PRESSURE OPTIMISED VISCOELASTIC VIBRATION AND IMPACT INSULATION

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Abstract:

Within this contribution we present recently published findings [1] on the new way of utilizing polymeric materials for vibration damping. We present and demonstrate patented dissipative bulk and granular systems technology [2], based on which we have developed granular damping elements (GDE). The damping elements consist of granular viscoelastic material encapsulated and pressurized within a woven container made of basalt, carbon, and/or glass fibres. The hydrostatic pressure changes material properties and consequently the performance of the vibration isolation. Within this contribution, properties of three TPU materials in solid state are investigated, which after granulation are potential candidates for producing new GDE damping elements. We have demonstrated that for the case of TPU materials the stiffness and energy absorption capability of insulation may be increased between 10 to 100 times.

Keywords: vibration insulation, viscoelasticity, granular damping elements, pressure

VISKOELASTIČNE VIBRACIJE OPTIMIZOVANE PRITISKOM I IZOLACIJA OD UDARCA

Apstrakt:

U okviru ovog rada predstavljamo nedavno objavljena otkrića [1] o novom načinu korištenja polimernih materijala za prigušenje vibracije. Prikazujemo i demonstriramo patentovanu tehnologiju disipativnih i granularnih sistema [2] na osnovu kojih smo razvili granularne elemente za prigušivanje (GDE). Elementi za prigušivanje se sastoje od granularnog viskoleastičnog materijala koji je ugrađen pod pritiskom u kalup istkan od bazalta, ugljenika i/ili staklenih vlakana. Hidrostatički pritisak mijenja svojstva materijala, a samim tim i svojstva vibroizolacije. U okviru ovog istraživanja su ispitana svojstva tri tipa termoplastičnih (TPU) materijala u čvrstom stanju, koji su nakon granulacije potencijalni kandidati za proizvodnju novih granularnih elemenata za prigušivanje. Pokazali smo da se u slučaju termoplastičnih materijala krutost izolacije i njena sposobnost absorpcije energije može povećati između 10 i 100 puta.

Ključne riječi: vibroizolacija, viskoelastičnost, granularni elementi za prigušivanje, pritisak

1. INTRODUCTION

Controlling and damping of vibrations and noise is becoming increasingly important element of engineering. On one hand due to machine and element protection against wear and fatigue. On the other hand, to protect people for example from earthquakes. The role of vibrations control is to minimize the vibration transmission between source and receiver by appropriate selection of vibration isolation elements, where system parameters such as mass, stiffness and damping of material determine the effectiveness of vibration isolation [3]. Due to their good damping properties polymers are commonly used for isolation of vibration. Besides their good damping, low specific density and good design and production flexibility makes them appealing for the use in vibration damping engineering applications [4]. However, there is one major drawback - their low stiffness [5], especially when damping elements should carry large loads, such as in the case of earthquake damping elements. In addition, properties of polymeric materials are very different; polymers with high damping (energy absorption capability), typically elastomeric materials, have lower stiffness compared to polymers with lower damping, typically thermoplastic polymers [6], [7]. Due to their lower stiffness, polymers with higher damping usually cannot be used for vibration isolation. In addition, these materials exhibit maximal values of damping (energy absorption) at very high frequencies, often at frequencies far away from the working range of machines and devices. It becomes clear, that at present, we do not have a solution allowing us to utilize the full damping potential of (especially) elastomeric materials. To summarize, the ideal material for damping would combine sufficient stiffness with maximal damping values in the frequency range of excitation. We have solved the two challenges by using the patented Dissipative bulk and granular systems technology [2], which utilizes two scientific findings:

- We found that exposing polymeric materials to selected hydrostatic pressure [8], [9], causes a shift of mechanical properties to lower frequencies. Hence, by selecting a proper (elastomeric) material with high damping properties and exposing it to a properly selected hydrostatic pressure, we can match the frequency range where material exhibits its maximal dissipation properties with the excitation or resonance frequency range of a vibrating structure. Using this principle, materials energy dissipation properties can be enhanced for several orders of magnitude. Unfortunately, pressures required for adjusting the frequency range of damping properties may be quite high, i.e., from 50 - 100MPa, and even higher. Exposing bulk materials to such pressure levels in uniaxial compression will inevitably lead to appearance of cracks due to excessive accompanying shear stresses, and eventually to material failure.

