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The Influence of the Number of Polyurethane Anti-Vibration Mount on the Vibration Damping Efficiency of Steel Structure

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VIBRATIONS AND ANTI-VIBRATION MOUNTS

Vibrations are defined as a physical phenomenon characterized by alternating movements of material points in relation to the equilibrium position, spreading in gaseous, liquid (Kolekar et al., 2019) and solid media (Kang, 2017). The concept of vibration, often in literature, is synonymous with the concept of vibrations, is defined as vibrations occurring in mechanical systems (Rimasauskiene et al., 2019), (Zhang & Xu, 2019) having a harmful effect on the environment, human or construction (Koradecka, 2008, Engel & Zawieska, 2010, Uzarczyk, 2006). Due to the need to protect the health of employees, the values of the permissible vibration level at the workplace are expressed as an acceleration of vibrations [m/s^2].

Vibration is a nuisance or harmful factor that occurs in most industrial processes. Vibrations sources are the following:

- floors, landings, piers in production halls and other rooms where work stations are located,
- steel constructions subjected to mechanical treatment,
- vibrating platforms,
- seats and floors in the means of transport,
- seats and floors of construction machinery (Lis & Nowacki, 2005, Indulski, 1999)

During long-lasting impact of vibrations in tissues, organs and human systems irreversible acute or chronic changes occur. After exceeding the adaptive capacity of the body, employees notice health changes commonly referred to as a vibrational disease.

Vibration damping is a physical phenomenon which essence is the dissipation of mechanical energy. Internal damping in metals, being an element of basic sources of vibrations, is insignificant (Malburet & Krysinski, 2007, Mayer et al., 2014). Therefore, to limit the emission of vibrations, it is recommended to use additional damping layers, single or multi-layer. As a result, the amplitude of the vibration displacement is reduced, the free vibration fades out faster and the waves reverberate through the resilient elements. The most recommended damping layers include polymers, elastomers, organic glasses, rubbers, felt and bituminous materials (Arenas & Crocker, 2010, Wang, 2017, Cao, 2018, Rafiee et al., 2019, Yano et al, 2019, Hu et al., 2018). There is no information in the literature about the impact of the number of layers of silencing systems on their properties in this area. The research carried out, presented in this study, complements this knowledge gap.

RESEARCH METHODOLOGY

The research material consisted of one-, two- and three-layer sound insulation systems built on the basis of polyurethane foam (PU) foamed secondarily with a density of 40 to 220 kg/m^3 with dimensions of 470 x 470 mm and thicknesses of 2, 4 and 6 cm (Kozioł 2015, Małysa 2016).

The tests included the measurement of vibration acceleration on the author's research stand (Fig. 1) without and with the use of anti-vibration mounts.

Fig. 1 Author's research standpoint

The obtained results of vibration acceleration measurements allowed to determine the damping abilities of the investigated layered systems, according to the formula 1.

$$STD = (1 - \frac{X_O}{X_B}) * 100\% \quad (1)$$

where:

STD – effectiveness of vibration damping

X_O – arithmetic mean of the results of vibration acceleration measurements with the use of a damping mat [m/s^2],

X_B – arithmetic mean of the vibration accelerations of the unloaded structure [m/s^2].

The impact force of the analysed variables was determined on the basis of constructed multiple regression models, the so-called multifactor models and determination of the standardized value β. Models built on the basis of over 1000 measurements of damping properties of layered systems.

