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ANALYSIS OF CIVIL ENGINEERING STRUCTURES VIBROISOLATION EFFECTIVENESS

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Abstract

A properly designed and manufactured vibration isolation system of railroads and civil engineering structures has a decisive influence on the reduction of vibrations caused by crossing trains, trams and subway transferred to residential buildings This article presents an overview of current vibration isolation systems of railroads and civil engineering structures. Based on the effectiveness of the protection of residential and industrial buildings from vibrations the ranking of vibration isolation systems was proposed. The article also attempts to assess the effectiveness of vibration isolation systems currently used in rail trails. For this purpose, a discrete-continuous model of vibration isolation system of railway and tramway rails was build. For this model, dynamic analysis was carried out. Performed analysis allowed determining range of the natural frequency of vibration isolation system. The results of dynamic analysis allow pitching shift the natural frequency of the system under consideration from the frequency of excitation, which in turn is a fundamental condition for the proper operation of the vibration isolation. As part of work on a physical model of vibration isolation system there was also developed one-level crossings of roads and railroads. The work was carried out in a research project 4875/B/TO2/2010/38 financed by Ministry of Science and Higher Education.

Keywords: *vibration analysis, discrete-continuous model of vibration isolation system*

1. Introduction

Intense progress of the civilization in the current century, connected closely with the development of the technique and the industry, caused the coming into existence of many outstanding technical solutions but also increasing occurrences jeopardizing natural elements of the human environment. In the threat, a constantly developing transport and a motorization have a significant contribution being one of important conditions of the economic development of states and development progressing along with them of the road network both of track as well as car communication. In countries being characterized by a rapid development of the transport and the motorization phenomena of raising protests by the number of social organizations are being observed about the significant amount of voices of the support which are often they taken into account.

Roads of the rail transport, car, and especially dual carriageways, are exerting the adverse environmental effect. In the explicit way, they are dividing the area through which they are proceeding, occupy significant areas of lands relatively, moreover are troublesome because of intensity of the move. The problem existing already in R.P. of the influence of roads on the natural environment, albeit not as drastic as industrial pollutants, exists and just enough expansions of the road network will be deepening. For the situation on roads, a development of the automotive industry is decisive. The rising number of cars causes the accretion of the number of held journeys by car and transports on road transport. In Poland, these occurrences led to the surcharge of the road arrangement. Hence, also at every stage (of the planning, the design, the structure, the maintenance and the use of roads) one should aspire for avoiding mistakes being able to affect the natural environment negatively and as far as possible minimize adverse effects of the influence of the road transport in wide of this word for meaning.

Establishing and priori we are dealing with influences adversely affecting for surrounding the man, it is essential statement, that one from the most of adverse effects of the rail transport and road, into the huge way littering the natural environment there are pulses. Pulses are an arduousness about the universal social reach and in all fields human activities are appearing, concern all citizens, are adversely affecting their health, are hindering their rest and the recuperation, reducing effects of their work and increasing the probability of the appearance of accidents of examinations in the course of work Z conducted and analyses it results that they are applying about 30-40% of populations of our society and them in the main measuring cup, tram, motor, air, sea rail transport are a source). Peculiarly residents of large urban agglomerations and cities are exposed to pulses about industrial character, which the heavy traffic of means of transport carrying supply of raw materials out and the transport of produced products are appearing in. The same cities additionally are encumbered with pulses coming from public service vehicles and individual vehicles. In this place, one should emphasize that the road transport, under the condition of the surface correctly carried out and kept, is posing a smaller threat to surrounding, from a point of view of pulses, than the tram or train transport relatively.

Pulses have a significant influence on the construction of buildings, causing their damage, of which repairs that are more frequent are a consequence, and in drastic coincidences as a result of neglecting on the part of the public service, can lead to the construction disaster. Peculiarly pulses provoked by the communication for historic buildings located mainly in historical centres of cities, by narrow small streets, on lands about disadvantageous geotechnical properties are dangerous. As a result of the propagation of pulses in ground also a degeneration of the functional usefulness of such public buildings like hospitals, schools, residential buildings is coming (pulses passed on to the body of residents). One should also recall that pulses are the source of the noise emission of seeing influencing the human organism harmfully or evoking adverse feelings immediately psychological comfort.

