

The Effect of the Limit Transition and the Formulation on its Basis of the Limit Transition Method for Determining the Damping Coefficients of Various Structural Materials and Systematization of Damping Coefficients

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Abstract. The main feature of this article is the identification and application of a new mechanical effect in the field of elasticity theory of oscillating systems. This effect has a conventional name - **the effect of the limit transition**. This effect manifests itself in the form of damping properties of various structural materials. The specific purpose of this study is to determine the damping properties of various materials (steel, duralumin, carbon fiber composite, organic glass) based on the measurement of oscillations in air and liquid (water). At the same time, a reliable and stable manifestation of the effect and the limit transition point, namely point A, which made it possible to reliably and accurately determine the damping coefficients of the materials under study. The ultimate goal was to determine the damping coefficients of the oscillating structure material.

The research methodology is original. Its originality lies in the use of a new idea of limit transition and the implementation of experiments based on a laser vibrometer. The results obtained on the basis of experimental studies are also original. The technique was designed for practical application and allows to determine the amplitude-frequency characteristics of systems oscillating in various liquids and consisting of various materials.

INTRODUCTION

One of the most important aspects of combating the harmful effects of vibration and fatigue is to take into account the damping properties of structural materials at the stage of computational design. To do this, these properties (coefficients) must be known. This method allows them to be reliably determined.

In recent years, it has become standard practice to regulate vibration aspects for new buildings on a contractual basis. In the newbuilding contract, limit values must not be exceeded during the operation of the ship are defined as being part of the specification.

At the preliminary design stage or during the design stage of the structure, the shipyard will carry out an appropriate analysis or commission it to an independent consultant. Among other things, the extent of the theoretical studies considered necessarily in a given case depends on the agreed limit values, type of vessel, propulsion system, and so on.

Essentially, there are three areas that are often included in the building specification for vibration limits:

- Impact of vibrations on human beings
- Structural vibrations
- Vibrations of engines and equipment items

If the impact of vibrations concerns a human beings, in general it should be noted that the existing standards are aimed solely at ensuring comfort and well-being. The word “habitability” is often used in this connection. If the recommended limits are not exceeded, health damage is unlikely.

In the problems of studying the amplitude-frequency characteristics of structural materials, it is important to know the damping coefficient of these materials. Damping provides reduction of the vibration process and is necessary for a reliable assessment of the resonance area and the appearance of vibration cracks in structural materials. [1,2]

1 INTRODUCTORY EXPLANATION (ABOUT NOVELTY)

It is known that the damping coefficient is determined experimentally. At the same time, it is practically impossible to conduct a clean and correct experiment, there is always an objection that it is not the damping coefficient (attenuation, internal resistance) of the material under consideration that is experimentally determined, but the damping properties (amplitude-frequency characteristics, and hence the coefficients) for the structure as a whole, i.e., are determined taking into account the influence of the scale factor, the boundary conditions of the method, fixing and excitation i.e. for the structure as a whole. It also takes into account the influence of the external environment.

In this article, the authors set as their goal and task the determination of the damping coefficients for various materials from which the oscillating object is made (steel, duralumin, carbon fiber composite and organic glass).

Previously, similar studies have already been carried out under the guidance of one of the authors of this article (Professor N.A. Taranukha), but they did it on a primitive experimental basis and the main goal was to find the manifestation of the proposed new physical (mechanical) effect for such problems - the effect of limit transition. This effect has been discovered and proven. The proof is the existence of limit point A in the experimental graphs 8,9,10,11,12,13,14 and 15. Such a limit point A was found in all other experiments with other materials and liquids. The existence of the limit point A is the key point (result) of this article. In this article, the authors, in order to achieve the stated goal of determining the damping coefficient of the material, use the new effect discovered and proven by them earlier - the effect of limiting transition. An explanation of this effect is given in Section (5) of this article. This is a new effect that eliminates the influence of the scale factor and design features of the object under study. The application of the limit transition effect is the first circumstance that speaks of the novelty of the research method proposed in the article for determining the damping coefficient of the material of an oscillating object.

This method is based on the use of the limit transition effect and is described in this article. It is correct and universal, in a sense, is a breakthrough in the field of determining the damping properties of various elastic materials.

2 EXPERIMENTAL METHODOLOGY

The experimental setup was designed, developed and manufactured at the shipbuilding department of KnASU. The setup includes a laser vibrometer (Polytec High Speed Laser Vibrometer HSV2001, Polytec GmbH, Germany). It is designed to determine the vibration parameters of mechanical systems with a point mass at the free end, which makes it possible to determine the amplitude-frequency characteristics. The work uses one investigated beam and models with different A_{beam} areas. When measuring, the mass at the end of the vibrating beam remained the same in all cases. The amplitude-frequency characteristics are measured by using a laser vibrometer: "Polytec High Speed Laser Vibrometer HSV2001, Polytec GmbH, Germany". To take readings in the experiments, the Polytec vibrometer software program (Polytec High Speed Laser Vibrometer HSV2001, Polytec GmbH, Germany) was used. Processing of experimental data and plotting were carried out by using the program "Microsoft Excel". In this case, the idea of the limit transition was used. The main feature of this research is the study of a new mechanical effect "the effect of limit transition". At the same time, a reliable and stable manifestation of the effect and the limit transition point, namely point A, was found, which made it possible to reliably and accurately determine the damping coefficients of the materials under study, which makes it possible to improve the accuracy of solving dynamic problems (vibration, fatigue) for oscillating structures.

The experimental procedure is presented in the form of a block diagram.

