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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.
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 determined 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, $C_l = \left(\frac{2hf}{k}\right)$, 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 $C_l = \left(\frac{2hf}{k}\right)$ 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.
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: \( f = nC_l/2l \), 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 $\omega$. 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 $E = 3.456 \times 10^{10}$ N/m$^2$, the viscosity $E = 5000$ (N)s/m$^2$, and the density $\rho = 2400$ 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 $f_1$ 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

$$\begin{bmatrix} M \end{bmatrix} \{\ddot{u}\} + \begin{bmatrix} C \end{bmatrix} \{\dot{u}\} + \begin{bmatrix} K \end{bmatrix} \{u\} = \{F\},$$

(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 $\{F\}$ is the applied-force vector.

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

$$\{u\} = \{u_{\text{max}} e^{i \phi}\} e^{i \omega t},$$

(2)

where $u_{\text{max}}$ is the displacement amplitude, $\Omega$ is the circular frequency of forced vibrations, and $\phi$ is the displacement phase shift.

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

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

or

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\[ \{u\} = (\{u_1\} + i\{u_2\})e^{i\omega t}, \quad (3) \]

where \( \{u_1\} = \{u_{max} \cos\Phi\} \) and \( \{u_2\} = \{u_{max} \sin\Phi\} \).

Similarly, the force vector can be represented as

\[ \{F\} = (\{F_1\} + i\{F_2\})e^{i\omega t}, \quad (4) \]

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

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

(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 \( \rho = 2400 \) kg/m\(^3\), the Young modulus \( E = 3.456 \times 10^{10} \) N/m\(^2\), and the Poisson ratio \( \sigma = 0.2 \). 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.](www.intechopen.com)
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 $\alpha = 0.04$ 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. 

![Model of a slab](https://www.intechopen.com)

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 $h = C_{ul}/2f$, where $f$ is the frequency of the longitudinal wave’s first mode and $C_{ul}$ 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 $300 \times 300 \times 30$ cm.

Note that the resonance frequency of the longitudinal wave’s first mode in the 0.3-m-thick concrete slab ($f_{1s} = 6400$ 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 $C_{sl} = \sqrt{\frac{E}{\rho(1-\sigma^2)}}$ 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 $\rho$) the Poisson ratio $\sigma$. Calculating the velocity $C_{sl}$ at $\sigma = 0.2$ 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 $f = C_0/2h$. 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.

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.

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 $\lambda$ 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.

<table>
<thead>
<tr>
<th>Geometric form</th>
<th>Condition</th>
<th>Formula for velocity calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infinite space</td>
<td>$\lambda &lt;&lt; \text{medium dimensions}$</td>
<td>$C_i = \sqrt[2]{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}}$</td>
</tr>
<tr>
<td>Thin rod of length $l$ and diameter $d$</td>
<td>$\lambda \approx l, \lambda &gt;&gt; d$</td>
<td>$C_r = \sqrt[2]{\frac{E}{\rho}}$</td>
</tr>
<tr>
<td>Extended slab of length $a$, width $b$ and thickness $h$</td>
<td>$\lambda \approx h, \lambda &lt;&lt; a, \lambda &lt;&lt; b$</td>
<td>$C_s = \sqrt[2]{\frac{E}{\rho(1-\sigma^2)}}$</td>
</tr>
</tbody>
</table>

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 $k = C/C_r$, 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, $C = C_s$. In this case,

$$k = \frac{C_s}{C_l} = \frac{1-2\sigma}{(1-\sigma)^2}.$$

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 $C_s$: $h = kC_s/2f$.

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:

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

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 $d/\lambda$; 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 $h << a$ and $\lambda << b$ are not satisfied, depends on the ratios $a/\lambda$ and $b/\lambda$.  

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\[ b/\lambda. \] 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 \( d/\lambda \) and \( a/\lambda \) 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 $80 \times 50 \times 30$ 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 $80 \times 50 \times 30$ cm (simulation at $C_l = 3000$ m/s).](image)

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.
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
the multichannel multiplicative method for testing compact articles (Kachanov, V.K., Sokolov, I.V., & Avramenko, S.L., 2008; Avramenko, S.L., 2008), which made it possible for the first time to use both the resonance and IE methods for testing the thicknesses of compact BCs.

