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# STUDY OF FACTORS INFLUENCING VIBRO-ISOLATING PROPERTIES OF MATERIALS FOR PASSIVE ELASTIC BEARING OF MACHINES

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Machinery or instruments are subjected to external forces from a base in many cases. It can have a negative influence on manufacturing accuracy, tightness, wear of machine parts, work safety etc. Therefore, it is necessary to perform suitable passive elastic bearings of machinery to eliminate external vibration from the base. An application of suitable vibro-isolating materials is one way of the vibration elimination. The aim of the paper is to study vibration damping properties of different materials by means of a non-destructive method of forced mechanical oscillations. Different factors influencing transfer damping of mechanical vibration were investigated in this work, e.g., material type and its thickness, excitation frequency of mechanical oscillations, size of mass load and effect of material composition. These factors were subsequently evaluated. Finally, suitable recommendations for passive damping of mechanical vibration were described.

**KEYWORDS**: Mechanical vibration, transfer damping function, excitation frequency, inertial mass, thickness, material structure

## 1 INTRODUCTION

Vibration is defined as oscillation of a mechanical or structural system about an equilibrium position [**Kelly 2012**]. It is any motion that repeats itself after an interval of time [**Rao 2011**]. Vibration can be desirable in some cases (e.g., ramming machines, mobile phones, vibrating screens and healthcare applications). However, mechanical vibration is undesirable [**Ratna 2004**, **Wang 2011**, **Li 1999**, **Balazikova 2019**, **Machu 2021**] in many cases (e.g., means of transport, home appliances and manufacturing processes). Mechanical vibrations can also have a negative influence on manufacturing quality and productivity (e.g., during machining processes), work safety, dynamic loading of different components and can create unwanted noise. For these reasons it is suitable to reduce mechanical vibration to an acceptable level. There are different possibilities [**Gu 2005**, **Schaller 2003**, **Xie 2002**, **Kormanikova 2016**] to reduce mechanical vibration, e.g., by increasing some inertial masses and by application of suitable materials with structural damping, anti-vibration coatings, multilayer composite materials and shaped elastic elements. The reduced vibration is achieved by converting the mechanical energy into heat energy dissipated by a suitable material during cyclic oscillations.

This paper is focused on study of structural damping properties of different types of materials on the basis of the forced oscillation method. Different factors, which have influence on damping of the mechanical vibration, were subsequently evaluated.

## 2 VIBRO-ISOLATING PROPERTIES

Vibro-isolating properties of tested materials can be expressed by different quantities. Mechanical vibration excited by the harmonic motion of a base with a single-degree-of-freedom is expressed by the displacement transmissibility $T_d$ (−) as follows [**Rao 2011**]:

$$T_d = \frac{y_2}{y_1} = \frac{a_2}{a_1} = \sqrt{\frac{1 + 4 \cdot \xi^2 \cdot r^2}{\left(1 - r^2\right)^2 + 4 \cdot \xi^2 \cdot r^2}} \tag{1}$$

Where:

$y_1$ - displacement amplitude on input side of the investigated material ($m$),

$y_2$ - displacement amplitude on output side of the investigated material ($m$),

$a_1$ - acceleration amplitude on input side of the investigated material ($m \cdot s^{-2}$),

$a_2$ - acceleration amplitude on output side of the investigated material ($m \cdot s^{-2}$),

$\varsigma$ - damping ratio (−),

$r$ - frequency ratio (−).

In general, there are three different types of mechanical vibration depending on the value of the displacement transmissibility, namely damped ($T_d < 1$), undamped ($T_d = 1$) and resonance ($T_d > 1$) vibration.

The frequency ratio $r$ is given by the formula:

$$r = \frac{\omega}{\omega_n} \tag{2}$$

Where:

$\omega$ - circular frequency of oscillation (rad$\cdot s^{-1}$),

$\omega_n$ - undamped natural frequency of oscillation (rad$\cdot s^{-1}$).

