Attenuation of Machinery Vibration – Design Methodology

Capt Sunil Tyagi, PhD

Directorate of Naval Design (Submarine Design Group), IHQMoD (Navy),
New Delhi –110066.

Abstract—*Machinery vibration is the principal contributor to the radiated noise of the 'boat'. Using machines with low vibration levels and employing the concept of 'raft', low-frequency mounts etc. have contributed to managing the noise due to machinery vibration to a certain extent. However, despite these measures, the machinery vibration remains the biggest contributor to the underwater radiated noise, especially in low-frequency bands. Thus, the use of Vibration absorbing measures is imperative to achieve optimum acoustic stealth. Vibration damping measures make it possible to noticeably reduce vibration levels of shipboard structures, attenuate vibration activity of machinery and thus diminish vibratory energy transmitted to ship hull. These measures include Vibration absorbing alloys, Fibrous vibration-absorbing structural materials, Polymeric viscoelastic vibration absorbing materials and Vibration absorbing fillers. These tools enable reduction of resonance structural vibrations in lower and medium acoustic frequency bands, as well as attenuation of vibration energy over propagation paths at higher acoustic frequencies. This paper discusses briefly the Classification and requirements of vibration damping tools, their Dissipative characteristics, Application of vibration damping tools in various types of structures, Estimation of vibration damping efficiency and Method for estimation of loss coefficient for damped structures.*

Keywords—Vibration damping means, structural damping, coatings, materials

1 INTRODUCTION

Vibration absorbing (damping) tools and measures make it possible to noticeably reduce vibration levels of ship board structures, attenuate vibration activity of propulsion plant machinery and thus diminish vibratory energy transmitted to ship hull, which is a major source of excessive under water radiated noise levels. Vibration damping tools enable reduction of resonance structural vibrations in lower and medium acoustic frequency bands, as well as attenuation of vibration energy over propagation paths at higher acoustic frequencies.

The efficiency of vibration damping means depends on the properties of vibration absorbing materials as well as on the service conditions of the structure to be damped, manufacturing requirements, sanitary chemical

***Corresponding author**: Capt Sunil Tyagi, PhD is with the *Directorate of Naval Design (Submarine Design Group), IHQMoD (Navy), New Delhi – 110066.* (Phone: +91 11-26161992; fax: +91 11-26194532; e-mail: sunil.tyagi@navy.gov.in).

regulations, and operating specifications. In this connection it is required, on the one hand, to select appropriate anti-vibration means for a specific structure, and, on the other hand, to find a rational arrangement to accommodate these tools.

The paper briefly covers the main features of anti-vibration design philosophy including:

- Classification (types) and main characteristics of vibration damping tools as well as properties of vibration absorbing materials used in these tools;
- Main requirements regarding vibration damping means;
- Dissipative characteristics of vibration damping tools;
- Procedures for application of vibration damping tools for various types of shipboard structures;
- Rules for selection and arrangement of vibration damping tools for various types of shipboard structures;
- Efficiency appraisal of vibration damping tools;
- Procedure for estimation of loss coefficients for vibration damping tools.

2 CLASSIFICATION (TYPES) OF USED TOOLS

By vibration absorbing (damping) we understand conversion of oscillatory (vibrational) mechanical energy into thermal energy.

Vibration damping is quantified by the loss coefficient. According to a classical definition, the loss coefficient is proportional to the ratio between the energy absorbed over a period of stationary harmonic oscillation and the total energy accumulated over the oscillation period. This definition implies that pronounced resonance frequencies are present. The loss coefficient η can also be defined as the ratio between the absorbed energy averaged over the analyzed band frequency or oscillating structure (part thereof) and the total energy of the structure (part thereof). It is a so-called energy (high-frequency) description of the structure vibration behaviour.

Rolling bearings consist of two concentric rings, called the inner raceway and outer raceway, with a set of rolling elements running in their tracks. Since most bearing rotations are periodical hence, it is easy to calculate characteristic frequency of defect.

Typically, the rolling elements in a bearing are guided in a cage that ensures uniform spacing and prevents mutual contact. There are five basic motions that are used to describe the dynamics of bearing elements, with each movement having a corresponding frequency.

Vibrations absorbing (damping) means are differentiated by their physical nature, properties, application methods and efficiency. Vibration damping means employed in shipbuilding include:

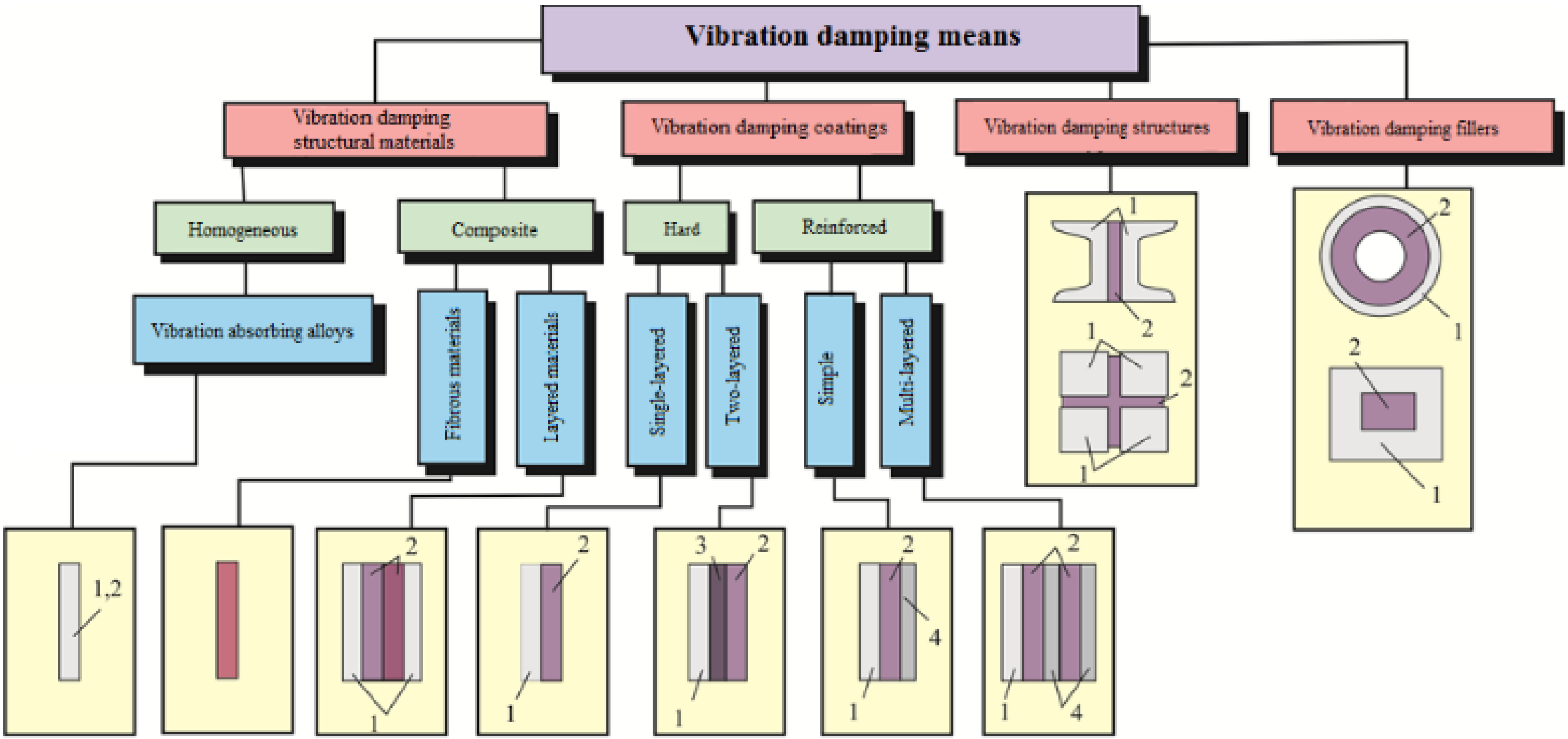
- Vibration damping structural materials;
- Vibration damping coatings;
- Vibration damping structures;
- Vibration damping fillers.

Let us now examine each of the means mentioned above.

2.1 Vibration absorbing structural materials

Vibration absorbing structural materials should, along with increased absorption of vibratory energy, have high strength and stiffness. In terms of their structure and vibration absorption mechanism, vibration absorbing structural materials are subdivided into homogeneous and composite.

Homogeneous structural materials (mainly, damping alloys, or “high-damping alloys”, as these are called by material scientists) ensure high strength and stiffness, and vibration absorption takes place within their entire volume.



1 – damped structure; 2 – vibration absorbing element; 3 – spacer gasket; 4 – reinforcing element

Fig.1. Vibration damping means applied for ship structures

Composite vibration absorbing materials have two types:

- Multi-layered fibre materials impregnated with viscous binder;
- Multi-layered materials consisting of two and more thin plates made of metal or rigid plastic and separated by a visco-elastic spacer.

2.1.1 Fibrous materials are practically traditional composite materials (GRPs or CRPs). Similarly to homogeneous structural materials, they have sufficiently high strength and stiffness. Dissipation characteristics of these materials (composite structures) are ensured by means of special binders offering high losses, as well as by means of their complex structure with non-uniform section.

2.1.2 Layered materials are “sandwich”-type, i.e. they consist of rigid outer layers (steel, light alloy, GRP) and the internal layer of vibration absorbing visco-elastic material, self-adhesive or attached with a special glue).Absorption of vibratory energy in layered structural materials is determined by shear straining of the medium vibration absorbing layer.

2.2 Vibration absorbing coatings

Vibration absorbing coatings are layered structures, they consist of different materials and always include visco-elastic vibration absorbing layers. The coatings are applied on engineering structures and are intended to reduce vibration of these structures by means of joint straining when vibration takes place.

The layers of viscoelastic materials applied in vibration absorbing coatings have higher (100 times and more) vibration loss coefficients than hull, foundations or power equipment structures.

2.2.1 Hard vibration absorbing coatings, in their turn, can be single-layered and two-layered. Single-layered coating has only one layer of the visco-elastic vibration absorbing material, whereas two-layer coating has a layer of light hard material between vibration absorber and damped structure, which increases tension-compression strains in the polymeric layer, thus increasing efficiency of the coating.

