A Multiplicative Method and A Correlation Method for Acoustic Testing of Large-Size Compact Concrete Building Constructions

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1. Introduction

New methods for acoustic testing of large-size (>1.5 m) concrete building structures (foundations, walls of buildings, airfield pavements, bridge pillars, slabs, blocks, beams, etc.) based on the use of methods of free and forced vibrations are reviewed.
Problems of inspection of large-size concrete building structures by the resonance and the impact-echo method are considered. These methods are the only possible acoustic methods for testing large concrete building structures, that cannot be inspected by other (conventional) ultrasonic testing techniques. However, the resonance and impact echo methods for testing large-size concrete building constructions can be used only for testing extended building structures (in extended building structures the inspected thickness h is much smaller than the other dimensions). The resonance and impact echo methods cannot be used in compact building structures (in which the tested dimension, e.g., the thickness h, is comparable with at least one of the other dimensions), because of the influence of geometrical effects (the noise of the article shape does not allow unambiguous determination of the desired maximum in the article's spectral characteristic).
A new multichannel acoustic method for testing large-size compact concrete building constructions is considered. The method is based on the use of the resonance and impact-echo methods with the subsequent multiplication of partial spectral characteristics. The multichannel multiplicative method allows performance of acoustic testing of large-size compact concrete building constructions (blocks, beams, columns, supports, and other standard articles).
The second problem of inspection of large-size compact concrete building structures determined the necessity of calculating the acoustic velocity in compact articles. It is impossible to determine the acoustic-vibration velocity C_l in a compact article because of the effect of geometrical dispersion of the sound velocity. The resonance and impact echo methods can be used only at a known value of the correlation coefficient of the velocity of longitudinal vibrations in a particular compact article. This can be done using the technique of numerical simulation of acoustic fields. A new correlation method for determining the velocity in a compact article with known dimensions is described. It allows monitoring of the strength of arbitrarily shaped large-size compact concrete building constructions.

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2. Problems of acoustic testing of large-size concrete building structures

Unfortunately, failures in residential and industrial buildings due to aging of concrete, which destroys the strength of building constructions (BCs), have occurred more frequently in recent years. To prevent such failures, special attention should be given to the problems of inspecting large-size concrete objects of BCs.
Unfortunately, conventional ultrasonic nondestructive testing (NDT) methods allow inspection of concrete articles of only limited thicknesses. The most informative ultrasonic echo method allows one to test BCs only to a maximum depth of 1–1.5 m even if low-frequency signals are used ($f_0 \leq 100$ kHz).
To solve the problem of testing large-size concrete BCs by acoustic methods, inspection methods based on the analysis of eigenfrequencies of an article (the impact method and, less frequently, the resonance method) were developed in the United States approximately 20 years ago (Carino, N.J., 2001; Sansalone, M. & Carino, N.J., 1986 ; Carino, N.J.; Sansalone, M. and Hsu, N.N., 1986; Sansalone, M. and Streett, W.B., 1997). The essence of the impact-echo (IE) method is illustrated in Fig. 1, which shows a diagram of testing of an extended concrete article (hereinafter, the term "extended article" is defined by the condition that the inspected thickness h is much smaller than the other dimensions). Using a small steel ball or a special impactor device, a short but strong mechanical impact is delivered to the BC surface (Fig. 1). This impact initiates free decaying acoustic oscillations in the tested extended article. These oscillations are detected by a broadband receiving PET and then by a spectrum analyzer (SA). The free-oscillation spectrum is the informative parameter for analyzing BCs. The form of the spectral characteristic allows determination of the eigenfrequency f at which a BC thickness resonance is observed. The frequency of the resonance peak allows calculation of the thickness h at a known propagation velocity C_l of a longitudinal acoustic wave: $h \approx C_l/2f$ (Figs. 1, 2).

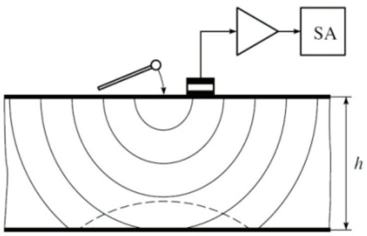

Fig. 1. Schematic diagram of testing of a flaw-free concrete article (h = 0.5 m) by the acoustic IE method.

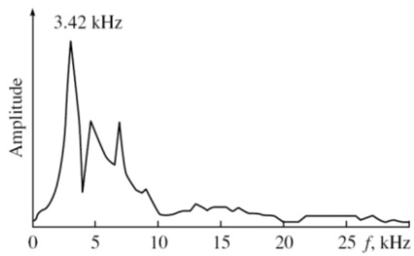

Fig. 2. AFC of an extended flaw-free concrete article: f = 3.42 kHz and h = $C/2f = C\lambda/2$.

The IE method, based on the excitation and measurement of natural oscillations in an article, qualitatively differs from conventional ultrasonic testing methods, based on location principles.

First, when the IE method is applied, a resonance of the article itself arises; the resonance frequency f is determined by the article size ($h \approx \lambda/2$), and, for large-size articles, this frequency may be within the range of tens of hertz to several kilohertz. At such frequencies, the attenuation of acoustic signals in concrete is negligibly low; therefore, it is possible to test concrete BCs with a thickness of up to 10–20 m by the IE method.

Second, the analysis of the resonance characteristics yields only indirect information on the presence of flaws. The presence of a flaw in a BC (Fig. 3) can be determined in comparing the spectral characteristics of a flaw-free (Fig. 2) and a defective article (Fig. 4).

Third, during testing of large-size concrete BCs, the most important task is to determine neither the BC dimensions nor flaws of the article's internal structure, but the structure strength, which is determined mainly by the concrete strength (grade). For this purpose, in some cases, the problem of determining the propagation velocity of acoustic vibrations inside a concrete article becomes predominant because the velocity of longitudinal acoustic vibrations C_l in concrete is directly related to the concrete strength characteristics (Ermolov, I.N. & Lange, Yu.V., 2004).