- We have solved this problem with an inventive patented solution described below. We have realized that granular materials with a proper particles size-distribution may exhibit a flow-like behavior while maintaining all properties of a bulk material. To study the flowability of granular materials we have used the self-developed GFA apparatus (Granular Friction Analyzer) [10], which allows studying the ability of granular materials to flow in case when driving force is high (hydrostatic) pressure. Based on the studies of granular materials flowability we have concluded that polymeric granular materials with proper particles size-distribution may be used as a pressurizing media (similar as air in tires) to impose hydrostatic pressure on themselves (i.e., self-pressurization) and, as a result, change frequency dependence of their own damping properties. With a proper adjustment of the hydrostatic

pressure, we can also adjust the stiffness of the damping element (again, similar as with air in tiers). Since energy dissipation of a damping element is proportional to the volume of used granular materials, whereas the stiffness in addition depends on geometry of a damping element, the two parameters (damping and stiffness) may be adjusted independently.

Utilizing described approach Granular damping elements (GDE), were developed. GDE consists of a container, made of woven basalt, carbon and/or glass fibers, which is filled and pressurized with polymeric granular materials with multi-modal particles size-distribution (Fig. 1a). Due to the flow-like behavior of granulated polymers, the generated pressure within the container will be hydrostatic and will act on polymeric particles themselves, and consequently modify frequency dependence of their energy absorption properties. Hence, with a proper pressurization we may shift the material energy absorption maximum to any desired frequency (Fig. 1b).
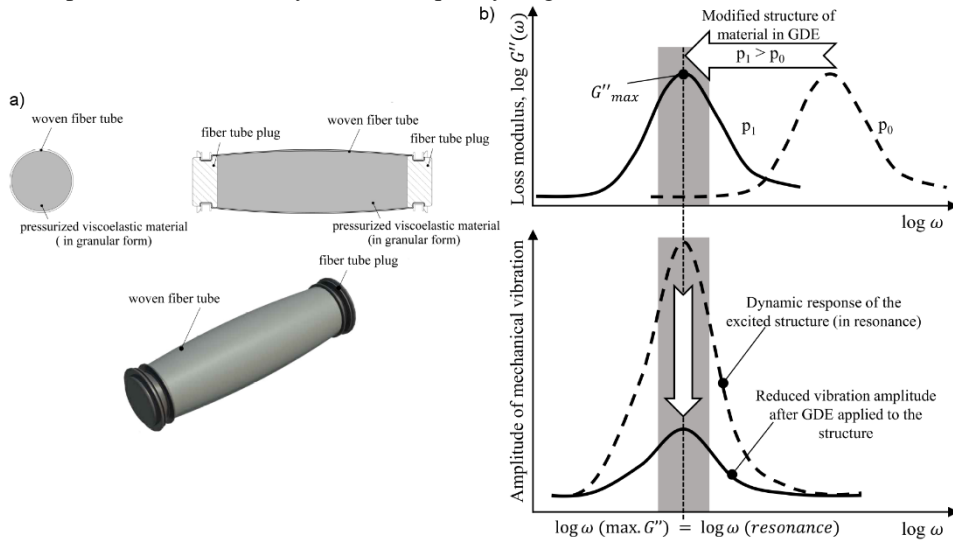

Figure 1. a) Granular damping elements (GDE) and b) working principle of GDE elements , addopted from [1].

More specifically, let us assume that a vibrating structure is equipped with a damping element made of a polymeric material of which its frequency dependent damping properties at environmental pressure p_0, expressed with the loss modulus G"(ω), are shown in Fig.1b as a dashed line in upper diagram. In the frequency range where the structure is in resonance, indicated as a shadowed area, the damping properties of this material are low. Consequently, the structure vibration amplitudes in the resonance frequency range will be large, as shown with a dashed line in Fig.1b - lower diagram. Now, if we take the very same material in a granular form with a proper particles-size distribution and self-pressurize it within a woven container, we obtain the new GDE damping element described in previous section. This is achieved by selecting a proper hydrostatic pressure p_1 within the container that shifts the loss modulus maximum to the resonance frequency range of the structure, as shown in upper diagram of Fig.1b with a solid line. As a result, the vibration amplitudes of the structure will substantially diminish, as shown as a solid line in lower diagram of Fig.1b.

In light of the presented GDE element the goal of this contribution is to analyze the effect of pressure on frequency-dependence of three polyether-based thermoplastic polyurethane (TPU) materials. The investigated materials are three BASF Elastollan TPU materials: (i) 1190A, (ii) 1175A, and (iii) 1195D. We investigated properties of TPU materials in solid state, which after granulation are potential candidates for producing the new generation GDE damping elements.

