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SIMULATION RESEARCH OF RAILWAY CROSSINGS WITH STIFFNESS CONTROL

Summary. This research presents the existing problem of railway elements and motor – vehicle road elements at their intersections. The work also concerns issues of designing and constructing railway crossings at the intersections of motor-vehicle and rail transportation. A new conception of vibroisolated railway crossing is introduced, based on the analysis of a discrete-continuous system.

SYMULACJA PRZEJAZDU KOLEJOWEGO ZE STEROWANĄ SZTYWNOŚCIĄ

Streszczenie. W pracy przedstawiono koncepcję wibroizolacji przejazdu kolejowo drogowego, którego system izolacji jest kontrolowany ze względu na obciążenia dynamiczne pochodzące od pojazdów mechanicznych, tak aby jego oddziaływania dynamiczne na otoczenie były minimalne.

1. INTRODUCTION

Rapid technological development in present times, closely associated with technical and industrial development, was on the one side the cause of conception of a variety of modern technological resolutions, on the other side it exacerbated the negative phenomena that can constitute a serious threat to humans and their natural environment.

An industry branch significantly contributing to this threat is rapidly developing transportation, either in terms of railway transportation (railway trains, tramway cars) as well as automobile transportation. Steady growth of automobile roads' network and increasing number of vibrational-transport applications is inseparably linked to interference with natural environment. Automobile transportation, as well as railway transportation, separates in an unambiguous manner the terrain through which it runs, occupies large areas and through its intensity exerts detrimental influence on the environment being the source of noise and vibrations.

As transportation, in a broad sense, is associated with inherent dynamic influence on the environment, causing mechanical vibrations of foundations, ground and engineering constructions, it is necessary to minimize their damaging effect by conceiving new concepts of transportation devices with limited emission of vibroacoustical energy as well as complex vibroisolating systems, standing as an obstacle to vibrations radiating to natural environment.

In the past decade motor-vehicle traffic increased several limes over. Side effects of this sort are not only increasing air pollution, but also expedited wear of road and street surfaces, run over by loaded trucks. Damaged surface on many railway crossings presents a threat to vehicle traffic safety and continuity. One of the most crucial spots is an intersection of a motor-vehicle road with railway tracks, especially with railway embankment.

Present-day constructions of railway crossing as one-level intersection of rail transportation (railway, tramway) and automobile transportation do not meet the current requirements of modern-day transportation in terms of necessary speed limits imposed on both types of transportation, dynamic influence on the environment (noise, vibrations), which comes from railway and automobile vehicles, concrete slabs' "keyboarding" and resulting technical degradation of a crossing based on shift of slabs positioning and change of slabs' fulcrum points. It is accompanied by transmission of vibrations and noise to neighboring objects and detrimental dynamic influence on the environment. The construction of these crossings is specific, in terms of dynamics and acoustics, in that dynamic effects coming either from railway vehicles as well as automotive vehicles are transmitted entirely and directly on concrete slabs of the crossing, which affects railway ties as well as the ground.

At present research includes new conception of such construction of a railway crossing that would eliminate or at least reduce those detrimental phenomena.

2. CONCEPTION OF VIBROISOLATED RAILWAY CROSSING

The purpose of this research is modeling of vibroisolated railway crossing based on discrete-continuous model and its dynamic analysis with respect to minimization of dynamic influences on the environment, coming from motor vehicles. For this purpose construction requirements were formulated for the model and analysis was executed of algorithms used for engineering design assistance. Railway-crossing model was constructed in SolidWorks system, and then, after determining the parameters of kinematic bonds, a simulation model was conceived in MSC.VisualNastran 4D system. Vibroisolation parameters and materials for the model prototype and actual vehicle were assigned. Then the simulation of distortions and railway-crossing vibrations was executed with respect to influences on the environment at different loads and speeds of vehicles. Also model test of vehicle's wheel slide were carried out on a rubber plate with various types of goffering. This work also includes creating a date base of structural elements of railway crossing.

The idea of constructional solution of railway crossing presented in this research involves mutual independence of railway and motor-vehicle road with each other, reduces interactions between both types of transportation (railway and motor-vehicle) and preserves more evenly distributed static and dynamic loads.