The multiple regression model allows to study the influence of several independent variables (X_1, X_2, ..., X_k) on one dependent variable (Y). The most commonly used variation of multiple regression – linear multiple regression was

used to build the models. It is an extension of linear regression models based on Pearson's linear correlation coefficient.
The linear multiple regression model takes the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k \tag{2}$$

where:
Y – dependent variable (defined),
$X_1, X_2, \dots X_k$ – independent variables (defining),
$\beta_0, \beta_1, \beta_2, \dots \beta_k$ – parameters,
ϵ – random component (the rest of the model).
In the models that have been built, the significance level was estimated at $p < 0.05$. The step method consists in the subsequent elimination of variables for which the highest p-value was obtained, until reaching a state in which all p-values are lower than the estimated level. This means a statistically significant influence of the selected independent variables on the dependent variable.
To obtain the correct regression model, the basic assumptions about the model rests were checked, which may disturb the regression equation, due to their large influence on the values of the coefficients of this equation. If the rest is more than 3 standard deviations from the average value, then such observation can be considered as a standing out observation. The removal of the standing out observation can make a significant contribution to improving the model.
After elimination of the standing out observation, for such a set of data, multifactor models were built again using the step method. For each statistically significant explanatory variable, the standardized value of the coefficient was determined β. These values, unlike raw parameters $\beta_0, \beta_1, \beta_2, \dots \beta_k$, expressed in, depending on the variable described, different units of measure (which makes it impossible to compare them directly), allow to compare the contribution of individual variables in explaining the variability of the dependent variable Y (Aczel 1989)

THE RESEARCH RESULTS

Determination of the impact of the analysed variables, such as: vibration frequency, number of polyurethane layers of vibroacoustic scheme, vibroacoustic system thickness and density of secondarily foamed polyurethane from which vibroacoustic systems were constructed, on the efficiency of the steel structure vibrations damping, required building multifactor linear statistical models and determining standardized values β for selected variables. Statistical models were built, for this purpose, using the measurement data of damping effectiveness. The research was carried out using the PQStat version 1.6.6.164 software. As a level of significance, $p < 0.05$ was assumed for individual variables as well as for the whole model.
Three statistically significant linear multivariate models for one-third frequencies were constructed:

- 0-20000 Hz – a model for the entire frequency spectrum analysed during the tests,

- 0-400 Hz – a model for frequencies generating construction vibrations that may affect the worker as general vibrations,
- 50-20000 Hz – a model for frequencies that generate construction vibrations that can cause auditory sensations (noise).

Coefficients b, standardized values b and selected statistical parameters of the models are presented in Tab. 1-3. For each of the constructed models a value of p < 0.00001 and satisfactory correlation coefficients of R2 in the range of 0.25-0.32 were obtained.

Table 1 Coefficients of statistical models

The frequency range of the model [Hz]	Tertiary frequency [Hz]	Number of layers	Thickness [cm]	Density [kg/m^3]
0.8-20000	-0.000012	0.010	-	0.0011
0.8-400	-0.000682	0.042	-	0.0007
50-20000	-0.000003	-0.022	0.011	0.0013

Source: own study

Table 2 Selected statistical parameters of models

	The frequency range of the model [Hz]		
	0-20000	**0-400**	**50-20000**
Cardinality	2035	1265	1218
R	0.501	0.547	0.572
R^2	0.251	0,299	0.328
Value p	< 0,000001	< 0.000001	< 0.000001

Source: own study

Table 3 Standardized values β of statistical models

The frequency range of the model [Hz]	Tertiary frequency [Hz]	Number of layers	Thickness [cm]	Density [kg/m^3]
0.8-20000	-0.338	0.051	-	0.359
0.8-400	-0.436	0.210	-	0.246
50-20000	-0.114	-0.131	0.127	0.552

Source: own study

To measure the acceleration of mechanical vibrations, a four-channel digital SVAN 958 meter was used, which allowed narrow-band analysis and an analysis in one-third bands. The measurements were made using a three-axis acceleration transducer to measure local and general vibrations. The SvanPC ++ program, ver.3.2.8, dedicated to the data processing of sound and vibration measurements, was used to analyse the measured values. The programme made it possible to configure measurement settings, analyse measurement data and export results to Microsoft Excel for Office 365.