2. EXPERIMENTAL PROCEDURE

Due to space limitation the experimental methodology is briefly explained here and some details are given in continuation of this chapter, a detailed description on every step can be found in our published paper [1].
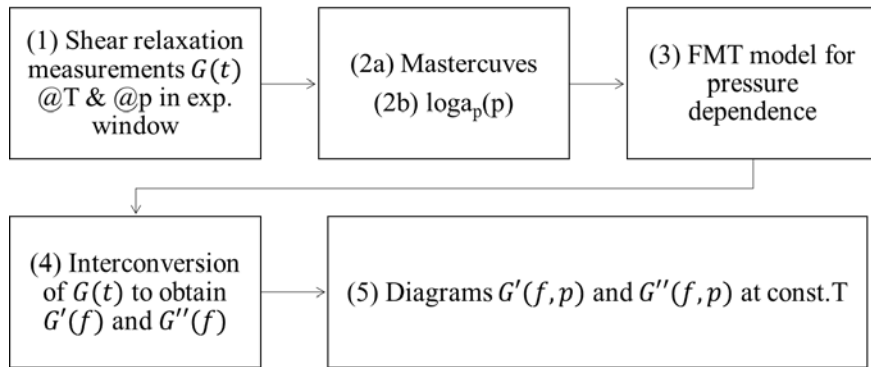

Figure 2. Shematical repersentation of experimental procedure.

As a first step (1) shear relaxation experiments were done at selected temperature and pressure range within a selected experimental window. Measured segments were assembled into mastercuves (step 2a) using time-temperature-pressure superposition. In this step we have also obtained pressure shift factor (step 2b). In the third step we have modeled the pressure behavior of tested material using the FMT model (step 3). In order to obtain the dynamic data, we have used interconversion procedure (step 4) and finally we have assembled dynamic data and pressure sensitivity of materials into 3D diagrams (5) for the analysis of GDE potential.

2.1. SAMPLE PREPARATION

We have investigated three polyether-based thermoplastic polyurethane (TPU) materials from the Elastollan® 11 series, i.e., (i) 1190A, (ii) 1175A, and (iii) 1195D, produced by BASF, that are already used in manufacturing of vibration insulation. Since Elastollan® is hygroscopic material, all materials were dried at 100°C for at least 3 hours in a commercial dryer (SP105-C, Kambič, Slovenia), to avoid bubbles formation during the extrusion process.

Due to measuring limitations of the CMS apparatus (described in next sub-chapter), we had to prepare samples with different diameters for measurements at different pressure-temperature boundary conditions. Samples were prepared with PolyLab HAAKE Rheomex PTW 16 extruder (Thermo Haake, Germany) equipped with two co-rotating 16mm screws. Thicker samples (ϕ=~6mm and ~11mm) were prepared by extrusion into glass tubes that were coated from the inside with a silicon rubber (Tesacoma, silicone

pastry board), to prevent the extruded melt from sticking to the glass. Coated glass tubes were pre-heated to 100°C before they were filled with materials, and then-after naturally cooled at room conditions. Thinner samples (ϕ=~2mm and ~4.5mm) were prepared by continuous extrusion into a water bath. The speed of a subsequent conveyor belt together with the screw speed enabled us to alter diameters of thin samples. After extrusion, the thin samples were let to free hang under their own weight for about 12 hours at room conditions, to make them straight. Next, materials were cut with a razor blade to the specified length and the cut surfaces were finished with a sand paper (using very fine P220 and super fine P1200 sand paper).

To remove residual stresses in samples resulting from extrusion, cutting, and gluing, all samples were annealed prior measurements. The starting point of this procedure was raising the temperature in the commercial dryer (SP105-C, Kambič SP105-C, Slovenia) from room conditions to 90°C. The temperature was held constant for three hours, followed by slow cooling. Cooling was done in two stages, 1st stage was done inside the oven to room conditions, around 20°C, and in the second stage samples were removed from the oven and placed inside insulation box (to assure required rate of cooling) that was placed inside a freezer. Using this procedure temperature of -20°C was achieved. During the cooling, the average cooling rate was ~0.15°C/min.

2.2. EXPERIMENTAL SETUP

All experiments were performed on unique apparatus, called CEM Measuring System, shortly CMS [8], [9]. CMS enables measurements of shear relaxation and bulk creep compliance properties of polymers in solid state. Measured specimens can be simultaneously subjected to pressures up to 500MPa, with a precision of ±0.1MPa, and to temperatures ranging from -40°C to +120°C, with a precision of ±0.01°C. The CMS apparatus is shown schematically in Fig.3. More details on the CMS apparatus may be found elsewhere [9].
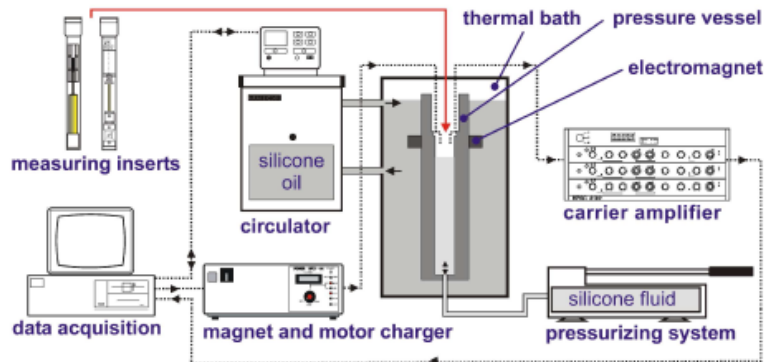

Figure 3. Schematic representation of CMS apparatus [9].