Resilient elements are introduced in railway crossing construction which purpose is to isolate railroad from the automobile road in order to minimize dynamic effects of vehicles passing through the crossing and the slabs centring relatively to the rails.

The main structural element transmitting vibrations coming from railway transportation and automotive vehicles presented in this solution is string system, composed of carrying elements – strings – with appropriately selected tension. Application of resilient vibroisolating and sound-absorbing materials between rails, slabs and bedding significantly lowers the dynamic and acoustical effects carried across on natural environment. Thus the bedding (ground) of the railway crossing is subject to much lower stresses and dynamic effects transmitted to the surrounding from railway and motor-vehicle transportation is reduced. Distribution of structural vibrations, which are one of the noise source emitted to the environment during the overpass of railway and motor vehicles, is limited.

The application of this type of crossing construction does not require modernizing of railway subgrade during its assembly, preserves from water and pollution penetration to the sub-track and is favourable in maintenance and repairs.

3. MATHEMATICAL MODEL OF VIBROISOLATED RAILWAY CROSSING

Mathematical model accepted to dynamic analysis must be significantly simplified for the reason of achieving possibly a simple solution in the closed (analytical) form. It does not make allowance for, among other things, non-linear phenomena that must occur with this type of technical solution at the early stage of problem solving.

In the analysis the eigenfrequencies of the model presented in fig.1 are determined, which will enable to select such vibroisolation parameters of elastic railway crossings that in effect would result in avoiding the phenomena of excessive influences on the surrounding and the expedited degradation of these crossings. In vibroisolation system of railway crossing enclosed in fig.1 mass m is substitute mass corresponding to truck-vehicle mass, , ρ - string density, F – string's cross section, , H_{st} - static horizontal component of string tension, H_d - dynamic horizontal component of string tension

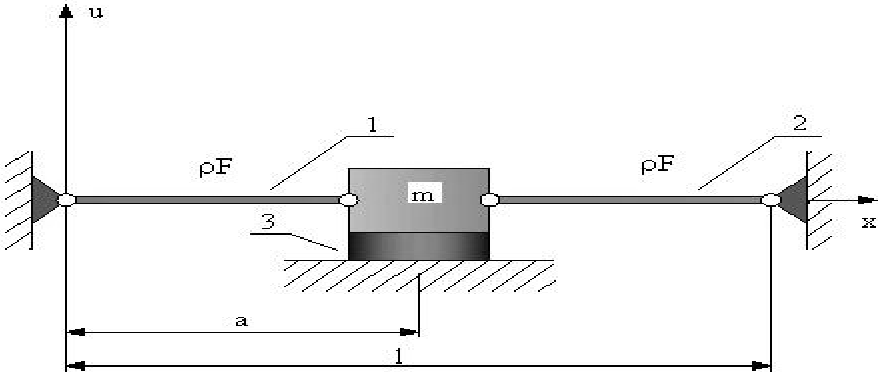


Fig.1. Mathematical model of railway crossing
Rys1. Model matematyczny przejazdu kolejowego

Differential equations describing free vibrations of this system have the form of:

$$\rho_1 F_1 \frac{\partial^2 u_1}{\partial t^2} = H_{st} \frac{\partial^2 u_1}{\partial x^2} + y_1'' H_d \tag{1}$$

$$\rho_1 F_1 \frac{\partial^2 u_2}{\partial t^2} = H_{st} \frac{\partial^2 u_2}{\partial x^2} + y_2'' H_d \tag{2}$$

$$\frac{\partial^2 u_1(a,t)}{\partial t^2} = a^2 \frac{\partial^2 u_1(a,t)}{\partial x^2} \tag{3}$$

where: $a^2 = \sqrt{\frac{E^*}{\rho}}$, E^* - dynamic module of rubber element, ρ - rubber element's density;

with boundary conditions:

$$u_1(0,t) = u_2(l,t) = 0 \tag{4}$$

$$u_1(a,t) = u_2(a,t) \tag{5}$$

$$m\frac{\partial^2 u_1(a,t)}{\partial t^2} + \frac{EF}{l}\frac{\partial u(a,t)}{\partial x} + H_d[y_1'(a) - y'(a)] + [H_{st} + H_d]\cdot[\frac{\partial u_2(a,t)}{\partial t} - \frac{\partial u_2(a,t)}{\partial x}] = 0 \tag{6}$$

