

doi: 10.18720/MCE.74.5

Vibroisolating properties of polyurethane elastomeric materials, used in construction

Виброизолирующие свойства полиуретановых эластомеров, применяемых в строительстве

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Key words: polyurethane; vibroisolation of buildings; testing unit; natural frequency; vibroisolation coefficient

Ключевые слова: полиуретан; виброизоляция зданий; испытательный стенд; собственная частота; коэффициент виброизоляции

Abstract. The given study is reasoning the relevancy of replacing the conventional elastomer, that is, rubber, with more advanced polyurethane. The paper presents scientific reasoning for the demand to experimentally study the physical and mechanical properties of polyurethane in cases when it is used as plates for vibroisolation of buildings or industrial equipment and is subjected to considerable load. Due to the regulated rate of motor rotation of the testing unit, it is possible to study the course of vibroisolation in a polyurethane bulk, in relation to the forced frequency, vibration amplitude and static deformation. Based on the considerable amount of test measurements of the vibration amplitude with the piezoelectric accelerometers in various stress modes, an empirical statement has been acquired to determine the natural frequency of the polyurethane-unit system for the polyurethane elastomers of varying hardness depending on the degree of relative compression. The present work offers certain recommendations for determining the ultimate static deformation for the polyurethane plates of varying hardness.

Аннотация. В работе обоснована актуальность замены традиционного эластомера – резины на более совершенный полиуретан. Представлено научное обоснование необходимости экспериментального исследования физико-механических свойств полиуретана, в тех случаях, когда он используется в виде пластин для виброизоляции зданий, промышленного оборудования и находится под действием больших нагрузок. Благодаря регулируемой частоте вращения электродвигателя испытательного стенда возможно изучение процесса виброизоляции в полиуретановом массиве в зависимости от частоты вынужденных колебаний, амплитуды колебаний и величины статической деформации. На основании большого количества экспериментальных замеров величины амплитуды колебаний с помощью пьезоэлектрических акселерометров при различных режимах нагружения, получено эмпирическое выражение для определения частоты собственных колебаний системы агрегат-полиуретан для полиуретановых эластомеров различной твердости в зависимости от величины относительной деформации сжатия. В работе представлены конкретные рекомендации по определению предельной статической нагрузки для полиуретановых пластин различной твердости.

Introduction

From the mid-twentieth century the advanced industrialized countries have substituted rubber with polyurethanes in many engineering applications, as the latter have significant constructional, technological and operational features, even while polyurethanes are 1.5 to 3 times more expensive than rubber.

Polyurethane, as well as rubber, falls within the type of construction materials conventionally called elastomers. Elastomers as construction materials for machine components different from, for instance, metals, are characterized by two features:

- Elasticity – the capacity of significant initial distortion, up to 300 %, different from metals, which have the value of distortion limited by fractions of a percent;

- High internal friction, which can absorb mechanical vibrations, while getting warm and dissipating part of energy as heat into the surrounding environment.

The potential of polyurethanes for the contemporary industry is conditioned by the fact that their properties remarkably complete the application capacities of other elastomers, resins, rubbers etc. Considering their constructional and technological capacities polyurethane is the most universal polymeric material. Polyurethane is characterized by notable physical and mechanical properties, has a significant range of hardness, low wearability, high density, high tear strength, oil-and-petrol resistance, acid resistance, and operational temperature from $-35\text{ }^{\circ}\text{C}$ to $+75\text{ }^{\circ}\text{C}$ [1-6].

Polyurethane elastomers currently have a broad application as a vibroisolating material in contemporary machine and civil engineering to protect the facilities from vibrations created by the movement of subsurface metropolitan trains, railway trains, etc.

Oscillatory damping is based on transforming the kinetic energy of a damped unit into the thermal energy with its following dissipation into the surrounding environment. The transformation of mechanical energy into the thermal one is provided by the internal friction (hysteresis), induced by the viscosity of a polyurethane bulk of the damper [7-12].

