while running on the curved path have sinusoidal shape (Fig. 10) and corrugations of rail-juncture appear due to passing track irregularities at the junction (Fig. 11) [6, 7]. Therefore in this work both types of these corrugations are selected as the object of study.

The corrugations of sinusoidal shape may be expressed by formula (1):

$$\eta_o^h(t) = a_h \cdot \sin\left(\frac{2\pi}{l_h} \cdot x\right) = a_h \cdot \sin\left(\frac{2\pi}{l_h} \cdot v \cdot t\right), \tag{1}$$

here, a_h – amplitude of corrugation wave, m; t – time, s; l_h – corrugation wave length, m; v – wagon movement speed, m/s.

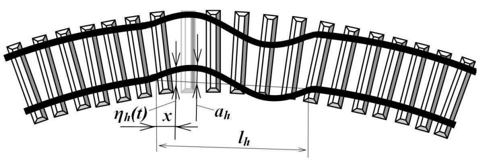


Fig. 10. Isolated rails' sinusoidal shape corrugations on the plan

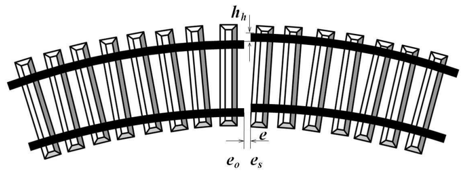


Fig. 11. Isolated rails' two rails hogging on the rail-juncture corrugations

Corrugations of the second type – rail-juncture corrugations (Fig. 11) may be expressed by formula (2):

$$\eta_s^h(x) = \begin{cases} 0, & \\ \dfrac{e}{h_h}\cdot(x), & \text{if} \quad \begin{matrix} 0 \le x < e_0, \\ e_0 \le x \le e_s, \\ x > e_s, \end{matrix} \\ e_0, & \end{cases} \tag{2}$$

here h_h – size of rails passing, m; e – size of gaps between the rails, m; v – wagon movement speed, m/s; t – time, s.

While testing the driving along the curved path (curve radius is 2 km) with irregularities of sinusoidal shape, we changed wagon movement speed from 10 km/h to 160 km/h, increasing every 10 km/h. We selected corrugation wavelengths equal to 10, 20, 30 m, and amplitudes of corrugation wave were 0.001 m, 0.003 m and 0.005 m.

Investigations were carried out at irregularities of both rails of sinusoidal shape running on the curved path and wavelength of 10 m, with amplitudes of corrugations 0.001 m, 0.003 m and 0.005 m.

Table 2. Parameters used for testing the movement along the curved path

Sinusoidal shape irregularity a_h, m	Wavelength l_h, m
0.001	10
0.003	20
0.005	30

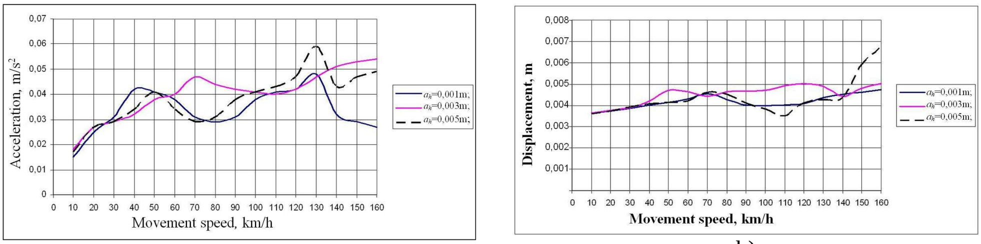
Figs. 12-14 provide the results of the numerical simulation of movement of the passenger wagon on the curved path over symmetric irregularities of sinusoidal shape in plan.

Fig. 12 provides the acceleration characteristics at different irregularities and different movement velocities. From the diagram one can observe that at wavelength equal to 10 m, accelerations of vibrations caused by excitation forces increase up to speed of ~130 km/h, and then decrease.

Fig. 12b indicates that maximum displacements increase uniformly and are achieved (when sinusoidal wave amplitude is 0.005 m) at a speed of 160 km/h.

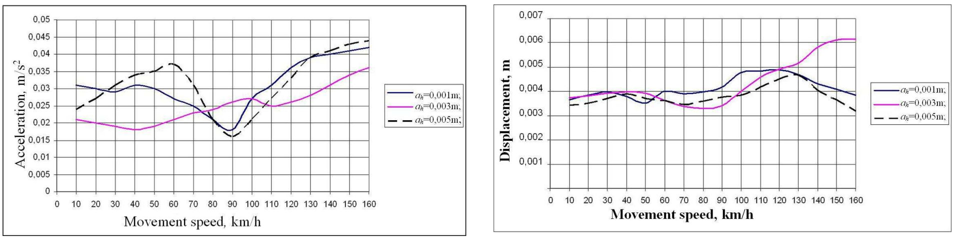
Investigations were carried out at irregularities of both tracks of sinusoidal shape running along the curved path and wavelength of 20 m, amplitudes of irregularities were 0.001 m, 0.003 m and 0.005 m.

