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EXPERIMENTAL METHOD FOR STRUCTURAL CONCRETE DAMPING PROPERTIES EVALUATION

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Abstract. This article proposes a solution for structural materials such as concrete and cement mortars dynamic properties investigation using experimental modal analysis technique. The studied dynamic characteristics of structural materials include the dynamic modulus of elasticity and the loss factor or its derivatives: the logarithmic oscillation decrement or the relative damping coefficient. Closed expressions are presented for determining the loss factor of mechanical vibrations, obtained on the basis of solving the differential equation for vibrations of a single-mass dynamic system. A method for calculating the loss factor based on the analysis of the spectrum of the transfer function of an oscillatory system loaded with an impulsive dynamic force is presented, in which the results of measuring accelerations at various points of the sample are used as a response. The experiments were carried out on short and long samples made from samples of structural materials - cement mortars with a density of 1500 - 1900 kg/m^3 with special aggregates. Based on the solution of the equation of oscillations of a beam with distributed masses, a formula is presented for determining the dynamic modulus of elasticity of the beam material.

Keywords: dynamic tests, modal analysis, loss factor, modulus of elasticity, damping

ЭКСПЕРИМЕНТАЛЬНОЕ ОПРЕДЕЛЕНИЕ ДЕМПФИРУЮЩИХ ХАРАКТЕРИСТИК КОНСТРУКЦИОННЫХ МАТЕРИАЛОВ

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Аннотация. В работе с применением метода экспериментального модального анализа исследуется возможность определения динамических характеристик конструкционных материалов, таких как бетоны и цементные растворы. К исследуемым динамическим характеристикам конструкционных материалов относят динамический модуль упругости и коэффициент потерь или его производные: логарифмический декремент колебаний или коэффициент относительного демпфирования. Представлены замкнутые выражения для определения коэффициента потерь механических колебаний, полученные на основании решения дифференциального уравнения колебаний одномассовой динамической системы. Представлен метод вычисления коэффициента потерь на основании анализа спектра передаточной функции колебательной системы, нагруженной импульсной динамической силой, в которой в качестве отклика использованы результаты измерения ускорений в различных точках образца. Эксперименты проводили на коротких и длинных образцах, выполненных из образцов конструкционных материалов – цементных растворов плотностью 1500 – 1900 кг/м^3 со специальными заполнителями. На основании решения уравнения колебаний балки с распределёнными массами представлена формула для определения динамического модуля упругости материала балки.

Ключевые слова: динамические испытания, модальный анализ, коэффициент потерь, модуль упругости, демпфирование

INTRODUCTION

The main parameters necessary for calculating the amplitudes of forced vibrations of structures are their dynamic characteristics - primarily the coefficient of mechanical energy loss, as well as the dynamic modulus of elasticity of the structural material. As a result of the application of external or internal loads, finite deformations will occur in the structural elements, which, under certain conditions, will lead to oscillations with very large amplitudes or to the loss of stability of the processes of static or dynamic deformation. It is very important for modern engineering practice to be able to predict the occurrence of such movements, instability or vibrations with large amplitudes in order to be able to control the level of static and dynamic stresses, the magnitude of the amplitudes during dynamic behavior, as well as the levels of transmitted or radiated noise in accordance with the needs of practical applications [1].

The importance of taking into account damping parameters is also due to the fact that the presence of damping can cause the process of energy transfer between the forms of oscillations of superstructures, which can, under certain conditions, lead to their destruction. Such an effect was noted and studied in [2, 3].

DYNAMIC MODEL

To determine the dynamic characteristics of samples of structural materials, ultrasonic research methods [16], methods of experimental modal analysis [11, 13–15], as well as methods with the application of a given forced external load [7, 8, 12] are used.