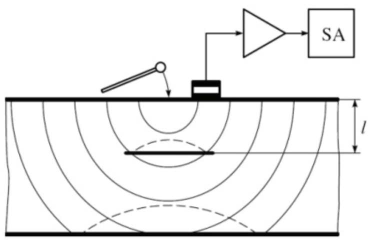

Fig. 3. Schematic diagram of testing of an extended concrete article (h = 0.5 m) with a flaw (l = 0.25 m) by the acoustic IE method.

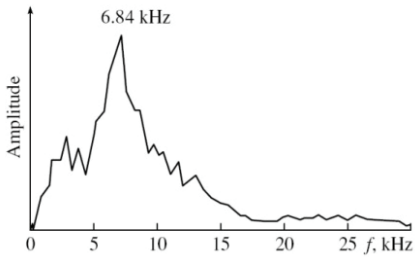

Fig. 4. AFC of an extended concrete article with a flaw: f = 6.84 kHz and l = 0.25 m.

Note that, at present, the problem of measuring the velocity of acoustic vibrations in large-size concrete BCs is far from being solved. The known methods for determining the velocity C_l in concrete from the surface velocity C_{sur} of acoustic vibrations do not always yield precise information on the actual velocity C_l inside a large-size BC because the strength of the concrete surface layer often does not correspond to the strength of its deeper layers. The velocity C_l of an acoustic wave calculated through the surface velocity C_{sur} is usually 10–20% lowers than the actual velocity in the volume of a concrete structure (Ferraro, C.C., 2003).

This phenomenon, which is explained by a change in the concrete properties near the surface due to constant contact with the atmosphere, is additionally aggravated by the presence of steel reinforcement bars inside reinforced-concrete constructions. The velocity of acoustic waves in steel is higher than that in concrete; therefore, the wave propagation velocity in reinforced concrete is higher than that in plain concrete.

The velocity of ultrasonic vibrations in large BCs cannot always be measured by the echo-pulse (shadow) method. Moreover, the velocity of longitudinal ultrasonic vibrations measured by the echo-pulse (shadow) testing method is not equal to the velocity of longitudinal acoustic vibrations deter-mined using the IE method because of the effect of geometrical dispersion in articles at $\lambda \sim h$ (Ermolov, I.N. & Lange, Yu.V., 2004; Bolotin, V.V. 1999). In fact, the velocity C_l is measured using the ultrasonic echo-pulse (shadow) testing method provided that $\lambda << h$; as a result, $C_l = 2h/T$. The velocity of longitudinal vibrations measured by the IE method is measured under the condition of $\lambda \sim h$; as a result, $C_l = (2hf/k)$, where k is the velocity correction factor ($k \neq 1$). For slabs and piles, $k = 0.96$ and 0.95, respectively (Carino, N.J., 2001). Hence, the BC strength can be measured by the IE method only in articles where the velocity correction factor k is strictly defined.

Proceeding from the above, we can conclude that eigenfrequency methods are the only possible acoustic methods for testing large BCs that cannot be inspected by other (conventional) acoustic testing techniques. However, the IE method allows testing of only extended BCs (for which the factor k is known) and excludes testing of compact concrete BCs.

Hereinafter, we define a compact article as an object for which the ratio of the measured thickness to the two other dimensions (width and length) is <1:5 or >5:1. Note that, according to this definition, both a large concrete article (2x3x4 m) and a small object (2x3x4 cm) are compact.

Figure 5 shows examples of (a) extended and (b) compact BCs; arrows indicate surfaces accessible to testing and determining surfaces of the impactor location. Figure 6 illustrates the problem of testing compact articles. The article has a limited width (a) and a thickness-to-length ratio $h/l \approx 1 : 1.5$.

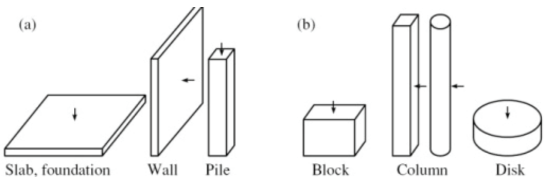

Fig. 5. Examples of (a) extended and (b) compact BCs.

As a result, in addition to a thickness resonance, numerous supplementary resonance peaks caused by geometrical effects appear in the spectral characteristic. Against the background of numerous resonances, it is impossible to unambiguously determine the main thickness-resonance peak at the desired frequency $f \sim 1/h$ (Fig. 6b). In addition, the velocity $C_l = (2hf/k)$ measured by the IE method in a compact article differs from the velocity C_l in an extended article: in a compact article, the velocity correction factor k requires special determination for each article. It is precisely for these reasons (ambiguity of the spectral characteristic and uncertainty of C_l) that, to date, compact concrete BCs are not tested by acoustic methods. Hence, the IE method, which is widespread abroad, is used to test only extended concrete BCs.

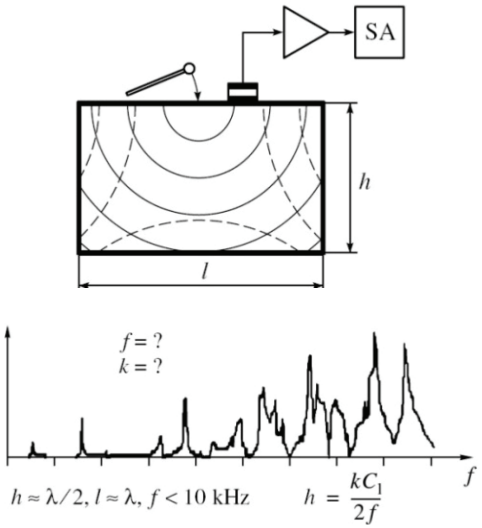

Fig. 6. (a) Schematic diagram of the acoustic IE method for a compact concrete article; (b) AFC of a compact concrete arti-cle. Parameters of the IE method in testing of compact articles.

The IE method is one of the oldest NDT methods. The first paper devoted to the IE method (Mary Sansalone, United States) allowing determination of the thickness and the presence of flaws in extended BCs was published in 1986 (Sansalone, M. & Carino, N.J. 1986). In 1998, the American Society adopted this method for Testing and Materials (ASTM) as a standard (ASTM C1383. Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method). The simplicity of the impact method, the high capacity, and the relative cheapness of testing devices has made it quite widespread in industrially advanced countries.