The pressure inside the pressure vessel is generated by the pressurizing system using silicone oil. The pressure vessel is contained within the thermal bath, where another silicone oil circulates from the circulator, used for precise temperature control.

The apparatus utilizes two separate measuring inserts, which can be inserted into the pressure vessel, the relaxometer and the dilatometer. Signals from the measuring inserts pass through the carrier amplifier prior to being collected in digital format by the data

acquisition system. The magnet and motor charger supplies current to the electromagnet, which activates the measurement. The same charger also supplies current to the electric motor of the relaxometer, which pre-loads the spring that then applies the desired torsional deformation (angular displacement), to the specimen.

2.3. MEAUSRING PROCEDURE

For obtaining the shear relaxation properties, experiments were performed at two different sets of boundary conditions. The 1st Set of experiments was performed at constant pressure p = 0.1MPa, and different constant temperatures between -20 and 60°C. The exact temperatures are provided within diagrams. The 2nd Set of experiments was performed at isothermal conditions, at constant temperature T = -20°C, and different constant pressures ranging between 0.1 and 300MPa. Fig.4. schematically shows boundary conditions of both sets of experiments, while the corresponding temperature and the pressure loading profiles for each of the three TPU's are presented in Fig.5.
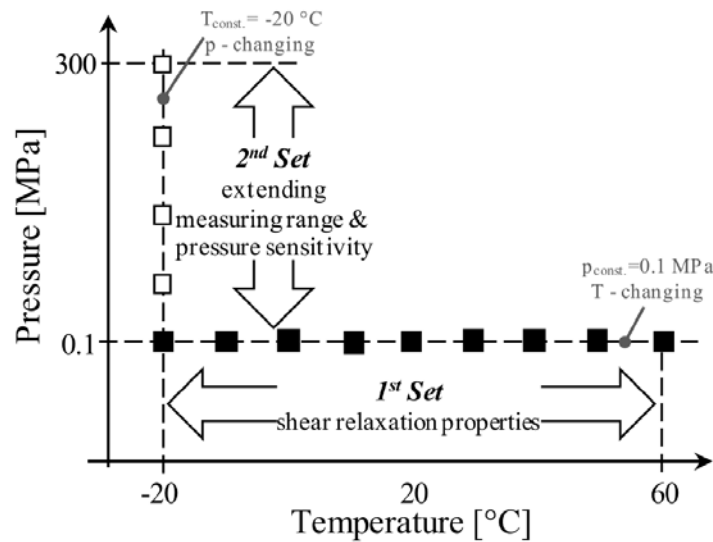

Figure 4. Boundary conditions for determining shear relaxation properties and pressure sensitivity of selected materials [1].