3.1 Taking into Account the Influence of the Article Shape on the Longitudinal-Wave Velocity

In testing of compact structures, the resonance frequency of the first mode of a longitudinal wave depends not only on the article thickness but also on its compactness \( m \). To study this dependence, we calculated the spectral characteristics of blocks with the same thickness \( h = 30 \) cm and different values of \( m \) between 1 and 5. Then, the resonance frequencies \( f \) of the first mode of a longitudinal wave were determined for each of these characteristics and the correction coefficient of the longitudinal-wave velocity was calculated from the formula \( k = \frac{2f}{h/C} \). The dispersion characteristic for parallelepipeds corresponding to the dependence of \( k \) on \( m \) was obtained via calculation (Fig. 15). The result of a similar calculation performed for a set of articles in the form of 30-cm-thick disks with diameters in the range 30–150 cm is also shown in Fig. 15.

![Fig. 15. Dispersion characteristics for a disk and a parallelepiped.](image)

Note that both characteristics for parallelepipeds and disks coincide if the \( m \) axis of the characteristic is multiplied by a factor of 1.22. The analysis of the obtained dispersion characteristics allows us to draw a number of important conclusions that must be used in calculating compact concrete BCs.

1. The dispersion characteristics for articles of the most widespread standard shapes (parallelepipeds and disks) show that, regardless of the shape of an article at \( m > 5 \), the velocity-correction coefficient \( k \) tends to 0.96. This is a quite expected result in view of the fact that, as \( m \) increases, the shape of the tested article becomes more similar to an extended slab, for which \( k = 0.96 \).

2. The obtained dispersion characteristics show that, in articles in the form of a disk and a parallelepiped at \( m < 3 \), the velocity-correction coefficient \( k \) changes (increases to an appreciable degree).

3. It is of importance that the obtained dispersion characteristics are independent of the scale of BCs; i.e., a proportional change in all dimensions of a BC does not affect the dependence of \( k \) on \( m \). In fact, when the scale increases by a factor \( a \), the compactness \( m \) remains constant, the resonance frequency \( f \) of a longitudinal wave decreases by a factor of \( a \), and the thickness \( h \) increases by the same factor. Substituting these results into formula \( k = \frac{2f}{h/C} \), we obtain that the value of the velocity-correction coefficient in the article remains:
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\[ k' = \frac{2(f/a)(ha)}{C_1} = \frac{2fh}{aC_1} \]

\( k' \) is the velocity-correction coefficient for an article that is larger than the article with the coefficient \( k \) by a factor of \( a \). Owing to this property, the obtained dispersion characteristics can be used for articles of a given shape and an arbitrary thickness.

4. Similarly, the dispersion characteristic is also independent of the longitudinal-wave velocity in a BC. For example, when the velocity \( C_1 \) increases by \( a \) times, the resonance frequency \( f \) also increases by the same factor, while the velocity-correction coefficient remains unchanged:

\[ k' = \frac{2(f/a)h}{(aC_1)} = \frac{2fh}{aC_1} \]

5. In addition, \( k \) is independent of the attenuation of an acoustic wave in concrete. Figure 16 shows the calculated spectral characteristics of a concrete block with dimensions of 80x50x30 cm at values of attenuation \( \alpha_1 = 0.05 \) dB/m, \( \alpha_2 = 0.1 \) dB/m, and \( \alpha_3 = 0.2 \) dB/m. As is seen, a change in \( \alpha \) results in a change in the \( Q \) factors of resonance peaks, but not in the resonance frequencies.

Fig. 16. Dependence of the spectral characteristics for a block with dimensions of 80x50x30 cm on acoustic attenuation.

The practical value of these characteristics is that they make it possible to recalculate the longitudinal-wave velocity \( C_1 \) in articles of these shapes (in compact articles) into a longitudinal-wave velocity in an infinite space and vice versa. The use of these characteristics makes it possible to calculate the thickness of a compact article if \( C_1 \) is known or, vice versa, to calculate \( C_1 \) if the thickness of a compact article is known. In other words, the dispersion characteristics obtained in this study allow testing of large-size compact concrete BCs by eigenfrequency methods.