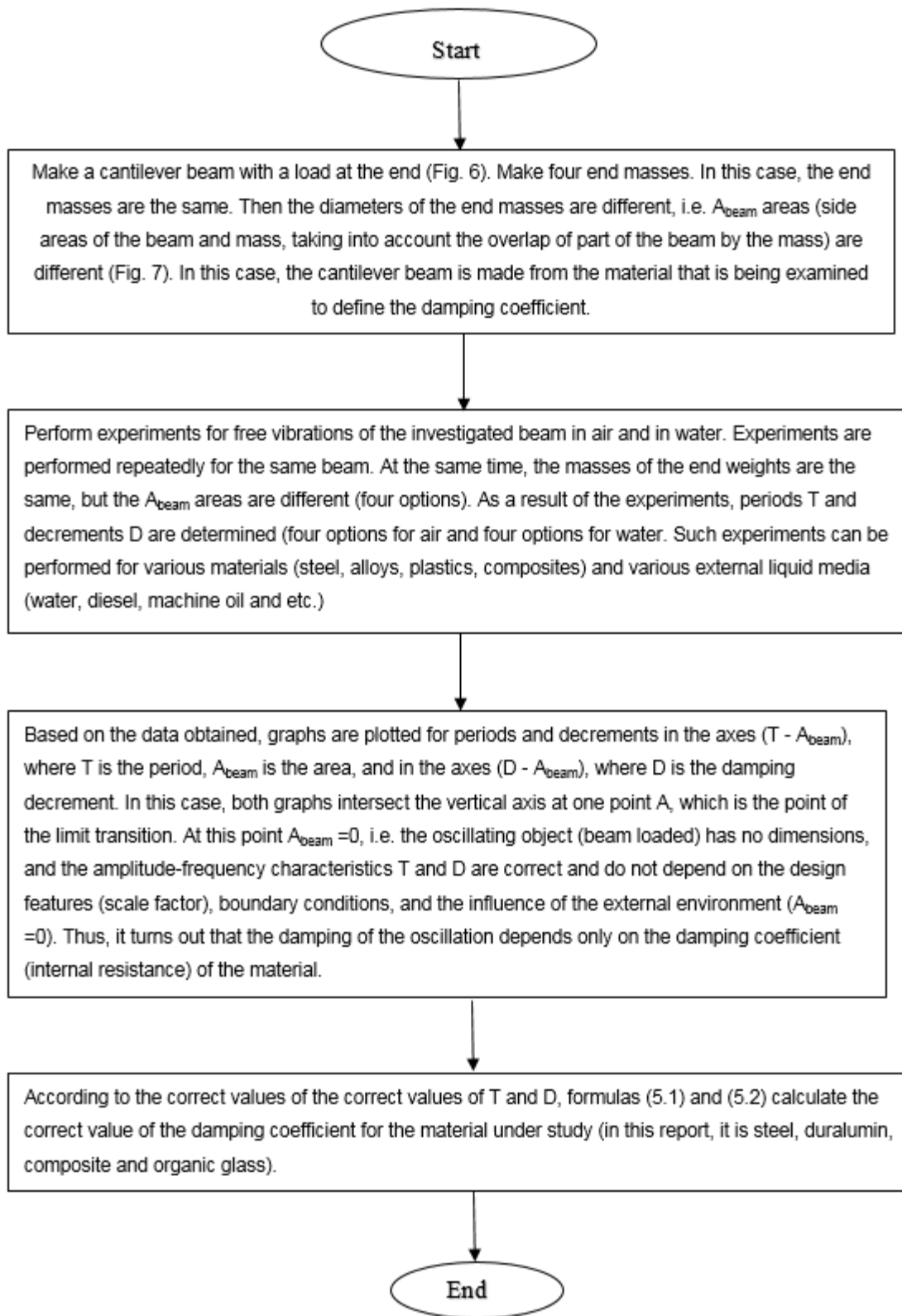


FIGURE 1. Block diagram of the method for determining the damping coefficient based on the effect of limit transition

3 GRAPHS OF FREE VIBRATIONS OF THE STUDIED BEAMS

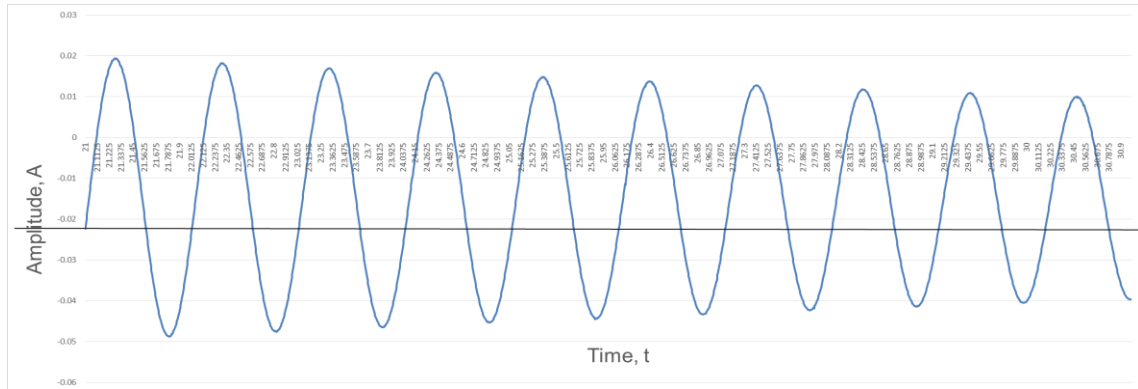


FIGURE 2. Graph of damped oscillations of the cantilever beam (steel)

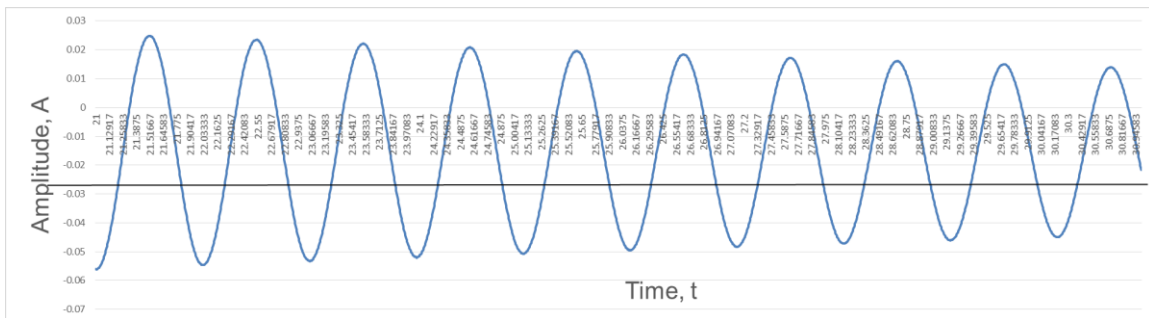


FIGURE 3. Graph of damped oscillations of the cantilever beam (duralumin)

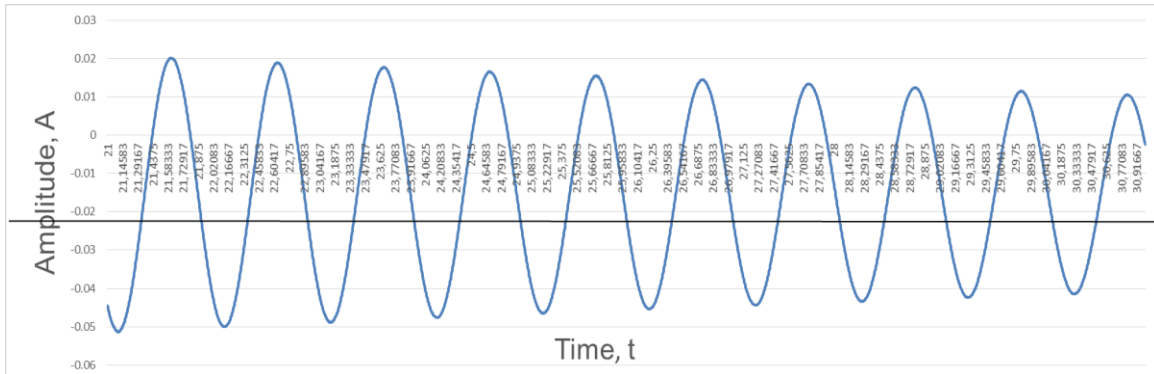


FIGURE 4. Graph of damped oscillations of the cantilever beam (carbon fiber composite)