Since widely inseparable a dynamic influence is accompanying the understood transport, in particular on one-level intersections of car and train roads which pulses of engineering structures of different type are calling, the aspiration to the minimization of their detrimental action is a need and in consequence led to the creation of new solutions of structural members participating in the transport about the limited vibroacoustic broadcasting, and what with it inseparably is tied up, of filed arrangements vibroisolation obstructing in diffusing oneself of pulses to surroundings.

Problem of appearing of dynamic influences, of which direct pulses are causing mechanical objects is known from the moment of the fast industrialization, which started in the 19th century From it of also a moment an issue of the minimization of this adverse influence is appearing. This issue is being named vibroisolation. They were and they are a subject of many works scientifically - research, which works are applying both vibroisolation active consisting in reducing moved forces to a minimum for surrounding by machines of different type and devices as well as passive which relies on the isolation from pulses of employees and peculiarly sensitive for pulses of elements of measurement devices.

In the light above problem of limiting dynamic influences to surrounding from the rail transport and road, he appears as one of serious problems of the modern science and constitutes the basic problem appearing at the roads design of the rail transport and car. This issue should be solved comprehensively i.e. a conducted dynamic analysis of the model containing both dynamics of track vehicles, and dynamics of base in oneself including the element he is which should be vibroisolation. By now these issues are being solved individually dynamics of the vehicle are being considered on the path and independently vibroisolation and limiting dynamic influences from these vehicles to the environment.

Of arrangements, moreover in order to automate the process of designing filed vibroisolation systems were used the CAD/CAM [1] which are an indispensable tool for designing and constructing in the routine work at present. As the modern tool, they are replacing the traditional drawing board and “paper” library of norms, of catalogues, and offering the help of different kind in analyses, the modelling and the simulation. They let with the computer prepare the entire project along with documentation, it is possible also with their help to create the model of the designed device, to examine him from different sides, to effect endurance calculations to carry out an analysis, and what's more to simulate his action.

Taking all these elements into account allows for projects but next of implementing real arrangements vibroisolation of roads of the rail transport which were carried out at home and abroad and concerned both of engineering structures (bridges, flyovers, platforms of railway stations) as well as of rides on the crossroads track and vibroisolation of train roadbeds.

2. Theoretical bases of the description and analyses of arrangements vibroisolation of structural elements of roads of rail and automobile transport

Theory of vibroisolation is distinguishing into two cases i.e. restrictions of sending powers of the dynamic type triggered through machines and means of transport to surroundings (vibroisolation weight) or of limiting their influence on surrounding (vibroisolation transfer). In both these cases of mum for making f pulses with frequencies f < 100 Hz and it results from the accepted model of the system vibroisolations as the discreet agreement about 1-st degree of freedom. Since a problem of tracks is not only pulses understood as dynamic influences but also material pulses which are responsible for material sounds, the above theory isn't appropriate in case of the withdrawal of pulses about frequencies in the period f = 100-5000 Hz. Since among others solving a problem of the influence on surrounding the track and car communication is a purpose of this work one should take aspects of material pulses into account also. Analysing courses known in literature of the fluctuation in the function of the frequency of extortions of pulses, already at the quotient $\frac{\omega}{\omega_0}=10$ (ω frequency of the extortion, ω_0 - frequency of own pulses of the arrangement vibroisolation) the insularity of material pulses is equal to 35-40 dB and at the quotient $\frac{\omega}{\omega_0}=100$ value is equal to 60-80 dB. In practice, values of such a great insularity are not possible to achieve the layout on account of the structure vibroisolation.

Mathematically it is possible to determine such issues as the optimisation process with certain restrictions. Functions of the objective, in this process are determined depending on the considered type of organising changes of the vibration amplitude resulting from the technological process e.g. as the minimum for the given frequency, at least applications energy, minimum of the dynamic influence on surrounding the extortion for the determined frequency.

