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Adjustable epoxy based vibration damping material for constrained-layer systems

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Vibration damping of mechanical structures is of interest in relation to noise, vibration and strength of structures and it includes both internal material damping and the additional damping caused by the whole mechanical structure. The most efficient way to prevent the harmful effects of vibration is to increase damping using constrained-layer systems that provide weight-efficient, high-level damping even for heavy machinery structures. The novel Noisetek ELASTE high damping epoxy product family is specially designed for these layered structures. Utilization of this adjustable vibration damping material is based on accurate control of location of its glass transition temperature region. In the middle of it the maximum mechanical damping is achieved and the measured loss factor values vary from 1.3 to 1.7. In practice, the properties of a given cured epoxy system are designed so that the maximum peak of damping is set to appear in the property window of predetermined thermal and mechanical vibration conditions. Temperature and frequency dependent material properties of epoxies were measured and a visco-elastic model for describing frequency temperature dependent properties was developed. Accurate material model enables to use of finite element modeling tools to simulate efficiency of different damping treatments on vibration behavior of real structures.

1 Introduction

Mechanical vibration causes problems in many applications. Vibration damping of mechanical structures is of interest in relation to noise, vibration and strength of structures. Vibration damping is usually divided into five different damping mechanisms: internal material damping, interface damping (friction damping), radiation damping, energy losses occurring as a result of reflection at discontinuities of structures, and viscous damping caused by visco-elastic material or by surrounding fluid.

Because the reason for noise and vibration problems is often resonating vibration, the most efficient way to prevent the harmful effects of resonances is to increase damping. Constrained-layer damping (CLD) systems provide very weight-efficient damping option also for heavy machinery structures.

To optimize the efficiency of CLD systems designers need the knowledge of the visco-elastic properties of the damping material. Their dependence on frequency and temperature aids in the selections of materials for specific applications. The problem has been the lack of information on the materials from their producers. Additionally there has not been a product or a material in the market that can be accurately adjusted so that the peak damping effect appears in the property window for predetermined thermal and mechanical vibration conditions of the application.

With the novel Noisetek ELASTE high damping epoxy materials, the mechanical damping is based on precise control of the location of the glass transition temperature regions; the greatest damping is achieved in the middle of the region. Temperature and frequency dependent material properties of high damping epoxies were measured using dynamic-mechanical thermal analysis (DMTA). Based on these measurements visco-elastic model for describing frequency temperature dependent properties was developed. Accurate material model enables the use of FE modeling tools to simulate efficiency of different damping treatments on vibration behavior of real structures.

2 Vibration and damping

Vibration controlling efforts can be focused on different fields: excitation, transfer paths, joints, damping and sound radiation. One attractive way to solve the vibration problems is to increase the damping capacity of structural materials.

Noise and vibration problems in machines are often generated by vibrating surfaces of components that exhibit low inherent material damping. Internal material damping, the transformation of mechanical energy into heat, is often described using a quantity called the loss factor, which indicates the fraction of the vibratory energy lost in one cycle of the vibration. This damping mechanism, as all the other damping mechanisms, is dependent on various factors like frequency, temperature and material composition. [1]

2.1 Sound radiation of a vibrating structure

Equation (1) is the basic formula for the calculation of sound power radiated by a vibrating structure [1]

$$P = \rho c A \sigma \left\langle v^2 \right\rangle. \tag{1}$$

The surface area of the vibrating structure (A), the density (ρ) of the surrounding fluid and the speed of sound (c) in the surrounding fluid are constants. The average mean square velocity ($\langle v^2 \rangle$) of the radiating surface and the radiation efficiency (σ) are the quantities that have to be calculated.

In certain cases, with big and thick structures, the fact that the radiation efficiency is unity well above coincidence frequency can be utilized i.e. radiated sound power level can be estimated using only the FE calculated velocity distribution of the structure. For steel and aluminum structures the coincidence frequency can be calculated by dividing 12 kHz with the plate thickness expressed in millimeters.