2.2.2 Reinforced coatings are also subdivided into simple and layered. Simple reinforced coating consists of viscoelastic vibration absorbing layer adjoining the structure, and the reinforcing layer made of a rigid material (metal, plastic, GRP, CRP). Layered reinforced coating is a structure with alternating vibration absorbing and reinforcing layers.

2.3 Vibration absorbing structures

Vibration absorbing structures are the elements of hull, foundations or power equipment. Their internal layers are made of

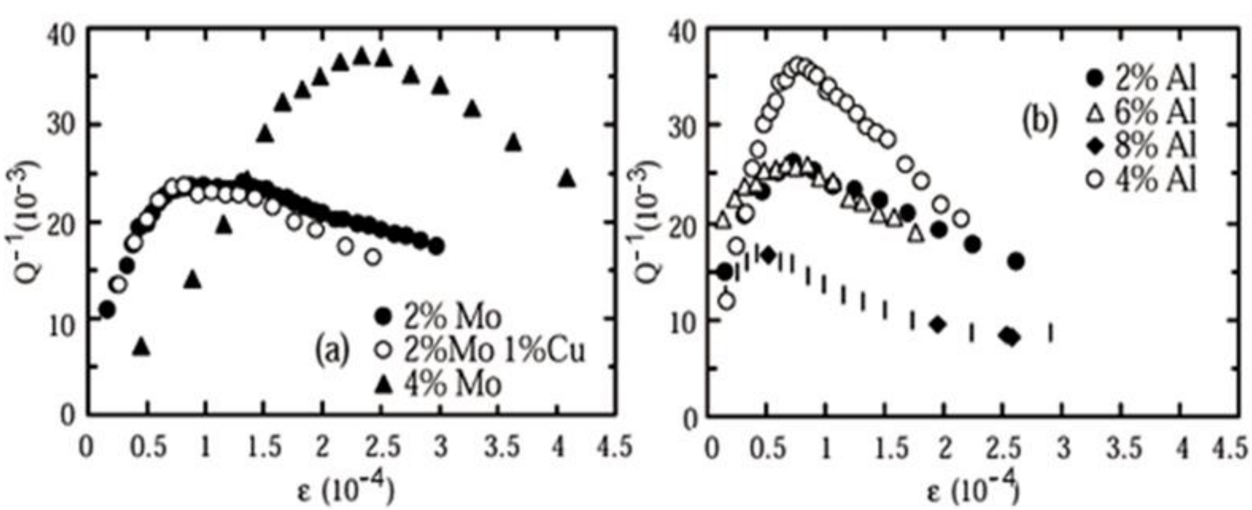


Fig. 2. Variation of damping capacity (Q^{-1}) verses strain amplitude (ε).
(a) Ferromagnetic alloy with different Mo additions (b) Different Al additions

Table 1 : Young's moduli and maximum loss coefficients (at high stresses) of some vibration absorbing alloys

Alloy	Content of components, %	Young's modulus,N/m^2	Maximum loss coefficient
Fe-Cr	16% Cr	$1.73 \cdot 10^{11}$	0.11
Fe-Cr-Mo-Cu	12% Cr2.5% Mo; 1% Cu	$1.8 \cdot 10^{11}$	0.13
Fe-Cr-Al	12% Cr; 3% Al	$1.65 \cdot 10^{11}$	0.19
Cu-Mn	40% Cu	$0.74 \cdot 10^{11}$	0.10
Ni-Ti	54.5% Ni	$0.71 \cdot 10^{11}$	0.13
Cu-Zn-Al	9.6% Zn;8.1% Al	$0.5 \cdot 10^{11}$	0.13

viscoelastic or structural vibration absorbing materials. In the first case, vibratory energy dissipates due to shear strains in the layer of viscoelastic vibration absorbing material. In the second case, it dissipates within the entire volume of the structural element are the elements of hull, foundations or power equipment. Their internal layers are made of viscoelastic or structural vibration absorbing materials. In the first case, vibratory energy dissipates due to shear strains in the layer of viscoelastic vibration absorbing material. In the second case, it dissipates within the entire volume of the structural element.

2.4 Vibration absorbing fillers

Vibration absorbing fillers are viscoelastic or bulk materials used to fill the volumes (voids) in the elements of hull, foundations and power equipment so as to increase their vibration absorption capacity. Here, vibratory energy dissipates either due to friction between particles (bulk fillers) or due to tension-compression strains (viscoelastic fillers).are viscoelastic or bulk materials used to fill the volumes (voids) in the elements of hull, foundations and power equipment so as to increase their vibration absorption capacity. Here, vibratory energy dissipates either due to friction between particles (bulk fillers) or due to tension-compression strains (viscoelastic fillers).

3 VIBRO ABSORBING MEANS

As seen from the previous section, each type of vibration damping tools provides high transmission losses in structures using one or another type of vibration absorbing materials. Let us now investigate the parameters of these materials in more details.

3.1 Vibration Absorbing Alloys

Vibration absorbing alloys, or high-damping alloys, belong to the group of homogeneous structural vibration absorbing materials featuring enhanced absorption of vibrational energy in the entire volume of the structure combined with sufficient robustness and plasticity of these materials. High damping capacity of vibration absorbing alloys is mainly determined by the following physical processes:

- Relaxation of stresses at the boundary between phases within the interval of phase transition temperatures;
- Relaxation of stresses at the boundaries of compound crystals;
- Relaxation of stresses due to boundary displacements of ferro-magnetic domains.

Each of these processes takes place at rather high vibration stresses, and the energy of elastic vibration is used to move the surface of the boundary. This internal similarity of the processes at question can be seen from coinciding amplitude relationships of internal friction for different vibration absorbing alloys: there exists an area where vibration decay sharply increases. As amplitude grows further, this area becomes horizontal, and sometimes internal friction decreases. **Fig. 2** shows the curves of damping (as **Q-1**) versus strain amplitude (**ε**) occurring in the fixed end of the sample. It can be noted that damping depends strongly on strain. This behaviour is well known in ferromagnetic materials and it is related to the difference between the energy provided to the system and the energy absorbed by magnetic domains.

Movement of boundary surfaces is completely reversible, i.e. crystal lattice is not violated. For this reason, long-term exposure to vibration does not deteriorate the capacity of these alloys to absorb vibratory energy.

The highest losses are offered by the alloys of group Fe-Cr, group Mg, Mg+0.6%Zr, Mg+0.7%Si, group Ni-Ti and group Cu-Mn. The alloys of the latter group not only offer high internal losses but also feature high strength and the possibility of cold and hot processing entitles these alloys to be regarded as technological structural materials. One of the most popular doped Cu-Mn alloy used for ship building has a loss coefficient η_{al} = 3 – 6×10^{-2}.

Similarly to all vibration absorbing alloys, Cu-Mn ones absorb vibratory energy at rather high vibration amplitudes. Thus, for example, at the stresses not exceeding 0.01 kg/mm2, internal loss coefficient of the alloy with 60% Mn content is 0.02, and at higher amplitudes of cyclic straining it grows up to 0.1.

An important peculiarity of Cu-Mn alloys is that their dissipation properties are temperature-dependent. The alloys of this group maintain their loss coefficients at the level of 0.1 and higher up to the temperatures of 70–80°C, then their damping capacity drops sharply.

Counterparts of R alloys are British alloy Sonoston (37% Cu, 54.25% Mn, 4.25% Al, 3% Fe, 1.5% Ni) and American alloy Incramute (58% Cu, 40% Mn, 2% Al).

Ni-Ti alloys, in particular, well-known NIVCO (Co-Ni-Ti-Al), as well as alloys based on chrome and magnesium, also feature high loss coefficients. For convenience of comparison, Table 1 provides the data on some of these alloys.

The vibrations of machinery housings, pipelines, frames, foundations, hull structures, typically have low stresses with loss coefficients of all vibration damping alloys not exceeding 0.01 – 0.03. So these alloys are recommended for manufacturing heavy-duty parts and joints of machinery where dynamics determines high levels of exciting forces exerted on fixed structures of ship equipment.

3.2. FIBROUS VIBRATION ABSORBING STRUCTURAL MATERIALS

Fibrous vibration absorbing materials are essentially conventional composites (GRPs or CRPs), i.e. a warp impregnated with binder. This warp can be made of GRP, CRP or organic fiber, as well as of tissues and rovings (twisted threads) based on them. Binders in composites are usually resins of various chemical compositions. Dissipation of vibratory energy in fibrous materials takes place due to viscoelastic and structural relaxation. Loss coefficients of traditional GRPs and CRPs do not exceed 0.01, i.e. they are similar to the ones of vibration damping alloys.

Dissipation performance of fibrous materials can be improved through the following measures:

- •Selection of binder composition;
- •Selection of grade (type) for reinforcing material;
- •Variation of cutting angles, i.e. angles at which the elements are cut with respect to the direction of fibres);
- •Inclusion of viscoelastic layers;
- •Application of short fibers;
- •Optimal selection of reinforcement angles and structure.

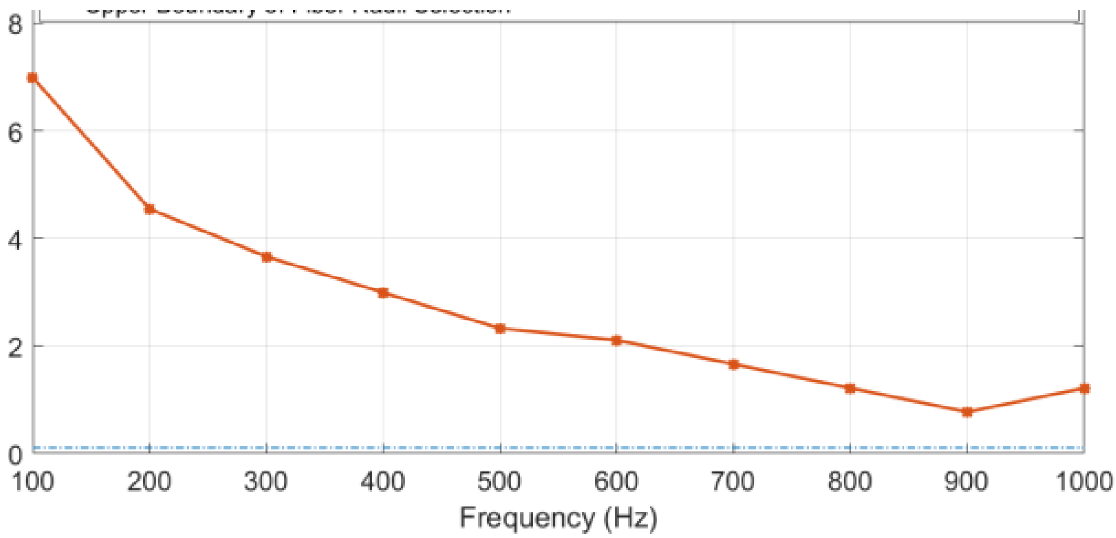


Fig. 3. Optimal Fibre size for Optimal Damping

Thus, for example, in comparison with conventional GRP (loss coefficient η_{GRP} = 0.01), the composite based on “soft” binder and polypropylene reinforcing fibres have the loss coefficient higher by more than an order of magnitude. Varying directions of cutting and rationally selecting reinforcement angles and structure, it becomes possible not only to obtain the losses 2.5–3 times higher as compared to the standard structure, but also to detune from dangerous resonance frequencies.