These restrictions in the process of designing train tracks, of roadbeds of track vehicles, result from structural restrictions to which they belong: arranging elements elastics and damping, acceptable static diffractions, arranging mass, technological possibilities of the realization of resilient elements about demanded parameters, as well as from outside restrictions e.g. of dynamic influences on the environment.

Selection of parameters of elements elastics should in the modern presentation be conducted in the support analysis of the model vibrating along with equations, which are taking into account dynamics of transportation equipments. For roadbeds, bed on elements elastics - suppressing in the general case I am entertaining one another model about six degrees of freedom, treating these arrangements as stiff lumps supported on without mass elements elastics and damping - suppressing. Appearing in the reviewed arrangement is an effect of such an approach of six frequencies of own pulses. If a frequency of the extortion will appear in the analysed arrangement is level one from frequency of own pulses, then a phenomenon of the resonance will appear. The address can cause occurrences of the resonance disadvantageous, from a technological point of view growth of the fluctuation of the device and in extreme cases for breaking is holding prisoner resilient. In order to prevent it, in the course of the process of designing, one should conduct the dynamic analysis of forced pulses, letting the correctness of the selection of elements the evaluation elastics - mass. Classic approach towards the circuit design vibroisolation consists in bringing dynamics of the arrangement about to the model about one or two degrees of freedom. It is possible by such a selection and arranging elements elastics- suppressing so that the movement of the model of the system occurs along one of main central pivots of the inertia. So that it is fulfilled, the following condition must occur: arranging resilient elements under the arrangement vibroisolation must assure so that the middle of their stiffness corresponds to the middle of mass of the arrangement vibroisolation. It requires proper arranging resilient elements above all with regard to main central pivots of the inertia. Such a climb allows for bright determining characteristics amplitude - frequency and meeting the conditions of scopes vibroisolation for individual types of objects vibroisolation, provided that a structure is assumed without mass of damping – suppressing elements. Such a case is not appearing in an accident vibroisolation of roads of the rail transport and car, where mass of the element is significant. In this case, when we are dealing with placed dynamic objects, selection vibroisolation is based on the model analysis about the structure discreet – constant.

The theoretical research on minimizing vibration isolation should be distinguished from the effects of dynamic environment at low frequency f<50 Hz and isolation of components due to the high-frequency vibrations in materials known as acoustic isolation, which is not the subject of this work. We have two types of vibration isolation: force and displacement. The first concerns the limitations of dynamic influence on the substrate, the second is intended to reduce vibration transmitted from the ground to object. In the case of machinery and transport equipment, we have in principle to deal with force vibration isolation. The condition for proper operation of vibration isolation system is to fulfil the condition:

$$\frac{f}{f_0} \geq \sqrt{2}\,, \tag{1}$$

where:

f – excitation frequency,

f_0 – natural frequency.

The condition (1) is not always feasible because the mechanical system, which is vibroisolated can be exposed to multiple resonances. Hence, it is necessary to weaken the condition of vibration isolation:

$$f_{0i} < f_w < f_{0(i+1)}, \quad i = 1,2,...,6\,. \tag{2}$$

This means that the frequency of excitation should be contained within the range bounded by two consecutive natural frequencies. If the mass of the vibration isolation element is significant, as is the case of machinery and transport equipment, where the geometrical elements of the vibration isolation, assimilated to a belt or a sheet modelling of vibration isolation system as a discrete system carries certain risks. The most important of these is the phenomenon of elastic wave elements because you can no longer assume that these elements are massless. In such a flexible element may appear so. internal resonances, which can cause the effect of isolation would be counterproductive, i.e. reduction of dynamic impact on the environment. To prevent this possibility, it is necessary to determine the natural frequency of vibration isolation element based on consideration of the vibration isolation system as a model of continuous or discrete-continuous.

Vibration isolation element in our model is the rubber plate with continuous distribution of mass, which is regarded in model as a longitudinally vibrating rod. In the vibration isolation system of roads (Fig. 1) mass m_p is the mass of the platen (so-called inertial platen), and coefficient k_g is the stiffness of constant-weight distribution element (rubber plate) [2].