3.2 Selecting the optimal positions of transducers

It should be noted that, in existing foreign techniques of applying the IE method, the question of selecting the positions of the transmitter and receiver on the BC surface is not considered. This is probably associated with the fact that, for extended articles, for whose testing the IE method is intended, the positions of the transmitter and receiver are not so important as for compact articles. As was shown above, the spectral characteristic of a compact article contains many resonance peaks, which impede the determination of the resonance frequency of the first mode of a longitudinal wave. However, the results of the performed calculations and experiments on actual concrete structures have shown that, when a source-receiver pair moves over the surface of a BC in the form of a parallelepiped,
all resonance peaks remain at constant frequencies, but their amplitudes undergo substantial changes. It has been established that, at the surfaces of compact articles, there are areas subjected to ultrasound where the first-mode peak amplitude of a longitudinal wave reaches a maximum and, in most cases, predominates over the amplitudes of other peaks. Thus, such areas should be preferred for placing transducers on the surface of a compact article.

On the basis of the analysis of a large number of calculated and experimental characteristics, it was concluded that the resonance amplitude of a longitudinal wave in compact articles is maximized when the transmitter and receiver lie on one of the axes of symmetry parallel to the BC sides. To confirm this inference, let us consider the calculated spectral characteristics of a symmetric compact block (60×60×30 cm) obtained for different positions of the transmitter and receiver. Special attention will be given to the amplitude of a peak at a frequency of 730 Hz (this is the resonance frequency of the first mode of a longitudinal wave).

Fig. 17. Dependence of the spectral characteristics for a block with dimensions of 60×60×30 cm on the position of the transmitter–receiver pair.

Figures 17a and 17b show the spectral characteristics corresponding to the positions of the transmitter and receiver on an axis of symmetry parallel to two sides of the block. The characteristic in Fig. 17a was obtained for the transmitter positioned at the point of intersection of both axes of symmetry. As is seen, in this case, the amplitude of the resonance peak for the first mode of a longitudinal wave has a maximum. In the characteristic in Fig. 17b, this peak is still distinguished unambiguously, but the amplitudes of other peaks are higher than those in Fig. 17a. The characteristics in Figs. 17c and 17d were obtained at arbitrary positions of the transmitter and receiver that were not related to the axes of symmetry parallel to the block faces. When the characteristics in Figs. 17c and 17d were calculated, the transducers were positioned along the diagonal axis of symmetry and beyond any axes of symmetry, respectively. In both cases, a useful resonance peak is present in the characteristic but its amplitude is hardly discernable against the background of other
peaks. Hence, as a result of the performed studies, it has been established that a necessary condition for obtaining a good spectral characteristic of a compact article is a correct position of the transmitter–receiver pair on the surface of the tested object: the transmitter–receiver pair must be placed on one of the axes of symmetry.

The dispersion characteristic for parallelepipeds shown in Fig. 15 was obtained as a result of calculating the spectral characteristics of symmetric blocks with identical lengths and widths. Let us determine the possibility of using this characteristic for testing asymmetric parallelepipeds with a length unequal to their width. To do this, let us consider the spectral characteristics of an asymmetric compact block with dimensions of 80×50×30 cm (Fig. 18).

Fig. 18. Spectral characteristics for a block with dimensions of 80×50×30 cm as functions of the position of the transmitter–receiver pair.

In this case, let us place the transmitter and receiver on both axes of symmetry parallel to the sides of the block. In positions (a) and (b), the transmitter and receiver are on the longitudinal axis of symmetry of the compact article perpendicular to the block width. The peak at a frequency $f_w = 8025$ Hz predominates in the spectral characteristics corresponding to these positions. In positions (c) and (d), the transmitter and receiver are on the transverse axis of symmetry of the compact asymmetric block perpendicular to the block length and the peak at a frequency $f_l = 6730$ Hz predominates in the spectral characteristics.

The peak at a frequency of 8025 Hz is also observed, but its amplitude is lower. In position (e), the transmitter–receiver pair lies not on the axes of symmetry. The complex form of the spectral characteristic, containing a large number of resonance peaks, once more suggests the problem of correct arrangement of transducers on the surface of a compact article. As a result, it can be concluded that the resonance peak at a frequency $f_w = 8025$ Hz (the subscript indicates the side that is perpendicular to the axis of symmetry) predominates on the longitudinal axis, perpendicular to the block width, whereas the resonance peak at a frequency $f_l = 6730$ Hz predominates on the transverse axis, perpendicular to the block length.