Application of short minced fibres ensures maximum damping for given composite only if length and diameter of its fibres are in the ratio of 1:20. However, the fibers this short are practically impossible to obtain in practice, and besides, such a composite would loose its

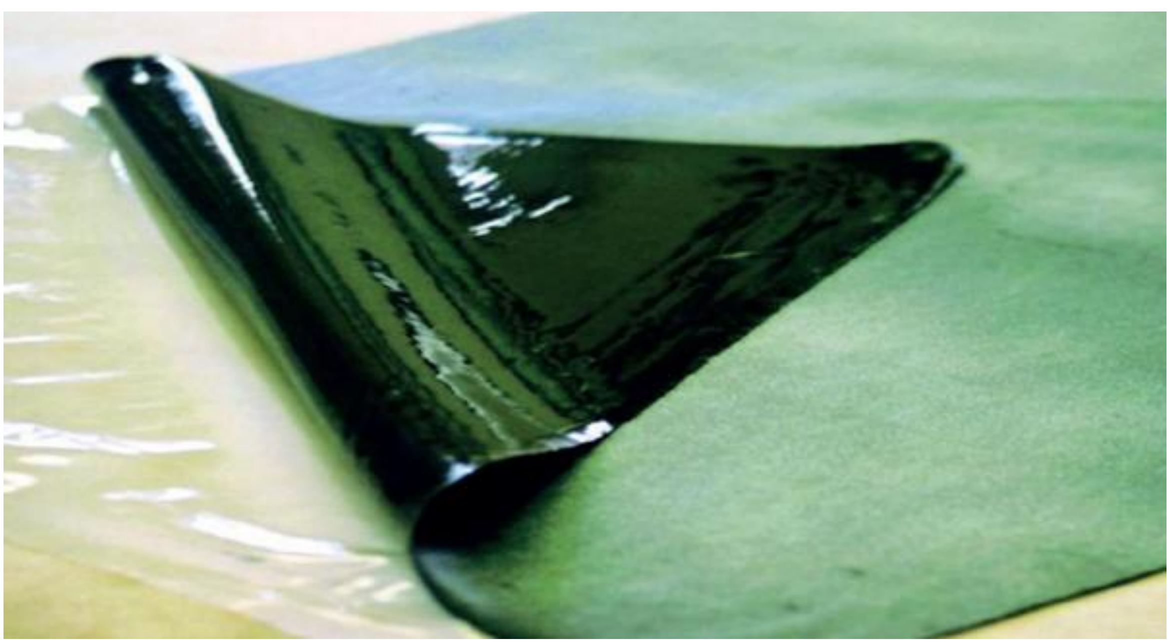


Fig. 4 PVA based Damping Sheets by H&H Acoustic Technologies

strength and stiffness. For this reason, the length of fibres is usually equal to 25 – 50 mm, i.e. it is many times more than the optimal one. The frequency dependence of optimal fibre radii is given in **Fig. 3**.

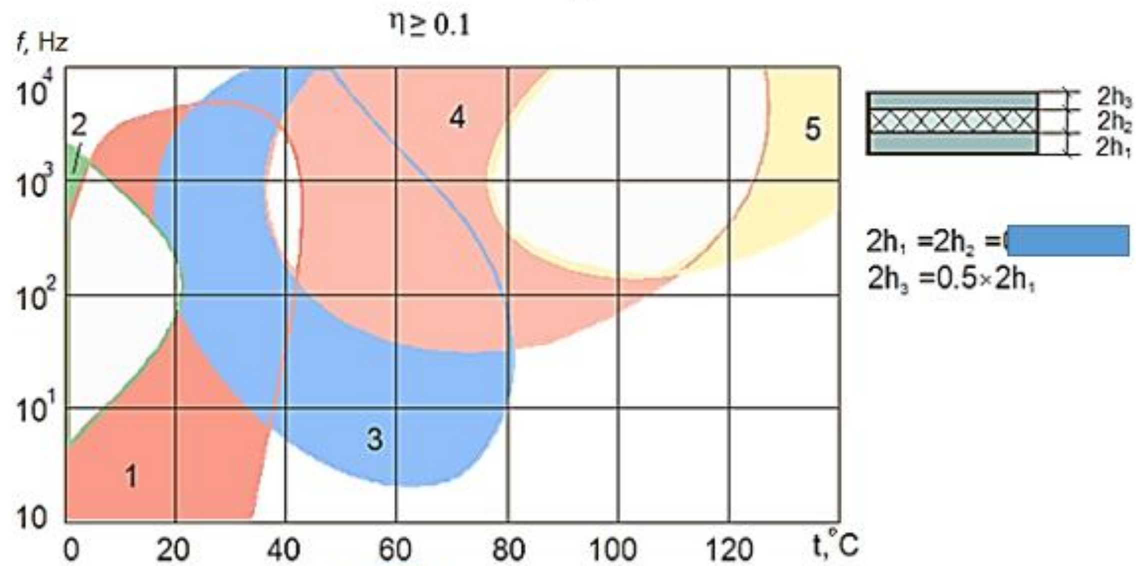
2.3. POLYMERIC VISCO-ELASTIC VIBRATION ABSORBING MATERIALS

Polymeric visco-elastic vibration absorbing materials are pastes, resins and plastics of various kind, e.g. based on polyvinyl acetate (PVA), etc. Viscoelastic vibration absorbing materials **(Fig. 4**) are installed atop the damped structure (hard vibro-absorbing coating) or between hard elastic layers (layered vibro absorbing structural materials, reinforced vibro absorbing coatings, vibration absorbing structures). All vibration damping tools that involve vibro absorbing materials are typical layered structures. Their loss coefficients can be as high as 0.2–0.3. High losses in layered structures are primarily due to high dissipation performance of visco-elastic vibration absorbing materials. **Table 2** provides physical & mechanical properties of common viscoelastic materials of 'R' origin.

A typical peculiarity of polymeric viscoelastic materials is temperature-frequency relationship of their dissipation parameters, i.e. for each material there exists a temperature at which loss coefficient reaches its peak value. This peak value is determined by chemical composition of the material, and corresponding temperature is determined by the transition of

Table 2: Physical & mechanical properties of common viscoelastic vibration absorbing materials

Material	Type	Based on	Temperature of maximum vibration absorption, °C	Loss coefficient, $\eta_{E_2}^{MAX}$	Density ρ, 10^{-3}kg/m^3
Ag	Plates	PVC	20	0.25	1.35
A NSh-2	Paste	PVA	20	0.36	1.8
A-NSh-M-2R	Paste	PVA	20	0.30	1.8
A-T-2	Paste	PVA	75	0.20	1.7
AntiV-5M	Paste	Epoxy resin	25	0.80	1.35
AntiVt-7M	Paste	Epoxy resin	80	0.70	1.53
VipoK family	Paste	Epoxy resin	20–80	0.40	1.4
VML-25	Plates	PVC	30	0.40	1.57
VPS-1	Self-adhesive rolls	PVA	55	2.0	1.5
VPC-2.5	Self-adhesive rolls.	PVA	25	2.5	1.5
PVC linoleum	Plates	PVC	20	0.03	,,
Neva	Paste	PVC	20	0.02	„
Vipt	Layered structural material	Al+*VPS-2.5*+Al	25	0.3	,,



1 – VPS-2.5; 2 – IRP-1[redacted] – VML-25; 4 – *Antivibrit*-5M; 5 – *Antivibrit*-7M

Fig. 5. Comparison of efficiency areas for three-layered structures with different vibroabsorbing materials

the material from the glassy state to the highly elastic one (α-transition). As seen from the table, 'R' materials are mostly effective at the operational temperatures of 0–100° C.

Similarly there are various brands of western origin vibro absorbing materials that enable efficient damping within a wide temperature range. It shall be noted that both R and western materials intended for the temperature range of 0 – 100° Coperate efficiently at the temperatures of 30–50°C, whereas for the temperatures over 100°C it is practically impossible to achieve thermal ranges of efficient operation so wide. High-temperature vibro absorbing materials efficient at 200°C and more are silicon-based, and their maximum loss coefficients are relatively low.

A better judgment about dissipation performance of materials in specific structures can be obtained from the frequency-vs-temperature plot of their efficiency domains. These domains are formed by the plane $\eta = 0$ intersecting the complex spatial temperature-frequency relationship of the loss coefficient offered by a layered structure. The boundary of this domain corresponds to $\eta = 0$ .1, and the internal part corresponds to $\eta > 0$. **Fig. 5** provides the simplest examples of efficiency areas for a three-layered structure with viscoelastic internal layers made of both "soft" VPS-2.5 material and hard vibroabsorbing materials. It can be seen that transition to the polymeric structures offering higher stiffness and operation at higher temperatures is accompanied by the shift of these areas towards higher frequencies and temperatures.

2.4. VIBRATION ABSORBING FILLERS

As it was mentioned above, vibration absorbing fillers can be polymeric viscoelastic vibroabsorbing materials or bulk materials. The former group was described in the previous section.

Bulk vibro absorbers are usually sand or molded cast-iron shots. Vibro absorbing effect of these shots is practically independent of their diameter, if the latter varies within the limits of XX to YY mm. Due to their considerable weight, bulk vibroabsorbers additionally act as a vibration-retarding mass.

4. REQUIREMENTS OF VIBRATION DAMPING MEANS

Vibration damping tools used for reducing vibration levels of ship structures should meet a set of requirements:

- Vibroacoustic requirements;
- temperature requirements;
- sanitary chemical requirements;
- manufacturing requirements;
- service requirements.