The undamped natural frequency is expressed by the equation [**Stephen 2006**, **Beranek 1988**, **Thomson 2004**]:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{3}$$

Where:

$k$ - material stiffness ($N \cdot m^{-1}$),

$m$ - mass (kg).

Under the condition $dT_d/dr = 0$ in the Equation (1), it is possible to obtain the local extreme of the displacement transmissibility (i.e., $T_{dmax}$) at the frequency ratio $r_0$ [**Stephen 2006**, **Rao 2011**] as follows:

$$r_0 = \frac{\sqrt{\sqrt{1+8\cdot\xi^2}-1}}{2\cdot\xi} \tag{4}$$

It is evident from the Equation (4) that the local extreme of the displacement transmissibility is generally shifted to lower values of the frequency ratio $r$ with the increasing damping ratio $\varsigma$

In this work, vibration damping properties of the investigated materials were evaluated by means of the transfer damping function $D$ ($dB$) [**Vasut 1994**], which is defined for harmonically excited mechanical vibration by the equation:

$$D = 20\cdot\log\frac{a_1}{a_2} = 20\cdot\log\frac{1}{T_d} \tag{5}$$

As in the case of the displacement transmissibility, there are three different types of mechanical vibration depending on the value of the transfer damping function, namely damped ($D > 0$), undamped ($D = 0$) and resonance ($D < 0$) vibration.

## 3 MATERIALS

The vibration damping ability of a material is related to the internal viscous damping under harmonic loading of the material and is usually described by the loss tangent tan $\delta$, which is given by the ratio of the loss modulus to the storage modulus [**Muthusamy 2010**]. Better vibration damping properties are generally obtained at higher values of tan S. Some types of solids, such as metals and concrete, are characterized by lower values of the loss tangent (i.e., tan $\delta \rightarrow 0$). Conversely, some materials with high viscous damping (e.g., plastics, elastomers, and composite materials) are characterized by higher values of the loss tangent [**Chung 2001**, **Misun 1998**].

### *3.1 Types of investigated materials*

Different materials, which are often used as mechanical vibration dampers, were compared in terms of their damping properties. In this work, both commercially available materials purchased at the local hobby market (i.e., polyurethane foams and cork) and newly developed rubber mixtures were tested. The designation, characterization and density of the investigated materials are shown in **Table 1**. The detailed composition of the tested rubber mixtures is shown in **Table 2**. The rubber components are expressed in phr units (i.e., parts per hundred rubber), meaning parts of any non-rubbery material per hundred parts of raw gum elastomer [**Ciesielski 1999**]. The used carbon black N 320 nanofiller in the investigated rubber composites consists of the particles measuring (26 ÷ 33) nm in diameter and is characterized by these parameters: density $\rho$ = 535 kg/m$^3$, oil absorption number OAN = 46 ml/100 g and iodine number IN = 65 mg/g (according to ASTM D-1510). The carbon black N 320 nanofiller is applied in rubber composites to absorb ultraviolet radiation [**Cox 2011**, **Le 2014**].

### *3.2 Production of rubber mixtures*

The investigated rubber mixtures were produced by two-stage mixing. The time record of the rubber mixing process of the RUB_0 rubber mixture is shown in **Table 3**. Similarly, the manufacturing process of the remaining four rubber mixtures is described in **Table 4**. The first stage was performed on a Pommini Farrel kneader at the temperature of 70°C and at the speed of 99 rev/min. After this immixture, the mixture was drained out from the Pommini Farrel kneader. Subsequently, vulcanization accelerator TBBS and sulphur were added to the mixture on a Farrel double roller. The second stage was realized at the temperature of 70°C and at the speed ratio of 12/15 of both rollers. After this mixing process, the rubber mixture was stored for its further processing for a period of 24 hours at an ambient temperature of 23°C. Finally, rubber samples were pressed from the produced rubber mixtures at the temperature of 165°C.