DISCUSSION OF THE RESULTS

The general model, corresponding to the third octave frequencies up to 20 kHz, allowed to state that statistically significant influence on the vibration damping of steel structure by polyurethane layered structures has three variables: thirds frequency of vibrations, number of layers of the system and density of polyurethane foam foamed secondarily. In the case of vibration frequencies, a negative correlation was found (Fig. 2), while in the other two cases a positive correlation.

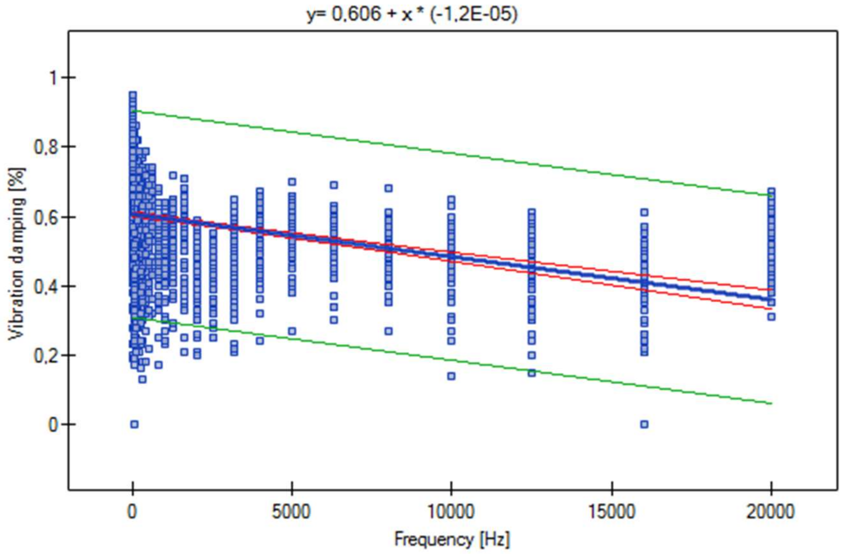

Fig. 2 Dependence of effectiveness of vibration damping on frequency (vibration frequency 0.8-20000 Hz)

In other words, as the frequency of vibrations increases, the effectiveness of vibration damping decreases (Fig. 2), while the number of layers increases (Fig. 3) and density of polyurethane foam (Figure 4), the effectiveness of suppression of systems is increasing.

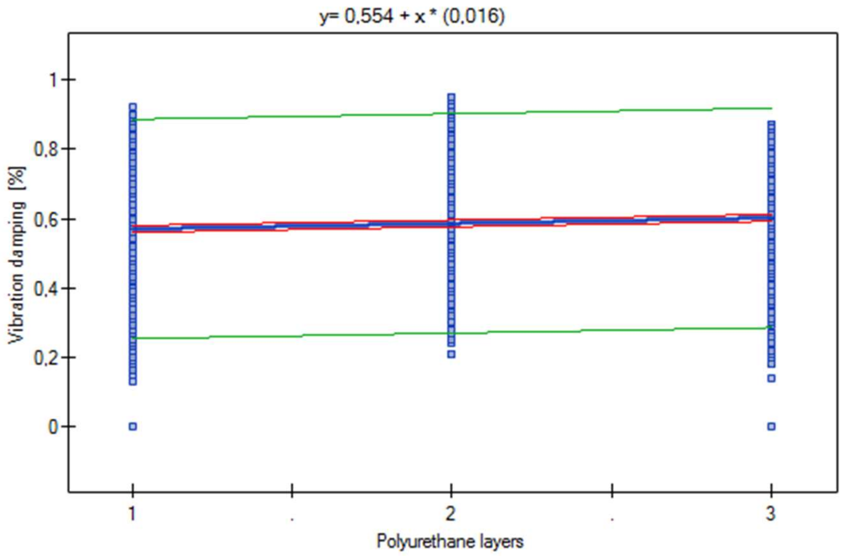

Fig. 3 Dependence of effectiveness of vibration damping on number of polyurethane layers (vibration frequency 0.8-20000 Hz)

Analysing the impact of particular explanatory variables of the model on the explanatory variable expressed in the value of the standardized coefficient b, it was found that in the analysed case, the impact of vibration frequencies and polyurethane foam density on the steel vibration damping effectiveness is about 6 times greater than the influence of the number of vibroacoustic system layers.