The problems of physical and mechanical properties of polyurethane under dynamic loading were studied by many researchers, particularly Sheng Li, Marcos Pacheco, Janusz Datta [13-15]. Under dynamic loading polyurethane, due to the destruction of secondary chemical bonds, undergoes the process of gradual fluxing, with the modulus of elasticity reducing by approximately 15 %. Moreover, under dynamic load polyurethane molecules do not manage to distort at the speed more than 0.4 mm/sec (the given speed is set as a standard for the test determining the compression modulus of elasticity) and the material is also hardening. The phenomenon in question is considered in the papers and the monograph by S.N. Yakovlev [16-18].

Such a wide-spread application of polyurethane elastomers as vibroisolating materials invokes the necessity of an experimental study of physical and mechanical properties of polyurethane and the problems, related to its application in engineering the buildings and constructions, subjected to vibrations.

The aim of the given paper is to provide the empirical equation to determine the natural vibration frequency of the polyurethane-unit system for any value of the relative compression for the polyurethane plates of varying hardness.

To accomplish the desired goal it is necessary to solve the following problems:

1. To design and produce the special testing unit to simulate the loading of polyurethane vibroisolating plates in the frequency range from 10 to 50 Hz.
2. To conduct the tests of polyurethane vibroisolating plates of three degrees of hardness with varying oscillatory amplitude and the value of static deformation.
3. To process the obtained test measurements by means of mathematical statistics and to derive the required equation.

Materials and methods of the study

Polyurethane vibroisolators are used for amplitude loss in the induced cyclical oscillations caused by the stationary underbalanced units. They are also used to dissipate large amounts of energy of the impact force.

Vibroisolators that use the polyurethane elastomers in their design should provide the vibroisolation of buildings, constructions and industrial equipment from the oscillations in the frequency range 20 to 50 Hz, induced by the subsurface metropolitan, trams, large trucks etc. High-frequency oscillations, according to [19, 20] are of low intensity and well-filtered by the ground.

The design parameters of a polyurethane vibroisolator are its hardness and the capacity to decline (dampen) the oscillatory amplitude by means of inner friction of the material (hysteresis losses). The lower is the hardness of a polyurethane vibroisolator, the higher is its deformation and the lower is the natural vibration frequency. Vibroisolation is the better, the higher is the ratio of natural to induced frequencies.

At present the polyurethane elastomers produced by Synair (USA), Getzner Werkstoffe GmbH (Austria), etc are widely spread as a vibroisolating material. The materials are microcellular polyurethane elastomers with mixed vesicular structure, specifically designed to solve the problems of vibroisolation. For the materials in question the following peculiarities are characteristic:

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- Not subjective to hydrolysis, as well as to the effects of dilute alkali, acids, dissolvents and oils;
- Carry the long-term repeated load;
- Withstand significant overload;
- During the impact of stationary load the materials do not lose their properties in at least 30 years.

For the study of vibroisolating properties of polyurethane elastomers a special testing unit was designed and produced, allowing the simulation of various kinds of load in a broad range of induced oscillations frequency. The testing unit can simulate the simplest instance of uniaxial harmonic load for a polyurethane vibroisolator.

Polyurethane vibroisolators, while being used, go through an asymmetric load cycle, presented in Figure 1.

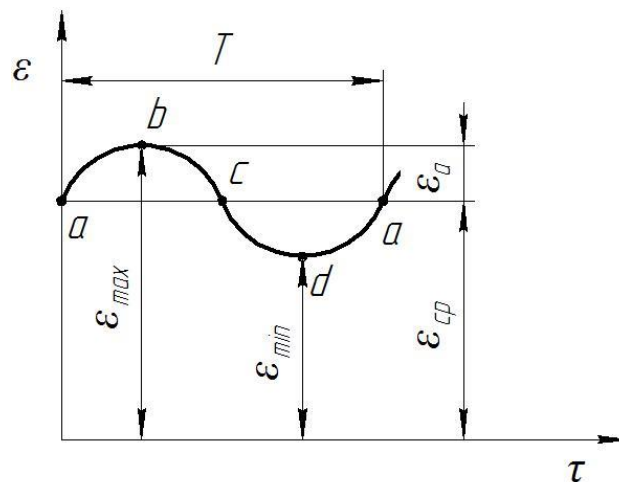


Figure 1. Asymmetric load cycle mode: ϵ_{cp} – average deformation; ϵ_a – deformation amplitude; ϵ_{max} – maximal deformation; ϵ_{min} – minimal deformation; T – time of oscillation