$$y_1(x) = f_a \frac{2\mu \cdot l \cdot x + (l - x)x}{(1 + 2\mu)a \cdot b}$$

$$y_2(x) = f_b \frac{2\mu \cdot a + (l - x) + (l - x)x}{(1 + 2\mu)a \cdot b}$$

$$H_d = \frac{EF}{l}\left[\int_0^a \frac{\partial u_1}{\partial x} y_1'(x)dx + \int_a^l \frac{\partial u_2}{\partial x} y_2'(x)dx\right]$$

where: $\mu = \dfrac{m \cdot g}{\rho \cdot l}$, $f_{a,b}$ - bending at the point $x = a$.

After specifying the eigenfrequencies ω_i (i=1,2,…υ), the tension of the string H can be controlled so that vibroisolation condition could be fulfilled in the form of:

$$\frac{\omega_w}{\omega_{i\,\max}} > \sqrt{2} \tag{7}$$

In case of discrete-continuous system, sometimes the condition (7) cannot be met and technical vibroisolation condition should be applied:

$$\omega_i < \omega_w < \omega_{i+1} \tag{8}$$

where: i=1,2,3,…,n

Hence, after comparing excitation frequencies during the overpass of motor vehicles and eigenfrequencies of elastic railway crossing according to the accepted calculating model (fig1), it can be stated that condition (8) was fulfilled. Conception of railway crossing was founded on this. The elasticity and mass parameters of the crossing were selected based on the analysis of a discrete-continuous model discussed in this section.

4. RAILWAY CROSSING AS A STRING SYSTEM

In pull-string systems the main element is a string, that transfers tensile forces, and in some cases slight bending moments, transverse forces and torques. Narrow range of transferred loads causes that a string as a structural element – within its correct operational limitations from material-strength point of view – is a perfect element. Its material is fully exploited, and acceptable tensile stresses are much bigger than for other one-dimensional objects. Therefore strings are eagerly and more and more often applied as carrying structural elements in building industry and machine constructing. In the solution applied the string system is tensed by a constant force that can be controlled – string tension depends on external loading.

From an engineering point of view individual strings as well as string systems composed from stings are certain type of carrying elements of utility structure (such as rods, disks, plates or coating) and their only purpose is to appropriately transfer the loads affecting the structure. For this reason they should, depending on the type of the structure, be appropriately shaped, so that apart from basic material-strength requirements they could, in a possibly maximal extent, ensure lightness, reliability and economy of the designed construction. Computing string systems, like in every engineering problem, is inseparable element of designing those systems. The final effect of the computation is in determining the forces in individual strings and checking if they do not surpass the acceptable values and also examining the system distortions and assessing if they can fit within acceptable limits.

The following loads decide about the magnitudes of those forces and distortion values:

- specific weight of strings,
- external forces concentrated and distributed in a continuous manner,
- internal forces of string tension in constructions,

- internal forces caused by temperature changes and assembly conditions,
- dynamic loads,

Internal forces, corresponding to purposefully introduced distribution of internal load specific to other constructions, play important role in string systems. In consequence, string load or string-system load is a direct function of their geometry. Additionally, the problem of string calculation is generally geometrically non-linear issue. It is not as much a result of significant lines' deformability (relatively small Young's modules), that of the fact string geometry depends on its loading and the initial dimensions principle cannot be applied (e.g. the shape of the line hanging loose is totally different if we put a concentrated force at one of its points. Therefore calculations by means of superposition method cannot be carried out unlike in many problems of statics of other objects.