4.1 VIBRO-ACOUSTIC REQUIREMENTS

Vibro-acoustic requirements determine the frequency band and the level of vibration damping efficiency that should be attained. There are two ways to specify the vibro-acoustic requirements. The first approach is to determine the vibration efficiency level as a dB difference between rms values of vibration velocity (or acceleration) of the structure before and after introduction of damping measures in a given frequency band. This difference can be found from comparative vibro-acoustic tests of the damped structure in question and another undamped structure of a similar standard type, or by calculation of vibration levels using mathematical models.

To be practicable for ship structures, vibration damping means must have the efficiency not lower than 3–5 dB. The maximum effect can be about 25 dB.

Another approach to estimate the vibro-acoustic efficiency is direct comparison of vibration damping characteristics of the structures, i.e. finding how much the loss coefficient of the damped structure η_D exceeds the loss coefficient of the undamped structure η_0 .This method is most often used in preliminary vibroacoustic efficiency estimates and predictions for the vibration damping tools under design. According to this approach, vibration damping tools are deemed efficient if their loss coefficients $\eta_D \geq \left(\frac{1.5 \cdot \eta_0}{2}\right)$

4.2 TEMPERATURE REQUIREMENTS

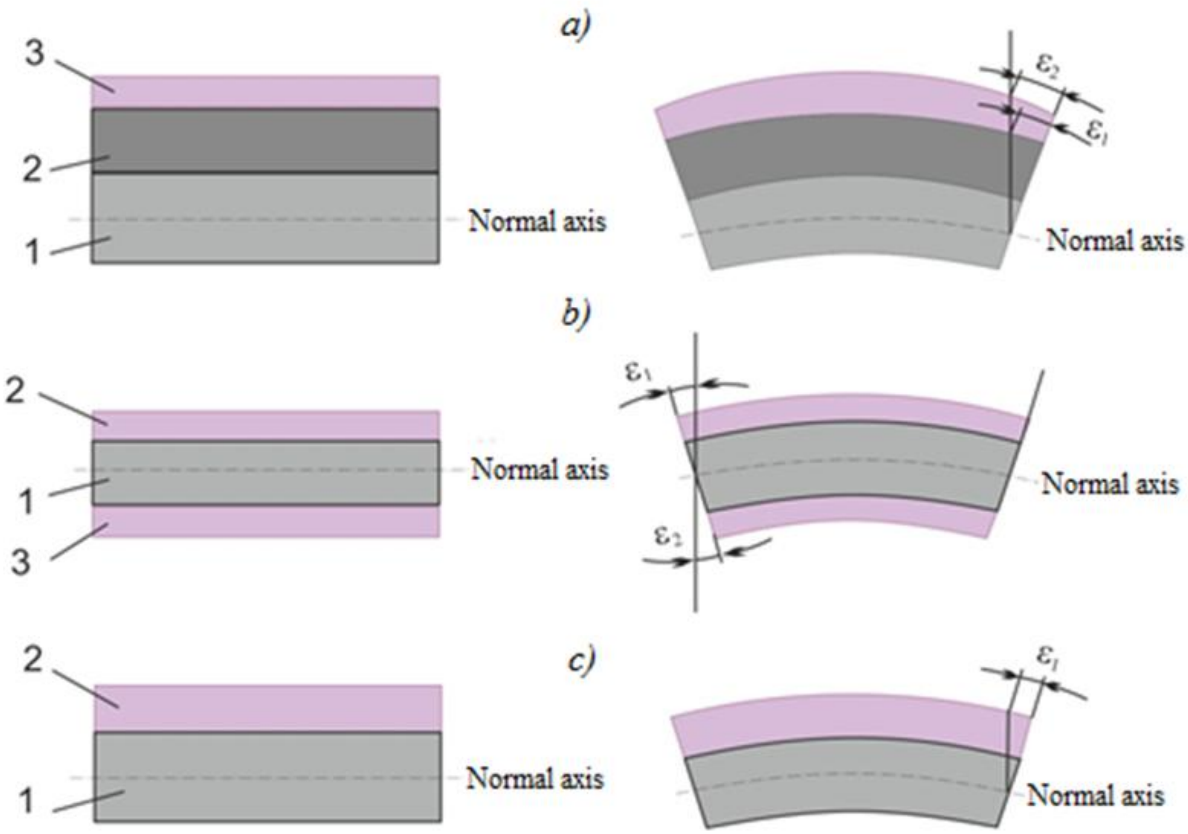
Temperature requirements are specified because vibro-acoustic characteristics of the applied vibration damping materials depend on temperature. These requirements take into account both normal temperature conditions as well as possible extreme temperature exposures of damped structures. The thermal range of maximum vibration absorption for the materials, both structural and applied in vibro-absorbing elements and coatings must correspond to the normal range of operational temperatures of the damped object.

4.3 SANITARY CHEMICAL REQUIREMENTS

Sanitary chemical requirements are mainly applied to polymer materials and structures incorporating or made of these materials. These requirements are based on allowable concentrations of harmful substances emitted by polymer materials during service life. Allowable amount of polymer materials are

Table 3: Regulations for application of polymeric vibro-absorbing materials

Material	Class of ship spaces		
	Living quarters and frequently visited spaces	Periodically visited spaces	Seldom visited spaces
VML-25	0.1 m^2/m^3 at $t \leq 20^{\circ}C$	1 m^2/m^3 at $t = 25^{\circ}C$ 0.1 m^2/m^3 at $t \leq 80^{\circ}C$	1 m^2/m^3 at $t \leq 40^{\circ}C$ 0.3 m^2/m^3 at $t \leq 60^{\circ}C$



1 – damped plate; 2, 3 – vibration absorbing material

Fig. 6. Layouts and straining patterns of vibration absorbing coatings

regulated for each type of ship compartment depending on the design of vibration dampers and ventilation conditions. As an example, **Table 3** provides the sanitary regulations adopted for some vibration absorbing materials.

4.4. MANUFACTURING REQUIREMENTS

Manufacturing requirements are determined by the methods of fastening vibration absorbing coatings, attaching their reinforcing layers, manufacturing of vibroabsorbing structures, possibility of mounting activities, including welding, in presence of vibration damping tools, etc. These requirements vary depending on specific types of vibration damping means, ship design and shipyard production facilities.

4.5. SERVICE REQUIREMENTS

Service requirements determine mechanical strength, water absorption, resistance to aggressive media and weathering, fire resistance, bio-stability, ozone resistance, impact toughness, etc. Applicable scope of above-mentioned parameters are indicated in technical specifications for vibro-absorbing materials.

5. DISSIPATIVE CHARACTERISTICS OF VIBRATION DAMPING STRUCTURES

Dissipative properties of vibration damping means are determined by their transmission loss coefficients. If vibration damping tools are using homogeneous damping structural materials, their dissipative characteristics are fully described by losses in these materials. Dissipative properties of structures made of damping fibre materials are estimated concurrently with their strength calculations using special-purpose methods.

Vibration damping means incorporating layers of visco-elastic polymers (vibration absorbing coatings and structures) are commonly considered as N-layer structures (including damped plate). Dissipative properties of such structures are described by the complex bending stiffness, i.e. dynamic stiffness and loss coefficient in function of oscillation frequency (and temperature). In this case the exact solution for the complex stiffnessis found from expressions for the full energy of elastic deformations in each layer. Dissipative properties of multi-layer structures are investigated taking into account temperature-frequency dependence of dynamic characteristics of visco-elastic material layers. The expressions for loss coefficients of layered structures with different combinations of visco-elastic layers are provided below.

5.1. LOSS COEFFICIENTS OF HARD VIBRATION ABSORBING COATINGS

The loss coefficient of layered structure is the ratio of imaginary part and the real part of the complex stiffness and it is expressed as given below:

$$\eta = \mathrm{Im}K / \mathrm{Re}K .$$

As a rule, feasible and practicable hard vibro-absorbing coatings consists of not more than three layers (metal layer and two layers of hard plastic). Dynamic stiffness expression for the general case of such three-layered structure is given as below:

$$K^R_{3-layers} = E_1I_1 + E_2I_2 + E_3I_3 + \frac{(h_1+h_2)^2}{K_0}E_1S_1E_2S_2 + \\ + \frac{E_3S_3}{K_0}\left[(h_1+2h_2+h_3)^2 E_1S_1 + (h_2+h_3)^2 E_2S_2\right].$$

Fig. 6 provides the layouts of the most common hard vibro-absorbing coatings, as well as their straining pattern. Longitudinal stiffness of steel layer 1 is described by expressions $E_1S_1 >> E_2S_2$ and $E_1S_1 >> E_3S_3$, so for system **steel layer (1) + visco-elastic layer (2) + visco-elastic layer (3)** (see Sketch *a* in Fig. 6), loss coefficient will be as per Eq. 1:

$$\eta_{st+l+l} = \frac{\left[E_2I_2 + (h_1+h_2)^2 E_2S_2\right]\eta_{E_2} + \left[E_3I_3 + (h_1+2h_2+h_3)^2 E_3S_3\right]\eta_{E_3}}{E_1I_1 + E_2I_2 + E_3I_3 + (h_1+h_2)^2 E_2S_2 + (h_1+2h_2+h_3)^2 E_3S_3} \quad \text{..... 1}$$

For the second case of hard vibro-absorbing coating, i.e visco-elastic layer (2) + steel layer (1) + visco-elastic layer (3) (Sketch b in **Fig. 6**), loss coefficient is expressed as per Eq. 2:

$$\eta_{l+st+l} = \frac{\left[E_1I_1 + (h_1+h_2)^2 E_1S_1\right]\eta_{E_1} + \left[E_3I_3 + (h_2+h_3)^2 E_3S_3\right]\eta_{E_3}}{E_2I_2 + E_1I_1 + E_3I_3 + (h_1+h_2)^2 E_1S_1 + (h_2+h_3)^2 E_3S_3} \quad \text{..... 2}$$

The expression for loss coefficient of single-layered hard coating, i.e. hard layer (1) + visco-elastic layer (2) (Sketch c in **Fig. 6**) is given as Eq. 3:

$$\eta_{st+l} = \frac{E_2I_2 + (h_1+h_2)^2 E_2S_2}{E_1I_1 + E_2I_2 + (h_1+h_2)^2 E_2S_2}\eta_{E_2} \quad \text{..... 3}$$

5.1.1. Comparative efficiency analysis for different layouts of hard vibro-absorbing coatings

According to (Eq 3), loss coefficient of the plate tiled with single-layered hard vibro-absorbing coatings is directly proportional to loss coefficient of vibration absorber, η_{E_2}, and to its Young's modulus E_2. For steel plates and vibro-absorbing materials with Young's moduli two orders of magnitude lower than Young's modulus of steel, Eqn. 3 provides an approximate calculation formula for the loss coefficient of two-layered structure:

$$\eta_{st+l} \cong \frac{E_2 I_2}{E_1 I_1} \eta_{E_2} . \qquad ....4$$

necessary to increase inertia moment I_2 of the damping layer. Practically, this is achieved by installing an additional layer between the steel plate and the vibration absorber, and the function of this layer is to increase the distance between the plate and the neutral bending plane of the damping layer, thus increasing compression-tension strainings in this layer.