A standard IE complex consists of a computer, an amplifier, a PET, and a set of steel balls of different diameters used to excite free oscillations in BCs.

In some cases, steel balls are replaced by a special device — an impactor, a mechanism for delivering a force- and duration-normalized impact on a surface and situated in one unit with the receiving PET. The latter is built as a transducer with a point contact ensuring a good "dry" acoustic contact with a rough concrete surface. The impactor ensures better stability of the exciting-signal spectrum, thereby contributing to the improvement of the reproducibility of the spectral-characteristic measurement results. In addition, the impactor solves the problem of synchronizing the onset of measurement with the moment of striking.

The resonance method, which involves excitation of forced vibrations in an article using an external generator of a linearly changing voltage, is similar to the IE method based on the analysis of free vibrations in a tested article. In this case, a ball or an impactor is replaced by a broadband emitting PET and signals are received with a broadband receiving probe. The amplitude–frequency characteristic (AFC) of forced vibrations in an article is similar to the spectral characteristic obtained in the IE method. However, the resonance method has a number of advantages over the IE method.

First, a Fourier transform of the received signal is unnecessary. To obtain the resonance characteristic of a test object, it is sufficient to record the received-signal amplitude at each frequency. This allows a detailed study of the AFC in the frequency ranges of interest at as small a step as possible, thus increasing the measurement accuracy.

Second, the resonance method is more sensitive because, in the IE method, excitation is performed by a short impact whose energy is distributed over the entire spectrum (in the resonance method, the signal energy can be concentrated at each individual frequency).

Third, if there is a good acoustic contact between the PET and the article, the reproducibility of measurements is ensured.

Fourth, the AFC of the electroacoustic channel can be corrected by setting the required amplitude of the emitted signal or selecting the gain of the input signal for each frequency.

The resonance method has also not found practical application in the quality control of actual concrete BCs, but the resonance method is indispensable for laboratory studies (when it is necessary to carefully study the AFC of an article in some frequency range, to find the optimal arrangement of probes, to perform identical measurements many times, or to conduct other investigations). For this reason, we actively used the resonance method for detailed studies of the characteristics of concrete articles and the development of new testing techniques.

The IE method is used mainly to determine the thickness of large-size (>1.5 m) concrete BCs. In this case, reliable measurement results are obtained in testing of extended slabs (foundations, walls, floors, etc.) whose lengths and widths exceed the tested thickness by a factor of 5 or more. As a rule, testing of such extended articles allows one to unambiguously determine the BC thickness according to the frequency of the maximum resonance peak in the article's spectral characteristic.

The value of the velocity of acoustic vibrations necessary for the subsequent determination of the BC thickness is determined according to the American standard ASTM C1383 through the surface-wave velocity despite all the aforementioned drawbacks of this method. Note that it is the method of eigenfrequencies that allows determination of the longitudinal-wave velocity in the bulk of an article. However, the field of application of these methods is limited by the shape of tested articles: only extended slabs (with lengths and widths far exceeding the thickness) and long piles (with lengths far exceeding other dimensions) may undergo testing. For compact articles, the value of the coefficient k is unknown; therefore, it is impossible to use the methods of eigenfrequencies for monitoring the wave velocity in such articles.

The analysis of publications on the application of the IE and resonance methods allows us to draw the following conclusions.

(1) To date, the IE method (in some cases, the resonance method) is a quite widespread technique for acoustic testing of concrete BCs (abroad) and is virtually the only acoustic method enabling testing of extended articles thicker than 1.5 m in the case of one-way access.

(2) The IE method has certain limitations: the testing techniques and devices allow inspection by the IE method of virtually any thickness but only for extended articles (foundations, walls, floors, and piles) whose lengths and widths exceed their thicknesses by a factor of >5. The existing testing techniques are unsuitable for testing compact articles (for which at least one dimension differs from the thickness by a factor of <5, a feature typical of supports, columns, blocks, etc.).

2. A correlation method for determining the propagation velocity of an acoustic wave in large-size compact concrete articles

A review of the methods for testing large-size concrete BCs shows that the impact echo method helps to inspect extended concrete BCs (in extended BCs, the tested dimension differs from the other dimensions by a factor of at least 5) (Carino, N.J., 2001). Thus, it becomes possible to measure the thickness h of (at a known velocity C_l) or the velocity C_l in (at a known thickness *h*) foundations, walls, building floors, bridge supports, piles, etc. However, it is shown in (Carino, N.J., 2001). that one cannot achieve an unambiguous result in compact articles. In fact, in compact articles (in which the tested dimension, e.g., the thickness *h*, is comparable with at least one of the other dimensions), numerous amplitude peaks (resonances) appear in the spectral characteristics and a shift of the resonance-peak frequency is observed due to the effect of geometrical dispersion of the wave velocity, which leads to ambiguous testing results.

These problems determined the necessity of calculating the acoustic fields in compact articles appearing under the action of a driving force. As is known, either free vibrations (when the action of a driving force has a short-term pulsed character) or forced vibrations (initiated by continuous action of a driving force) arise in an elastic body (Skuchik, E., 1971). Analytical calculation of the vibration spectra for elastic solids of different shapes involves intricate mathematical calculations. It is relatively simple to obtain analytical expressions for the spectral characteristics of natural vibrations only for the simplest geometrical forms—rods and extended slabs (plates) (Ermolov, I.N. & Lange, Yu.V., 2004). For more complex shapes, a solution leads to differential equations of the fifth and higher orders that cannot be solved analytically. Meanwhile, an analytical solution allows one to more deeply understand the essence of the processes proceeding in a tested object affected by an external driving force.