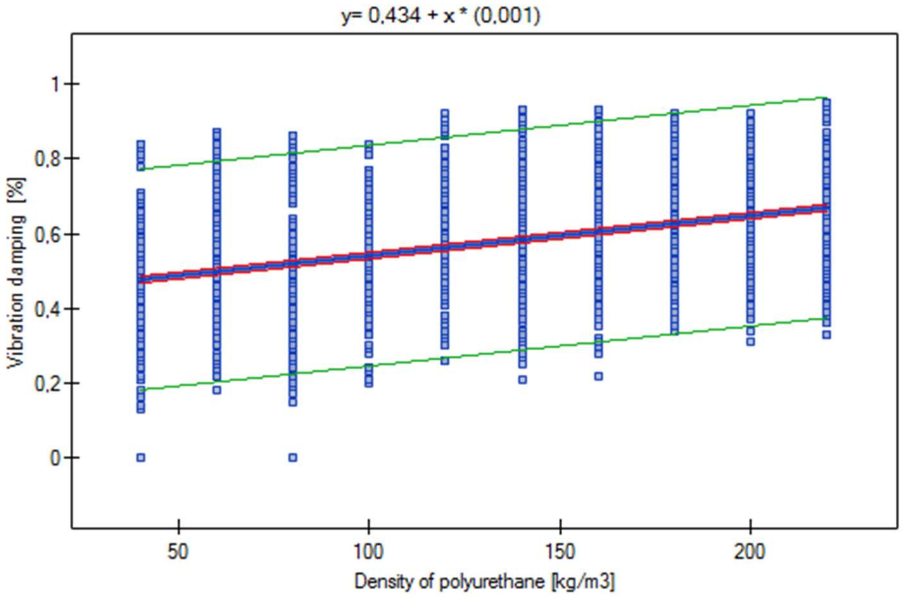

Fig. 4 Dependence of effectiveness of vibration damping on density of polyurethane (vibration frequency 0.8-20000 Hz)

Research in the field of vibrations of steel structures, in the range up to 400 Hz, so the range recognized in hygienic norms as a range of vibrations affecting the human body, on the basis of built linear multifactor model, showed statistical significance of three of the analysed variables: third octave frequency, the number of layers of the system and the density of the polyurethane foam foamed secondarily. Similarly to the previously discussed model for the frequency range up to 20 kHz, a negative correlation was found (Fig. 5), while in the other two cases a positive correlation (Fig. 6 and 7).