Note that two compactness factors can be calculated at once for an asymmetric parallelepiped: the width $m_w = 50/30 = 1.67$ and length $m_l = 80/30 = 2.67$ factors. Two
velocity-correction coefficients, \( k_w = 1.22 \) and \( k_l = 1.01 \), can correspondingly be determined from the dispersion characteristic. In order to find out whether it is possible to use the dispersion characteristic of a symmetric parallelepiped, obtained earlier, for an asymmetric block, let us calculate twice the thickness \( h \) according to the sets of values \( f, m, \) and \( k \) for each side (as in all previous cases, the elastic properties of the material during simulation are set such that \( C_l = 4000 \text{ m/s} \)).

As is seen, the calculated thickness exactly coincided with the model thickness:

\[
h_w = \frac{k C_l}{2 f} = 0.30 \text{ m}, \quad h_l = \frac{k C_l}{2 f} = 0.30 \text{ m}.
\]

First, this means that the dispersion characteristic calculated for a symmetric object is also suitable for asymmetric compact parallelepipeds. Second, this means that the frequency of the resonance peak that predominates in the article’s spectral characteristics depends on the axis on which the transmitter and receiver are positioned. In our case, when the transducers are positioned along the longitudinal axis, we determined a resonance corresponding to the width of the studied block. For the transducers lying on the transverse axis of symmetry, we determined a resonance corresponding to the length of the studied block. In other words, the frequency of each of these peaks allows us to determine either the thickness (if the velocity is known) or the velocity (if the thickness is known). The possibility of calculating these values by two methods in asymmetric compact blocks allows one to additionally verify the results of thickness measurements at a known velocity \( C_l \).

Let us consider the following example of calculating the thickness of a compact article under the assumption that the block thickness is unknown but the velocity is known, \( C_l = 4000 \text{ m/s} \). For definiteness, the spectral characteristics are taken from the previous example. The frequency of the first mode of a longitudinal wave \( f_w = 8025 \text{ Hz} \) is determined from the spectral characteristic (Fig.19a). Because the thickness is not known, the value of the coefficient \( m \) cannot be found; therefore, the thickness can be calculated only via numerical solution of the equation

\[
h = \frac{C_l k(h)}{2 f}
\]

The bisection (half-division) method (Demidovich, B.P. & Maron, I.A., 1970), which involves the comparison of the expression

\[
h - \frac{C_l k(h)}{2 f}
\]

to zero at some values of \( h \) lying in the range \( h_{\text{min}} - h_{\text{max}} \), can be used as one such method of solution. If the expression resulting from the substitution of \( h \) equal to the middle of the segment \( (h_{\text{min}}, h_{\text{max}}) \) (i.e., \( h = (h_{\text{max}} - h_{\text{min}})/2 + h_{\text{min}} \)) is positive (negative), the interval from \( h_{\text{min}} \) to \( h \) (from \( h \) to \( h_{\text{max}} \)) is chosen at the next iteration. Hence, the tested-object thickness can be calculated quite accurately after 10 – 15 iterations. The solution of the numerical problem by the bisection method yielded \( h = 0.3 \text{ m} \).

### 3.3 Multiplicative processing of spectral characteristics

The examples considered above show that the use of dispersion characteristics fundamentally allows determination of both the thickness and the velocity of acoustic vibrations in compact concrete BCs. However, these examples prove that this method is
quite laborious and requires unwieldy preliminary calculations. In addition, multiple experiments intended for searching for optimal methods for testing concrete BCs have shown that the techniques proposed above also have other limitations. First, it is not always possible to mount transducers in an optimal zone on the surface of an actual BC. This can be due to several reasons: a BC is not always a symmetric article of the parallelepiped type; it is not always possible to find the lines (point) of symmetry, or to set a transducer on the lines (point) of symmetry because of a rough, porous, or damp surface or the presence of structural reinforcing elements on the surface, etc. As a result, one has to mount transducers not at prescribed places but where it is merely possible. The negative consequences of this effect were shown above.