The analytical solution for the simplest shape — a thin rod of finite length *l* — is known (Fig. 7). In our context, “thin” means that the thickness of the rod is many times smaller than the wavelength and its length l is comparable with the wavelength ($l \approx \lambda$). In the simplest variant, we assume that only longitudinal waves propagate in the rod; flexural and torsional waves are not considered here. In the case of forced vibrations, the behavior of the rod is analyzed under the assumption that a constant harmonic force $F = F_0 e^{i\omega t}$ is applied to one end of the rod (x = 0) and its other end ($x = l$) is free. As a result of this analysis, the values of the rod resonance frequencies are determined: $f = nC_r/2l$, where n = 1,2,3,.. .(Korobov, A.I. 2003).

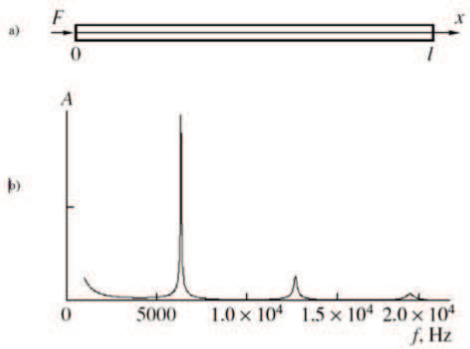

Fig. 7. (a) Thin concrete rod and (b) spectrum of forced vibrations in the rod.

Hence, the rod is a distributed vibratory system with many degrees of freedom (modes), each of which has an eigenfrequency ω. Fig. 7b shows the calculated spectral characteristic of a thin rod of length l = 0.3 m. The following parameters typical of concrete were used in the calculation: the Young modulus E = 3.456x1010 N/m^2, the viscosity E = 5000 (N_s)/m^2, and the density ρ = 2400 kg/m^3. The propagation velocity C_r of an acoustic wave in such a rod calculated taking into account the above values of the Young modulus and density is C_r = 3795 m/s. The resonance frequency f_{1a} of the first mode of a longitudinal wave obtained analytically is 6325 Hz.

In practice, we most frequently deal with concrete articles of a more complex shape than rods. Because it is difficult to analytically calculate the vibration spectra of such articles, it becomes necessary to simulate the physical processes occurring in compact BCs by numerical methods. Simulating physical processes is necessary for determining the character of the acoustic-field distribution in BCs, the optimal testing algorithm, and the optimal arrangement of probes on the article surface. In other words, the possibility of constructing a numerical model of a BC with specified dimensions, boundary conditions, and material properties is a necessary condition for studies.

The finite-element method (FEM) is most frequently used for this purpose (Bolotin, V.V. 1999). This method is based on the approximation of a continuous function by a discrete model, which is constructed on a set of piecewise-continuous functions defined on a finite number of subdomains called finite elements. The geometrical domain under study is partitioned into elements so that, on each of them, the unknown function is approximated by a trial function (as a rule, a polynomial). These trial functions must satisfy the continuity boundary conditions coinciding with the boundary conditions imposed by the problem itself. The choice of the approximating function determines the corresponding type of element.

Partition of the geometrical domain into a large number of finite elements and solution of the main equation of motion for each element allow calculation of the spectra of free (transitional analysis) and forced (modal analysis) vibrations. The main equation of motion has the form

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{U\}=\{F^a\}, \tag{1}$$

where $[M]$ - is the mass matrix, $[C]$ - is the damping matrix, $[K]$ - is the elasticity matrix, $\{\ddot{u}\}$- is the nodal acceleration vector, $\{\dot{u}\}$- is the nodal velocity vector, $\{u\}$- is the nodal displacement vector, and $\{F^a\}$ is the applied-force vector.

In the modal analysis, it is considered that the displacements of all elements obey the harmonic law

$$\{u\}=\{u_{\max}e^{i\Phi}\}e^{i\Omega t} \tag{2}$$

where u_{max} is the displacement amplitude, Ω is the circular frequency of forced vibrations, and Φ is the displacement phase shift.

The use of complex form of representation allows reduction of expression (2) to a more compact form:

$$\{u\}=\{u_{\max}(\cos\Phi+i\sin\Phi)\}e^{i\Omega t}$$

or

$$\{u\} = (\{u_1\} + i\{u_2\})e^{i\Omega t}\,, \tag{3}$$

where $\{u_1\} = \{u_{\max}\cos\Phi\}$ and $\{u_2\} = \{u_{\max}\sin\Phi\}$.
Similarly, the force vector can be represented as

$$\{u\} = (\{F_1\} + i\{F_2\})e^{i\Omega t} \tag{4}$$

Substituting (3) and (4) into (1), we obtain

$$([K] - \Omega^2[M] + i\Omega[C])(\{u_1\} + i\{u_2\}) = \{F_1\} + i\{F_2\} \tag{5}$$

Note that, for forced vibrations, this equation does not include the time *t* (only stationary vibrations are considered in the modal analysis).
The solution of Eq. (5) allows calculation of the displacement amplitude of each element of the model at the current frequency of the driving force. Multiple solution of this equation for each frequency in the range of interest makes it possible to construct the spectral characteristic of forced vibrations of the model in this frequency range for the element of interest.
To date, several software packages allowing FEM-based computer calculations have become widespread. In this study, the FEM calculations were performed according to the ANSYS program with the Multiphysics package (Chigarev, A.V.; Kravchuk, A.S., & Smalyuk, A.F., 2004; Kaplun, A.B.; Morozov, E.M., & Olfer'eva, M.A., 2003; Basov, K.A., 2002). The ANSYS graphical environment facilitates constructing a 3D model, specifying the material properties and the boundary conditions, and visualizing the calculation results. In this study, the ANSYS package was used to calculate the spectra of free and forced vibrations in concrete articles with different shapes. The calculation of the spectra of free and forced vibrations for a thin rod similar to that considered above is presented below and is intended for primary verification of the simulation results.
The simulation procedure consists of several stages. A geometrical model of the rod is created — a cylinder with a diameter d = 0.01 m and a length l = 0.3 m (Fig. 8a). The elastic properties of the material are specified — the density ρ = 2400 kg/m^3, the Young modulus E = 3.456×10^{10} N/m^2, and the Poisson ratio σ = 0.2. A grid is imposed on the geometrical model. In this case, the cylinder is partitioned into 100 elements along the length.