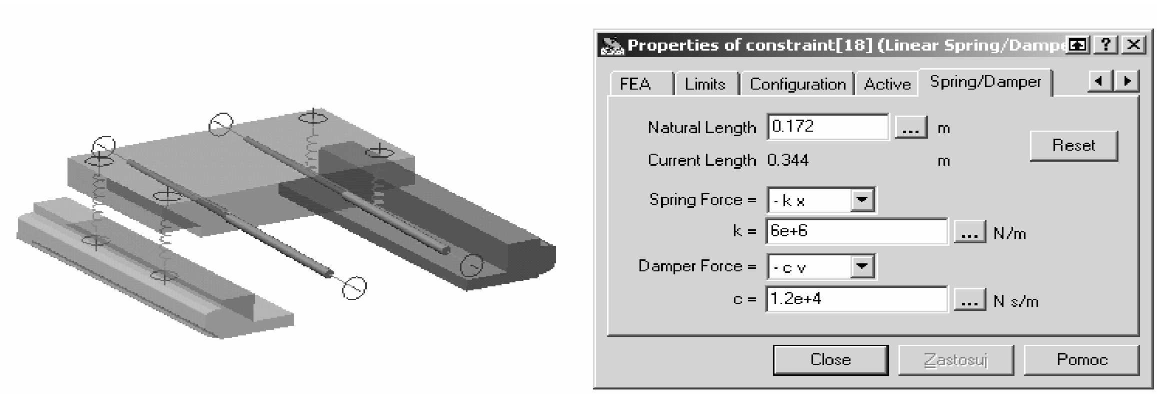
5. SIMULATION RESEARCH OF RAILWAY-CROSSING DYNAMICS

Simulation of railway-crossing dynamics was carried out by means of MSC VisualNastran 4D system. The purpose of this research was determining vertical displacements and accelerations of reinforced-concrete slabs in relation to different railroad-crossing loads and lines tensions.

Also the influence of sliding on elastomer slab surface was taken into consideration, as well as different goffering types. Contact between the wheel tyre and railway-crossing elements was modeled. Component elements of the crossing: external and internal beam and rail were fixed.

6. CHARACTERISTIC OF THE SIMULATION OBJECT AND MSC VISUALNASTRAN 4D SYSTEM

Every railway-crossing element was modelled as a stiff body, which then were connected by appropriate kinematic bonds. Those kinematic bonds were assigned to specific elasticity and damping parameters according to the accepted solution. Contact between the wheel tyre and railway-crossing elements was modeled. Component elements of the crossing: external and internal beam and rail were fixed. Every mobile element was deprived of the appropriate freedom degrees. External slabs have the possibility of vertical movement under the influence of external load and displacements along *x* and *y* axes on a horizontal plane. Fig.2 presents basic values of elasticity and damping parameters.



Properties of constraint[18] (Linear Spring/Damp

Natural Length 0.172 m

Current Length 0.344 m

Spring Force = - k x

k = 6e+6 N/m

Damper Force = - c v

c = 1.2e+4 N s/m

Fig. 2. Example values of parameters of elasticity and damping in vertical plane
Rys.2. Prykładowe wartości sprężystości tłumienia w płaszczyźnie pionowej

Model of railway crossing was created in SolidWorks system as a composition of the following elements:

- vibro- and sound-isolating beam;
- external surface slab;

- internal surface slab;
- strutting screw;
- string with a tightening sleeve;
- railway or tramway rail;
- railway tie.

Fig.3 presents graphical sketch of the railway-crossing model.

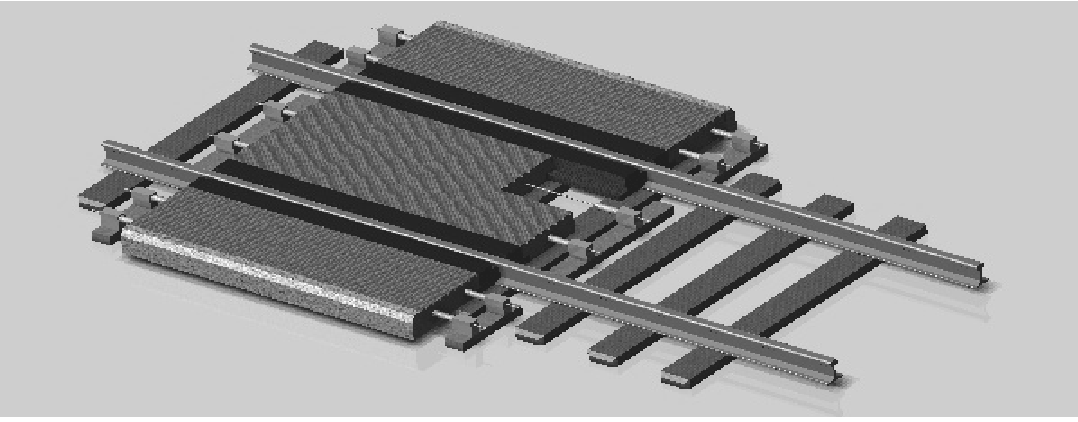


Fig. 3. Railway crossing performed in SolidWorks software
Rys.3 Model przejazdu kolejowego wykonany w systemie SolidWorks