Consider the simplest single-mass model of vibrations of a damped system, shown in Fig. 1. The equation of oscillations of the system under consideration under the action of a harmonic load is written as:

$$m\frac{d^2w}{dt^2}+C\frac{dw}{dt}+kw=F\cos\omega t\ . \tag{1}$$

A particular solution w_p is a certain function w(t) that satisfies an inhomogeneous differential equation and, in particular, has the form [1, 2]:

$$w_p=\frac{F\cos\left(\omega t-\varepsilon\right)}{\sqrt{\left(k-m\omega^2\right)^2+\omega^2C^2}},$$
$$\varepsilon=arctg\left[C\omega/\left(k-m\omega^2\right)\right]. \tag{2}$$

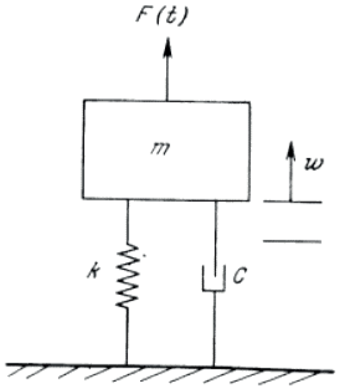

Figure 1. System with one degree of freedom and viscous damping

Then the general solution of equation (1) can be written as:

$$w=w_c+w_p=e^{-at}\left(C_1\sin\omega_Dt+C_2\cos\omega_Dt\right)+A_1\cos\left(\omega t-\varepsilon\right),$$
$$A_1=F/\sqrt{\left(k-m\omega^2\right)^2+\omega^2C^2}. \tag{3}$$

Arbitrary constants C_1 and C_2 are determined by the initial conditions.

One of the general methods for assessing damping, as noted in [1, 7, 10], is to determine the width of the resonant peak of oscillations at those points of the curve for dynamic displacements, at which the dynamic displacement makes up a certain proportion of the resonant dynamic displacements of the system, for example, points A and B in figure 2. It is usually assumed that points A and B correspond to frequencies at which the amplitude of dynamic displacements is several times less than the maximum amplitude.

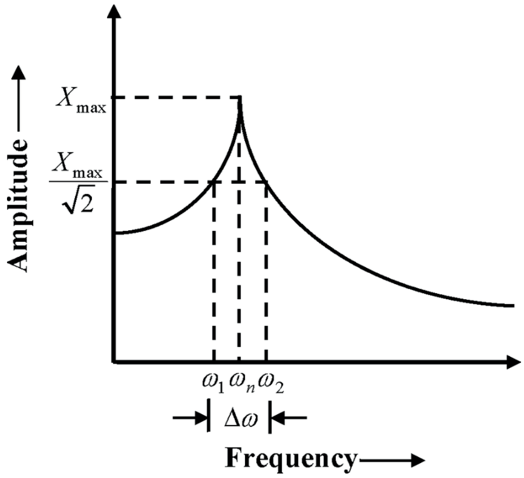

Figure 2. Frequencies that determine the bandwidth of the resonant amplitude

Consider the viscous damping of the system. The frequency of resonant vibrations is determined by the expression [1, 9, 11]:

$$\omega_{рез} = \sqrt{\frac{k}{m}\left(1 - \frac{C^2}{2km}\right)} \quad (4)$$

Substituting (4) into (3), we find the oscillation amplitude at resonance:

$$W_{p,рез} = \frac{F}{k}\left[2\left(C/2\sqrt{km}\right)\left(1 - C^2/4km\right)^{1/2}\right]^{-1} \quad (5)$$

In order to find the frequencies corresponding to points A and B, in which the amplitude is n times less than the resonant $W_{p,res}$, the dynamic displacement determined by the expression $\left|w_p/F\right| = 1/\sqrt{\left(k - m\omega^2\right)^2 + \omega^2 C^2}$ should be equated to the dynamic displacement (5) multiplied by 1/n at resonance, as a result of which we obtain:

$$\left(\frac{m\omega_i^2}{k}\right)^2 - 2\left(1 - \frac{2C^2}{4km}\right)\frac{m\omega_i^2}{k} + 1 - 4n^2\frac{C^2}{4km}\left(1 - \frac{C^2}{4km}\right) = 0. \quad (6)$$