In all experiments, each loading step consists of 3 hours stabilization time and 1000s (~ 15min) measuring time. All experiments started at conditions where material is closer to glassy state, i.e., at lowest temperature for the 1st Set and at highest pressure for the 2nd Set of experiments. In all cases at least three repetitions of measurements were performed, where for each repetition different sample was used. After averaging segments measured at the same boundary conditions, we have applied the Closed Form Shifting algorithm to create the shear relaxation, G(t) mastercurves. The latter were then interconverted into the frequency domain, to obtain the storage G'(ω), and the loss G''(ω), moduli for the three examined materials.
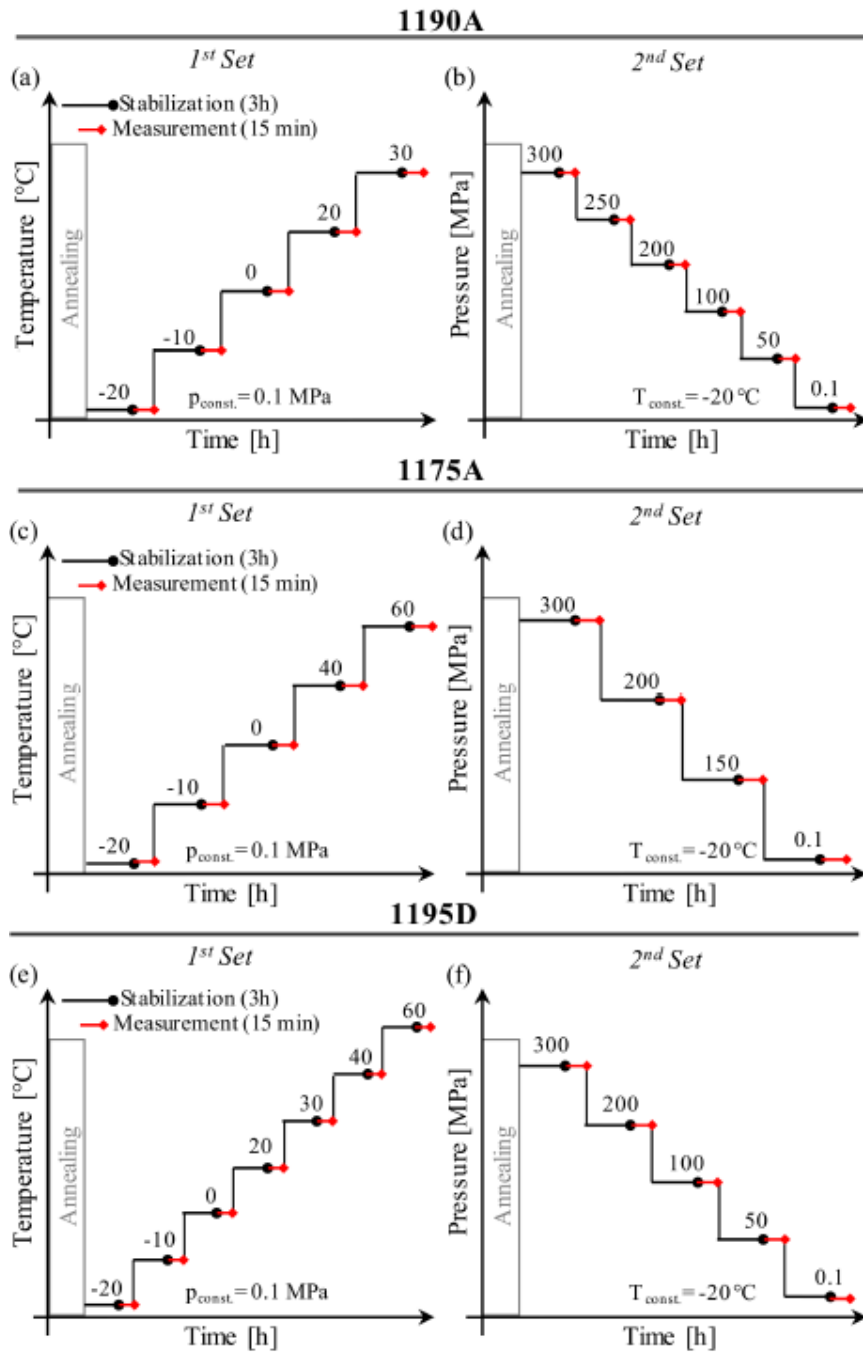
1190A

1175A

1195D

Figure 5. Temperature/pressure loading profiles for individual materials used in shear relaxation experiments [1].

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3. RESULTS AND DISCUSSION

As we have mentioned, to model the effect of pressure, we have used the FMT model, proposed by Fillers, Moonan and Tschoegl [11], [12]. The FMT model can be viewed as an extension of the WLF equation to account for the effect of pressure in addition to that of temperature. The shift factor as function of temperature and pressure is given in the form:

$$\log a_{T,p} = -\frac{C_1^{00}\left[T - T_0 - \theta(p)\right]}{C_2^{00}(p) + T - T_0 - \theta(p)},$$

(1)

where

$$\theta(p) = C_3^0(p)\ln\left(\frac{1 + C_4^0(p)}{1 + C_4^0(p_0)}\right) - C_5^0(p)\ln\left(\frac{1 + C_6^0(p)}{1 + C_6^0(p_0)}\right),$$

(2)

and C's follow as

$$C_1^{00} = B / 2.303 f_0,$$

(1)

$$C_2^{00} = f_0 / \alpha_f(p),$$

(2)

$$C_3^0(p) = 1 / k_e \alpha_f(p),$$

(3)

$$C_4^0 = k_e / K_e^*,$$

(4)

$$C_5^0(p) = 1 / k_\phi \alpha_f(p),$$

(5)

$$C_6^0 = k_\phi / K_\phi^*.$$

(6)

The 00 superscript indicates that the parameter is referred to the reference temperature T_0(first place) and to the reference pressure p_0 (second place). A single 0 superscript refers to the reference temperature only. The * superscript refers to zero (in practice, atmospheric) pressure, while subscripts e and f stand for "entire-" and "free-" volume, respectively. Eq.1 is the Fillers-Moonan-Tschoegl (FMT) equation. K_e^* and k_e and thus C_4^0, can be determined from separate volume-pressure measurements through a fit to the equation

$$\ln\frac{V}{V_0} = -\frac{1}{k_e}\ln\left[\frac{K_e^*(T) + k_e p}{K_e^*(T) + k_e p_0}\right],$$