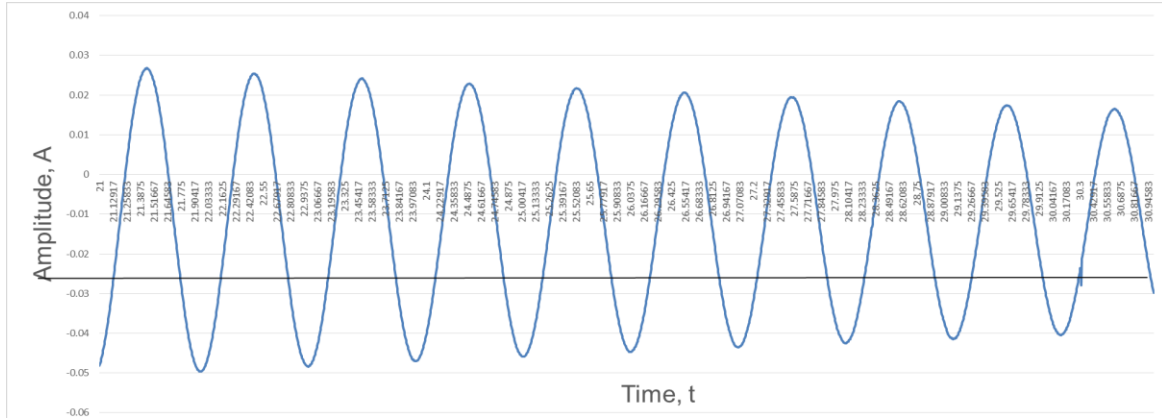


FIGURE 5. Graph of damped oscillations of the cantilever beam (organic glass)

A cantilever beam is necessary to determine the parameters of free oscillations of a mechanical system with a point mass, which is the same in all cases.

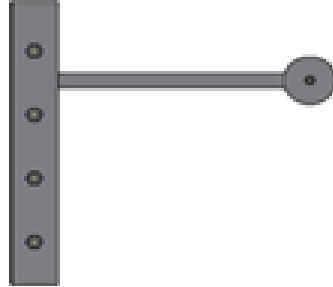


FIGURE 6. 3D view of the cantilever beam

The console consists of the material that is being examined to determine the damping coefficients.

The measurements of the amplitude-frequency characteristics of the console are made by using a laser vibrometer. The measurements of the amplitude-frequency characteristics on the model and on the flag are carried out in the Polytec vibrometer software. The work uses four models with different A_{beam} areas (Fig. 7). All models have the same end weight mass. Graphs of the amplitude-frequency characteristics for the materials studied here with free vibrations are shown in fig. 2,3, 4 and 5.

The A_{beam} area is the area of the lateral surface of the oscillating beam. This area undergoes fluctuations in the resistance of the external environment (air or liquid). The A_{beam} area includes the lateral area of the end weight and the lateral area of the beam itself (see Fig.4). The area of the end weight covering the beam is subtracted.

TABLE 1. Calculations of the total A_{beam} area (for Steel)

	$d_{\text{mass}}, [\text{m}]$	$A_{\text{mass}}, [\text{m}^2]$	$A_{\text{bar}}, [\text{m}^2]$	$A_{\text{overlap}}, [\text{m}^2]$	$A_{\text{beam}}, [\text{m}^2]$
1	$67 \cdot 10^{-2}$	$3.526 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	$0.82 \cdot 10^{-3}$	$9.706 \cdot 10^{-3}$
2	$58 \cdot 10^{-2}$	$2.642 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	$0.72 \cdot 10^{-3}$	$8.922 \cdot 10^{-3}$
3	$47 \cdot 10^{-2}$	$1.735 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	$0.60 \cdot 10^{-3}$	$8.135 \cdot 10^{-3}$
4	$35 \cdot 10^{-2}$	$0.926 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	$0.46 \cdot 10^{-3}$	$7.502 \cdot 10^{-3}$

TABLE 2. Calculations of the total A_{beam} area (for Dural Aluminum)

	$d_{\text{mass}}, [\text{m}]$	$A_{\text{mass}}, [\text{m}^2]$	$A_{\text{bar}}, [\text{m}^2]$	$A_{\text{overlap}}, [\text{m}^2]$	$A_{\text{beam}}, [\text{m}^2]$
1	$67 \cdot 10^{-2}$	$3.526 \cdot 10^{-3}$	$14.2 \cdot 10^{-3}$	$1.84 \cdot 10^{-3}$	$15.726 \cdot 10^{-3}$
2	$58 \cdot 10^{-2}$	$2.642 \cdot 10^{-3}$	$14.2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$15.082 \cdot 10^{-3}$
3	$47 \cdot 10^{-2}$	$1.735 \cdot 10^{-3}$	$14.2 \cdot 10^{-3}$	$1.76 \cdot 10^{-3}$	$14.735 \cdot 10^{-3}$
4	$35 \cdot 10^{-2}$	$0.926 \cdot 10^{-3}$	$14.2 \cdot 10^{-3}$	$0.962 \cdot 10^{-3}$	$14.2 \cdot 10^{-3}$

TABLE 3. Calculations of the total A_{beam} area (for Carbon fiber composite)

	$d_{\text{mass}}, [\text{m}]$	$A_{\text{mass}}, [\text{m}^2]$	$A_{\text{bar}}, [\text{m}^2]$	$A_{\text{overlap}}, [\text{m}^2]$	$A_{\text{beam}}, [\text{m}^2]$
1	$67 \cdot 10^{-2}$	$3.526 \cdot 10^{-3}$	$13.94 \cdot 10^{-3}$	$2.13 \cdot 10^{-3}$	$15.334 \cdot 10^{-3}$
2	$58 \cdot 10^{-2}$	$2.642 \cdot 10^{-3}$	$13.94 \cdot 10^{-3}$	$1.89 \cdot 10^{-3}$	$14.696 \cdot 10^{-3}$
3	$47 \cdot 10^{-2}$	$1.735 \cdot 10^{-3}$	$13.94 \cdot 10^{-3}$	$1.40 \cdot 10^{-3}$	$14.275 \cdot 10^{-3}$
4	$35 \cdot 10^{-2}$	$0.926 \cdot 10^{-3}$	$13.94 \cdot 10^{-3}$	$0.962 \cdot 10^{-3}$	$13.94 \cdot 10^{-3}$