Equation (1) is often presented in a logarithmic form Equation (2)

$$10\log\left(\frac{P}{10^{-12}\,\mathrm{W}}\right) = 10\log(\sigma) + 10\log\left(\frac{v^2}{\left(10^{-9}\,\mathrm{m/s}\right)^2}\right) + 10\log\left(\frac{A}{1\,\mathrm{m}^2}\right) + 10\log\left(\frac{\rho_i c_i \left(10^{-9}\,\mathrm{m/s}\right)^2}{10^{-12}\,\mathrm{W}}\right) \tag{2}$$

$$\Rightarrow L_W = L_\sigma + L_v + L_A - 33.9\,\mathrm{dB}.$$

Sound power level (L_W) is a sum of radiation index (L_σ), velocity level (L_v) and surface area level (L_A). Constant –33.9 dB is defined by the air density (ρ_i = 1.188 kg/m^3, 20 °C and 1x10^5 Pa) or surrounding fluid density, the speed of sound in the air (c_i = 343.3 m/s, 20 °C) or surrounding fluid and the standardized reference values.

2.2 Damping

Structural damping, the transformation of mechanical energy into heat, is often described using a quantity called the loss factor (η), which indicates the fraction of the vibratory energy lost in one cycle (radian) of the vibration. Some other terms like damping ratio (ζ), half power bandwidth (b), decay time (T), logarithmic decrement (Λ), tan δ and sharpness of resonance (Q) are also used to describe the amount of damping in a structure. The relation between all these quantities is presented in Equation (3) [2]

$$\eta = 2\zeta \Big/ \sqrt{1-\zeta^2} = b/f = 2.2/T_D f = \Lambda/\pi = \tan\delta = Q^{-1}. \tag{3}$$

Typically the measured machine damping is a combination of several damping mechanisms which are not separable.

2.3 Free-layer and constrained-layer damping

Damping materials can be used for a wide variety of noise and vibration applications. To take full advantage of their vibration-reducing potential, product designers often must make a choice between using free-layer or constrained-layer damping (CLD) systems. While either system will provide good results for thin substrate panels, thick or heavy structures - 6 mm or thicker - require a CLD system to achieve high damping and effective noise reduction.

In free-layer damping the material is usually attached with a strong bonding agent or troweled onto the surface of a vibrating structure. Energy is dissipated as a result of extension and compression of the damping material under flexural stress from the base structure. Best damping for a structure with a free-layer damping treatment is achieved when the loss factor, Young's modulus and the thickness of the damping layer are high.

Most CLD applications use a three-layer "sandwich" system that is formed by laminating the base layer to a damping layer and then adding a third constraining layer on the top. Typically, the constraining layer is of the same material as the base layer, but exceptions are common. In these structures with multiple layers, when the system flexes during vibration, the damping material layer is forced into a shape that shears adjacent material sections. This alternating shear strain in the CLD material dissipates the vibration as frictional heat more efficiently than the extension and compression in the free-layer damping system.

3 Material development

Polymer based damping treatments are one of the most common methods to increase damping of the structure and thereby to decrease resonant vibration and noise. In practice, by using only polymer-based coatings on the surface of the structure, the desired reduction in vibration and noise cannot be achieved for heavy structures, or the thickness of the damping layer becomes impractically thick. That is why the material development was focused on CLD materials.

The properties of polymers are highly dependent on temperature and also on excitation frequency, and as a result, one damping material cannot cover all of the needs. Adjustable epoxy based materials were developed and the utilization is based on very accurate control of location of glass transition temperature region.

3.1 Noisetek ELASTE high damping materials

Epoxy systems are versatile because of the large number of potential epoxy resin, curing agent and modificator combinations. Examples of typical applications of epoxy materials include adhesives, functional joints, shock absorbing pads, abrasion resistant coatings and flexible laminates.

The Noisetek ELASTE high damping epoxy materials provide high mechanical damping properties in the middle of glass transition region and are relatively easy to adjust with regard to the location of the glass transition region by altering the ratios of the components of the epoxy material. In practice, the properties of a given cured epoxy system are designed so that the maximum peak of damping is set to appear in the property window of predetermined thermal and mechanical vibration conditions. A DMTA measurement curve for epoxy system designed for approx. 60 °C and 10 Hz operational conditions is presented in Figure 1. Additionally a review for the dimensions (shape of the damper and thicknesses of the different layers) of a particular damper must be made to achieve optimal damping in the desired frequency range.