(7)

by a non-linear least-squares procedure. In Eqs.1-9, α_f denotes expansivity (i.e., the isobaric cubic thermal expansion coefficient) of the fractional free volume, $f_0 = f(p_0)$ is the fractional free volume at reference pressure, $K_e^*(T) = K_e(T)|_{p=0}$ is the bulk modulus at atmospheric pressure, and k_e is a proportionality constant deemed independent of either pressure or temperature. FMT constants C_1 and C_2 were obtained through time-temperature-pressure superposition. Volumetric measurements were used to determine material parameters K_e^* and k_e (and thus C_4 using Eq.6) by fitting the Eq.9. For the calculation of the remaining constants C_3, C_5 and C_6, experimental shift factors obtained from measurements at constant temperature ($T = -20°C$) and varying pressures, were

fitted to Eq.1 using Levenberg-Marquardt algorithm (MATLAB R2015a). Table 1 shows FMT parameters for all three materials.

Table 1. FMT paramaters.

Mater.	C1	C2 [°C]	$\alpha_f \times 10^{-4}$ [°C-1]	Ke [MPa]	ke	Kϕ [MPa]	kϕ
1190A	31.24	202.43	1.26	2763	12.54	3092.74	12.59
1175A	11.46	52.35	1.87	2434	12.89	2494.02	13.97
1195D	24.92	105.19	1.98	2762	13.44	2877.39	15.21

Due to the space limitation, we do not show results on shear relaxation, G(t), mastercurves, which were interconverted into the frequency domain, to obtain the storage G'(ω), and the loss G''(ω), moduli for the three examined materials. Frequency domain material functions, the storage G'(ω), and the loss G''(ω), moduli, are shown in Fig.6, in double logarithmic and semi-logarithmic coordinate systems. Figs.6(a) and (c) show the storage modulus G'(ω), whereas Figs.6(b) and (d) the loss moduli G''(ω).

The storage modulus G'(ω), which defines the vibro-isolation stiffness, increases with excitation frequency for about 100 times for 1190A and 1195D, and for about 10 times for 1175A. However, as seen from the semi-logarithmic diagrams, within the frequency range indicated as shaded area that is of interest for engineering applications, their stiffness is quite low. In the case of 1175A we may see that it behaves elastically, i.e., its storage modulus is almost constant, up to 10^4Hz, whereas, within the same frequency range, the stiffness of other two materials exhibit quite strong frequency dependence. From double logarithmic diagram, we see that 1175A exhibits abrupt transition at 10^4Hz, while for the other two materials this transition is much more gradual.
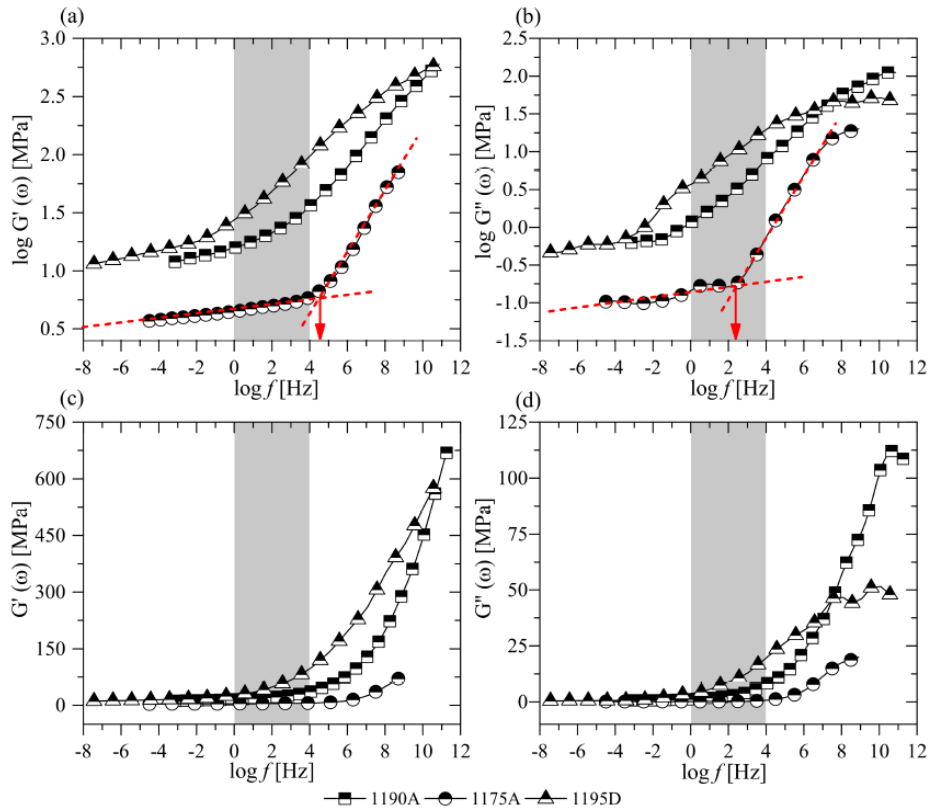
Figure 6. Shear storage modulus G'(ω) in (a) double logarithmic and (b) semi-logarithmic coordinate systems; and shear loss modulus G''(ω) in (c) double logarithmic and (d) semi-logarithmic coordinate systems. All figures are shown at Tref=20°C and pref=0.1MPa [1].