**Table 1**. Specification of investigated materials

| Material designation | Material characterization | Density, kg·m$^{-3}$ |
|---|---|---|
| RUB_0 | Rubber mixture without N 320 concentration | 949.0 |
| RUB_15 | Rubber mixture with N 320 concentration of 15 phr | 1010.1 |
| RUB_30 | Rubber mixture with N 320 concentration of 30 phr | 1062.3 |
| RUB_50 | Rubber mixture with N 320 concentration of 50 phr | 1122.0 |
| RUB_70 | Rubber mixture with N 320 concentration of 70 phr | 1172.8 |
| CORK | Cork (Korek Jelínek Ltd., Chrastava, Czech Republic) | 191.5 |
| PUR_1 | Open-cell polyurethane foam with small pore sizes | 24.1 |
| PUR_2 | Open-cell polyurethane foam with mean pore sizes | 30.8 |
| PUR_3 | Open-cell polyurethane foam with large pore sizes | 30.2 |
| PUR_REC | Recycled polyurethane foam | 92.8 |

**Table 2**. Composition of rubber mixtures (in phr)

| Ingredient | Type of rubber mixture | | | | |
|---|---|---|---|---|---|
| | RUB_0 | RUB_15 | RUB_30 | RUB_50 | RUB_70 |
| SBR-1500 | 100 | 100 | 100 | 100 | 100 |
| N 320 | 0 | 15 | 30 | 50 | 70 |
| ZnO | 3 | 3 | 3 | 3 | 3 |
| Stearin | 1 | 1 | 1 | 1 | 1 |
| TBBS | 1 | 1 | 1 | 1 | 1 |
| Sulphur | 1.75 | 1.75 | 1.75 | 1.75 | 1.75 |

**Table 3**. Time record of rubber mixing process of the RUB_0 rubber mixture

| Mixing equipment | Sequence of additive feeding | Time, min |
|---|---|---|
| Pomini Farrel kneader | SBR-1500 | 0 |
| | ZnO + stearin | 1 |
| | Batch drainage | 4 |
| Farrel double roller | Mixture from 1st stage | 0 |
| | TBBS + sulphur | 3 |
| | Ending the 2nd stage | 7 |

**Table 4**. Time record of rubber mixing process of rubber mixtures containing the carbon black N 320 nanofiller

| Mixing equipment | Sequence of additive feeding | Time, min |
|---|---|---|
| Pomini Farrel kneader | SBR-1500 | 0 |
| | ZnO + stearin | 1 |
| | 1st half of N 320 | 2 |
| | 2nd half of N 320 | 3 |
| | Batch drainage | 8 |
| Farrel double roller | Mixture from 1st stage | 0 |
| | TBBS + sulphur | 3 |
| | Ending the 2nd stage | 7 |

## 4 MEASUREMENT METHODOLOGY

Frequency dependencies of the transfer damping function of the tested materials were evaluated by the method of the harmonically excited vibration [**Rao 2011**, **Botelho 2006**] under the harmonic motion of a base. Schematic diagram of the measuring system with a single-degree-of-freedom is shown in **Figure 1**. The measuring equipment (Brüel & Kjaer, Denmark) consists of vibrator device (BK 4810) in combination with PULSE multi-analyzer (BK 3560-B-030) and power amplifier (BK 2706). Sin-wave oscillations of the displacement $y$, the velocity v and the acceleration a (see **Figure 1**) in the frequency range of 21000 Hz were generated by the vibrator device in this case. The vibrator device is a compact electrodynamic exciter with force ratings of up to 10 N. The transfer damping function at a given excitation frequency was subsequently determined from the Equation (5) on the basis of the acceleration amplitudes $a_1$ and $a_2$, which were measured by means of accelerometers $A_1$ and $A_2$ (BK 4393). The measurements were performed for three different inertial masses mi (in this case for 85 g, 190 g and 500 g) that were located on the upper side of the tested material samples. The ground plane dimensions of the studied material samples were 60 mm x 60 mm. Each measurement was repeated 5 times at an ambient temperature of 23 °C.