TABLE 4. Calculations of the total A_{beam} area (organic glass)

	$d_{\text{mass}}, [\text{m}]$	$A_{\text{mass}}, [\text{m}^2]$	$A_{\text{bar}}, [\text{m}^2]$	$A_{\text{overlap}}, [\text{m}^2]$	$A_{\text{beam}}, [\text{m}^2]$
1	$67 \cdot 10^{-2}$	$3.526 \cdot 10^{-3}$	$14.08 \cdot 10^{-3}$	$1.84 \cdot 10^{-3}$	$15.766 \cdot 10^{-3}$
2	$58 \cdot 10^{-2}$	$2.642 \cdot 10^{-3}$	$14.08 \cdot 10^{-3}$	$1.68 \cdot 10^{-3}$	$15.042 \cdot 10^{-3}$
3	$47 \cdot 10^{-2}$	$1.735 \cdot 10^{-3}$	$14.08 \cdot 10^{-3}$	$1.00 \cdot 10^{-3}$	$14.815 \cdot 10^{-3}$
4	$35 \cdot 10^{-2}$	$0.926 \cdot 10^{-3}$	$14.08 \cdot 10^{-3}$	$0.962 \cdot 10^{-3}$	$14.08 \cdot 10^{-3}$

The designations adopted in the table are:

1, 2, 3 and 4 – a variant of the scheme (see Fig. 7.);

$d_{\text{mass}}, \text{m}$ – the diameter of the weight surface;

$A_{\text{mass}}, \text{m}^2$ – the lateral weight surface area;

$A_{\text{bar}}, \text{m}^2$ – the lateral area of bar of the beam;

$A_{\text{overlap}}, \text{m}^2$ – the overlapping area;

$A_{\text{beam}}, \text{m}^2$ – total area of bar and mass (without touchable area of bar and mass)

The laser vibrometer directs to the beam and receives its beam back through a special hole in the wall of the bowl. In this case, the beam is directed to a reflective plate pasted on the surface of the end weight, oscillating bar. If the oscillation of the beam in the liquid is considered, then a special vertical rod with a reflective plate (flag) is attached to the end weight, which rises above the surface of the liquid. In this case, the light of the vibrometer is directed to this flag, on which a reflective plate is pasted.

To successfully capture data from the console with a flag in liquid environments, additional flag fluctuations must be taken into account. These additional fluctuations are determined by using special test experiments.

After taking readings of the amplitude-frequency characteristics on the weight and on the flag, the obtained data is processed by using the Microsoft Excel program. According to the obtained data, graphs of the dependence of the period T and the decrement D on the A_{beam} area are plotted.

4 EXPERIMENTAL RESULTS (THE LIMIT TRANSITION POINT)

As a result of experiments, each of the materials, each of the four beams, for each of the four A_{beam} areas, decrements D and periods T , and these characteristics are determined. We get separate points for these points (characteristics) T and D in Figures 8,9,10,11,12,13,14 and 15, graphs (polynomials) of the dependencies of periods are built T and decrements.... D from the A_{beam} area during vibrations in liquid and air. These graphs converge (cross) the vertical axis at one point A . This always happens for any liquids and any materials. This is the manifestation of the discovered new regularity - the effect of limit transition. Further explanations are given in section (5). The values of these limiting characteristics T and D in Figures 8,9,10,11,12,13,14 and 15 are limit transitions, i.e. with a A_{beam} area equal to zero, $A_{\text{beam}}=0$. T and D by which, using formulas (5.1) and (5.2), you can personally determine the damping coefficients for the materials under study.

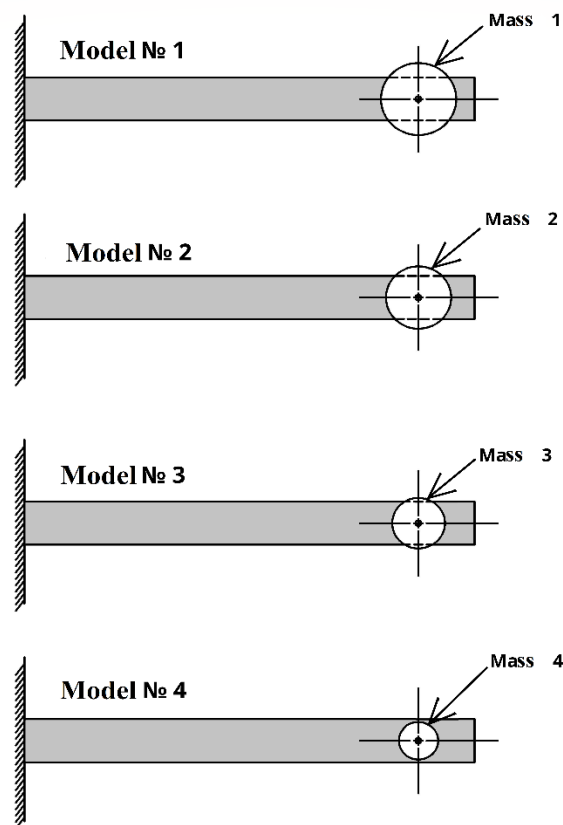


FIGURE 7. Models with different A_{beam} areas, but the same mass weights

4.1 Steel

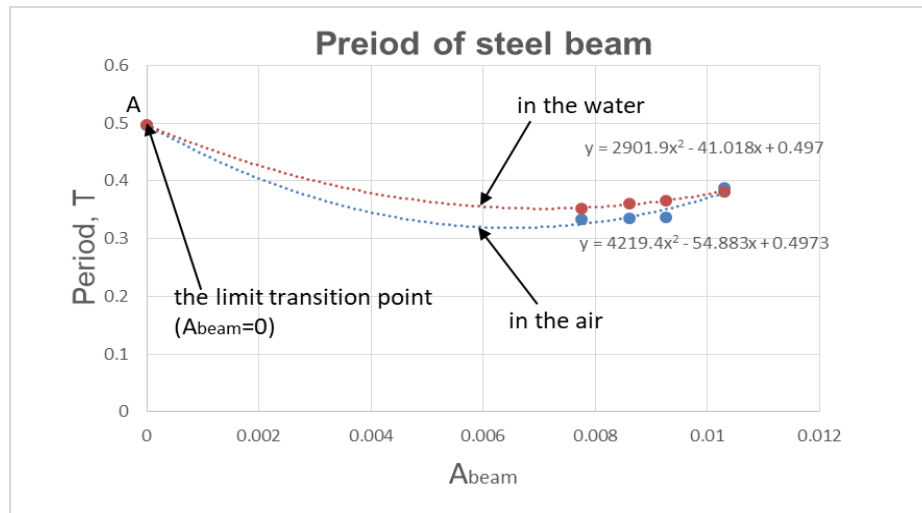


FIGURE 8. Graph of the dependence of the period T on the A_{beam} area (for a steel beam)