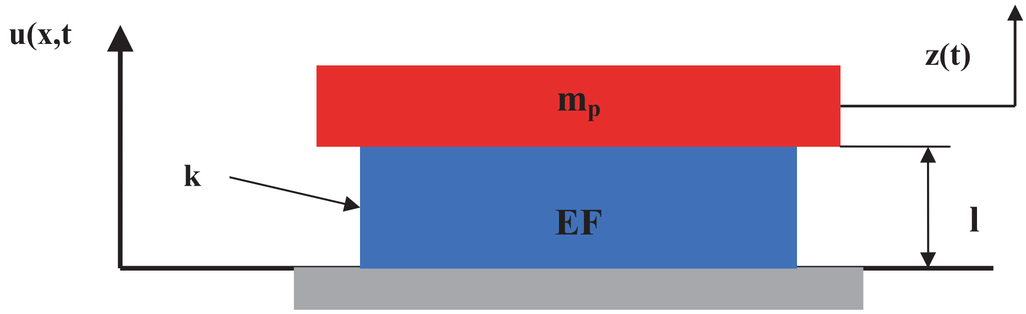

Fig. 1. Model of vibroisolated object

The differential equation describing this model takes the following form:

$$\frac{\partial^2 u}{\partial t^2} = a^2 \frac{\partial^2 y}{\partial x^2}, \tag{3}$$

where:

$a = \sqrt{\frac{E}{\rho}}$,

E – dynamic Young modulus,

ρ – density of the rubber material,

Using the Fourier method of separation of variables, we obtain the equation for the frequency of the initial-boundary problem of the form:

$$tan\frac{\omega}{a} l - \frac{EF}{m_z a\omega} = 0, \tag{4}$$

where:

$a = \sqrt{\frac{E}{\rho}}$,

E – dynamic Young modulus,

ρ – density of the rubber material,

F – cross-sectional area of rubber,

m_z – platen mass.

On the basis of this dependence, we determine ω_i - natural frequency of road vibration isolation system. After substituting the actual value, we can choose the natural frequencies of the element of vibration isolation system and the mass of the concrete platen, so that they do not coincide with excitation frequencies. For example, we show the calculations of vibration isolation system consisting of a rubber element with a thickness of 0.4 meters and manhole cover. Fig. 2 shows a chart based on which a natural frequencies of vibration isolation system were chosen.

The first three natural frequencies of vibration isolation system own are f_1 = 9.39 Hz, f_2 = 191 Hz and f_3 = 382 Hz.

In the destination of appointing amplitude-frequency characteristics discreet-constant model was considered, assuming that an inertial force coming from the track vehicle constitutes the extortion, levelling the movement, including suppressing, is accepting the form:

$$\frac{\partial^2 u}{\partial t^2} = a^2\left[\frac{\partial^2 u}{\partial x^2} + \mu\frac{\partial^2 u}{\partial t \partial x^2}\right] = \frac{q(x,t)}{\rho F}, \tag{5}$$

where:

$a = \sqrt{\frac{E}{\rho}}$,

ρ – density of the rubber material,

F – cross-sectional area of rubber,

μ – damping coefficient,

$q(x,t)$ – load perpendicular to vibroisolation.

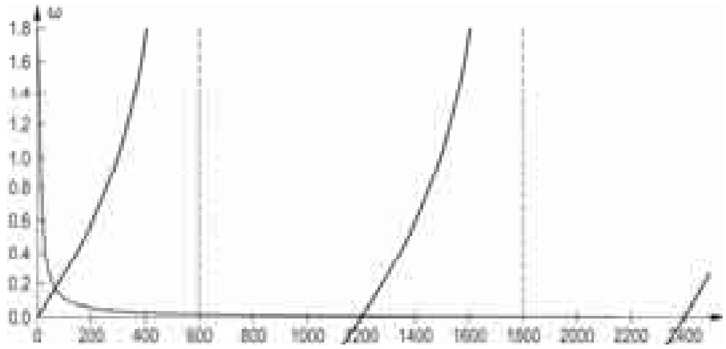

Fig. 2. Estimation of natural frequencies

We will be seeking the solution in the form of the series of own functions.