Simulation of railway crossing was carried out by means of MSC VisualNastran 4D system. Every railway-crossing element was modelled as a stiff body, which then were connected by appropriate kinematic bonds. Those kinematic bonds were assigned specific elasticity and damping parameters according to the accepted solution. For simulation purposes models of vehicles were built: a motorcar of a mass of 1300[kg] and a van of a mass of 2500[kg]. Fig. 4 shows the visualisation of a car overpass in consecutive phases of coming-on and off the railway crossing.

1. Front wheels – coming onto the slab

2. Front wheels – coming off the slab

Fig. 4. Visualization of railway crossing in MSC VisualNastran 4D system
Rys.4. Ujęcie pojazdu w czasie symulacji (1 – wjazd przedniego koła na płytę, 2 – zjazd przedniego koła z płyty)

The parameters that can be changed during consecutive simulations include:

- magnitude of the force of horizontal tension in a string;
- damping value of rubber elements;
- force in strut screws;
- speed of a vehicle coming onto the crossing;
- vehicle mass;
- vehicle-suspension stiffness;
- surface type.

6.1. Dynamic analysis results

Table 1 contains variable parameters (tensile force, damping, stiffness, drive-through speed) for executed simulations. Also a simulation for traditional railway crossing, without application of vibroisolation, was carried out.

Tab.1

Simulation parameters

Simulation number	Type of motor vehicle	Vehicle mass [kg]	Vehicle speed [km/h]	Damping coefficient of resilient element [Ns/m]	Tension force in the string [kN]	Force in the stud bolts [N]
1	motor car	1300	30	12000	40	500
2	van	2500	30	12000	40	500
3	motor car	1300	50	12000	40	500
4	van	2500	50	12000	40	500
5	motor car	1300	70	12000	40	500
6	van	2500	70	12000	40	500
7	motor car	1300	100	12000	40	500
8	van	2500	100	12000	40	500
9	motor car	1300	70	12000	10, 20, 40, 60, 80, 100	500
10	van	2500	70	12000	10, 20, 40, 60, 80, 100	500
11	motor car	1300	70	1000, 5000, 12000, 20000, 30000	40	500
12	van	2500	70	1000, 5000, 12000, 20000, 30000	40	500

Fig.5 and 6 present the example results of simulation carried out for a motorcar as functions of velocity, tensile force and damping of vibroisolation system.