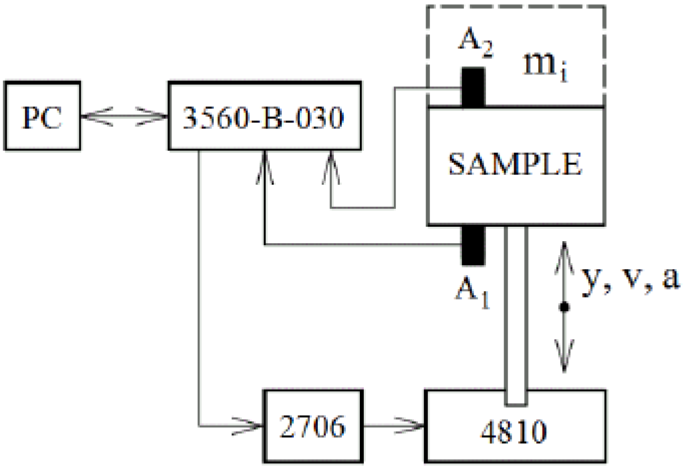

**Figure 1**. Schematic diagram of measuring equipment

## 5 RESULTS AND DISCUSSION

Different factors, which have an influence on vibro-isolating properties of the investigated materials for passive elastic bearing of machines, are evaluated in this chapter.

### *5.1 Influence of material type*

The effect of material composition on frequency dependencies of the transfer damping function of the studied rubber mixtures measuring $t = 25$ mm in thickness, which are loaded with an inertial mass $m_i$, = 500 g, is shown in **Figure 2**. It is evident that better damping properties were generally observed for rubber mixtures with lower concentrations of the carbon black N 320 nanofiller. It is given by the fact that higher N 320 nanofiller concentrations lead to a higher stiffness of the rubber samples [**Arayapranee 2008**]. It is also visible that the first resonance frequency $f_{R1}$ ($\sim D_{min}$) peak position of the tested rubber mixtures is in general increasing with increasing the carbon black N 320 nanofiller concentration and is shifted to the right (see **Figure 2** and Table 5). It is given by higher material stiffness k (or by lower damping factor ς), which is in accordance with the Equations (3) and (4). Similar results were also found for the rubber samples measuring $t = 20$ mm in thickness regardless of the value of the inertial mass, as shown in **Table 5**.

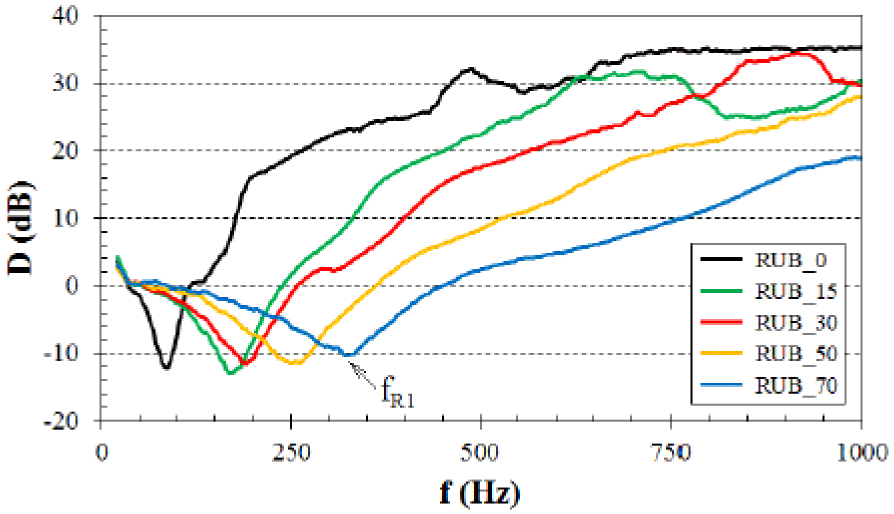

**Figure 2**. Frequency dependencies of the transfer damping function for rubber mixtures of the thickness $t = 25$ mm loaded by inertial mass $m_i = 500$ g