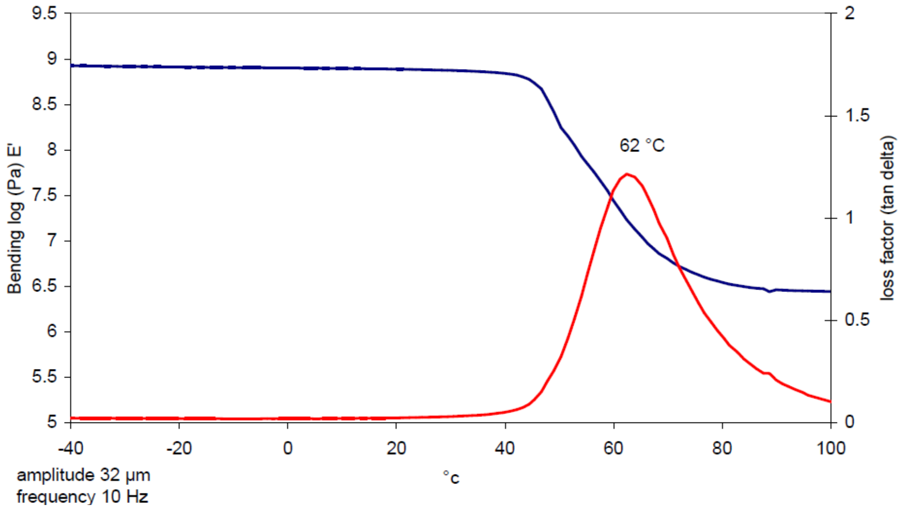

Figure 1: A typical DMTA measurement curve of a high damping epoxy system displaying a change in storage modulus (black curve) and change in loss factor (red curve). The limits of T_g region are 40 °C 90 °C and the value of peak loss factor of 1.25 is at 62 °C. The region exceeding loss factor of 1.0 is located in between 55 °C 70 °C when frequency is 10 Hz and amplitude is 32 µm.

Glass transition temperature region is a phenomenon featured especially in polymeric materials. When rising the temperature to reach this transition region, the modulus of elasticity undergoes a significant change from glassy state of high modulus (a state below T_g region) to rubbery state (a state above T_g region). In about the middle of the glass transition region, there occurs an intensive rise of mechanical damping as in Figure 1. Damping capacity at this state may increase a tenfold compared to true glassy state, and multiply the damping capacity compared to true rubbery state. Peak loss factor values exceeding 1.2 are not uncommon. This is a natural phenomenon, caused by the effect of thermal energy in interaction of polymer chains. This phenomenon is also reversible and essentially a state of thermodynamical equilibrium which may be set by adjusting it into some preferred region, for example at peak loss factor. [3]

As a phenomenon, the T_g region and related intensive rise of damping have been known for a long time. The actual problem has been in how to prepare a polymer to respond to some predetermined thermal and vibration conditions. Because practical manufacturing of polymers with such adjustable and repeatable properties at reasonable costs has been difficult, previously such materials have not been available for industrial applications. A great success in this challenge has been met with high damping Noisetek ELASTE materials. For example by simple mixing of well defined commercial raw materials it is possible to gain very accurate control in adjusting maximum damping along temperature axis for a given predetermined thermal and vibration conditions. The maximum of the mechanical damping can be adjusted by ± 5 °C, preferably ± 2 °C of the temperature of the vibrating body. As the properties of polymers are also frequency dependent, the T_g region of a epoxy system transfers approx. from 5 °C to 8 °C higher every time the testing frequency increases tenfold for example from 10 Hz to 100 Hz and from 100 Hz to 1000 Hz.

The Noisetek ELASTE materials provide an excellent vibration damping performance over a wide temperature and vibration frequency range. The temperature range from -10 °C to +160 °C is covered with different material combinations, where a loss factor greater than 1.0 is achieved.

4 Case study and results

Noisetek ELASTE high damping epoxies were demonstrated as constrained dampers on cable sheaves. The sheaves are made by welding and the sheave body forms a big plate-like sound radiator where vibration was detected to be highly resonating. The width of the sheave is 1.2 m and the thickness of the plate structure is 0.012 m.

The demonstration work consists of modelling the sheave with finite element method and simulating its vibration response with add on devices based on the principle of constrained layer damping. The simulation findings were verified by vibration measurements.

Due to the wide operational temperature range of the sheave, two different Noisetek ELASTE materials were used in the damper design. One is optimal for 0 °C and another for 25 °C. In the model a damper with 0 °C epoxy was situated on one side and another damper with 25 °C epoxy on the opposing side of the sheave.

The used damper is a variant of a traditional constrained layer damper design consisting of a base plate (web plate of the sheave), a 0,003 m thick visco-elastic damping material layer (epoxy) and a 0,005 m thick constraining layer (steel plate). This damper principle is usable also with thick steel structures.