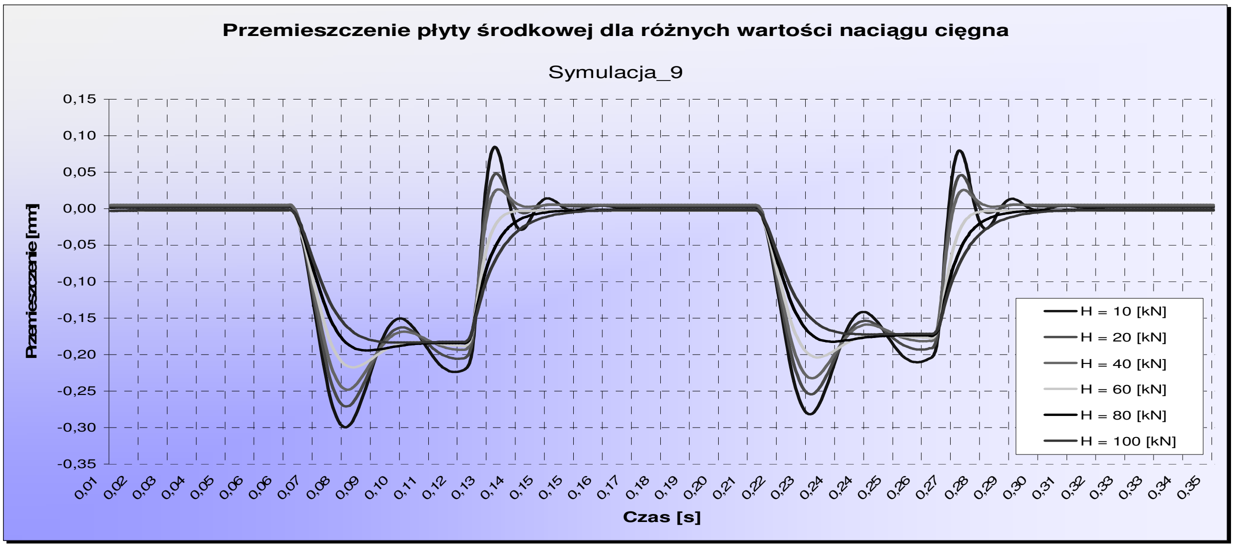


Fig. 5. Center slab displacements in case of a motorcar drive-through at the speed of 70 [km/h].
Rys.5 Przemieszczenie płyty środkowej podczas przejazdu samochodu osobowego z prędkością 70 km/h dla różnych sił naciągu cięgna

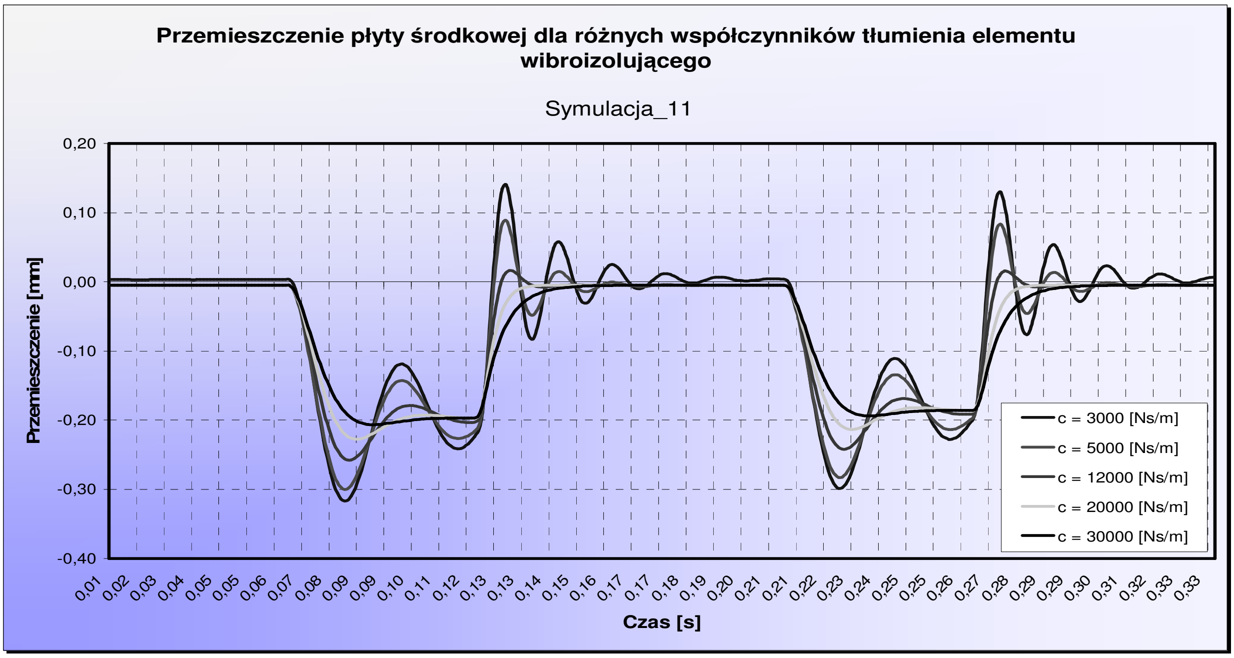


Fig.6. Center slab displacements in case of a motorcar drive-through at the speed of 70 [km/h]

Rys.6 Przemieszczenie płyty środkowej dla różnych współczynników tłumienia elementu wibroizolującego w trakcie przejazdu samochodu o masie 1300 kg i prędkości 70 km/h

Fig.7 shows displacements of centre slab of vibroisolated railway crossing and the crossing without vibroisolated elements. Comparing the vibration amplitudes of centre slab in both types of crossings is the index of assessing the efficiency of system vibroisolation. Amplitude-frequency characteristic for both cases are set together in fig.8 and 9.