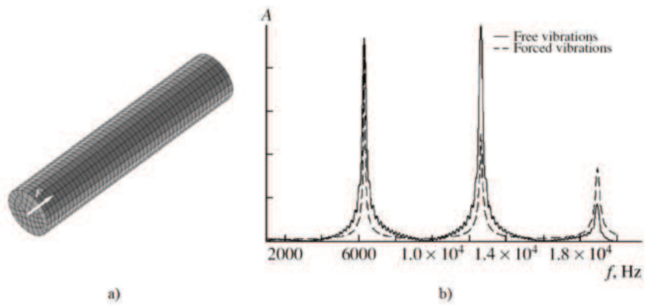

Fig. 8. (a) Model of a thin rod and (b) calculated spectra of free and forced vibrations in the rod.

The boundary conditions are set. An external force is applied to all nodes of the grid positioned at one end of the cylinder. In simulating free vibrations, a short impulse of force in the form of a sine-vibration half-period with a duration of 50 μs is used. A harmonic oscillator is used as an external force for modeling forced vibrations. Subsequently, the type of analysis is chosen — modal and transitional for forced and free vibrations, respectively. In addition, at this stage, the acoustic-wave damping in the rod material is specified.
(In this case, the coefficient of modal damping is 0.005, which corresponds to a damping α = 0.04 dB/m at a frequency of 5 kHz.) The modal analysis also requires that the frequency range and the frequency measurement step of the oscillator used as the source of the driving force be specified. Finally, the analysis is performed and the results are deduced. Because the result of the transitional analysis is the signal shape in the time domain, it is additionally necessary to calculate the spectrum.
The modal analysis results in a spectral characteristic; therefore, no additional calculations are required. Figure 8b shows the spectra of free and forced vibrations obtained as a result of the ANSYS simulation. Comparison of the spectra in Figs. 7b and 8b shows that the results of the numerical simulation for both types of vibration coincide with the analytical solution for the rod. The resonance frequency f_{1m} of the longitudinal wave's first mode resulting from the simulation is f_{1m} = 6250 Hz, $f_{1m} \approx f_{1a}$.
The application of the FEM also allows calculation of the spectra of articles with more complex shapes (Avramenko, S.L. & Kachanov, V.K., 2007). In such articles, first, one has to deal with a large number of degrees of freedom and, second, it is impermissible to disregard the existence of other wave modes, as was done in the analytical calculation for the rod. Below, we present the results of calculating the spectral characteristics of a homogeneous concrete slab with dimensions of 300×300×30 cm (Fig. 9). This slab can be considered an extended article because its length and width far exceed its thickness.

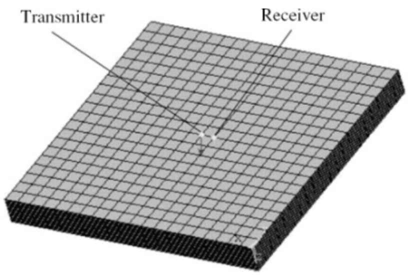

Fig. 9. Model of a slab with dimensions of 300×300×30 cm.

Let us divide the slab's faces into 40×40×10 elements. The elastic properties of concrete in this and all subsequent calculations are the same as those used in the calculation of the rod spectrum. Let us place the source of the external force at the center of the slab and the receiver (the element in which the spectral characteristic is calculated) at a distance of 7.5 cm from it. Figure 10 shows the spectra of free and forced vibrations in the slab obtained with the FEM. A resonance peak at a frequency f = 6400 Hz is clearly pronounced in both spectral characteristics. This resonance peak corresponds to the first mode of a longitudinal wave. The impact echo method for measuring the thickness of concrete slabs implies calculation of the slab thickness h from the formula $h = C_{sl}/2f$, where f is the frequency of the longitudinal wave's first mode and C_{sl} is the velocity of longitudinal waves in the slab. In our case, the calculation of the slab thickness from this formula yields h = 0.3 m, which exactly corresponds to the model thickness.

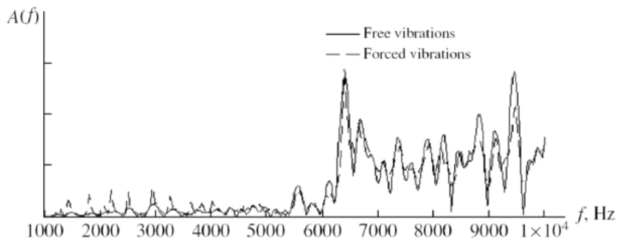

Fig. 10. Spectra of free and forced vibrations for a slab with dimensions of 300×300×30 cm.

Note that the resonance frequency of the longitudinal wave's first mode in the 0.3-m-thick concrete slab (f_{1sl} = 6400 Hz) differs from the resonance frequency of the 0.3-m-long rod of the same material (f_{1r} = 6250 Hz). This is because the velocity of a longitudinal wave C_{sl} in an extended slab differs from the velocity of a longitudinal wave C_r of acoustic vibrations in a rod. The formula $C_{sl} = \sqrt{\frac{E}{\rho}\frac{1}{1-\sigma^2}}$ is valid for a slab. In contrast to the velocity in a rod, the velocity in an extended slab depends on (in addition to E and ρ) the Poisson ratio σ. Calculating the velocity C_{sl} at σ = 0.2 typical of concrete yields C_{sl} = 3872 m/s (compare to C_r = 3795 m/s).

Comparing the two characteristics in Fig. 10 shows that the spectra of free and forced vibrations are identical. Slight differences in the quality factors and the peak amplitudes in the characteristics are related to the error in calculating the spectrum of free vibrations. This indicates that the spectral characteristic of a BC does not depend on the technique of vibration excitation (both a short impulse of force and a harmonic signal with a smoothly increasing frequency can be used as sources of external actions).