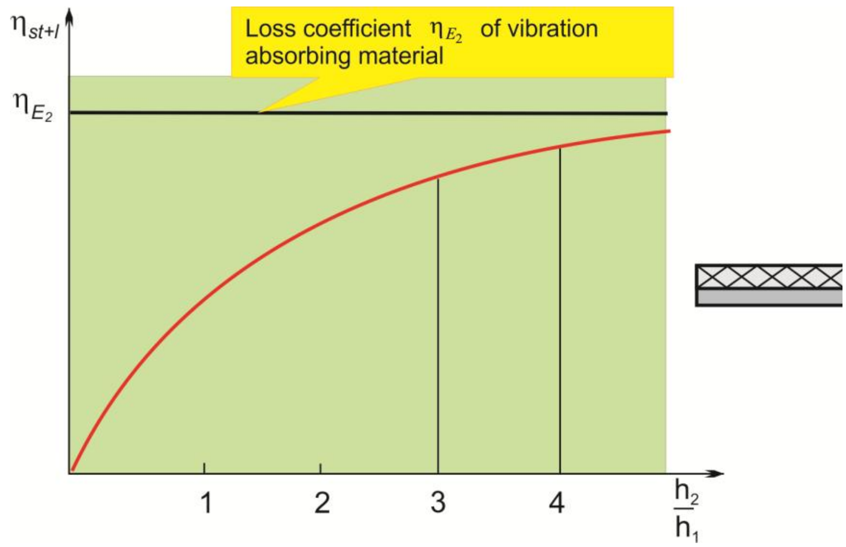


Fig. 7. Steel plate tiled with hard vibro absorbing coatings: loss coefficient Vs coating thickness

This formula highlights the effect of vibroabsorbing layer stiffness upon the total dissipation performance. This is exactly why these coatings are called hard.

Analysis of Eqn. 4 also shows that once vibroabsorbing layer thickness achieves the size when presence of the steel plate becomes insignificant, loss coefficient of two-layered structure η_{st+l} tends to η_{E_2}. Accordingly, loss coefficient of the coating material itself is asymptotic value for the loss coefficient of two-layered structure when vibroabsorbing layer thickness grows. **Fig. 7** plots $\eta_{st+l}(h_2)$, which shows that single-layered hard coating 3–4 times thicker than damped steel plate is sufficient to ensure the vibration absorption efficiency close to the maximum one.

According to 4.10a, to make the coating of specified thickness more efficient, it is

The expression for the loss coefficient of this structure is easy to derive from Eq. 1 assuming that damping layer is Layer 3 and for Layer 2 $\eta_{E_2} = 0$.

Comparison of Expressions Eq.1 and Eq.2 shows that if thicknesses of all layers are fixed and thickness (or mass) of coating is specified, it is more rational to install the coating from one side of the steel plate (Sketches a and b, **Fig. 6**) because for this case the following expression is always true:

$$\eta_{st+l+l} / \eta_{l+st+l} > 1 .$$

In this case, dissipation performance also improves due to greater tension-compression strains that are only possible if the vibration absorber is farther from the neutral axis of the steel plate, i.e. if the coating is unilateral.

Dynamic parameters of visco-elastic materials are temperature and frequency-dependent, so loss coefficients of rod or plate structures tiled with hard vibro-absorbing coatings shall also be functions of frequency and temperature. Fig. 8 provides 3D relationships calculated as per Eq. 1 for loss coefficients of

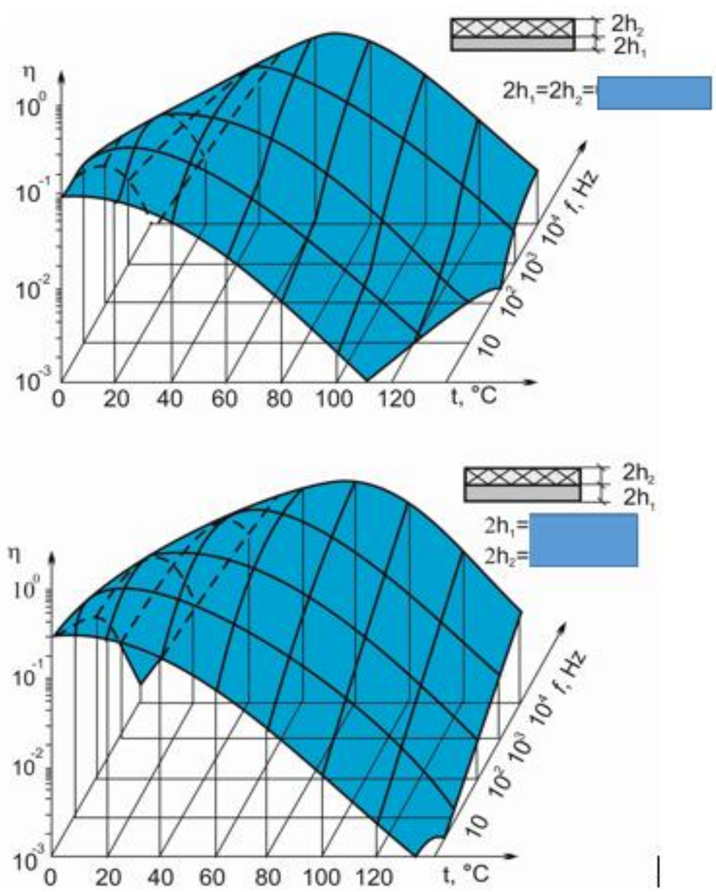


Fig. 8. Temperature-frequency relationships for loss coefficients of the plates tiled with Antivibrit-type hard vibro-absorbing coatings

ZZ-mm thick steel plates tiled with XX and YY-mm thick single-layered hard coating. The figures show that temperature and frequency ranges where this coating is efficient are determined by the type of vibro-absorber and thickness of its layer.

An additional way to assess the efficient operation domain of vibro-absorbing coating is dissection of constructed surfaces (of Fig. 8) by planes, e.g. $\eta(f,t)=\text{const}$, corresponding to required values of η. Projections of these sections upon plane (f,t) characterize operational ranges for the coatings of specified efficiency. As an example, **Fig. 9** provides efficient operation domains for single-layered hard coating determined as per inequality $\eta(f,t)\geq 0.1$ depending on coating thickness.

5.2 Dissipation performance of layered structures versus the number of their layers

For multi-layer configuration, the loss coefficients and weight & size of vibration absorbing structures vary with the increase of the layer number. **Fig. 10** shows the changes in maximum loss coefficients, thickness ratios h_Σ/h_0 and mass ratios m_Σ/m_0 of layered structure with the growth of layer number N. Here, h_Σ, m_Σ are total thickness and mass of layered structure respectively, h_0, m_0 being thickness and mass of corresponding non-damped structure. The calculation was based on the assumption that all the structures under investigation had the same parameters of their viscoelastic layers, and bending stiffness of layered structure was equal to bending stiffness of the prototype, i.e. $I_\Sigma = I_0 = const$. As seen from the figure, the sharpest increase of η_{MAX} occurs during transition from three-layered structure to five-layered one, i.e. from the structure with one internal viscoelastic layer to the structure with two such layers. Further increase in the number of viscoelastic layers does lead to a certain further increase of η_{MAX}, however, making such layered structure considerably heavier and larger.

The results provided in Fig. 10 do not take into account the thickness effect of viscoelastic vibroabsorbing layers themselves because they were assumed to be much thinner than the elastic layers covering them. **Fig. 11** provides η_{MAX} values for different numbers of layers as functions of H_Σ/h_Σ (ratio between total thickness of viscoelastic layers and total thickness of elastic layers). Analysis of the curves in Fig. 11 shows that H_Σ/h_Σ ratio, up to the values close to one has only a minor effect upon vibration absorption efficiency of layered structure.

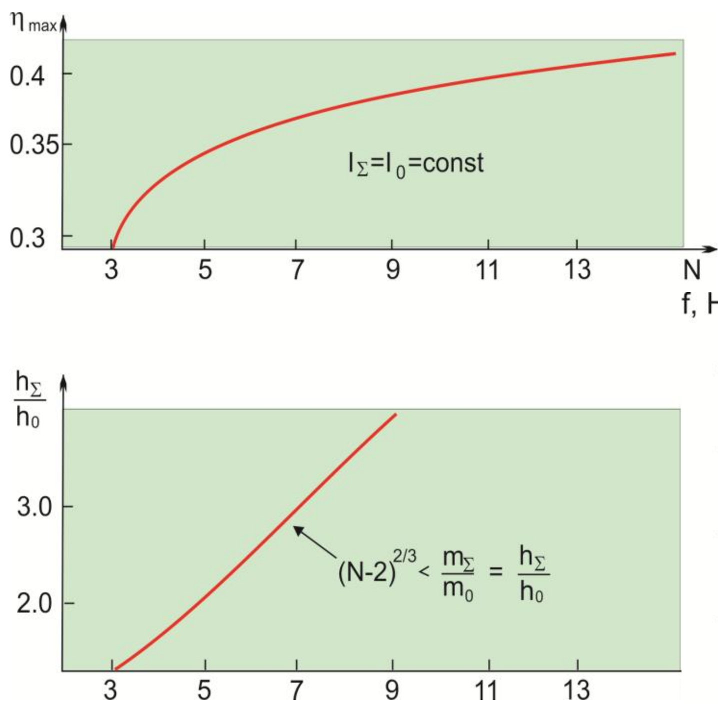


Fig. 10. Maximum loss coefficient η_{MAX}, per-u length mass ratio m_Σ/m_0 and thickness ratio h_Σ/h_0 of layered structure versus layer number *N*, static bending stiffness, i.e. total moment I_Σ being constant