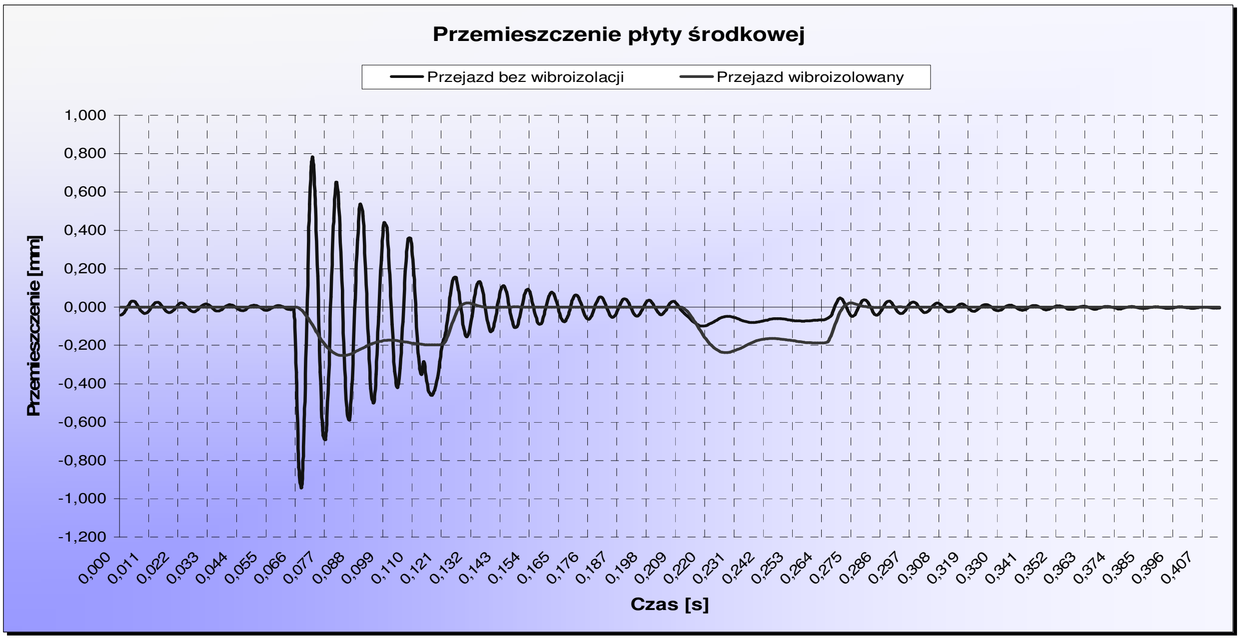


Fig 7. Center slab displacements for vibroisolated and traditional railway crossing in case of a 1300 [kg]-motorcar drive-through at the velocity of 70 [km/h]

Rys.7 Przemieszczenie w czasie płyty środkowej przejazdu wibroizolowanego i bez wibroizolacji w trakcie przejazdu samochodu o masie 1300 kg i prędkości 70 km/h