$$u(x,t)=\sum_{n=1}^{\infty}X(x)T(t) \quad (6)$$

After placing (6) to (5) and for dividing variables we receive the set of equations determining functions T(t):

$$T(t)+\omega_n^2\mu T(t)+\omega_n^2 T(t)=\frac{1}{\rho F}Q_n(t)\,. \quad (7)$$

We will be seeking solutions in the form of the special integral fulfilling zero initial conditions for the case of critical suppressing. This solution has a form:

$$u(x,t)=\sum_{n=1}^{\infty}A_n\sin(\omega t-\phi_n)X_n(l), \quad (8)$$

where:

A_n – amplitude of forced vibration,
ω_n – excitation frequency,
ψ_n – phase shift angle,
$Q(t)$ – excitation force.

Placing the relation (8) to (5) we receive the expression for the amplitude of excited vibrations in the following form:

$$A_n=\frac{Q_n(t)\gamma_n^2}{\rho F\sqrt{(\omega_n^2-\omega^2)^2+\mu^4\omega_n^4}}\,. \quad (9)$$

Taking into consideration first three natural frequencies in the case of vibroisolation of train roadbed and taking into consideration ρ = 1180 kg/m3 at the hardness 50-60° Sh; F - cross, F = 0.1 m^2; ω = 0-3400 s-1; μ = 0.1; then ω_n - natural frequencies - are: $\omega_1 = 59\ s^{-1}$, $\omega_2 = 1200\ s^{-1}$, $\omega_3 = 2400\ s^{-1}$, using the relation (9) we receive the amplitude - frequency characteristic presented in Fig. 3.

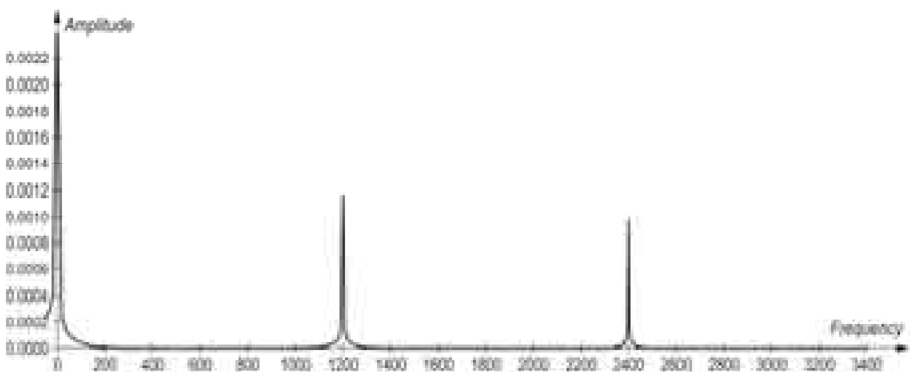

Fig. 3. Amplitude - frequency characteristics of roadbeds vibroisolation

Nowadays the structures of railroads from a point of view of dynamics and acoustics directly transfer the dynamics impact form trains to the ground (Fig. 4).