In vibration accelerations diagram (Fig. 13a) one can observe that accelerations increase until speed of 50-60 km/h and later decrease again, and by achieving 90-110 km/h increase to the end.



a) b)

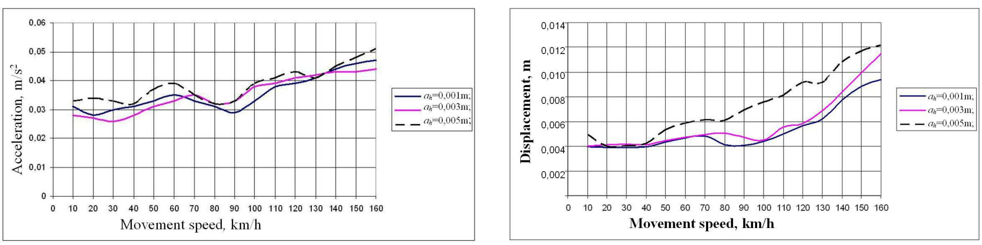
Fig. 12. Dependence of maximum values of lateral vibrations accelerations (a) and displacements (b) of front node of body on wagon movement speed along the curved path, when passenger wagon is affected by irregularities of isolated sinusoidal shape of both rails in plan, with wavelength l_h = 10 m and amplitude a_h = 0.001, 0.003, 0.005 m.



a) b)

Fig. 13. Dependence of maximum values of lateral accelerations (a) and displacements (b) of front node of body on wagon movement speed along the curved path, when the passenger wagon is affected by irregularities of isolated sinusoidal shape of both rails in plan, with wavelength l_h = 20 m, and amplitudes a_h = 0.001; 0.003; 0.005 m

Numerical investigations presented in Fig. 14, a and b were performed at irregularities of both tracks of sinusoidal shape running along the curved path and wavelength of 30 m, amplitudes of irregularities were 0.001 m, 0.003 m and 0.005 m.



a) b)

Fig. 14. Dependence of maximum values of lateral vibrations accelerations (a) and displacements (b) of front node of body on wagon movement speed along the curved path, when the passenger wagon is affected by irregularities of isolated sinusoidal shape of both rails in plan, with wavelength l_h = 30 m, and amplitudes a_h = 0.001; 0.003; 0.005 m

From the acceleration curves in Fig. 14a it is obvious that wagon movement acceleration starts to increase from 90 km/h and increases up to the end.

Fig. 14b presents diagrams of vibrations displacements of the point of study, indicating that they do not increase up to the moment when speed is 80 km/h and further increases to 0.012 m when movement speed is 160 km/h.

During the tests when passing track at the rail-juncture running on the curved path, we used the parameters of irregularities which are presented in Table 3.

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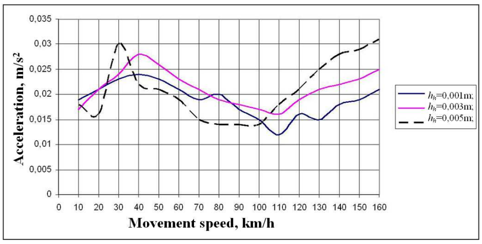
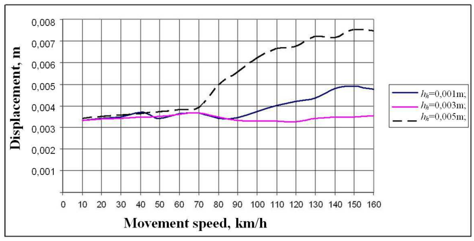
Table 3. Parameters used during tests

Size of rails hogging h_h, m	Size of gap between rails e, m
0.001	0.001
0.003	
0.005	

Fig. 15a illustrates that wagon accelerations increase from 30-40 km/h, then start to decrease and keep decreasing to 80-110 km/h and then increase again until speed 160 km/h.



a)



b)

Fig. 15. Dependence of maximum values of lateral vibrations accelerations (a) and displacements (b) of the node ,,Front“ at body front on movement speed, when the first wheel-set of front bogie of passenger wagon drives on rails passed (h_h – size of rails passing, m)

Displacement curves in Fig. 15b indicate that values at movement speed of ~10-30 km/h are slightly lower, and at the speed of 70 km/h they significantly increase.

Conclusions

This work considered a dynamics problem of a passenger wagon, i.e. horizontal dynamic processes that take place when the wagon moves along the straight and curved paths. During operation loads of various types acting between rolling-stocks and rails cause the forced wagon vibrations, which are useless to a wagon and its constituents, as well as to its passengers.

The following results were obtained by modeling passenger wagon moving through different irregularities in horizontal plane:

1. Moving along straight-line path through both rails over sinusoidal irregularities, the maximum acceleration values are reached at a wavelength of 30 m and running through the roughness of amplitude 0.005 m, and they reach 0.049 m/s^2 at movement speed of 150 km/h.
2. Moving along curved path through the same sinusoidal irregularities, the maximum acceleration values are reached at a wavelength of 10 m and running through the roughness of amplitude 0.005 m, maximum accelerations reach 0.059 m/s^2 at movement speed of 130 km/h.
3. During tests, moving in a straight line through rails passing rail-juncture, the maximum vibration acceleration reaches 0.024 m/s^2 at movement speeds of 30 km/h and 160 km/h.
4. Moving along the curved path through both rails passing rail-juncture, the maximum vibration acceleration (0.032 m/s^2) is reached running through irregularity of rails passing equal to 0.005 m, when movement speed reaches 30-40 km/h and 160 km/h.

The conducted research indicates that higher vibration accelerations are obtained when running along the curved path through irregularities of sinusoidal shape and through irregularities on rail-juncture. In addition, after the measurements and comparison of theoretical and experimental results, the data obtained could be used for theoretical studies of dynamic characteristics of a passenger wagon.

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