When $C^2/4km << 1$, we obtain:

$$\omega_{1,2}\sqrt{m/k} = 1 \pm \sqrt{n^2 - 1}\frac{C}{2\sqrt{km}}, \quad (7)$$

Where do we get ratio:

$$\frac{\Delta\omega}{\omega_{рез}} = \frac{\omega_2 - \omega_1}{\omega_{рез}} = 2\sqrt{n^2 - 1}\frac{C}{2\sqrt{km}}. \quad (8)$$

By $n = \sqrt{2}$ we obtain:

$$\frac{\Delta\omega}{\omega_{рез}} = 2\frac{C}{2\sqrt{km}} = 2\xi, \quad (9)$$

where $\xi = C/2\sqrt{km} = C/C_c$ - damping ratio; $C_c = 2\sqrt{km}$ - critical damping of the system.

Similar transformations can be performed for a system with hysteresis damping.
In this case, the amplitude at resonance is equal to:

$$W_{p,рез} = \frac{F}{k\eta}. \quad (10)$$

The frequencies corresponding to points A and B in Figure 2, in which the amplitude of dynamic displacements is n times less than the resonant amplitude $W_{p,res}$, are equal to:

$$\omega_{1,2} = \sqrt{\frac{k}{m}\left(1 \pm \eta\sqrt{n^2 - 1}\right)}. \quad (11)$$

Then with $n = \sqrt{2}$ we get:

$$\frac{\Delta\omega}{\omega_{рез}} = \sqrt{1+\eta} - \sqrt{1-\eta}\ , \qquad (12)$$

And with η << 1:

$$\frac{\Delta\omega}{\omega_{рез}} \approx \left(1+\frac{\eta}{2}\right) - \left(1-\frac{\eta}{2}\right) = \eta\ . \qquad (13)$$

The relation between $\Delta\omega / \omega_{рез}$ and η is linear only for small values of η. Note that for η > 1 there is no frequency ω_1 under the assumption of hysteresis damping, at which the amplitude of dynamic displacements would be equal to $\left|W_p\right| / \sqrt{2}$. In fact, for n > 1, the "peak" amplitude will be less than the static displacement F/k. This is true not only for the case of hysteresis damping, but also for those cases where the parameters η(ω) and k(ω) are determined from experiments with real materials.

The dynamic modulus of elasticity reflects only the elastic properties of the material without the influence of creep, since when the sample vibrates, stresses appear in it, which are very small in magnitude. For this reason, the dynamic modulus of elasticity is approximately equal to the initial modulus of elasticity determined during static tests, and is much higher than the static modulus of deformation [4, 9]. The difference in the values of the dynamic and static modules is also due to the fact that the heterogeneity of concrete affects these modules by a different mechanism.

Within the framework of this study, the parameters of the frequencies of natural vibrations were determined using the methods of experimental modal analysis [7, 8], according to the results of which the frequencies of bending vibrations of the samples were determined.

The modulus of elasticity of the structural material was determined by the well-known formula for a hinged beam:

$$\omega_k = \left(\frac{k\pi}{l}\right)^2 \sqrt{\frac{EI}{m}}\ , \qquad (14)$$

where m is the mass per unit length of the beam, l is the span of the beam, EI is the bending stiffness of the beam, k is the shape number.

Based on formula (14) and the relationship between the circular and technical frequency in the form $\omega = 2\pi f$, we get an expression for determining the modulus of elasticity of the specimen in the form:

$$E = \frac{4mf^2l^4}{k^4\pi^2 I}. \qquad (15)$$

EXPERIMENTAL MODEL

The tests were carried out on samples made from different concrete compositions obtained in [5, 6]. The size of the samples in the first batch was 40x40x160 mm, and the second - 800x50x30 mm, which were installed on a tooling with hinged support at the ends.

The tests were carried out according to the method of GOST ISO 7626-5-99. The perturbation was created by exciting vibrations of a concrete prism with an impact hammer, applying 5 successive pulses at each location of the acceleration sensors.