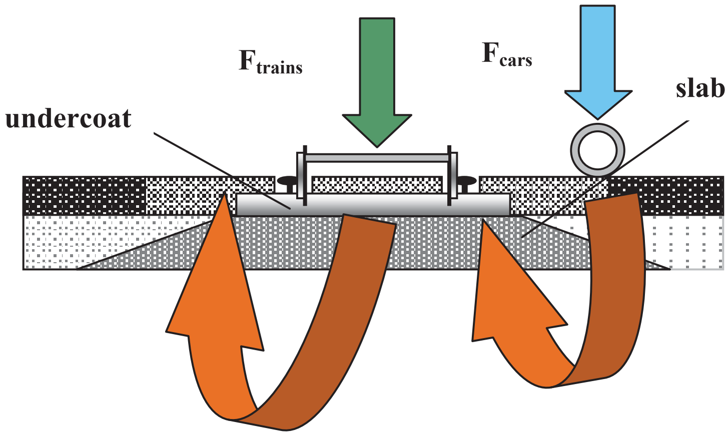

Fig. 4. Scheme of transfer the dynamics impact form trains to the ground

These influences are the source of mechanical as well as acoustic pulses all at the same time. All structural, technological or implementation interferences into the answer based on this concept, improvements don't prognosticate these rides i.e. prolonging the vitality, reducing dynamic influences and acoustic speeds moved to the environment or also a lack of restrictions of the ride for the functionality both of vehicles of the track communication. From here a need to draw up new constructions of tracks which they would let eliminate also arose or at least to limit these adverse phenomena based on examinations conducted in the country and with foreign countries in field vibroisolation of machines, devices and tram and train roadbeds of vehicles an idea was developed and then concept vibroisolation of train track which the scheme was presented on Fig. 4 to. Into untying the structure of the track elements elastic, having the task of separating train roadbeds in order to limit their dynamic influences to surroundings are being implemented.

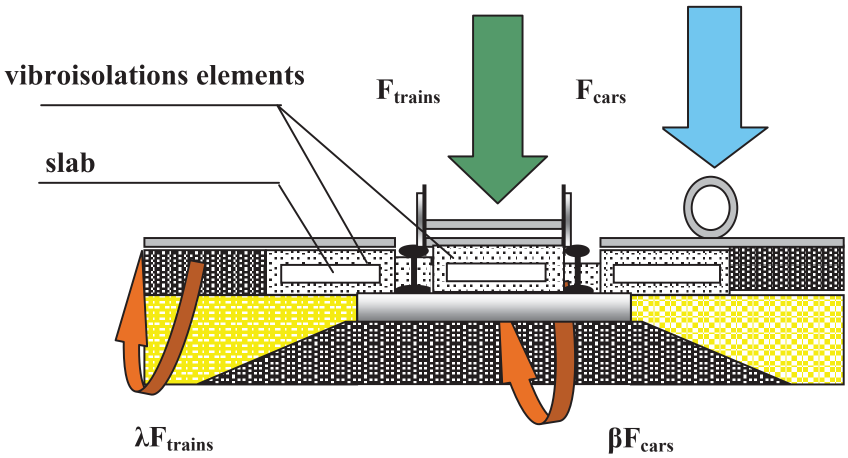

Fig. 5. Scheme of vibroisolations tracks

From the rail transport in this solution a track is a main element moving pulses with undercoat, which as a result of using an vibro- and acousticisolation materials much is limiting dynamic and acoustic influences sent to the natural environment. The values of λ and β coefficient should be less than 1. Comparing the structure of the traditional ride structure with the vibroisolated one it is possible to conduct one of measures of this effectiveness based on the dynamic analysis of simplified models introduced in Fig. 6. One of the vibroisolation effectiveness measure could be a relationship between R_w and R_d.

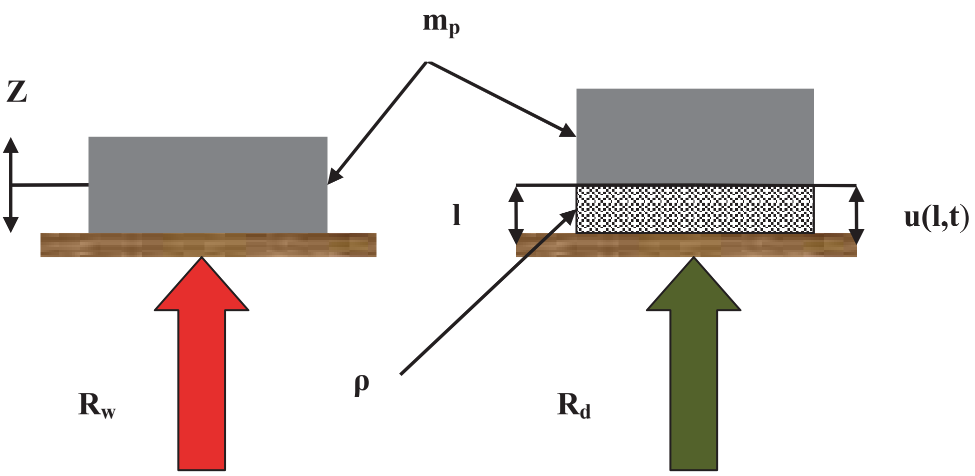

Fig. 6. Models of traditional (a) and vibroisolated (b) roadbeds (m_p- mass of the slab and mass of the vehicle, ρ - density of the rubber plate ,l - thickness of the rubber plate, u(l,t) - deforming the rubber plate)