**Table 5**. Values of the first resonance frequency $f_{R1}$ (Hz) of rubber mixture

| Rubber mixture | Thickness, mm | Inertial mass, g | | |
|---|---|---|---|---|
| | | 85 | 190 | 500 |
| RUB_0 | 20 | $237 \pm 9$ | $231 \pm 8$ | $176 \pm 8$ |
| | 25 | $132 \pm 6$ | $103 \pm 4$ | $78 \pm 3$ |
| RUB_15 | 20 | $304 \pm 12$ | $291 \pm 12$ | $203 \pm 10$ |
| | 25 | $247 \pm 9$ | $211 \pm 7$ | $164 \pm 6$ |
| RUB_30 | 20 | $373 \pm 13$ | $358 \pm 12$ | $243 \pm 10$ |
| | 25 | $296 \pm 11$ | $245 \pm 8$ | $183 \pm 6$ |
| RUB_50 | 20 | $442 \pm 17$ | $425 \pm 14$ | $290 \pm 9$ |
| | 25 | $399 \pm 12$ | $338 \pm 9$ | $252 \pm 7$ |
| RUB_70 | 20 | $532 \pm 22$ | $518 \pm 19$ | $332 \pm 14$ |
| | 25 | $492 \pm 17$ | $406 \pm 16$ | $318 \pm 8$ |

Some examples of the frequency dependencies of the transfer damping function of the selected polyurethane ($PUR$) foams and the cork material are depicted in **Figure 3**. It was found that better vibration damping properties were obtained for the porous PUR foams and the cork material compared to the tested rubber mixtures. This is due to a lower stiffness of the $PUR$ and cork materials. For this reason, these materials are characterized by higher viscous damping and lower values of the first resonance frequency (see **Table 6**) compared to the investigated rubber composites (see **Table 5**). However, these materials are applicable only for smaller inertial masses due to their lower stiffness in the area of elastic deformations of the harmonically loaded samples.

It is evident from the comparison of the $PUR$ foams measuring $t = 30$ mm in thickness (see **Figure 3** and **Table 6**), that lower values of the first resonance frequency were observed for the $PUR$ materials with large pore sizes (i.e., $PUR\_3$). For this reason, these materials are more suitable in order to damp mechanical vibration compared to the PUR foams with smaller pore sizes (i.e., $PUR\_1$ and $PUR\_2$). It was found that relatively good vibration damping properties were obtained for the investigated recycled polyurethane foam, as shown in **Figure 3**.

This utilization of waste materials has a positive effect on our environment. It is also visible from **Figure 3** that the first resonance frequency of the cork material (i.e., $f_{R1}$ = 114 Hz) loaded with an inertial mass of 85 g is significantly lower compared to the tested rubber compounds loaded with the same inertial mass.

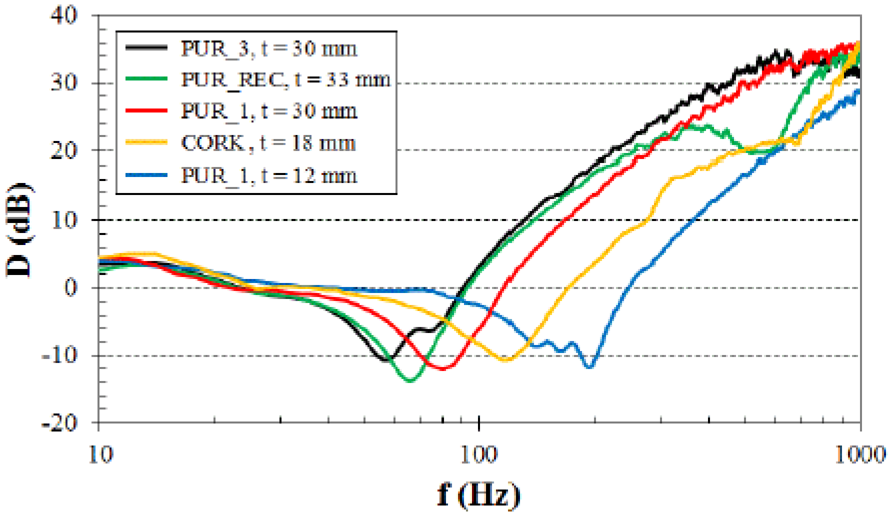

**Figure 3**. Frequency dependencies of the transfer damping function for polyurethane foams and cork loaded by inertial mass $m_i$ = 85 g