The fact that the simulation results obtained with the ANSYS package do not contradict the main formula of the impact echo method confirms the consistency of the chosen simulation technique. This circumstance makes it possible to apply simulation as an efficient tool for searching for optimal techniques for testing various concrete articles (including compact objects). The practical meaning of this conclusion is that spectral characteristics obtained using the impact echo and resonance methods will be identical. At the same time, in contrast to the impact echo method, the resonance method does not require calculation of the signal spectrum but takes a longer time. For this reason, all further calculated spectral characteristics were obtained as a result of modal analysis (forced vibrations).

Two main factors can be distinguished among the reasons for which the thickness of compact BCs cannot be successfully tested by the eigenfrequency methods: the effects of "noise of form" on the amplitude–frequency characteristics (AFCs) of compact articles and the geometrical dispersion of the longitudinal - wave velocity.

Let us consider the influence of the shape of a compact article. Here, it should be noted that a model based on the principles of geometrical acoustics is unacceptable for calculating the resonance characteristic of a compact article. In fact, determination of the signal profile on the surface of a BC from the interference of several echo signals reflected from the BC boundaries can be used only when the wavelength of a probing signal is many times smaller than the BC size. If the wavelength is of the same order of magnitude as the BC size, such an interference model cannot be applied for precise determination of the article's spectral characteristic. Instead of it, we should speak about the resonance properties of the article itself.

The above can be explained by the following example. It is known that, upon an impact on the surface of an infinitely long slab of a certain thickness h, a receiver positioned at a small distance from the point of action registers damped harmonic vibrations at a frequency $f = C_{sl}/2h$. It should be noted that vibrations obey exactly a harmonic law. It follows from this fact that the considered slab is a resonator and the frequency f its eigenfrequency. At the same time, being an elementary signal, a sinusoid (including a damped sinusoid) cannot be divided into simpler components and, consequently, cannot be obtained via any summation (interference) of any other simpler components. Hence, in considering free vibrations of a compact elastic article, the resonance nature of its spectral characteristic should not be explained as resulting from the reflection of wave fronts from boundaries. It is more correct to treat the test object as a body possessing a certain set of eigenfrequencies (Glikman A.G., 2009).

The infinite slab considered above is certainly an idealized example. A real extended slab always has borders and, as a result, can be represented in the form of a thin plate (whose dimensions far exceed its thickness). As shown in (Ermolov, I.N. & Lange, Yu.V., 2004; Bolotin, V.V., 1999), apart from a longitudinal wave, flexural and planar waves propagate in the plate and initiate resonances at frequencies $f_a(m, n)$ and $f_s(m, n)$, respectively. In these expressions, m and n indicate the numbers of wavelengths along the plate length and width, respectively.

Figure 11 shows several modes of flexural and planar vibrations of the plate. Note that the frequencies of the lowest modes of flexural and planar vibrations in extended concrete plates are much lower than the frequency of the first mode of a longitudinal wave because the BC length and width, determining the vibration frequency, are many times larger than the thickness. For the same reason, owing to the high acoustic damping in concrete, the amplitudes of both low and high modes of these vibrations are insignificant. However, in compact articles, whose dimensions are comparable with their thickness, the frequencies of flexural and planar vibrations lie within the same range as the frequency of the longitudinal wave's first mode. In addition, their amplitudes are substantially higher. Thus, a large number of resonance peaks with comparable amplitudes are present in the resonance characteristic.

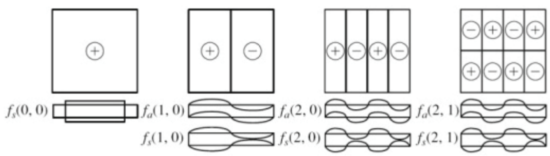

Fig. 11. Some forms of flexural and planar vibrations in a plate.

Let us demonstrate this by an example. To adequately characterize the compactness of a tested article, let us introduce the compactness factor m, equal to the ratio of one of its overall dimensions to its thickness. Figure 12 shows the spectral characteristics of concrete parallelepipeds with dimensions of 150×150×30, 120×120×30, 90×90×30, and 60×60×30 cm resulting from the simulation at an arbitrarily specified velocity of acoustic vibrations in the slab. The compactness factors m of these blocks are equal to 5, 4, 3, and 2, respectively.

Figure 12 shows that, as m decreases, the spectral characteristic becomes more complex. At $m = 4$, it is rather difficult to unambiguously determine the frequency of the first mode of the longitudinal wave, from which the thickness of the compact article should be determined.

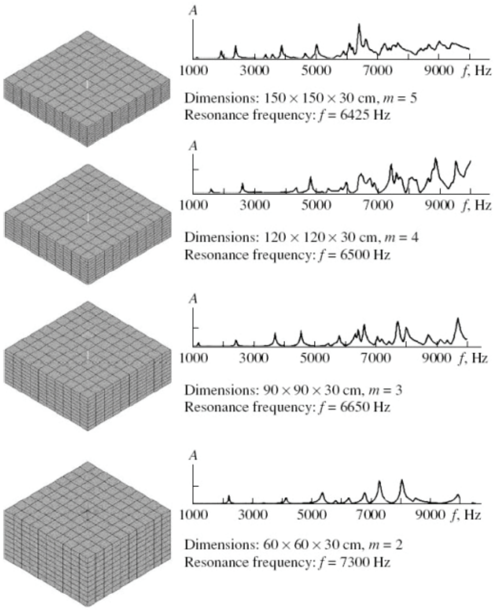

Fig. 12. Spectral characteristics of a compact slab with a thickness of 30 cm at different values of the compactness m.

As a rule, an unambiguous interpretation of the spectrum becomes absolutely impossible at $m < 3$. Thus, as m decreases, interpreting the spectrum on the basis of the feature that the "amplitude of the longitudinal wave's first mode is maximal", becomes problematic. The error in finding the frequency of the longitudinal wave's first mode increases, thereby reducing the reliability of the measurement results because the desired peak cannot be distinguished against a background of numerous other resonances forming a sort of noise disguising the useful signal. This noise can be called "noise of form" (in terms of noiseimmune ultrasonic testing of articles) (Kachanov, V.K. and Sokolov, I.V., 2007) because, on the one hand, it is the shape of a compact article that determines its AFC and, on the other hand, such an AFC with many peaks hinders determination of the sought resonance, i.e., is a sort of interference (noise) disguising the required article thickness. As follows from (Carino, N.J., 2001), the geometrical effects leading to the appearance of noise of form of a compact article do not allow reliable thickness measurements of compact articles with $m < 5$, as was confirmed by the simulation results

Let us now consider the effect of geometrical dispersion of the longitudinal-wave velocity during testing of compact BCs. As was mentioned above, the propagation velocity C_l of a longitudinal wave in an elastic body depends on the geometrical shape and dimensions of this body with respect to the wavelength. The table 1 presents the known analytical formulas for calculating the longitudinal-wave velocity for some very simple geometrical shapes.