4.1 Modelling results

Visco-elastic material models were used in modelling and developing the final dampers on the cable sheave. Few different damping treatments were considered and their efficiency simulated. The main parameters, besides the epoxy materials, were thicknesses of the damping material and the constraining layer and also the size of the constraining layer.

The temperature dependent behaviour of the epoxy damper is presented in Figure 3. The damper operates definitely better at the optimal temperature of 25 °C.

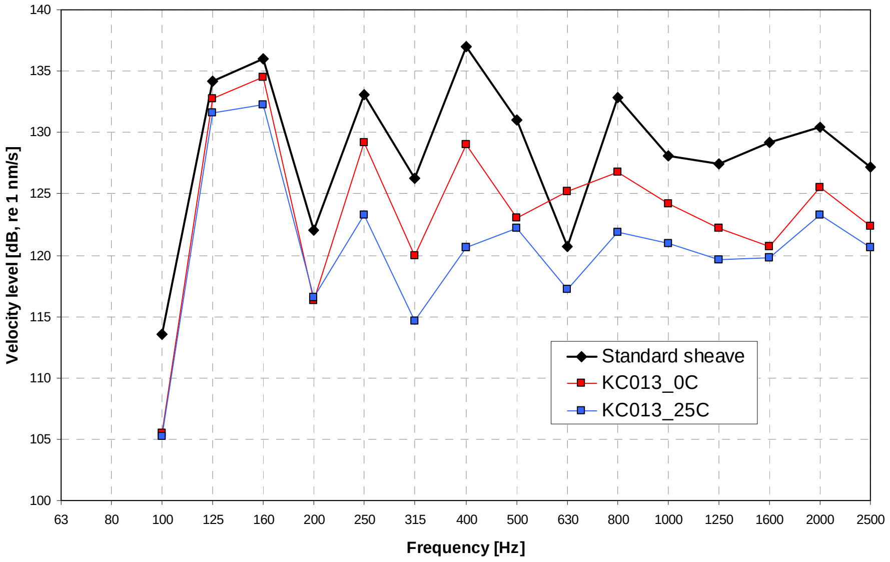

Figure 3: The effect of temperature on the behaviour of a single epoxy damper ELASTE_KC013. The optimal operational temperature of that epoxy system is at 25 °C.

The same kind of behaviour is seen with the modelling results of the damped sheave with two dampers. It seems that the damper design operates as it was planned; sufficient damping is achieved in a wide temperature range.

4.2 Measurement results

The effect of the damping devices was tested by measuring the damping and by comparison of the frequency responses. The measurements were made without damper, with a 25 °C damper on one side of the sheave and finally when the 0 °C damper had been installed on the opposing side.

The damping was determined with ME'scopeVES modal analysis software from the frequency responses measured between an impact hammer force and acceleration responses. The measurements were made with B&K 8202 impact hammer with a plastic tip, B&K 4137 accelerometers and LMS Scadas SC310 analyzer. The impulse excitation was given on the flange of the cable groove (the driving point) and responses were measured in four positions as in Figure 4. A-weighted velocity level in response point 2 for a unit force excitation in the driving point is shown in Figure 5.

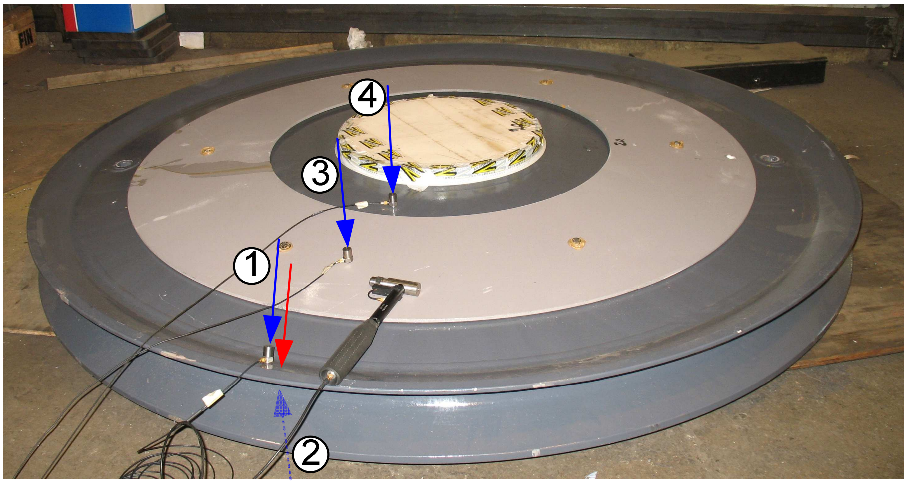

Figure 4: Measuring positions. Excitation position (the driving point) is shown with the red arrow and response accelerometers 1 to 4 with blue arrows. Response point 2 is on the underside of sheave. The light grey area is the constraint layer damper.