Second, an actual concrete BC is not so ideal in its internal structure as a model used in calculation of spectral characteristics. Apart from a coarse-grained filler and reinforcing bars, actual BCs often contain larger inhomogeneities—air cavities and flaws. The presence of the latter in BCs has a negative effect on the spectral characteristic. Hence, during testing of actual compact concrete articles, it is not always possible to unambiguously determine the value of a resonance peak, as was successfully done for a block of 80×50×30 cm in Figs. 18a and 18b (when the frequency \( f_w = 8025 \) Hz was determined) and in Figs. 18c and 18d (\( f_l = 6730 \) Hz).

We succeeded in solving these problems using the developed multichannel multiplicative testing method, which is a modification of eigenfrequency methods (the IE and resonance methods). This resonance–multiplicative method (RMM) implies a concept of multichannel testing of BCs. This means that testing must be performed either simultaneously or sequentially (with storing of the results in the instrument’s memory) at several points of the BC surface. Then, the spectral characteristics obtained as a result of multichannel testing were subjected to multiplicative processing. As an example of using the RMM, let us consider testing of a compact reinforced-concrete block with dimensions of 130×60×45 cm.

The concrete structure and the dimensions of the reinforced block are such that the maximum value of the longitudinal-wave mode cannot be determined from the block’s spectral characteristics that correspond to the position of the receiver on the longitudinal axis of symmetry (Figs. 19a, 19b). This maximum can be determined only after the multiplicative processing of the characteristics shown in Figs. 19a and 19b; for the characteristic shown in Fig. 6c, the frequency \( f_w = 6323 \) Hz corresponding to the maximum is determined unambiguously. Similarly, the positions of resonances in the spectral characteristics shown in Figs. 6d and 6e, which correspond to positions of transducers on the transverse axis of symmetry, can be determined only after multiplicative processing of these characteristics (the frequency \( f_l = 4462 \) Hz corresponding to the maximum in Fig. 19d is determined unambiguously). Table 2 presents the experimental data for a concrete block with dimensions of 130×60×45 cm.

<table>
<thead>
<tr>
<th></th>
<th>( h, m )</th>
<th>( m )</th>
<th>( k )</th>
<th>( F ), Hz</th>
<th>( C_l ), m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Along length</td>
<td>0.45</td>
<td>2.89</td>
<td>1.003</td>
<td>4462</td>
<td>4003</td>
</tr>
<tr>
<td>Along width</td>
<td>0.45</td>
<td>1.33</td>
<td>1.432</td>
<td>6323</td>
<td>3973</td>
</tr>
</tbody>
</table>

Table 2. Calculated and experimental data for a block of 130 x 60 x 45 cm.

Calculations yield the following results for velocities: \( C_{lw} = 3973 \) m/s and \( C_{ll} = 4003 \) m/s. The spread of the results and calculations is <1%. Calculations yield the following results for velocities: \( C_{lw} = 3973 \) m/s and \( C_{ll} = 4003 \) m/s. The spread of the results and calculations is <1%.
Fig. 19. Experimental spectral characteristics for a compact block with dimensions of 130×60×45 cm.

For comparison, Fig. 20 shows two spectral characteristics of the column obtained at a single point with the IE and resonance methods. In the first case, free vibrations were excited by an impact of a steel ball 10 mm in diameter against the longitudinal axis of symmetry of the column; in the second case, forced vibrations were excited by an emitting piezoelectric transducer (PET) at the same surface point. In both cases, a receiving PET was placed on the same axis at a point 15 cm lower than the point at which vibrations were excited. Measurements were performed at a height of 0.5 m from the floor level.

Fig. 20. Spectra of free and forced vibrations in a column.

As is seen from the plots, both spectral characteristics coincide quite well. On this basis, it can be concluded that any of the proposed methods can be used to obtain a spectral characteristic. When the column surface is dry and hard, the impact excitation is more expedient because it ensures an appreciably higher measurement rate. Therefore, all the subsequent experimental data for this column were obtained using the IE method. Using the spectral characteristics shown in Fig. 20, it is difficult to draw an unambiguous conclusion about the position of the main resonance peak. To obtain more precise information, we obtained a series of spectral characteristics corresponding to different positions of the impactor-receiver pair on the longitudinal axis of symmetry. The distance between the impactor and receiver was always 15 cm.