Semioscillation, shown in Figure 1 in letters *a b c*, corresponds to the compressive deformation, during which the vibroisolator drops as opposed to the average deformation, which in most cases is determined by the weight of a damped unit. Section *c d a* corresponds to the extensional strain of a vibroisolating polyurethane bulk.

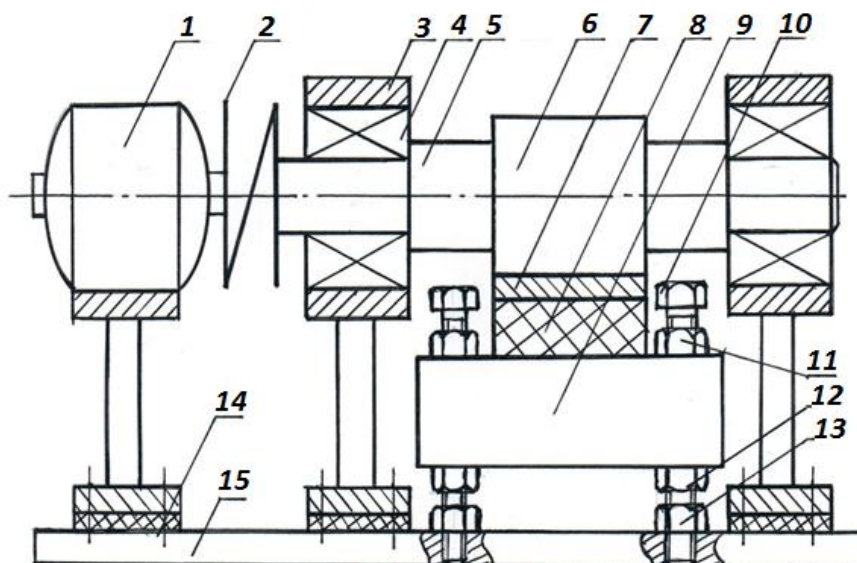


Figure 2. Kinematic diagram of a testing unit: 1 – electric motor; 2 – clutch; 3 – post; 4 – bearing; 5 – shaft; 6 – eccentric; 7 – cushion; 8 – polyurethane; 9 – platform; 10 – lead screw; 11 – lock nut; 12 – lifting nut; 13 – clamping nut; 14 – padding; 15 – base

A kinematic diagram of the testing unit for simulating the dynamic load of polyurethane vibroisolators, being in compression, is shown in Figure 2.

The testing unit consists of an asynchronous motor 5A171 V2 with the power $P_{mot} = 1.1$ KW, the rate of rotation $n_{mot} = 3000$ rpm and the variable rotation rate; elastic clutch and a camshaft, based on the rolling bearings. The motor and shaft-rolling bearings are set on a platform with the use of vibroisolating paddings 14, to diminish the transference of oscillations.

Due to the variable rotation rate of the motor shaft it is possible to study vibroisolating properties of the polyurethane elastomer in question on the whole range of regularly applied mechanical load frequencies. These frequencies are within the range of 10 to 50 Hz.

To create the stationary load in the polyurethane bulk under consideration, one should unscrew the lock nuts 11 and, rotating the lifting nuts 12, lift the platform 9 to the value of a certain stationary deformation of a polyurethane bulk 8, at which the following sequences of tests would be carried out. After that one should fasten the lock nuts and measure the stationary deformation value of the polyurethane prepared for tests.

Oscillating dynamic load, impacting the polyurethane bulk, is simulated by means of a rotating cam. Taking into consideration the fact that the oscillations follow the harmonic principle

$$U(t) = A \sin(\omega t + \varphi),$$

where A is the oscillatory amplitude or the divergence from zero position, ω is the rotating speed of the shaft, φ is the initial oscillatory phase, the eccentric profile precisely matches the harmonic form of loading of the cam gear with a flat lifter.