The loss modulus G''(ω), also increases with excitation frequency for all three materials, again for about 100 times for 1190A and 1195D, and for about 10 times for 1175A. Since the loss modulus G''(ω), defines the damping ability of a vibro-isolation, the higher values mean better damping. However, from the Figs.6(b) and (d) we may see that maximal measured values in all three cases are located at very high frequencies, between 108-1012Hz. In addition to this, it may also be seen that in the frequency range that is of interest in most engineering applications, shown as shaded area, values of loss modulus G''(ω), are relatively low, i.e., in the range between 0.1 to 25MPa, which is not bad in comparison to metals, however far away from real potentials of TPU materials.

Comparing the three TPUs shows that material 1175A has the lowest loss modulus G''(ω), through the whole frequency range. As in the case of storage modulus G'(ω), 1175A at about 103 Hz abruptly enters the transition state where its energy absorption properties are strongly excitation frequency dependent, before that its dissipation properties are more or less constant, see Fig.6(b). This transition is for 1190A and 1195D much more gradual.

3.1. ANALYSIS OF GDE POTENTIALS

Combining the information on dynamic viscoelastic material functions presented in Figs.6 with materials hydrostatic pressure sensitivity, we may construct 3D diagrams showing

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interrelation between the storage, G'(ω), and the loss, G"(ω), moduli, excitation frequency, and hydrostatic pressure to which material is exposed. The results are shown in Fig.7 for the storage modulus G'(ω), and in Fig.8 for the loss modulus G"(ω).

The 3D diagrams provide a general inside how the two material functions depend on hydrostatic pressure and excitation frequency. The differences between the three materials are obvious, particularly when comparing their loss moduli.
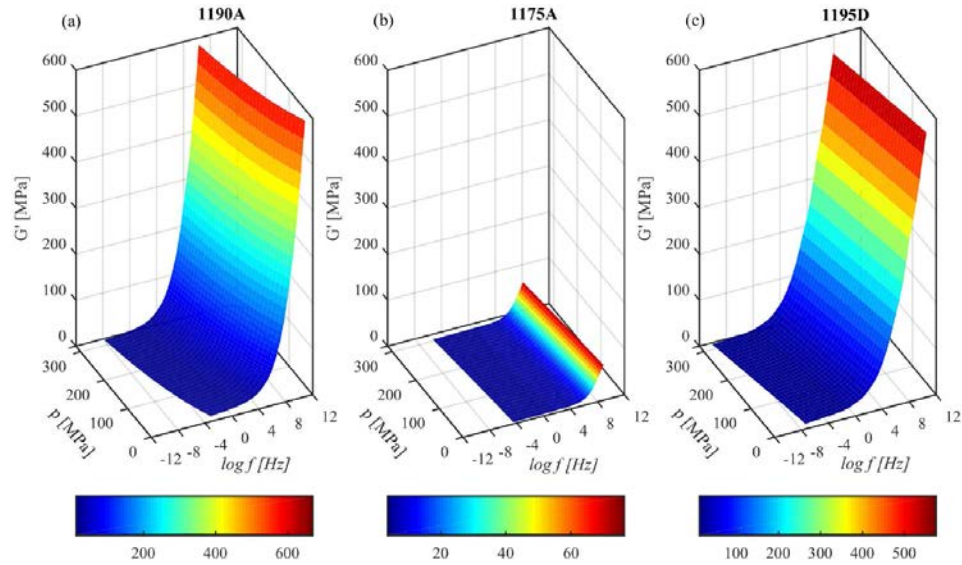

Figure 7. Frequency dependent shear storage modulus G'(ω) in dependence of hydrostatic pressure for (a) 1190A, (b) 1175A and (c) 1195D at Tref = 20°C.