A Bruel&Kjaer 8202 impact hammer (with a Bruel&Kjaer 8200 force sensor) was used to register the applied load, Bruel&Kjaer 4375 charge miniature accelerometers were used to register the response. does not affect test results. Synchronous recording of the excitation and response parameters was carried out by the SCADAS Mobile-I measuring system. The sample test scheme is shown in Figure 3.

After each impact, the signals from the force and vibration sensors are fed to low-pass filters (LPF), which allow avoiding the transfer of high-frequency components to the measurement frequency range during sampling, after which they are analog-to-digital conversion (ADC) to form a sample.

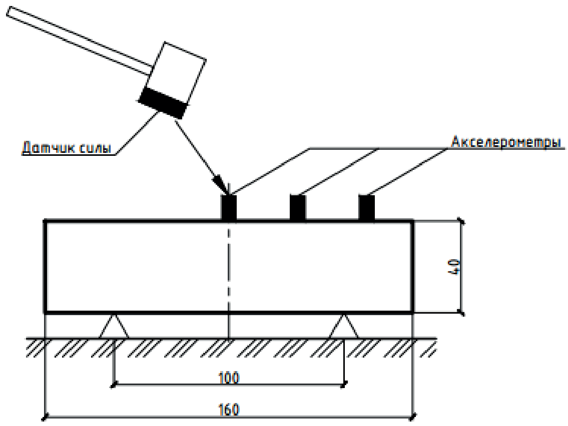

Figure 3. Experimental set-up for short specimen

Each digital entry corresponds to one impact. For each entry, the DFT is calculated. To improve the estimate, averaging over the frequency domain of several implementations of the frequency response obtained for the same measurement and excitation points can be applied.

For each point, at least 5 impulse actions were carried out with an impact hammer and the parameters of the input action - the applied force and the response of the structure - accelerations at different points were recorded, as shown in Figure 4 for one of the episodes of dynamic tests.

To obtain transfer functions, we analyzed the spectrum of the applied load, for which we built its auto spectral characteristic. For each block of impulse actions, the frequency response of the sample was built, which was averaged using a weighted average over several implementations.

a)

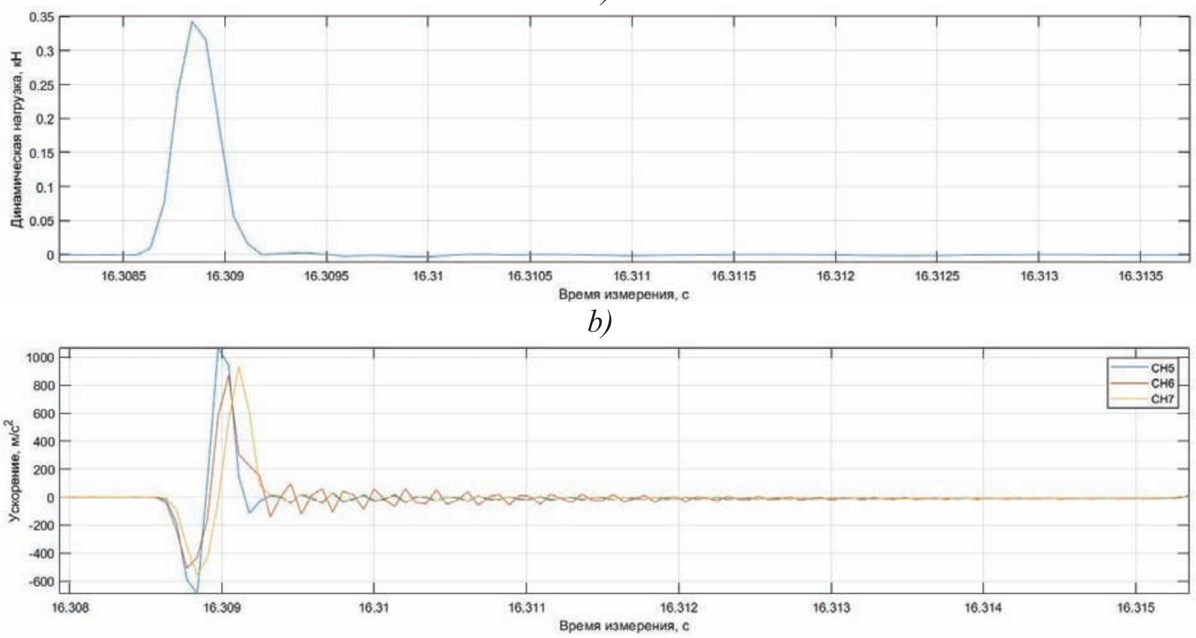

Figure 4. Dependence of applied force (a) on time and measured acceleration (b) on time