Based on presented above discussions a technical conception of train track vibroisolation was developed [3]. The resilient and mass parameters of proposed technical solution were selected based on analysis of the discrete-continuous model. The appointed average dynamic stiffness amounted to k_d = 610.94 kN/m and dissipation factor of the energy φ = 0.27 ÷ 0.33. In the course of the modernization, however other resilient element was applied in the form of the elastomer covered by geotextile (Fig. 7).

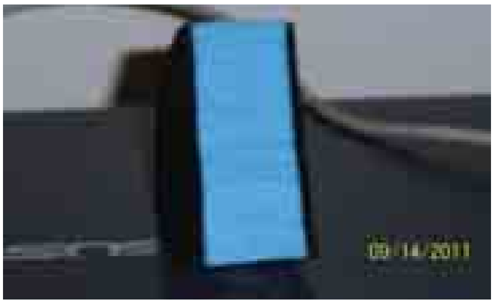

Fig. 6. Elastomer covered by geotextile

Examinations were performed using the machine of endurance static-dynamic Instron 1273 with the plumbing drive and the electronic guidance in the room temperature (Fig. 7). The machine enables performances both of examinations in quasi conditions of static burdens at the ± travel of a piston of 50 mm and the maximum force 100 of kN, as well as fast-changeable dynamic burdens about frequencies up to 100 Hz.

Fig. 7. Endurance machine static-dynamic of type Instron 1273

Of examination of the samples of sylomer elements, they made in hugging, in cycles with the strain and with relieving the spherical wrist with the application in order to eliminate possible nonparallelisms of surfaces of the samples and getting the even field of stresses in tested samples, applying the following parameters of the attempt:

1. measuring range of the ergometer – Fmax: 10.0 kN,
2. enlarging the scale of deformations – α = 100 times,
3. size of ruthless deforming samples / = travel of a piston of the machine/: 7 mm,
4. speed of deforming samples:
   - quasistatics – 0,1 mm/s,
   - dynamic – 1.0 mm/s.

In the course of attempts they were making the registration of the course of the stabilized terminus of the hysteresis of the mechanical work, which they appointed in way in accordance with norms of the value of the E module from the fragment of the terminus of the hysteresis corresponding to the load from pressing samples with power as well as the attenuation of rubbers from both fragments of the loop: of burdening and lightening. In some cases, a need for graphical averaging the course of the hillside growing at appointing the E module occurred towards the riot of little nonlinearities in both ends of the terminus of the hysteresis. In the result of those surveys a dynamic stiffness was established k_d = 6.895 [kN/m] and dissipation factor of the energy, being a measure of suppressing, φ = 0.82.

4. Conclusion

Applying as the element vibroisolation of material like this small rate of the stiffness can cause the fall in the effect vibroisolation, i.e. limiting dynamic influences on the environment, and in special cases, even worsening him. Mass along with the mass of the vehicle can lead plates for considerable stiffening used material of vibroisolation, creating the so-called "effect of the board".

References

[1] Bednarz, J, Targosz, J., *Finite elements method in analysis of propagation of vibrations wave in the soil*, Journal of KONES Powertrain and Transport, Warsaw 2011.

[2] Targosz, J., *Układy wibroizolacji w transporcie szynowym i samochodowym,* Rozprawy i Monografie, AGH,Wydawnictwa Naukowo-Dydaktyczne, Kraków 2007.

[3] Targosz, J., *Analiza i badania właściwości fizykomechanicznych ustrojów elastomerowych, minimalizujących dynamiczne oddziaływania podtorza kolejowego na otoczenie,* TTS Nr 5-6, str. 87-91, 2008.