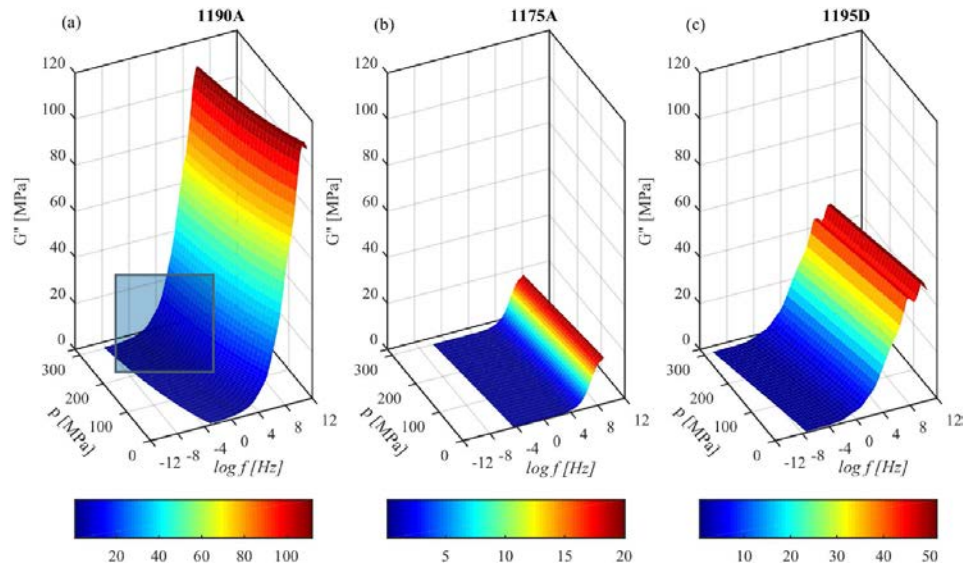*Figure 8. Frequency dependent shear loss modulus G"(ω) in dependence of hydrostatic pressure for (a) 1190A, (b) 1175A and (c) 1195D at Tref = 20°C.*

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Comparing the three diagrams in Figs. 7, we clearly see the huge difference between the three materials in the effect of pressure on improvement of isolation stiffness. Within the frequency range of interest TPU 1190A and TPU1195D are very sensitive, both, to pressure and to excitation frequency to which material (insulation) is exposed. In case of isolation energy absorption properties, displayed in Fig. 8, we again observe strong difference between the three materials, however, the effect of pressure is in this case even stronger and different than in the case of isolation stiffness.

High energy absorption and an increase of isolation stiffness caused by excitation frequency makes TPU 1190A a very attractive material for the new generation DGE damping elements. The two characteristics work hand-in-hand, high energy absorption diminishes vibrations per se, in addition an increase of isolation stiffness will move away mechanical system resonance frequency causing additional reduction of vibrations.

4. SUMMARY AND CONCLUSIONS

The paper presents analysis of pressure dependence of three Elastollan® materials, i.e., 1190A, 1175A, and 1195D in frequency domain, that are used in manufacturing of vibration insulation. The aim of the investigation was to analyze how much one can enhance performance of an insulation by using these materials in breakthrough Granular damping elements (GDE), that are based on the patented Dissipative bulk and granular systems technology. DGE insulation uses polymeric materials in granular form to enhance their dynamic properties by exposing them to hydrostatic pressure, which shifts material energy absorptions maximum towards lower frequencies, to match the excitation frequency of dynamic loading to which a mechanical system is exposed.

From the obtained results, one may draw the following conclusions:

- The three polyether-based thermoplastic polyurethane (TPU) materials from the Elastollan® 11 series, i.e., 1190A, 1175A, and 1195D, with similar chemical structure, exhibit significantly different frequency-dependent properties.
- All three materials are quite sensitive to pressure, and 1190A proofs to be the most sensitive of the three materials. At 300MPa, properties of 1190A are shifted along the logarithmic frequency scale for around 5.5 decades, for 1195D and 1175A this shift is about 3.5, and 1.5 decades, respectively. These shifts may be achieved by exposing materials to selected hydrostatic pressure.
- The storage modulus $G'(\omega)$, which defines the vibro-isolation stiffness within the frequency range of interest, may be increased with pressure for about 100 times for 1190A and 1195D, and for about 10 times for 1175A.
- The loss modulus $G''(\omega)$, which defines the vibro-insulation energy absorption capability within the frequency range of interest, may be increased with pressure for again about 100 times for 1190A and 1195D, and for about 10 times for 1175A.

In conclusion, among the three measured materials it was shown that material 1190A seems to be the most promising for the use in Granular damping elements. Besides having the largest values of loss modulus $G''(\omega)$ it is also the most sensitive to pressure. Meaning, that even at relatively small applied hydrostatic pressures the increase of loss modulus $G''(\omega)$ is higher compared to the other two materials.

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