The eccentric profile is shown in Figure 3.

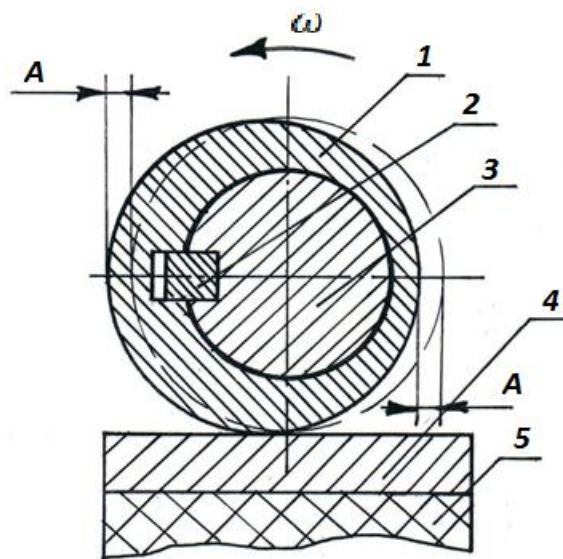


Figure 3. Cam profile, simulating the dynamic load of polyurethane: 1 – eccentric; 2 – connector; 3 – shaft; 4 – cushion; 5 – polyurethane

Eccentricity A of the cam matches the value ε_a – the deformation amplitude.

During the rotation of the cam, the cushion, working as a flat lifter and rigidly connected to the polyurethane bulk (by means of glue), simulates the dynamic load of a vibroisolator.

At the production stage the complex contour of the cam is formed as an envelope for various positions of an abrasive disk with a simple shape. The grinding of the cam surface was carried out on the optical profile grinding machine with the 50-times magnification. For the simpler setting of the coordinates and the following grinding of the cam profile, corresponding to the harmonic form of loading of a flat lifter, the polar coordinate system was used.

After the grinding the cams were nitrated to increase the wear-resistance.

For the experimental study three cams were produced with the eccentricity of 0.1; 0.2; 0.3 mm. These values approximately correspond to the amplitudes of the most prevalent mechanical oscillations of the current industrial equipment.

The load frequency of a polyurethane bulk under consideration was split into five fixed frequencies: 10, 20, 30, 40 and 50 Hz, at which the amplitude of forced oscillations of the platform was measured by means of a piezoelectric accelerometer.

Therefore it is possible to examine the process of vibroisolation in a polyurethane bulk of a damper depending on the amplitude of forced oscillations, oscillation amplitude and the value of stationary deformation.

As a drawback of the testing unit should be mentioned the heating of the cushion, transferring the heat from the area of sliding friction of the loading eccentric and the cushion to the polyurethane bulk of the damper.

To diminish the heating and wearing in the frictional contact the cushion was produced of tin bronze and, moreover, a drip-feed lubrication system was organized, with which a container was set above the rotating eccentric, and transmission gear oil dripped from there onto the rotating eccentric and then got into the frictional contact.

For the experimental study of vibroisolating properties of a polyurethane elastomer the samples produced by Synair (USA) were used, with the dimensions 80 × 80 mm and the width 25 mm, the hardness 45 ShA, 55 ShA, 65 ShA.

Research results

The dynamic properties of polyurethane elastomers at the forced oscillations in the stable conditions are described by a differential equation considering the elastic and viscous constants.

The solution to this equation, according to [21], is the assessment of the capacity of a polyurethane elastomer to dampen the oscillations. The efficiency of vibroisolators in dampening the oscillations amplitude is characterized by the vibroisolation coefficient η , which is determined by means of the following equation:

$$\eta = \frac{\sqrt{1 + \left(\frac{f_B}{f_c}\right)^2 \frac{4\vartheta^2}{4\pi^2 + \vartheta^2}}}{\sqrt{\left[1 - \left(\frac{f_B}{f_c}\right)^2\right]^2 + \left(\frac{f_B}{f_c}\right)^2 \frac{4\vartheta^2}{4\pi^2 + \vartheta^2}}}, \quad (1)$$

where f_B is the frequency of forced oscillations (frequency of the generating force oscillations), Hz;

f_c – frequency of the natural oscillations of the polyurethane-unit system, Hz;

ϑ – damping logarithmic decrement for the oscillations of the vibroisolating system.