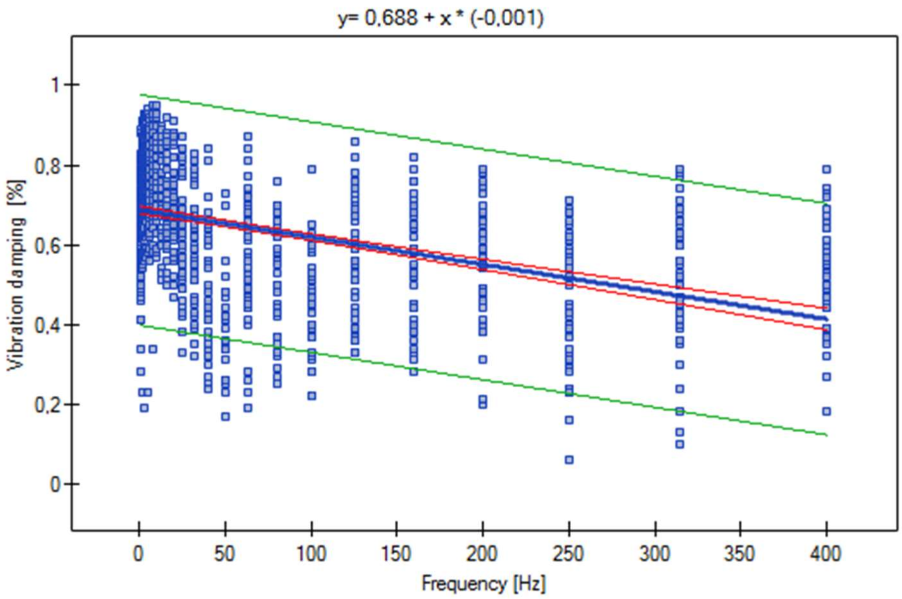

Fig. 5 Dependence of effectiveness of vibration damping on frequency (vibration frequency 0.8-400 Hz)

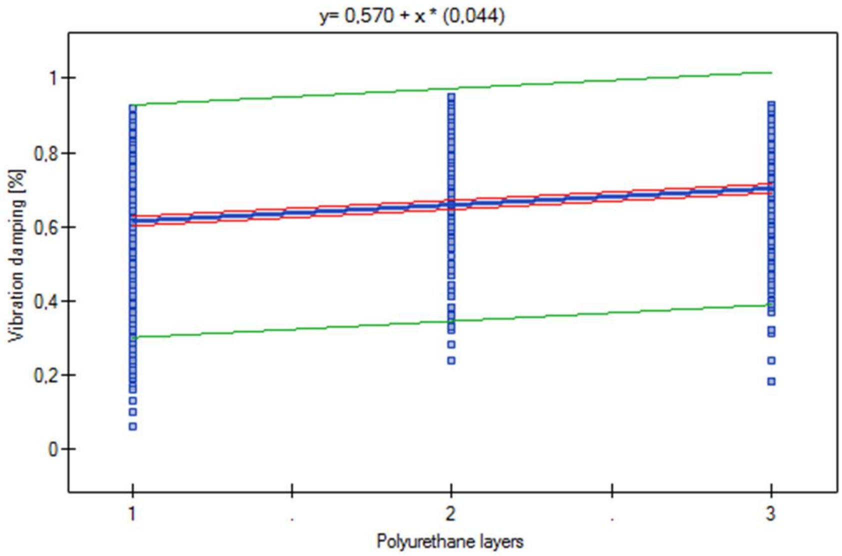

Fig. 6 Dependence of effectiveness of vibration damping on number of polyurethane layers (vibration frequency 0.8-400 Hz)

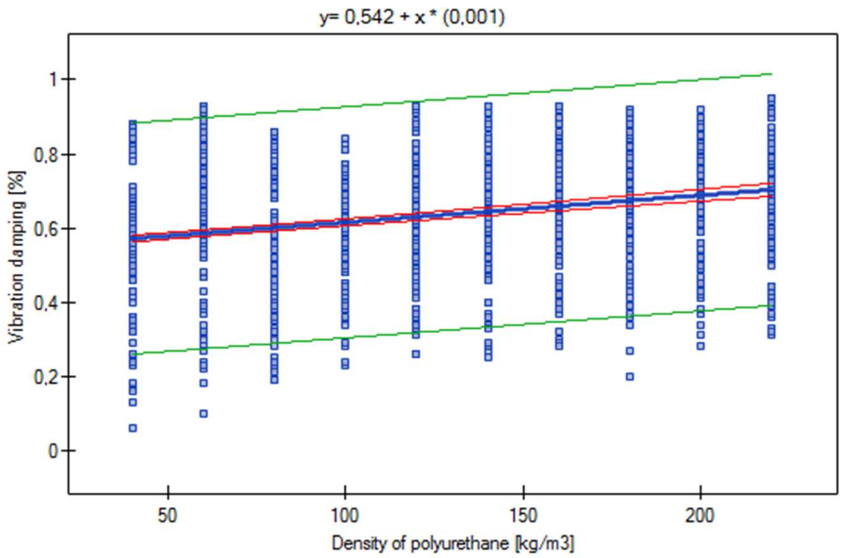

Fig. 7 Dependence of effectiveness of vibration damping on density of polyurethane (vibration frequency 0.8-400 Hz)

Analysing the impact force of selected variables on the effectiveness of damping steel structure vibrations in the range up to 400 Hz, it was found that there is about twice as much impact on the effectiveness of vibration dampening their third octave frequencies than the other two variables.