**Table 6**. Values of the first resonance frequency fm (Hz) of cork and $PUR$ foams

| Material type | Thickness, mm | Inertial mass, g | | |
|---|---|---|---|---|
| | | 85 | 190 | 500 |
| CORK | 18 | 114 ± 6 | 79 ± 4 | 71 ± 3 |
| PUR_1 | 12 | 191 ± 10 | 100 ± 6 | 76 ± 4 |
| | 20 | 120 ± 6 | 73 ± 5 | 55 ± 3 |
| | 30 | 79 ± 4 | 49 ± 3 | 30 ± 3 |
| PUR_2 | 30 | 70 ± 3 | 41 ± 3 | 28 ± 2 |
| | 50 | 50 ± 3 | 29 ± 2 | 21 ± 2 |
| PUR_3 | 30 | 56 ± 3 | 30 ± 2 | 17 ± 1 |
| PUR_REC | 50 | 48 ± 3 | 29 ± 2 | 22 ± 1 |

### *5.2 Influence of inertial mass*

A material's ability to dampen mechanical vibration is significantly affected by the value of the inertial mass mi located on the upper side of the tested material samples, as shown in **Figure 1**. The effect of the inertial mass mi on frequency dependencies of the transfer damping function for the RUB_30 rubber composite measuring $t$ = 25 mm in thickness is demonstrated in **Figure 4**. It is evident that the vibration damping properties of the RUB_30 rubber sample are in general increasing with increasing the inertial mass [**Schaller 2003**], which is accompanied by a shift of the first resonance frequency $f_{R1}$

peak position to lower excitation frequencies (see **Table 5**). This finding is related to the Equation (3), where a higher inertial mass leads to a decrease in the undamped natural frequency a„, and thus to a decrease in the first resonance frequency $f_{R1}$ [**Rajoria 2005**]. As shown in **Tables 5** and **6**, a positive effect of the inertial mass leading to a reduction of the first resonance frequency was also observed for the other material samples tested, independently of the material thickness.

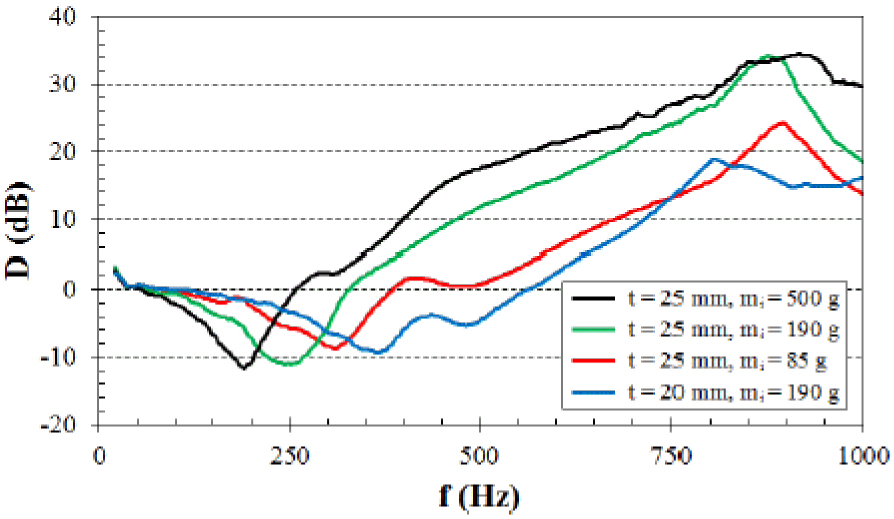

**Figure 4**. Effect of the inertial mass mi and the material thickness $t$ on the frequency dependencies of the transfer damping function for the rubber composite RUB_30.