An example of the computed transfer function for a rack of one of the samples is shown in Figure 5, together with a signal coherence plot (a value close to 1 indicates a high signal-to-noise ratio, which improves measurement accuracy).

Based on the results of determining the frequency response - modal analysis, a stabilization diagram is constructed, within the framework of which the oscillation modes that are stable in frequency and damping are determined.

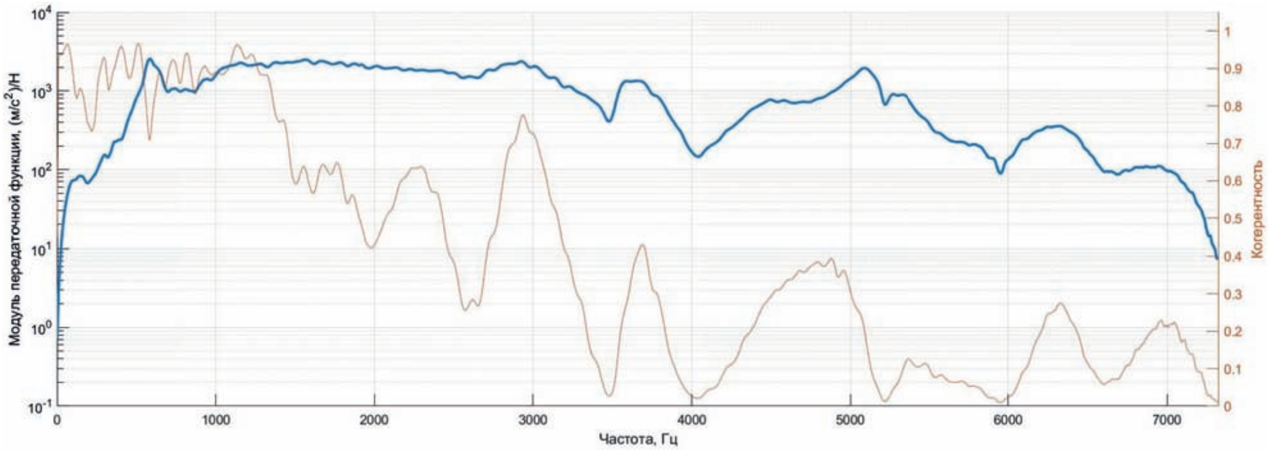

Figure 5. Representation of the results of calculating the frequency response of the sample

EXPERIMENTAL RESULTS

Based on the determination of a stable oscillation frequency corresponding to the bending shape, in which the maximum of the real part of the oscillation form corresponds to the antinode in the sensor located in the middle of the span of the test sample, and the phase shift (the imaginary part of the shape vector) between the sensor located in the middle and in thirds of the span the sample differs by π/2, the loss coefficient η and the relative damping coefficient ξ are determined. The test results for short specimens are shown in Table 1 and for long specimens in Table 2.