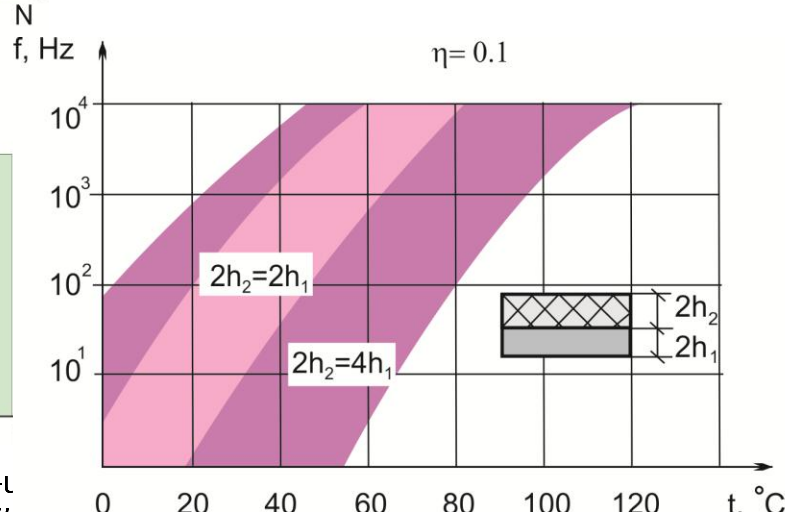


Fig. 9. Efficient operation domains of *Antivibrit*-type single-layered hard vibro-absorbing coatings

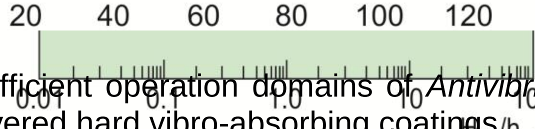


Fig. 11. Maximum loss coefficient η_{max} of layered structure versus the ratio between total thickness of viscoelastic layers H_Σ and the total thickness of elastic layers h_Σ

6. APPLICATION OF VIBRATION DAMPING TOOLS IN VARIOUS TYPES OF STRUCTURES

Equations 1 – 3 derived for loss coefficients of two layered virodamping layer and similar analysis for other combinations of vibration damping means, and, mainly, with respect to layered structures, enable us to formulate a set of rules for optimum use of vibration damping means for shipboard structures.

6.1. APPLICATION OF HARD VIBRO ABSORBING COATINGS

Hard anti-vibration coatings should be applied to supporting and hull structures (decks, floorings, bulkheads, platforms, etc.) no thicker than XX–YY mm.

Thickness of hard unilateral coating must be at least XX–YY times greater than thickness of damped plate, see Fig. 12, sketch *a)*.

In two-layer hard coating, see Fig. 12, sketch *c*, vibro-absorbing layer is made of the materials with parameters similar to those of the single-layer hard coating. Intermediate layer is usually made of some hard light material, e.g. hard foam, or of the vibro-absorbing material with maximum efficiency shifted towards higher temperatures, see Fig. 12 Sketch *d*.

In two-layer hard coating with the intermediate layer made of foam, damping layer thickness must be equal to XX–YY thicknesses of damped structure, and the intermediate layer must be ZZ as thick as this structure, see Fig. 12, sketch *c*.

In two-layer hard vibro-absorbing coatings with two layers of vibro-absorbing material, these layers must have the same thickness, equal to XX–YY thicknesses of damped structure, see Fig. 12, sketch *d*. The vibro-absorbing material with higher temperature of maximum vibration absorption must be applied directly onto the damped structure.

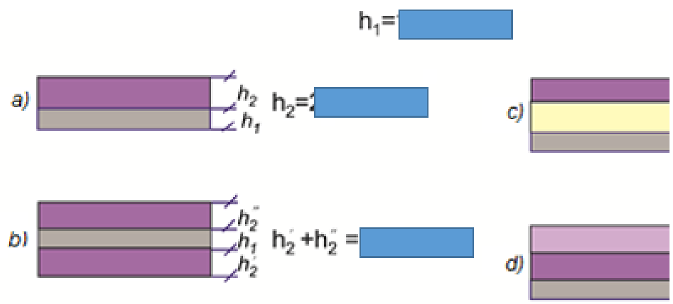


Fig. 12. Application of hard vibroabsorbing coatings

For technological reasons, hard vibro-absorbing coating is preferable to apply uniformly over the entire area of the damped plate. If there exist some restrictions due to follow-up mounting operations, vibro-absorbing coating can be applied in the middle part of the damped plate covering XX–YY% of its area.

Hard vibro-absorbing coating is applied on one side of the elements to be damped in supporting and hull structures. The structure tiled with hard vibro-absorbing coating from both sides (Fig. 12, sketch *b*) is less efficient than the structure with unilateral coating (Fig. 12, sketch *a*) where the thickness is equal to the total thickness of bilateral coating.

6.2. APPLICATION OF REINFORCED VIBRO-ABSORBING COATINGS

Similarly to hard vibro-absorbing coatings, reinforced vibro-absorbing coating is preferable to apply uniformly over the whole area of the damped plate. In case of technological limitations, reinforced coating can be applied in the middle part, on one side of the damped plate, covering 70–80% of its area.

Reinforced vibro-absorbing coatings are practicable to apply on plate elements of supports and hull, e.g. decks, bulkhead floors, platforms, etc.) refer Fig. 13.

If the damped plate is not thicker than XX–YY mm, the internal visco-elastic layer of coating must be equal to XX–YY thicknesses of the structure, and the reinforcing metal plate must be equal to XX–YY of its thickness.

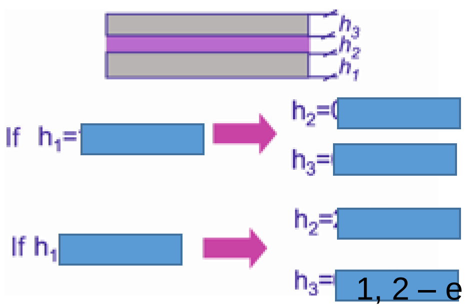
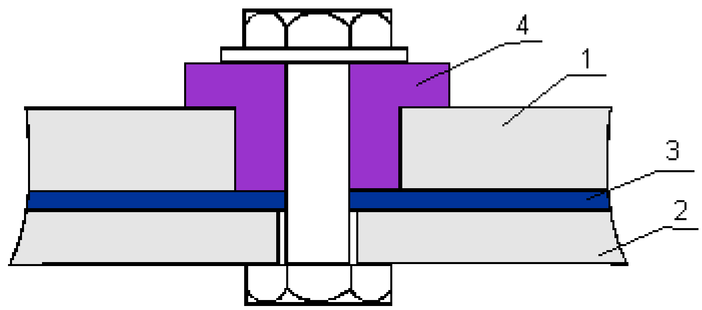


Fig. 13. Application of reinforced vibroabsorbing coating



1, 2 – elastic metal layers; 3 – vibroabsorbing layer; 4 – rubber bushing

Fig. 15. Bolted connection of compound elements

For structural elements thicker than 15 mm, it is practicable to apply reinforced coatings with increased stiffness of reinforcing plate. In these coatings, thickness of the internal visco-elastic layer can be XX–YY mm, and thickness of reinforcing metal plate can make XX–YY thickness of the damped structure.

To extend thermal range of efficient damping for XX–YY mm thick structures, a combination of reinforced and hard vibro-absorbing coatings

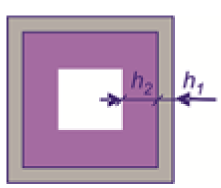


Fig. 14. Application of vibro-absorbing filler

can be used. Such hard coating must have its maximum efficiency at lower temperatures and be applied onto the reinforcing plate.

Thermal range of efficient damping for structures thicker than ZZ mm can be extended by applying reinforced vibro-absorbing coating on both sides of the structure. The vibroabsorbing materials used in such coatings must have their efficiency peaks at different temperatures.

6.3. Application of vibro-absorbing fillers

Hollow structural elements with wall thickness up to XX–YY mm are practicable to damp by means of vibro-absorbing fillers, bulk or visco-elastic. Bulk vibro-absorbers are the most efficient if thickness of their layer is equal to XX–YY wall thicknesses of the damped structural element (**Fig. 14)**.

6.4. Application of vibro-absorbing alloys

As per the characteristics provided in Section 3.1 above, vibro-absorbing alloys are practicable to apply in manufacturing of structural elements, parts and units that undergo high dynamic operational loads.

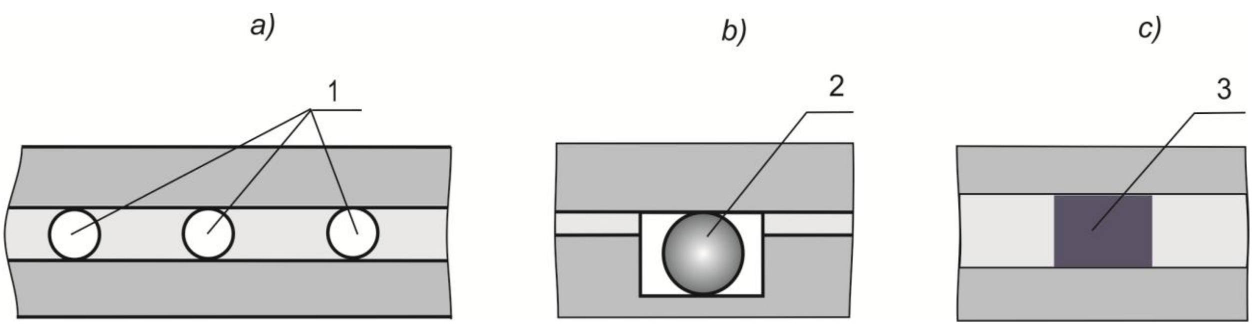
6.5. Mounting of vibration damping means

Visco-elastic layers of vibro-absorbing materials applied in vibration damping means must be tightly fastened (by means of glue or self-adhesion) to the elastic layers over not less than XX% of the contact area.

For visco-elastic vibro-absorbing materials applied in hard and reinforced coatings, as well as in internal layers of compound structures, sufficient adhesion strength for shearing is YY N/m^2.