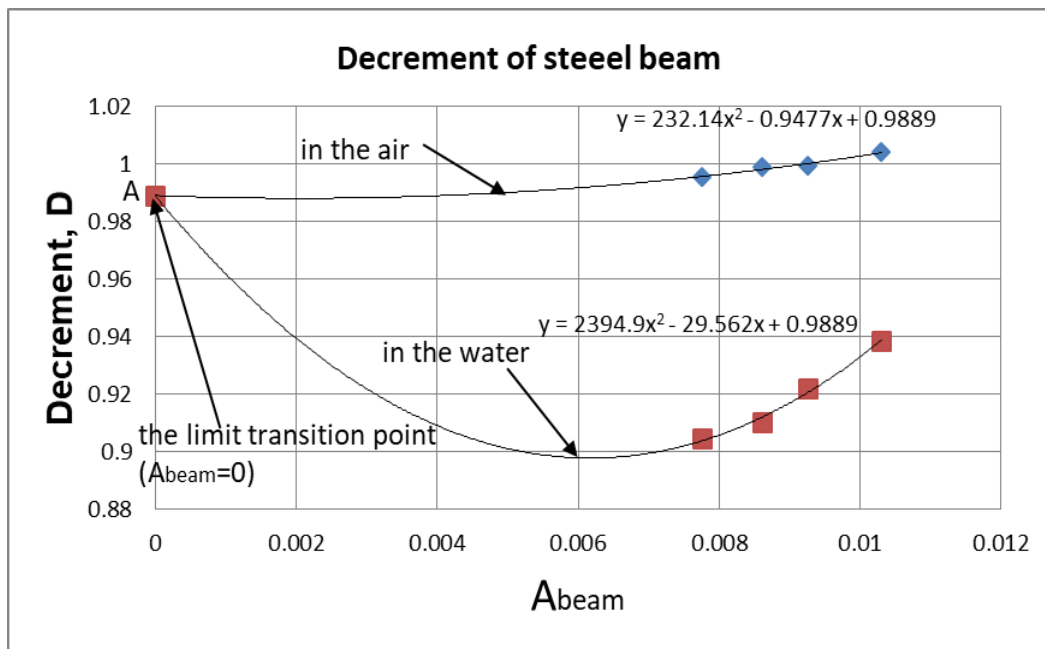


FIGURE 9. Graph of the dependence of the decrement D on the A_{beam} area (for a steel beam)

4.2 Dural Aluminum

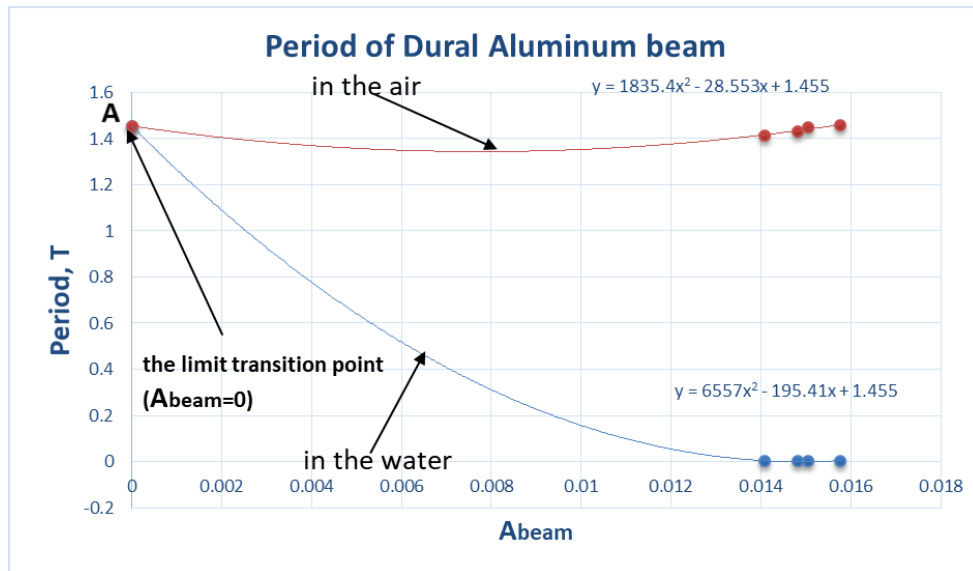


FIGURE 10. Graph of the dependence of the period T on the A_{beam} area (for a Dural Aluminum beam)