The velocity C_l in compact articles can also be determined by the shadow or echo-pulse method, but this is possible only under the obligatory condition that the wavelength λ of the probing signal is much smaller than the size of the article. However, in controlling large-size concrete articles, these methods cannot always be used because of relatively high damping of ultrasonic signals at the testing frequency.

Geometric form	Condition	Formula for velocity calculation
Infinite space	$\lambda <<$ medium dimensions	$C_l = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}}$
Thin rod of length l and diameter d	$\lambda \approx l, \lambda >> d$	$C_r = \sqrt{\frac{E}{\rho}}$
Extended slab of length a, width b and thickness h	$\lambda \approx h, \lambda << a, \lambda << b$	$C_r = \sqrt{\frac{E}{\rho}\frac{1}{1-\sigma^2}}$

Table 1. Propagation velocity of acoustic waves in bodies of different geometric forms

The testing methods based on the use of the eigenfrequencies of inspected articles do not allow direct determination of C_l. The value of C_l is calculated using the velocity correction coefficient $k = C/C_l$, where C is the velocity of a longitudinal wave in an article of a certain shape determined by one of the eigenfrequency methods. For example, if the tested article is an extended slab, $C = C_{sl}$. In this case,

$$k = C_{sl}/C_l = \sqrt{\frac{1-2\sigma}{(1-\sigma)^2}} .$$

Hence, the coefficient k for an extended slab depends only on the Poisson ratio; i.e., $k = f(\sigma)$. At $\sigma = 0.2$, we obtain the known velocity correction coefficient $k = 0.96$. This value of the velocity correction coefficient is used in the calculation of C_l in an extended slab at a known thickness h: $C_l = 2fh/k$, or in the calculation of h at a known velocity C_l: $h = kC_l/2f$.

If the tested article has the shape of a thin rod, $C = C_r$. In this case, the velocity correction coefficient is determined by the formula:

$$k = C_r/C_l = \sqrt{\frac{(1+\sigma)(1-2\sigma)}{1-\sigma}} .$$

At $\sigma = 0.2$ this coefficient in the rod is $k = 0.95$.

A general approach to the problem of determining the velocity of a longitudinal wave in compact articles can be found in studies by I.N.Ermolov (Ermolov, I.N. & Lange, Yu.V., 2004). In addition, according to (Bolotin, V.V., 1999), the propagation velocity of longitudinal waves in a rod generally (when the condition $\lambda >> d$ is not satisfied) depends on the ratio d/λ; consequently, $k = C/C_l = f(\sigma, d/\lambda)$. This phenomenon is called the geometrical dispersion of the velocity. For thin rods with $d/\lambda << 1$ the dispersion is insignificant and $k = C_r/C_l = f(\sigma)$. Similarly, the velocity of a longitudinal wave in a compact slab for which the conditions $\lambda << a$ and $\lambda << b$ are not satisfied, depends on the ratios a/λ and

b/λ. In this case $k = C/C_l = f(\sigma, a/\lambda)$. Attempts to obtain an analytical expression for the function $f(\sigma, a/\lambda)$ at least for some ranges of the ratios d/λ and a/λ yield a result with an error that may exceed 15% relative to experimental results.

Hence, in a general case, the form of the function $f(\sigma, a/\lambda)$ for a compact article of an arbitrary shape is completely unknown. This impedes determination of the velocity C_l by the eigenfrequency methods. The above is confirmed by the simulation results (Fig. 12) showing that, in some cases, it is impossible to unambiguously determine the thickness of a compact article by the impact echo method from the spectral characteristic because of its ambiguous character even if the velocity of acoustic vibrations in the compact article is known. It should be noted that, despite a constant article thickness, the frequency of the resonance peak corresponding to the longitudinal wave's first mode (diagrams in Fig. 12) increases with a decrease in m. Note that, for $m < 4$, the frequency increases so significantly that the geometrical-dispersion effect cannot be disregarded.

So, the problem of determining the wave velocity in compact concrete BCs is very important. It is obvious that the velocity of acoustic vibrations in a compact article determined by the shadow and echo-pulse ultrasonic methods or by measurement of the surface-wave velocity (in view of all limitations of such velocity measurements) is not equal to the true value of the velocity C_l observed in an actual compact concrete article.

Hence, one of the tasks of testing large-size compact concrete BCs by the impact echo method (thickness-measurement problem) remains unrealized because of the unknown velocity C_l in a particular compact article.

In addition, there exists another problem in testing large-size compact concrete BCs—determining the velocity C_l in a large-size compact article all of whose dimensions are known. This problem is aimed at the subsequent determination of the concrete strength and the strength of a concrete BC and the prediction of the failure-free service life of BCs. A similar problem of measuring the propagation velocity of acoustic vibrations in BCs with known dimensions is also necessary for determining the quality of concrete during construction of calibration characteristics for concrete specimens, in which the time-dependent velocity in a particular solidifying concrete block is measured. Thus, such a problem of determining the wave velocity in compact concrete BCs with known dimensions is independent and very important.

To test the propagation velocity of an acoustic wave in arbitrarily shaped compact BCs whose dimensions are known, a new correlation method based on the use of the spectral characteristics of BCs is proposed.

This method consists of the following stages.