Vibro-absorbing pastes (see Table 2) are applied as per technological procedures, layer after layer, by spraying or by means of spattles. Vibro-absorbing tiles are fastened to elastic elements by means of the glues indicated in respective technological procedures. Compound vibro-absorbing structures with self-adhesives produced in rolls are manufactured by means of mechanical assembling.

In compound structures, the load borne by the visco-elastic layer without prejudice to its vibro-absorption efficiency can be increased by means of restrictors, i.e. cylindrical (in case of unidirectional vibrations) or spherical metal inserts inside the vibro-absorbing layer, see **Fig. 16** a, b. Diameter of these inserts shall be slightly less than thickness of visco-elastic layer, see Fig. 16 a. In case of high static loads, diameter of the inserts can be increased, however, their arrangement layout must be more sophisticated to preserve their vibro-acoustic efficiency, see Fig. 16 b.



1, 2 – cylindrical or spherical inserts; 3 – rubber insert

Fig. 16. Illustrations for visco-elastic layer thickness in compound structures

Apart from reliable fastening between all the layers, connection joints in reinforced coatings and compound structures must allow minor mutual displacements between external elastic layers during vibrations, thus generating shearing strains in the internal visco-elastic layer.

An example of such connection joint is bolted connection, see **Fig. 15**. Mutual displacements of elastic layers during vibrations are maintained by means of the rubber bushing in the opening of one of the elastic layers.

The highest vibro-acoustic efficiency is achieved when compound element is fastened by its ends. Experience shows that mechanical fastening reduce vibro-absorption efficiency due to their shunting effect which can be avoided if the distance between bolted connections is at least XX mm.

Vibro-absorbing polymers applied in internal visco-elastic layers are yielding materials and cannot withstand the static load exceeding YY N/m2.

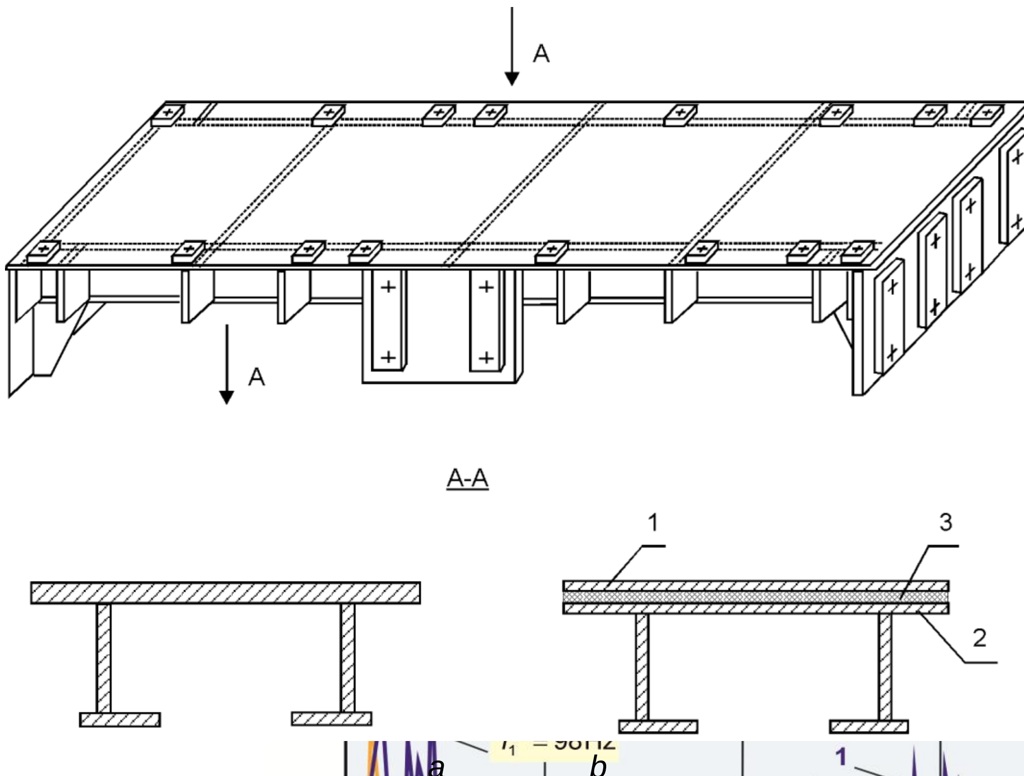
The minimum acceptable distance, between both inserts and bolted connections is XX mm. Rubber inserts (see Fig. 16c) are acceptable, under condition that total area of their contact with one of their elastic metal elements does not exceed YY% of the visco-elastic layer area.

7. PRACTICAL APPLICATION OF VIBRO-ABSORBING STRUCTURES

7.1. Compound vibro-absorbing structures with optimal configuration of elastic elements

Some practical examples of designing vibro-absorbing structures are discussed here to clarify their application. These examples are frames of separate mechanisms or assemblies. These frames are subdivided into platform frames, plate frames and beam frames.

Platform frames consist of grillages with unilateral and bilateral plating, as well as of un-stiffened plates. Compound platform frames have three layers of plating, or they have plates with internal vibro-absorbing layer, see Fig. 17 below.



1, 2 – elastic layers; 3 – visco-elastic layer; *a* – non-damped; *b* – damped

Fig. 17. Layered platform frame for modular assembly

Vibration of beam frames by all degrees of freedom can be efficiently damped by applying two mutually perpendicular internal vibro-absorbing layers in each beam

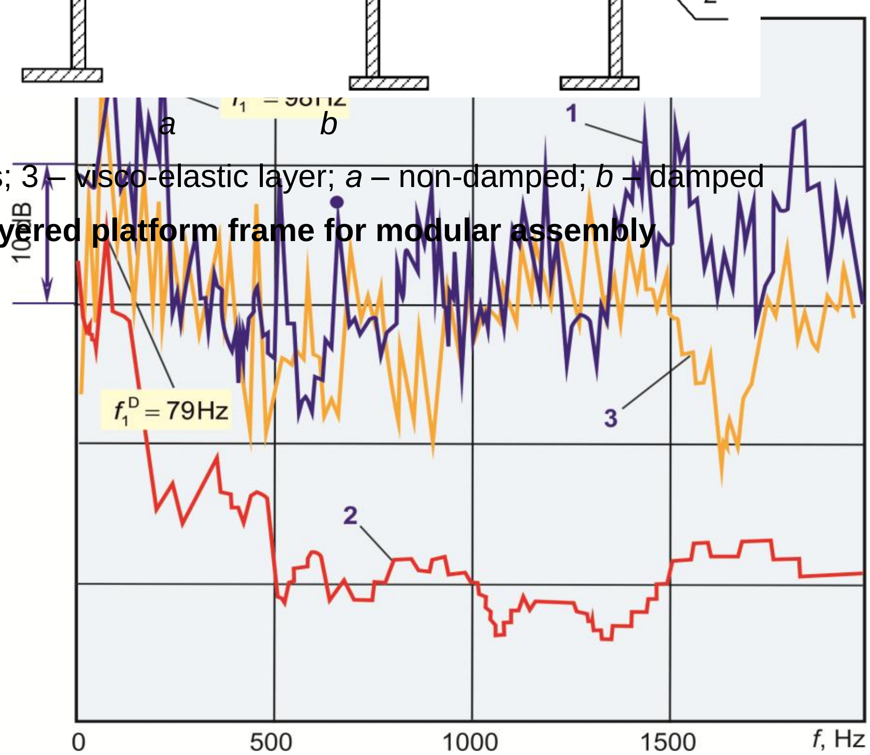
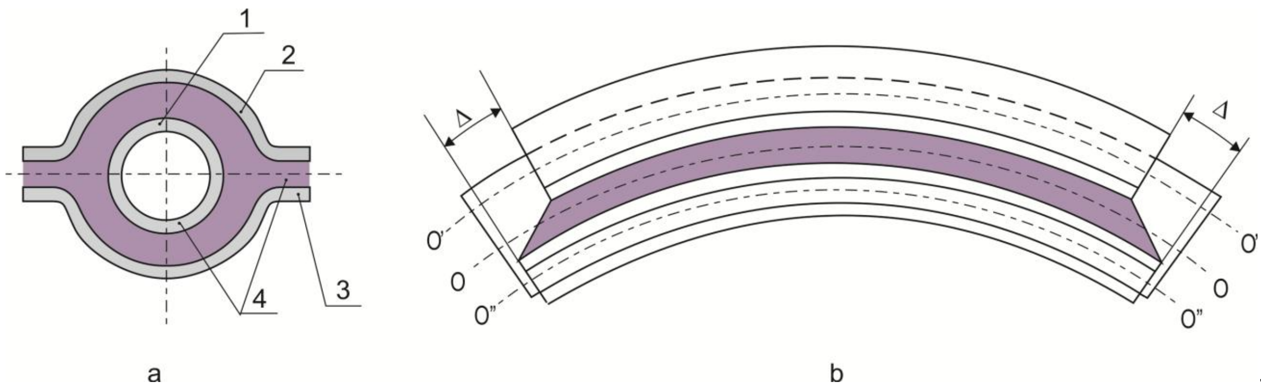


Fig. 18. Comparative vibro-acoustic test data for prototype (continuous) frame (1) for compressor assembly, its damped layered counterpart (2) and the frame made of *high damping Cu-Mn* alloy (3)



1 – internal pipe; 2 – segment of the external pipe; 3 – stiffener; 4 – vibro-absorbing visco-elastic layer

Fig. 19. Vibro-absorbing pipeline (*a*) and its first beam-type bending mode (*b*)

Vibro-acoustic tests of the prototype frame and its compound counterpart were performed in the same conditions: both frames were installed on the same shock mounting in turn. The places of excitation and vibration checks were selected at similar points of both structures. Average vibro-acoustic efficiency of the layered frame in each of the orthogonal directions was the same within the entire frequency band, so the test results could be presented as RMS vibration levels averaged by the three orthogonal directions, see Fig. 18.

Comparison of curves 1 and 2 in Fig. 18 shows that within the first resonance frequency band, 60–500 Hz, the effect was 10–15 dB, and at the frequencies over 500 Hz it was as high as 20–25 dB. For comparison, the same figure provides the test data for similar frame made of vibration damping alloy (Curve 3, Fig. 18). It is clear that in this case acoustic effect is ensured only at the frequencies over 500 Hz and is equal to 5 dB on the average.