The research in the field of vibrations of steel structures, in the range from 50 to 20000 Hz, and thus the range of vibrations that can generate a heard by a human sound wave in the gas medium, based on the built linear multifactor model, showed statistical significance of all analysed variables. On the basis of the coefficients β, a negative correlation of the third octave frequency (Fig. 8) and the number of polyurethane layers of the vibroacoustic system was noted (Fig. 9). In addition, a positive correlation was found in the thickness of the vibroacoustic system (Fig. 10) and the density of the polyurethane foam foamed secondarily, used for the construction of the vibroacoustic system (Fig. 11).

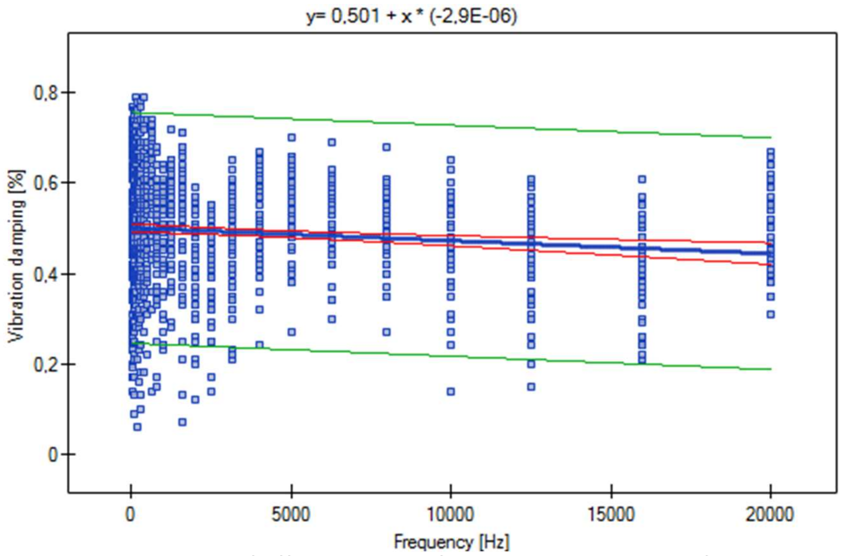

Fig. 8 Dependence of effectiveness of vibration damping on frequency (vibration frequency 50-20000 Hz)