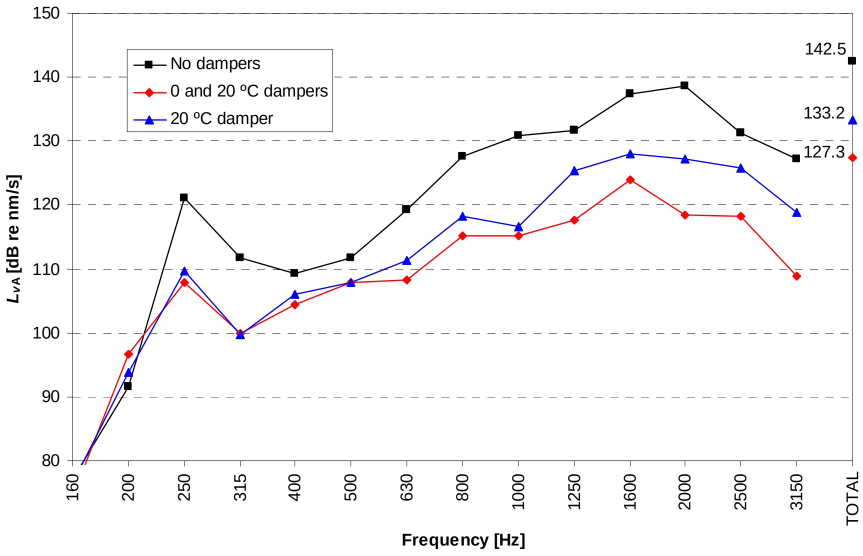

Figure 5: A-weighted velocity level in point 2 for a unit force excitation in the driving point.

The measured structural damping of the damped sheaves is 3 to 10 times higher than that of the original structure. The measured frequency responses in 20 °C give comparable results to the simulations in 25 °C. The effect on the vibration velocity level (insertion loss) is about 15 dB. Therefore we can presume that the simulated level reduction in 0 °C is also quite reliable. Since the earlier noise measurements of the sheaves have shown that their vibration in real operation is highly resonating it can be expected that the sound radiation of the damped sheaves is 10…15 dB lower.

5 Summary

Increasing structural damping is an efficient way to prevent the harmful effects of resonances. For heavy machinery structures constrained-layer damping (CLD) systems provide weight-efficient damping option. In addition to the right dimensions of a particular damper, designers need the knowledge of the visco-elastic properties of a damping material to properly utilize the potential of CLD damping systems.

With the adjustable Noisetek ELASTE materials, the mechanical damping is based on precise control of the location of the glass transition temperature regions; the greatest damping is achieved in the middle of the region. Typically loss factor values of over 1.2 were measured for various high damping epoxies in the temperature range of -10…+160 ˚C. Based on the measurements of temperature and frequency dependent material properties, visco-elastic model for describing frequency temperature dependent properties was developed. Accurate material model enables the use of FE modeling tools to simulate efficiency of different damping treatments on vibration behavior of real structures.

In the case study Noisetek ELASTE high damping epoxies are demonstrated as constrained dampers on a cable sheave. Due to the wide operational temperature range of the sheave, two different epoxy compounds are used on the opposing sides of the sheave. The measured structural damping of the damped sheaves is 3 to 10 times higher than that of the original structure. The measured frequency responses give comparable results to the simulations and satisfactory levels were achieved.

References

[1] L. Cremer, M. Heckl and E. E. Ungar, *Structure-Borne Sound: Structural Vibrations and Sound Radiation at Audio Frequencies* (Springer-Verlag, Berlin, 1988).

[2] D. J. Mead, *Passive Vibration Control* (John Wiley & Sons, Chichester, 2000).

[3] J. D. Ferry, *Viscoelastic properties of polymers, 2nd Ed* (John Wiley & Sons, New York, 1970).