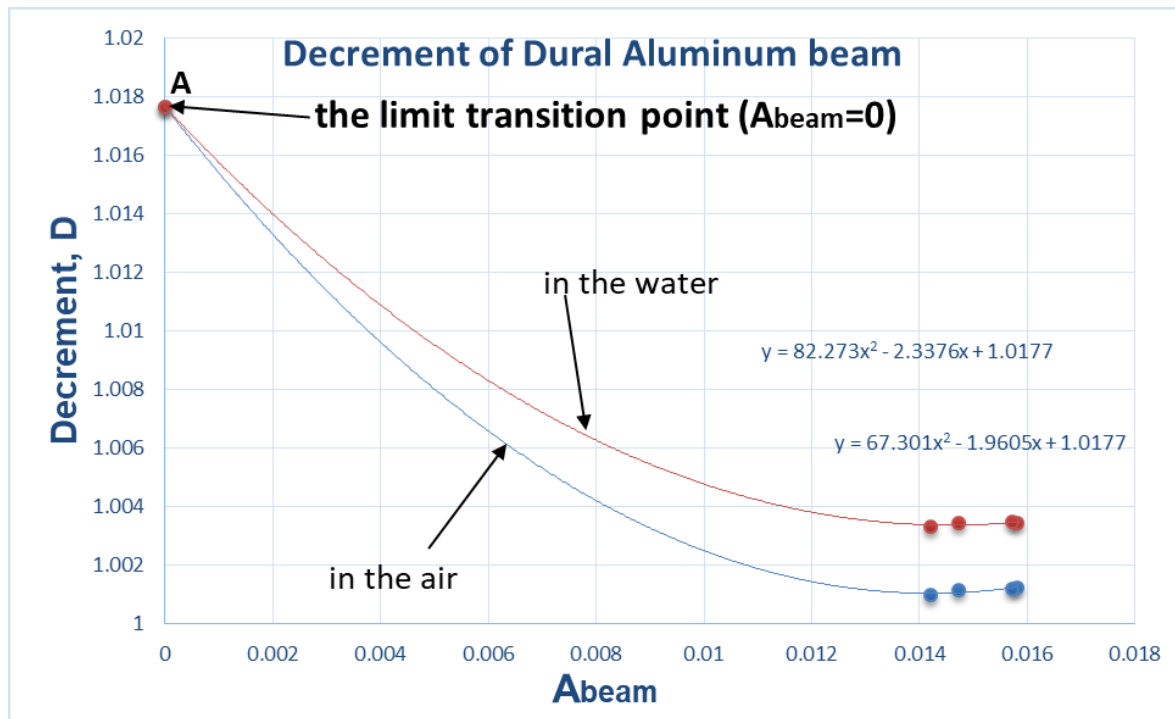


FIGURE 11. Graph of the dependence of the decrement D on the A_{beam} area (for a Dural Aluminum beam)

4.3 Composite Material (Carbon Fiber)

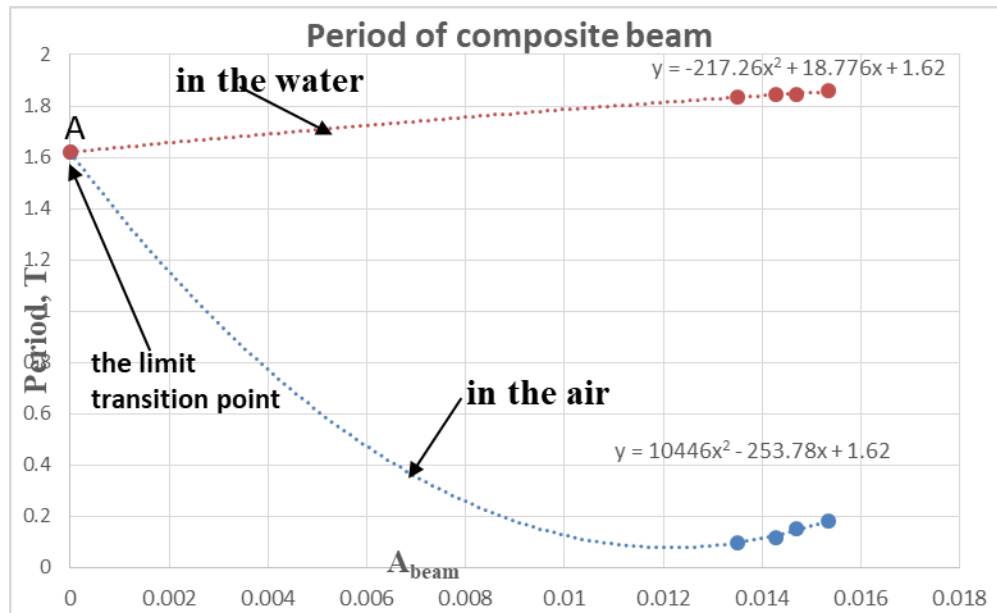


FIGURE 12. Graph of the dependence of the period T on the A_{beam} area (for a composite beam)

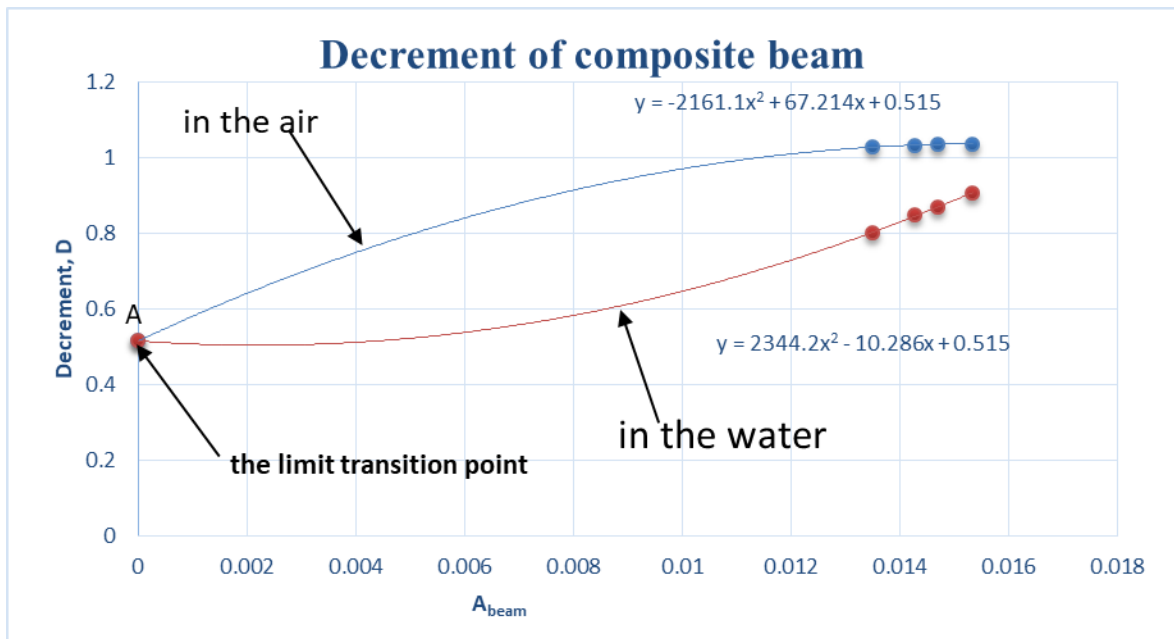


FIGURE 13. Graph of the dependence of the decrement D on the A_{beam} area (for a composite beam)