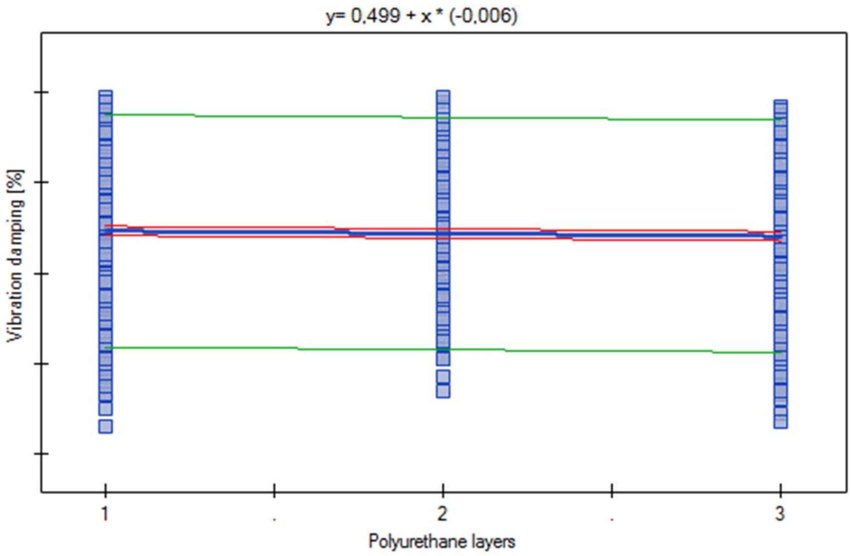

Fig. 9 Dependence of effectiveness of vibration damping on number of polyurethane layers (vibration frequency 50-20000 Hz)

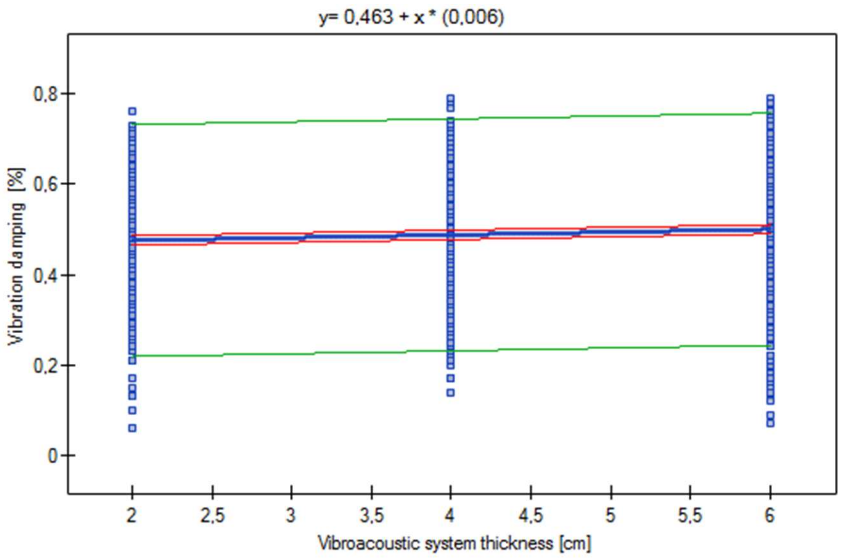

Fig. 10 Dependence of effectiveness of vibration damping on vibroacoustic system thickness (vibration frequency 50-20000 Hz)

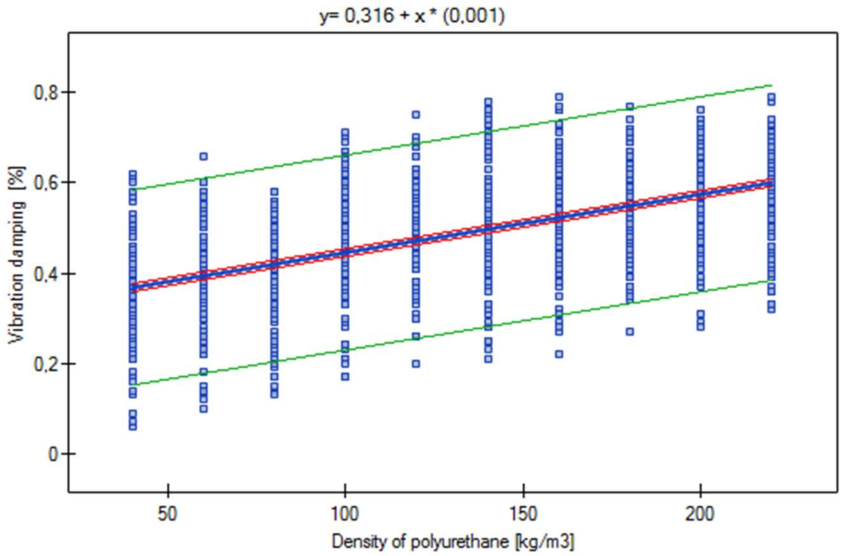

Fig. 11 Dependence of effectiveness of vibration damping on density of polyurethane (vibration frequency 50-20000 Hz)

Standardized values of β coefficients, allow to state that the greatest impact force on the effectiveness of damping of the analysed vibroacoustic systems in the third octave frequency range 50-20000 Hz has a density of polyurethane foam. The strength of the density impact on the explained variable is about four times greater than the strength of the number of layers of the body and their thickness, and about 5 times greater than the strength of the frequency of the vibrations of the structure.