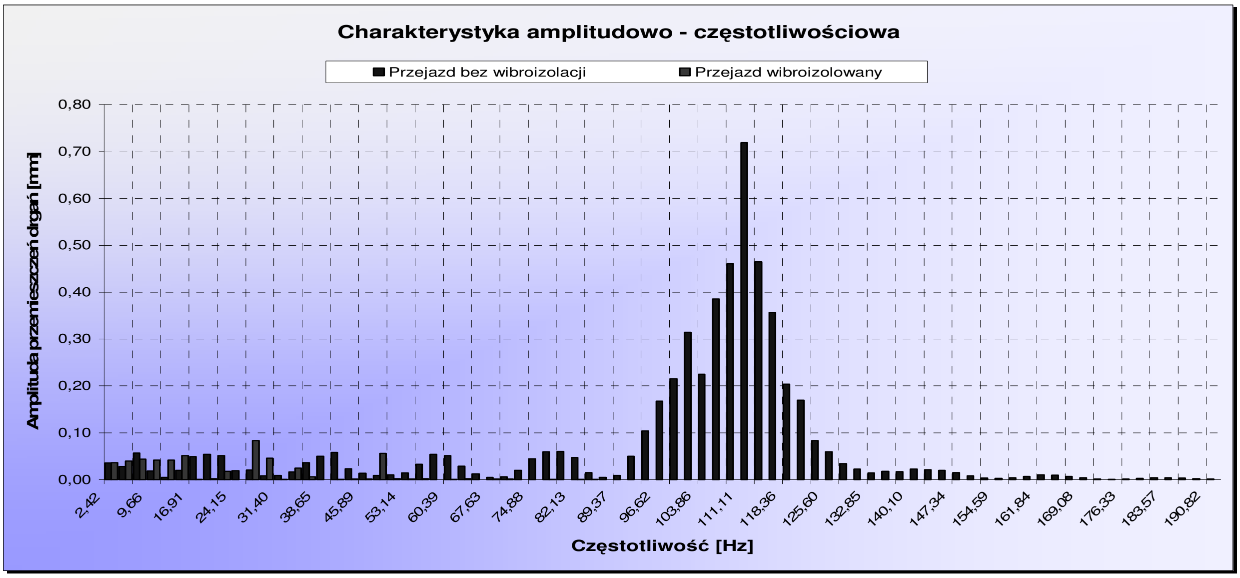


Fig.8. Amplitude –frequency characteristic for vibroisolated railway crossing and the one without vibroisolation
Rys.8. Charakterystyka amplitudowo –częstotlowościowa drań płytyśrodkowej wibroizolowanego (kolor czerwony) i tradycyjnego (kolor niebieski) – przejazd z prędkością 70 km/h

Based on amplitude- frequency characteristic frequency ranges of centre-slab vibrations for both types of railway crossings can be specified. In case of vibroisolated crossing frequencies in the range of 10 – 50 [Hz] are predominant, but then they are practically non-existent, whereas for the railway crossing without vibroisolation these frequencies are included in the range of 80 – 140 [Hz] and their displacement amplitudes are significant.

7. CONCLUSIONS

- Based on the simulation research of vertical displacements of concrete slabs (fig.7 and 8) and simulations involving velocities of 30 to 50 [km/h] it can be noticed that vertical displacements, for vehicle masses of 1300 and 2500 [kg], with velocity rising from 30 to 100 [km/h], are linearly dependent on the mass of a vehicle passing through the railway crossing.
- After executing consecutive simulations of line tension as the function of vertical displacements of external slab during the motorcar drive-over, a temporary loss of contact was observed between the concrete slab and vibroisolation beam. The slab deflection above zero-level increases in relation to the increase of motorcar velocity (from 30 to 100 [km/h]) and is directly proportional to the vehicle mass. That effect is reduced as the string tension increases (from 10 to 100 [kN]), which can be noticed in graphs (fig.5). For example, increasing the string tension from 10 to 60 [kN] (fig.6) during a motorcar drive-through at the speed of 70 [km/h], the phenomenon of slab leaping (deflection above zero-level) is practically eliminated.
- Having analysed graphs (fig.6) we can observe large influence of change in damping properties of isolating element (rubber beam) on displacement magnitudes of concrete slabs. By appropriately increasing damping magnitude we can control and reduce maximum slab deflection. For example, increasing damping magnitude by 66% form graph 10 we can observe decrease in centre slab deflection by approximately 12% (in case of a motor-car at the speed of 70 [km/h]).
- It can be concluded that the displacement of concrete slabs, both external and internal ones, depends to a significant extent on string tension-force magnitude. For example, by increasing the string's tension from 20 to 80 [kN] displacements were reduced by approximately 30% (in case of a motor-car at the speed of 70 [km/h]).
- Analysis of graphs in fig.7 and 8 proves the effectiveness of applied vibroisolation.

Summarizing, based on realized dynamic analysis it can be stated that the introduction of a string as an additional vibroisolation element is enormously favourable in designing the constructions of railway crossings. Adjusting the magnitude of string tension we can control, to a large extent, vertical displacements of slabs and eliminate the phenomenon of their skipping. String tension can be adjusted in relation to the load magnitude of railway crossing. Stiffness of the crossing can be very easily increased at the spots of congested traffic and greater loading. Damping magnitude of rubber vibroisolation elements applied in the construction of the railway crossing should be as high as possible in order to limit the vertical displacement magnitudes of rubber-reinforced concrete slabs, so at the same time reduce the risk of slabs leaping. The application of strut screws between extreme concrete slabs and resistive blocks enables to control the forces compressing slabs in the railway-crossing and consequently enhances the stability of the crossing and prevents from slab displacement along the tracks

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