4.4 Organic Glass

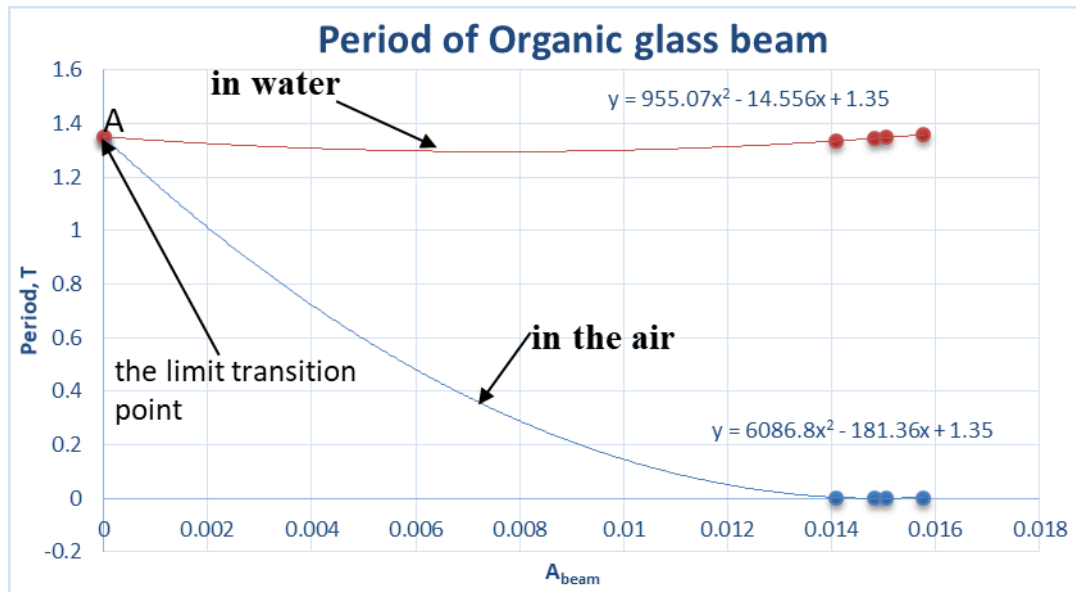


FIGURE 14. Graph of the dependence of the period T on the A_{beam} area (for an organic glass beam)

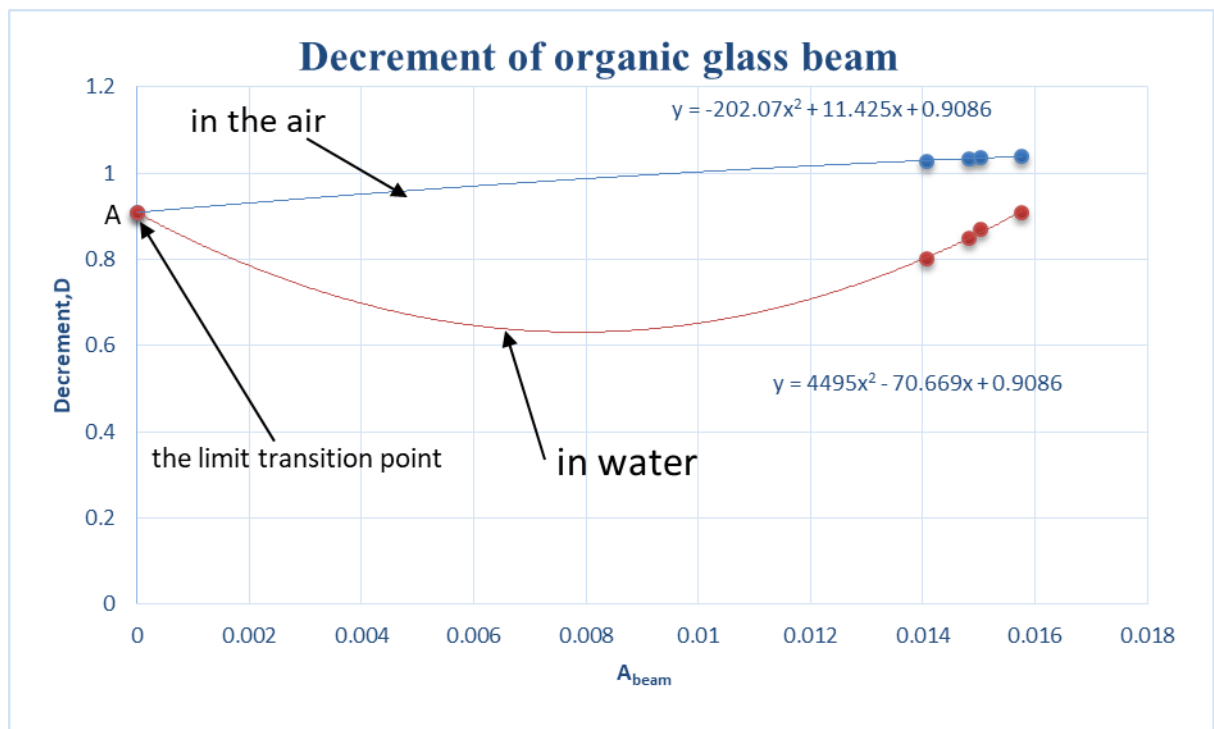


FIGURE 15. Graph of the dependence of the decrement D on the A_{beam} area (for an organic glass beam)

5 EXPLANATION OF THE IDEA AND EFFECT OF THE LIMIT TRANSITION

Fig. 8, 9, 10, 11, 12, 13, 14 and 15 show that all the graphs for air and liquid converge at one point A when the A_{beam} area of the vibrating beam decreases to zero. This always happens for any liquids and any materials. This is

the manifestation of the discovered new regularity - the effect of limit transition. This point is the transition point. Let's explain this. At this point A, the sail area of the oscillating structure is zero. This means that this structure has no real dimensions (the limiting state in terms of the size of the structure, and therefore there is no influence of the scale factor). The amplitude-frequency characteristics corresponding to this point (period T and decrement D) are limiting. It is impossible to obtain the limit point A by direct experiment. This point can only be obtained by extrapolating the values of the period T and the decrement D for other experimental values of the A_{beam} area of the structure under study. To perform the extrapolation procedure, a polynomial function is preliminarily constructed from the known experimental values.

This polynomial at $A_{beam} = 0$ gives the limit values of the period T and the decrement D, according to which the desired values of the internal resistance coefficient (damping coefficient) of the material of the oscillating structure are calculated:

Absorption coefficient:

$$\psi = 2 \ln D \quad (5.1)$$

Internal resistance coefficient (damping coefficient):

$$\gamma = \frac{\psi}{2\pi} \quad (5.2)$$

Since the A_{beam} area of the oscillating structure at the limit point A is zero (this is the intersection point with the vertical axis, then the influence of the external environment disappears at this point (the limit condition according to the influence of the external environment)).

That is why point A is the point of the limiting transition, because the oscillating structure seems to go into the limiting condition in it when the structure has no dimension (no A_{beam} area) and there is no influence of the resistance of the external environment (for example, the surrounding fluid).

For such an oscillating system, the resistance (damping of vibrations) is only caused by the presence of internal resistance of the material of the oscillating system, and not by the design features.

As mentioned above, it is unable to find the point of the limit transition A by the direct experiment, but it can be obtained by extrapolation over several experimental ones, by constructing a polynomial over several different A_{beam} areas, but with the same mass of the oscillating system. This is exactly what is done in this study and is shown in Fig. 8, 9, 10, 11, 12, 13, 14 and 15.

After that, by using the limited point A, it is possible to determine the limited values of the period T and the decrement D. By using formulas 5.1 and 5.2, calculate the damping coefficient that characterizes the damping properties of the internal medium (material).