SUMMARY AND CONCLUSIONS

Presented in Tab. 1-3 parameters of statistical models and analysis of results, allowed to state, in each of the constructed models, negative influence of the third octave frequency on the efficiency of damping. The impact of this variable on the effectiveness of vibration damping in the low frequency range (up to 400 Hz) was greater than the effect of other parameters, which may result from the inverse proportionality of the wavelength to its frequency. Waves of low frequencies are longer waves, and therefore harder to insulate, hence the dominant influence of this variable on the final result of the model.

The conducted analysis allowed, in each case, to state a positive correlation between the density of polyurethane foam used in the construction of the vibroacoustic system on the efficiency of damping of the steel structure. It was found that along with the increase in foam density, and hence the increase in the mass of vibroacoustic systems, their damping effectiveness increases. This is particularly evident in the higher frequency range, where this variable is dominant. The above mentioned phenomenon is justified on the one hand by a larger mass of systems, thus a greater structural load affecting positively its stiffness, on the other hand a higher frequency of vibrations, and therefore their shorter wave, which can be dispersed and looped in the porous structure of the analysed polyurethane vibroacoustic systems.

The third statistically significant variable, the effect of which on the effectiveness of vibration damping of the structure has been shown is the number of polyurethane foams layers from which vibroacoustic systems were built. The effects of 1, 2 and 3 layers were analysed. It was found:

- positive correlation of the number of layers in vibration damping systems with a third octave frequency of up to 400 Hz,
- negative correlation of the number of layers in vibration damping systems with a third octave frequency of 50 to 20000 Hz.

In the case of lower frequencies, a positive correlation may result from a larger wavelength, which is reflected from individual layers of adhesive inside the body, the adhesive which is an insulating barrier that largely reflects the propagating mechanical wave, makes it to loop inside the system and disperse at the interface, and what follows is a big reduction in its energy in the case. The significance of this phenomenon in the field of low frequencies is evidenced by the strength of the impact of variable, the strength comparable with the density of foams from which vibroacoustic systems are built. In the case of higher frequencies, above 50 Hz, a negative correlation was noted, but above all a lower impact force of the variable on the final result. This situation is mainly related to the wavelength. Higher frequency mechanical waves are shorter and therefore easier to insulate. Therefore, the porous structure of the secondarily foamed polyurethane foam is enough to provide a vibroacoustic barrier in which the insulating layers of adhesive are no longer as important as in the lower frequencies.

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Abstract.
The publication presents the results of research on the statistically significant impact of the number of layers on vibration damping properties of vibroacoustic mats. The research was carried out on the author's research stand. The research was carried out on sandwich systems made of polyurethane foam. The impact force of the analyzed variables was determined on the basis of constructed multiple regression models, the so-called multifactor models and determination of the standardized value β. The research was carried out using the PQStat software. In the models being built, the significance level was $p < 0.05$.
Three statistically significant linear multivariate models for one-third frequencies were constructed:
- 0-20000 Hz – a model for the entire frequency spectrum analysed during the tests,
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- 50-20000 Hz – a model for frequencies that generate construction vibrations that can cause auditory sensations (noise).

It was found: positive correlation of the number of layers in vibration damping systems with a third octave frequency of up to 400 Hz; negative correlation of the number of layers in vibration damping systems with a third octave frequency of 50 to 20000 Hz.

Keywords: anti-vibration, polyurethane, steel