### *5.3 Influence of material thickness*

Vibration damping properties of materials are also influenced by their thickness t. The influence of the thickness on the frequency dependencies of the transfer damping function for the RUB_30 rubber sample loaded with an inertial mass of 190 g is shown in **Figure 4**. It is obvious that a higher specimen thickness has a positive effect on vibration damping properties, which is accompanied by a reduction in the first resonance frequency from 358 Hz (i.e., for $t = 20$ mm) to 245 Hz (i.e., for $t = 25$ mm). This phenomenon was caused by higher viscous damping during the propagation of mechanical waves through the material structure. It is reflected in a higher transformation of input mechanical energy into heat during dynamic loading of the material sample with greater thickness. A similar effect of the sample thickness $t$ on a material's ability to damp mechanical vibration was observed for other rubber composites and PUR foams (see **Tables 5** and **6**).

### *5.4 Influence of excitation frequency*

As shown in **Figures 2-4**, the excitation frequency f of mechanical oscillations has a great effect on vibration damping properties of the investigated material specimens.

It is visible that the resonance mechanical vibration (i.e., $D < 0$) was generally observed at low mechanical oscillation frequencies depending on the sample thickness t and the applied inertial mass mi under dynamic loading of the tested materials. For example, for the RUB_70 rubber composite measuring $t = 20$ mm in thickness and loaded with an inertial mass $m_i = 85$ g, the resonance mechanical vibration was observed at the excitation frequencies $f < 828$ Hz. In the case of the soft PUR_3 polyurethane foam measuring $t = 30$ mm in thickness and loaded with an inertial mass $m_i =$

500 g, the resonance mechanical vibration was achieved at much lower excitation frequencies (i.e., at $f < 22$ Hz).

Contrariwise, the damped mechanical vibration (i.e., $D > 0$) of the investigated materials was generally obtained at higher mechanical oscillation frequencies, as demonstrated in **Figures 2-4**.

## 6 CONCLUSIONS

The purpose of this work was to investigate vibration damping properties of different materials that can be applied as passive elastic vibration isolations of machines and instruments. Vibration damping properties of the investigated materials were determined based on the transfer damping function by means of the forced oscillation method.

It can be concluded that the material's ability to damp mechanical vibration is significantly influenced by many factors.

It was found in this study that the vibro-isolating properties of the investigated rubber mixtures were influenced by the rubber composition that was given by the carbon black N 320 nanofiller concentration in the rubber mixtures. It was observed that the rubber stiffness is increasing with increasing the carbon black N 320 nanofiller concentration. For this reason, the vibration damping properties of the rubber materials decrease at higher carbon black N 320 nanofiller concentrations. Lower vibration damping properties were reflected in a shift of the first resonance frequency peak position to higher excitation frequencies. Better vibration damping properties were found for the tested cork and polyurethane materials, mainly in the case of the PUR foam with large pore sizes and the recycled PUR foam. It is given by a lower stiffness of these materials compared to the rubber materials that can be applicable for higher specific loads (or inertial masses) due their higher material stiffness. The application of the recycled $PUR$ foam in order to damp mechanical vibration is positive in terms of environment protection. It was also found in this study that better vibration damping properties were generally obtained at higher excitation frequencies of mechanical oscillations, inertial masses and material thicknesses.

The forced oscillation method is non-destructive, simple, fast and inexpensive, which are the main advantages of this method compared to conventional measurement methods (e.g., dynamic mechanical analysis, tensile and compression tests) in order to compare the mechanical stiffness of different materials. Based on the transfer damping function, this method can be used to optimize the design of a vibration damper (e.g., for vibration isolation of machinery) for specific operating conditions such as the frequency of oscillation and the weight of equipment. To increase the effectiveness of passive damping of mechanical vibrations under given operating conditions, it is possible to optimize the structure, composition and thickness of materials (e.g., composite rubber materials) and to apply multilayer multi-material composite structures.

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