Note that all the graphs from Fig. 8 to Fig. 15, for all materials and for all external environments (in other experiments) are confidently and constantly converging (intersecting the vertical axis) at point A. The Authors discovered that this point is the point of the limit transition and a proof of the existence of this effect. The existence of such an effect is a reflection of the fact that the damping properties of the material are some fundamental characteristics (dynamic) as well as their static characteristics (modulus of elasticity and Poisson's ratio). There is a material - there is its dynamic constant (i.e the damping coefficient).

6 CALCULATION OF DAMPING COEFFICIENTS

$D_{steel} = 0.9889$ (for steel)

$$\psi_{steel} = 2 \ln D_{steel} = 2 \ln(0.9889) = 0.022$$

$$\gamma_{steel} = \frac{\psi_{steel}}{2\pi} = \frac{0.022}{2\pi} = \frac{0.022}{2 \times 3.142} = 0.0035$$

$D_{duralu} = 1.0177$ (for Dural Aluminum)

$$\Psi_{\text{duralu}} = 2 \ln D_{\text{duralu}} = 2 \ln(1.0177) = 0.035$$

$$\gamma_{\text{duralu}} = \frac{\Psi_{\text{duralu}}}{2\pi} = \frac{0.035}{2\pi} = \frac{0.035}{2 \times 3.142} = 0.0056$$

$$D_{\text{comp}} = 0.198 \quad (\text{for carbon fiber composite})$$

$$\Psi_{\text{comp}} = 2 \ln D_{\text{comp}} = 2 \ln(0.198) = 3.2389$$

$$\gamma_{\text{comp}} = \frac{\Psi_{\text{comp}}}{2\pi} = \frac{3.2389}{2\pi} = \frac{3.2389}{2 \times 3.142} = 0.515$$

$$D_{\text{glass}} = 0.9086 \quad (\text{for organic glass})$$

$$\Psi_{\text{glass}} = 2 \ln D_{\text{glass}} = 2 \ln(0.9086) = 0.2$$

$$\gamma_{\text{glass}} = \frac{\Psi_{\text{glass}}}{2\pi} = \frac{0.2}{2\pi} = \frac{0.2}{2 \times 3.142} = 0.32$$

where,

D_{steel} – decrement of steel beam

D_{duralu} – decrement of Dural Aluminum beam

D_{comp} – decrement of carbon fiber composite beam

D_{glass} – decrement of organic glass beam

Ψ_{steel} - Absorption coefficient of steel

Ψ_{duralu} - Absorption coefficient of Dural Aluminum

Ψ_{comp} - Absorption coefficient of carbon fiber composite

Ψ_{glass} - Absorption coefficient of organic glass

γ_{steel} - damping coefficient of the steel

γ_{duralu} - damping coefficient of the Dural Aluminum

γ_{comp} - damping coefficient of the carbon fiber composite

γ_{glass} - damping coefficient of the organic glass

7 SYSTEMATIZATION OF DAMPING COEFFICIENTS

Table 5. Values of absorption coefficients and internal resistance (damping coefficient)

Material, Construction	Absorption Coefficient (ψ), [4,10,11,12]	Coefficient of Internal Resistance (Damping Coefficient) of Other Authors (γ), [1, 2, 5, 10,11,12]	Internal Resistance Coefficient (Damping Coefficient) by the Authors of this Article (γ), [9]
Materials			
Aluminum	0,02-0.04	0,003-0,006	
Concrete	0,26	0,041	
Oak	0,11	0,017	
Duralumin	0,2-0,6	0,003-0,009	0,0056
Reinforced concrete	0,25	0,040	
Brass	0,01	0,002	
Copper	0,33	0,053	
Nickel	0,03	0,005	
Rubber	0,20-1,20	0,032-0,190	
Pine tree	0,07	0,011	
Steel	0,01-0,03	0,002-0,005	0,0035
Fiberglass	0,20-0,40	0,032-0,064	0,032
Grey Cast iron	0,23	0,036	
Carbon composite (CFRP)	3,2389		0,515
Constructions			
Brickwork	0,25	0,040	
Wooden construction	0,30-0,35	0,048-0,056	
Reinforced concrete structure	0,50	0,060-0,090	
Steel structure	0,16-0,18	0,025-0,028	
Fiberglass construction	0,60-0,80	0,095-0,127	
Steel bridges	0,04-0,31	0,006-0,050	
Ship's steel bottom covers	0,40-0,60	0,064-0,095	
Ship's steel masts	0,20-0,45	0,032-0,072	

8 CONCLUSION

1. The use of this idea of the limit transition makes it possible in this work to determine the damping coefficient (internal resistance) of steel, duralumin, carbon fiber composite and organic glass as a material.

2. In this work, according to the obtained experimental data at the installation, using the Polytec vibrometer software program, graphs of the amplitude-frequency characteristics of the cantilever beam were plotted and the internal damping coefficient of various structural materials (steel, duralumin, composite and organic glass) was determined, obtained in the media "air" and "water". Graphs of the dependence of the period T on the A_{beam} area and graphs of the dependence of the decrement D on the A_{beam} area are obtained. In this case, a laser vibrometer (Polytec High Speed Laser Vibrometer HSV2001, Polytec GmbH, Germany) was used.

3. The damping coefficient (internal friction) $\gamma_{\text{steel}} = 0.0035$, is obtained experimentally for the steel beam material, is $\gamma_{\text{steel}} = 0.0035$ and fully corresponds to the known reference value obtained by other authors $\gamma_{\text{steel}} = 0.002-0.005$.

4. The damping coefficient (internal friction) $\gamma_{\text{duralu}} = 0.0056$, is obtained experimentally for the material of the duralumin beam is $\gamma_{\text{duralu}} = 0.0056$ and fully corresponds to the known reference value obtained by other authors, the damping coefficient (internal friction) duralumin $\gamma_{\text{duralu}} = 0.003-0.009$.

5. The damping coefficient (internal friction) $\gamma_{\text{comp}} = 0.515$, is obtained experimentally for the material of the carbon fiber composite beam is $\gamma_{\text{comp}} = 0.515$ and fully corresponds to the known reference value obtained by other authors, the damping coefficient (internal friction) of the carbon fiber composite $\gamma_{\text{comp}} = 0.35-0.92$.

6. The damping coefficient (internal friction) $\gamma_{\text{glass}} = 0.032$, is obtained experimentally for the material of the organic glass beam is $\gamma_{\text{glass}} = 0.032$ and fully corresponds to the known reference value obtained by other authors, the damping coefficient (internal friction) of organic glass $\gamma_{\text{glass}} = 0.032-0.064$.

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