Oscillatory damping logarithmic decrement $\vartheta = \ln \frac{x_1}{x_2}$ is used to indicate the damping of the oscillations and is determined by the base logarithm of the ratio of two adjacent oscillatory amplitudes.

The lower is the isolation coefficient η , the better is the isolation. The equation (1) for the instance $\frac{f_B}{f_c} = \sqrt{2} = 1.41$ at all values ϑ shows that $\eta = 1$, i.e. in the given case there is no vibroisolation.

If we set the oscillatory damping logarithmic decrement ϑ close to zero, i.e. consider the inner friction in a polyurethane bulk negligible, we get the following:

$$\eta = \frac{1}{\left[1 - \left(\frac{f_B}{f_c}\right)^2\right]}, \quad (2)$$

At $\frac{f_B}{f_c} < \sqrt{2}$ the value of $\eta > 1$, and in that case not only there is no vibroisolation, but, on the contrary, the amplitude of the common driving energy is increased. At $\frac{f_B}{f_c} > \sqrt{2}$ the value of $\eta < 1$ and the vibroisolation takes place. Examining the equation (1), it is possible to draw the conclusion that for a good isolation it is necessary to provide the natural frequency of the system being much less than the frequency of forced oscillations.

In case $f_B = f_c$, while solving the equation (2) theoretically, it results in $\eta = \infty$, which matches the resonance phenomenon.

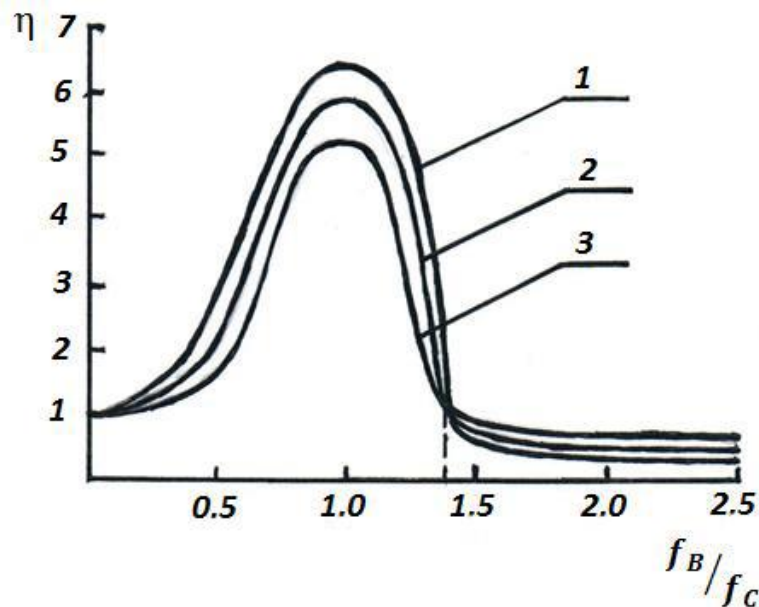
The assumption, underlying the equation (2), also largely holds for the metal spring vibroisolators without a considerable inner friction and providing vibroisolation by means of shaping metal in a certain way.

For polyurethane elastomers used in vibroisolating equipment, the value of ϑ , dependent on hysteresis losses, stays within the range 0.4 to 0.8. Thus a polyurethane vibroisolator provides a finite value of the vibroisolation coefficient η with the resonance as well.

While the increase of η at the resonance is not connected to the increase of the energy costs, in some instances the use of polyurethane vibroisolators is acceptable even in the vicinity of a resonating area, however, such a work, due to the inner friction in polyurethane, involves a significant heating of the polyurethane bulk and may cause the destruction of the material.