I. The experimental spectral characteristic of an arbitrarily shaped compact article is measured, but it does not allow unambiguous determination of the desired resonance frequency.
II. The spectral characteristic of an article similar to a real tested object is calculated by simulation; the velocity C_l is selected arbitrarily.
III. Then, the value of the velocity C_l at which the calculated and experimental characteristics are maximally alike is selected.
IV. The cross-correlation function (CCF) of both characteristics is calculated; the degree of similarity of these characteristics is determined from the CCF maximum.
V. The desired value of C_l is determined from the characteristic at which the CCF maximum is observed.

Note that, when the velocity is selected, it is unnecessary to perform simulation for each new velocity value — as C_l increases, the characteristic proportionally and linearly stretches along the frequency axis, i.e., the frequencies of all resonance peaks proportionally increase. It follows from the above that it is sufficient to perform only one simulation at the minimum selected velocity of a longitudinal wave.

An example of determining C_l according to the proposed method is considered below for a compact concrete block with dimensions of 80×50×30 cm.

First, we preliminarily calculate (simulate) the spectral characteristic of the model of this compact block in the frequency range 1–10 kHz. The initial "base" value of the longitudinal-wave velocity was selected equal to the minimum possible value of C_l for concrete articles: C_l = 3000 m/s.

Figure 13 shows the spectral characteristic of the block resulting from simulation and experiments on an actual block. In calculating the spectral characteristic, we used a velocity different from the velocity in the actual block (which is unknown); therefore, the spectral characteristics do not coincide. The problem is how to select a velocity at which the spectral characteristics coincide, thereby maximizing the value of their CCF. For this purpose, it is necessary to calculate the CCF of the experimental spectral characteristic with a set of calculated characteristics, each of which must correspond to a certain value of C_l.

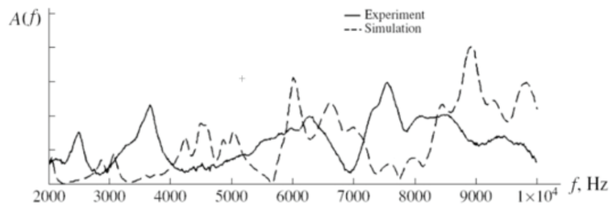

Fig. 13. Experimental and calculated spectral characteristics for a block with dimensions of 80 × 50 × 30 cm (simulation at C_l = 3000 m/s).

The calculated spectral characteristics are obtained by stretching the base characteristic along the frequency axis, i.e., via multiplication of the frequency axis by a coefficient equal to the ratio of the desired velocity to the base velocity (3000 m/s). For example, to obtain the characteristics corresponding to velocities of 3000, 3010, 3020, 3030, m/s, etc., the frequency axis of the initial characteristic should be multiplied by factors of 1, 1.0033, 1.0066, 1.0100, etc. As a result of calculating the CCF of the experimental characteristic with 150 calculated characteristics corresponding to the velocity range 3000–4500 m/s with a step of 10 m/s, we obtain the CCF depicted in Fig. 14a. Figure 14b shows the experimental characteristic and the calculated characteristic corresponding to a velocity of 3765 m/s, which coincide quite well. In this case, the obvious CCF maximum determines the velocity of acoustic vibrations in this compact object: C_l = 3765 m/s.

Hence, the proposed method allows measurements of the longitudinal-wave velocity in compact large-size arbitrarily shaped concrete articles all dimensions of which are known. The velocity is measured in the entire BC volume and not in some region or, especially, on the surface. In this case, the velocity is measured only using a preliminarily measured spectral characteristic of the compact article, which, owing to its compactness, has no clearly pronounced resonance peak.

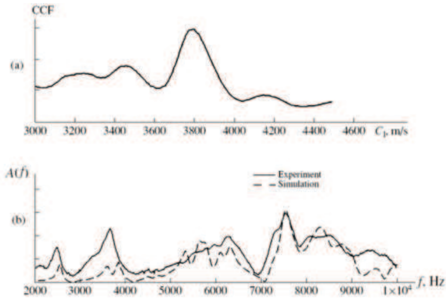

Fig. 14. (a) Dependence of the CCF on the velocity and (b) coincidence of the experimental and calculated spectral characteristics.

Another advantage of the proposed method is that it is less sensitive to the reinforcing structure and large-grained filler than ultrasonic methods because the wavelength of elastic vibrations is of the same order of magnitude as the BC dimensions. In addition, this method has no fundamental limitations on the maximum testing depth — as the BC dimensions increase, the frequency band of the spectral characteristic proportionally shifts toward lower frequencies and the vibration amplitude decreases, but the shape of the characteristic remains constant. Thus, this method is much more sensitive than the methods based on the use of the shadow or echo-pulse methods, in which the dimensions of an article limit the sensitivity. For this reason, the proposed correlation method allows measurements of the velocity of acoustic vibrations in large-size concrete BCs paneled with boards, tiles, etc., that cannot be accessed for measurements and selection of an optimal contact point. An analogous situation arises when the velocity is measured in such concrete BCs with known dimensions as supporting elements of bridges, foundations, piles driven into the ground, etc. Regular measurements of the velocity of acoustic vibrations aimed at the monitoring of strength characteristics of concrete constructions are of fundamental importance for such BCs, parts of which may be submerged, buried in the ground, etc.

One of the limitations of the proposed method for determining the velocity of acoustic vibrations is that the velocity measurement requires knowledge of all dimensions of a tested article and preliminary simulation of the spectral characteristic for each particular article.

3. A multichannel multiplicative method for acoustic testing of large-size compact concrete building constructions

In previous parts it was shown that the IE method for acoustic testing of large-size concrete BCs allows thickness measurements of only extended articles. It is impossible to measure the thicknesses of large-size compact concrete BCs by the IE or resonance methods because of the influence of geometrical effects (the noise of the article shape does not allow unambiguous determination of the desired maximum in the article's spectral characteristic) and the effect of geometrical dispersion of the sound velocity in a compact article (it is impossible to determine the acoustic-vibration velocity C_l).

The correlation method for determining the longitudinal-wave velocity C_l in compact articles with known dimensions requires preliminary simulation of the spectral characteristic of a BC, thereby limiting to a certain degree the acoustic velocity measurements in compact concrete BCs by this method. These problems can be solved by