Table 1. Test results for short specimens

Specimen name	Avg value		
	η	ξ	Dynamic modulus, Pa
1500к	0.042	0.021	1.69E+10
1500к-ф	0.028	0.014	1.88E+10
1500с	0.133	0.067	1.02E+10
1500с-ф	0.171	0.085	9.93E+09
1700к	0.051	0.025	1.98E+10
1700к-ф	0.038	0.019	2.19E+10
1700с	0.091	0.045	1.51E+10
1700с-ф	0.109	0.054	1.61E+10
1900к	0.070	0.035	2.56E+10
1900к-ф	0.071	0.035	2.73E+10
1900с	0.034	0.017	2.09E+10
1900с-ф	0.025	0.013	2.01E+10
ТБ	0.020	0.010	3.74E+10
ТБ-ф	0.017	0.008	3.95E+10

Table 2. Test results for long specimens

Specimen name	Avg value		
	η	ξ	Dynamic modulus, Pa
1500к	0.126	0.063	2.91E+10
1500к-ф	0.124	0.062	3.27E+10
1500с	0.157	0.079	1.94E+10
1500с-ф	0.161	0.080	1.94E+10
1700к	0.153	0.076	7.85E+10
1700к-ф	0.104	0.052	3.71E+10
1700с	0.105	0.053	1.06E+12
1700с-ф	0.358	0.179	1.43E+10
1900к	0.094	0.047	4.14E+10
1900к-ф	0.080	0.040	4.63E+10
1900с	0.136	0.068	3.08E+10
1900с-ф	0.088	0.044	3.77E+10
ТБ	0.069	0.035	6.27E+10
ТБ-ф	0.078	0.039	8.07E+10

The results of comparing tests of short and long samples are shown in Figure 6.

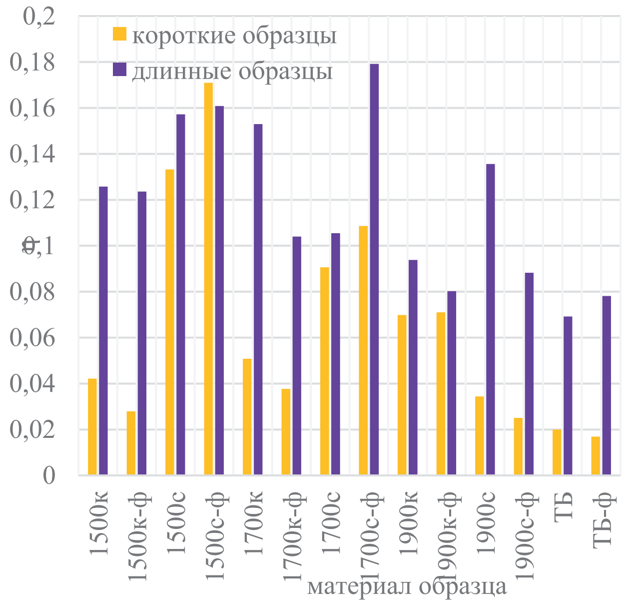

Figure 6. The results of comparing the damping parameters obtained on samples of different sizes

CONCLUSION

As the test results show, the introduction of ceramic microspheres increases the loss factor by 1.75 times with an increase in the density of the composition from 1500 to 1900 kg/m3. the introduction of spherical microspheres at the same time reduces the loss factor by 9 times. At the same time, the introduction of fiber into compositions with silicon spheres leads to a proportional decrease in the loss factor by a factor of 1.5 relative to compositions without fiber with an increase in the density of the composition. the introduction of fiber into compositions with glass microspheres increases the loss factor by 1.28 times relative to compositions without fiber.

The elastic modulus increases for all compositions with increasing sample density. At the same time, compositions with ceramic microspheres have a 30–40% higher elastic modulus than compositions with glass microspheres. The introduction of fibers into compositions with glass microspheres has very little effect on the change in their modulus of elasticity. The introduction of fiber into compositions with ceramic microspheres increases their modulus of elasticity by 11% compared to compositions without fiber.

For the base composition of heavy concrete (marking "TB"), the presence of fiber reduces the average value of the loss factor from 0.02 to 0.017 (34% reduction). In this case, the value of the modulus of elasticity increases by 12%.

The loss factor for samples depends on their shape and size. With an increase in the span of the sample (decrease in the first resonant frequency), the value of the loss factor increases.

To obtain adequate values of the damping coefficients, they should be determined on similar samples with close values of the frequencies of free oscillations. To take into account the dependence on frequency, it is recommended to carry out measurements on several samples with approximation of the results.

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