7.2. Damping of vibrations of pipelines and beams

Three-layered compound structure with the middle layer made of vibro-absorbing material can be implemented for damping of rod-shaped vibrations of pipelines and beams with circular cross-section, which ensures efficient vibration damping within the frequency band where conventional vibro-absorbing coatings are not efficient. Indeed, at beam vibration frequencies of the pipeline, bending stiffnesses of the pipe itself and hard vibro-absorbing coating applied on it (of any reasonable thickness) are so much different that even if the coating material has the highest loss coefficient possible, its acoustic effect will not be anyhow significant. In case of beam vibrations of layered pipelines, i.e. of two coaxial pipes with a layer of visco-elastic vibration absorber in between, both of these pipes have the same neutral bending plane that coincides with their axes, so only two cases of mutual displacements are possible for their elastic layers. The first case is co-phased movement of the external and the internal pipe. Here, shearing strains in visco-elastic layer will be low because of practically no mutual displacements between the outer surface of the internal pipe and the inner surface of the external pipe. The second case, i.e. anti-phase movement of the external and the internal pipes, is theoretically possible under condition that the vibration absorber is sufficiently soft and has considerable thickness. However, in this case, the straining will mainly be tension-compression locally concentrated in the vibro-absorber material near the intersection with the bending plane passing through the axes of these pipes.

To increase shear strains in the internal layer of three-layer pipe, the distance between bending planes of the reinforcing elastic layer and the internal pipe must be increased. An

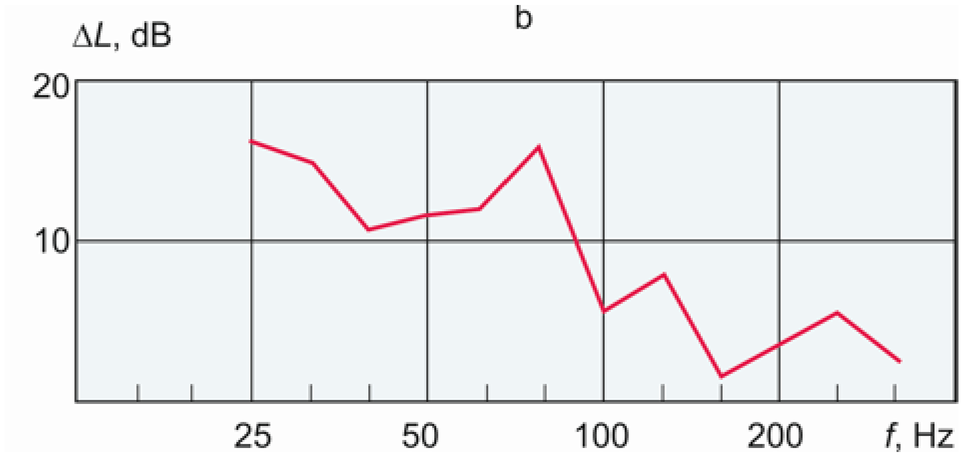


Fig. 20. Effect of applying vibration-damped pipes vs standard

example of the structure with great distance between bending planes of the pipe and of the reinforcing elastic layer is shown in Fig. 19a. To increase vibration damping effect, the external reinforcing pipe is cut along its generatrix into several (two or more) segments. All along their length, these segments have longitudinal stiffeners attached to them, and between the stiffeners there is a layer of the same vibration absorber as the one between the pipes. The plane of this additional visco-elastic layer is exactly the place of intense shearing strains when three-layered pipeline undergoes beam-type bending, see Fig. 19b.

Similarly to other compound structures, the greatest vibro-absorbing effect is achieved at equal bending stiffnesses of the internal pipe and the reinforcing segments, i.e. if

$$h_{segment} = (XX - 1YY)h_{pipe}$$
$$H_{stiffener} = (aa - bb)D_{pipe} \,,$$

where:

$h_{segment}$ – thickness of segments and stiffeners of the reinforcing structure;

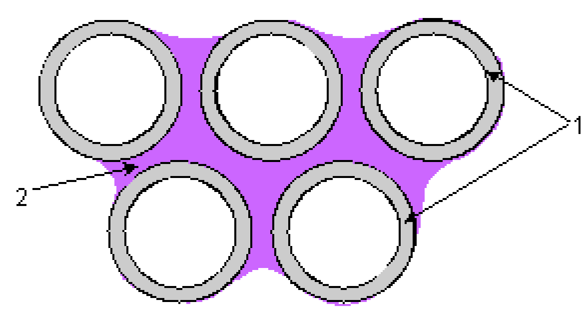
$H_{stiffener}$ – stiffener height;

h_{pipe} – thickness of damped pipe;

D_{pipe} – outer diameter of damped pipe.

The effect of applying vibration-damped pipes instead of standard ones is shown in **Fig. 20**. It is clear that within the frequency band up to 100 Hz, the effect is 10 dB on the average.

Following the principle of layered beam, it is possible to join long parallel pipelines into a single package, filling the gaps between pipes with visco-elastic filler, see **Fig. 21**. In this case, pipelines are a kind of reinforcing structures for each other, ensuring, as a package, high losses for beam vibration modes.



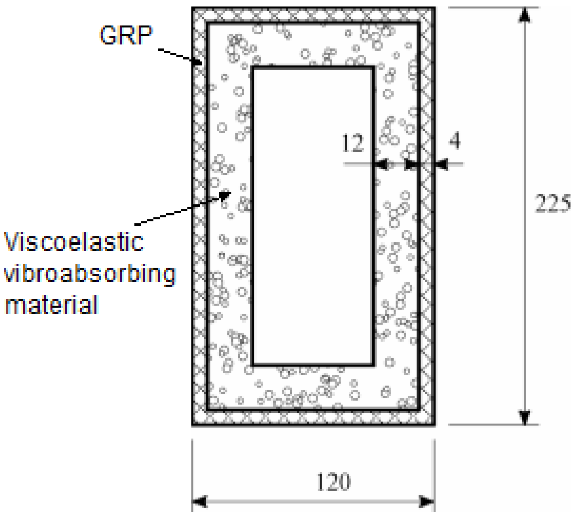
1 – pipelines; 2 – vibroabsorbing material

Fig. 21. Damping of long parallel pipelines

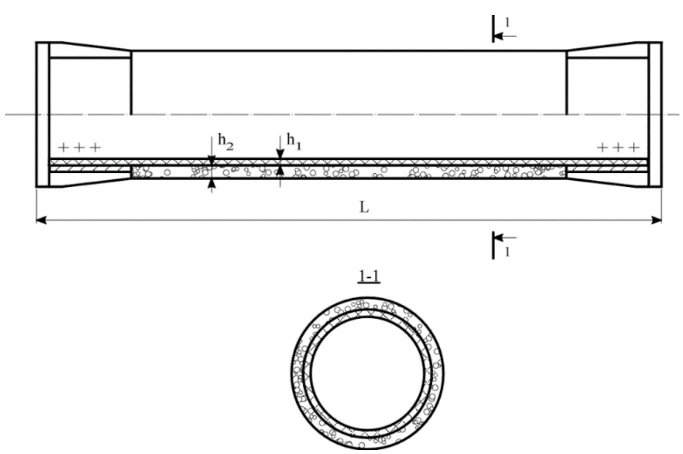
7.3. PCM-based vibro-absorbing structures for ships

Various vibro absorbing layered structures can be made up of polymeric composite materials (PCMs) such as:

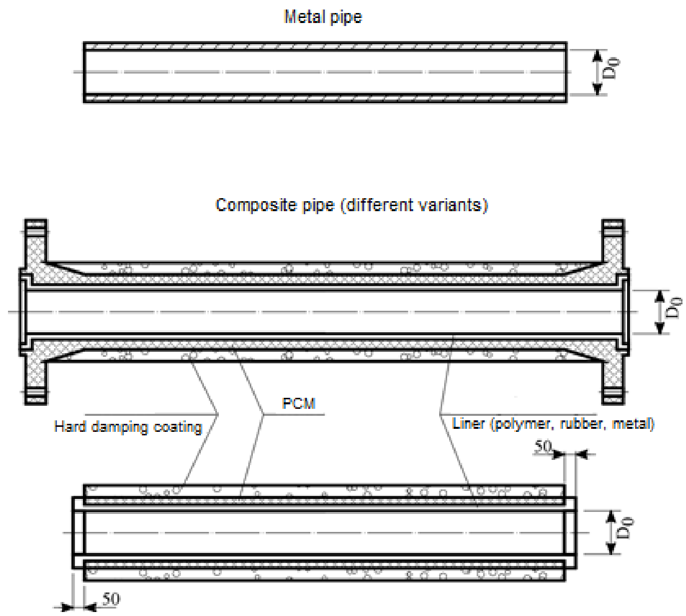
Beams.



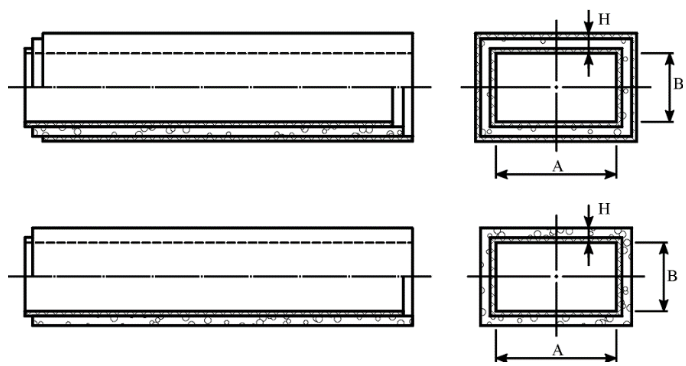
PCM based Pillar



PCM-based layered vibro-absorbing pipe



PCM-based vibro-absorbing air duct



NOMENCLATURE

Ei – modulus of elongation (Young's modulus) for the material of the ith layer;

Gi – shear modulus for the material of the ith layer;

M0, MD – weight of structure before and after damping;

K0, KD – stiffness of structure before and after damping;

hi – half-thickness of the ith layer (or the distance from the neutral axis of the layer to the plane of contact with neighboring layers (for sections with complex profiles);

R – shell radius;

$\boldsymbol{\eta_0}$, $\boldsymbol{\eta_D}$ – loss coefficient before and after application of vibration damping tools;

$\hat{\dot{\alpha}}_I$, $\hat{\dot{\alpha}}_{ID}$ – root-mean-square levels of vibration before and after application of vibration damping tools;

t_0, t_1 – temperature;

v_i – displacements of layers along x axis;

φ_i – section turning angles;

S – Cross-sectional area