On the basis of a considerable number of experimental measurements of oscillatory amplitude of the platform for various loading modes a ratio was obtained for the isolation coefficient of polyurethane elastomers in relation to the correlation of the frequencies of forced oscillations and the natural frequency of polyurethane-unit system for elastomers of varying hardness.

The obtained correlations are presented in Figure 4.



**Figure 4. The correlation of vibroisolation coefficient of polyurethane to the frequency ratio $\frac{f_B}{f_c}$:
1 – 45 ShA; 2 – 55 ShA; 3 – 65 ShA.**

Picture 4 shows that the less the value of ϑ is, the higher is the value of η in the resonating area. However, at the same time η is diminishing with the increase of the ratio $\frac{f_B}{f_c}$. While the oscillatory damping logarithmic decrement ϑ depends on hysteresis losses in polyurethane, they in their turn being determined by $\sin \varphi$ (phase angle between the force and deformation), the relation $\frac{4\vartheta^2}{(4\pi^2 + \vartheta^2)}$ in equation (1) can be substituted with $\sin^2 \varphi$, which is easy to determine by means of experiment, using the record of natural oscillations of the testing unit lever, being in rotational oscillatory motion around a stationary axis.

The given system is considered a single degree of freedom system, where a polyurethane bulk with a certain stationary deformation is used as a damping element. The lever oscillations are recorded by means of a Geiger recorder.

Table 1 presents the values of oscillatory damping logarithmic decrement ϑ , obtained by means of experiment in the area of the regularly applied working stationary deformations for polyurethane elastomers in three degrees of hardness.

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Table 1. Oscillatory damping logarithmic decrement for the polyurethanes of various degrees of hardness with varying values of a relative stationary deformation

Relative deformation, ε	Polyurethane hardness, ShA		
	45	50	55
0.10	0.48	0.53	0.58
0.15	0.50	0.55	0.60
0.20	0.52	0.57	0.62
0.25	0.54	0.59	0.64

As has been mentioned above, to provide the efficient vibroisolation, the frequency of natural oscillations of the polyurethane-unit system f_c should be less than f_b , the frequency of forced oscillations.

Following the results of a considerable number of experiments, an empirical correlation was obtained for the determination of the natural oscillations frequency for the polyurethane-unit system:

$$f_c = 18 + 0.1\varepsilon + 0.2(\text{ShA} - 45), \quad (3)$$

where ε is the value of relative deformation; ShA – the hardness of polyurethane according to Shore.

The proposed empirical correlation for the determination of the natural oscillation frequency of the polyurethane-unit system holds for the range of the values of relative stress deformation of polyurethane vibroisolating plates, prevalently used in practice.

Conclusions

According to the results of a wide experimental study of the vibroisolating polyurethane plates produced by Syniar (USA), it is possible to draw the following conclusions and to give certain recommendations for their application in engineering of various buildings and constructions:

1. With the known drop δ of a polyurethane vibroisolator, under the set stationary load, the natural frequency of the vibroisolator-unit system is determined; it would be the lower, the higher is the drop of δ . The drop of δ would be the more considerable, the lower is the elasticity mode of the polyurethane elastomer and the lower is the form coefficient (determined by the standard geometrical properties) of a vibroisolator.
2. The use of polyurethane vibroisolators with the height of more than 30 mm is not recommended, as it may cause the lateral displacement of a damped unit.
3. The vibroisolation coefficient, calculated according to the formula (1) and the experimental measurements of the oscillatory amplitudes by means of the piezoelectric accelerometer show the divergence in 6 to 8 %, which is considered a satisfactory value in engineering calculations. In practice the vibroisolational coefficient η has the value $\eta = 0.2 \dots 0.7$.
4. Considering the elastic posts made of vibroisolating polyurethane elastomer, used in engineering of buildings and constructions, the following values may be recommended as a limiting dead load: $[p] = 0.15$ MPa for polyurethane with the hardness 45 ShA, $[p] = 0.20$ MPa for polyurethane with the hardness 50 ShA, $[p] = 0.25$ MPa for polyurethane with the hardness 55 ShA.

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