Figures 21a and 21b show two spectral characteristics corresponding to positions of the impactor at heights of 0.5 and 0.8 m from the floor level (the corresponding positions of the PETs on the column are shown in Figs. 22a and 22b).
Fig. 21. Experimental spectral characteristics of a column with a square cross section of 60x60 cm measured with transducers positioned on the longitudinal axis of symmetry.

The fact that these characteristics, as well as all others, are identical indicates that the internal structure of the column is homogeneous. It is still difficult to unambiguously determine the position of the maximum at the resonance frequency even from these characteristics. However, after the resonance–multiplicative processing of the characteristics (a) and (b), the value of the maximum is determined unambiguously: Fig. 21c shows the result of the multiplication of characteristics, from which we obtain the resonance frequency \( f = 5524 \text{ Hz} \), the compactness \( m = 1 \), \( k = 1.733 \), and the calculated velocity \( C_l = 3825 \text{ m/s} \).

Fig. 22. Positions of the impactor and receiver during measurements on the column.

Figure 22c shows a situation where the impactor lies on the axis of the column, while the receiver does not. The corresponding spectral characteristic (Fig. 23) shows that the main resonance peak in this characteristic corresponding to the column thickness is not distinguished.

Fig. 23. Experimental spectral characteristic of a column with a square cross section of 60x60 cm.
This confirms the earlier conclusion that the axis of symmetry is the optimal position of the transmitter and receiver for effectively exciting the resonance of the first mode of a longitudinal wave. Thus, it can be concluded that the application of multiplicative processing to two spectral characteristics allows unambiguous determination of characteristics if the PETs are placed on axes of symmetry.

An increase in the number of spectral characteristics always improves the testing results. This is observed in the following example of measurement of the acoustic-wave propagation velocity in a reinforced-concrete block with dimensions of 50x50x25 cm with a computerized multifunctional flaw detector.

These measurements were performed by the resonance method. The spectral characteristics corresponding to four different positions of the transmitter-receiver pair on the block surface are shown in Figs. 24a–24d.

Fig. 24. Experimental spectral characteristics of a compact block with dimensions of 50x50x25 cm.

Because the block is symmetric (its length and width are identical), only one resonance of the first mode of a longitudinal wave is expected in the spectral characteristic, but, owing to a complex structure of the reinforced-concrete block, additional measurements are necessary. For this reason, the characteristics obtained on both the longitudinal and transverse axes of symmetry were included in the resonance–multiplicative processing.

The result of the resonance–multiplicative processing of all four characteristics is shown in Fig. 24e. As is seen, a resonance peak at a frequency $f = 7963$ Hz is unambiguously determined in this characteristic. The experimental data for the block with dimensions of 5x50x25 cm are listed in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>$h$, m</th>
<th>$m$</th>
<th>$k$</th>
<th>$F$, Hz</th>
<th>$C_l$, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Along length</td>
<td>0.25</td>
<td>2</td>
<td>1.095</td>
<td>7963</td>
<td>3636</td>
</tr>
<tr>
<td>Along width</td>
<td>0.35</td>
<td>1</td>
<td>1.095</td>
<td>7963</td>
<td>3636</td>
</tr>
</tbody>
</table>

Table 3. Calculated and experimental data for a block of 50 x 50 x 25 cm
When the zones of optimal arrangement of transducers are inaccessible for design reasons, an increase in the number of multiplied characteristics also allows detection of the resonance of a longitudinal wave’s first mode.

Figure 25 shows four spectral characteristics of a block of 80x50x30 cm additionally measured at different points of the block surface near the longitudinal axis of symmetry. We see that a departure from the axis of symmetry complicates an unambiguous interpretation of the spectrum using individual characteristics. Figure 25e shows the result of multiplication of these characteristics, which is a clearly pronounced single resonance peak corresponding to the desired thickness of the measured compact article.

Fig. 25. (a–d) Spectral characteristics for a block with dimensions of 80x50x30 cm at four different positions of the transmitter and (e) the result of their multiplication

4. Conclusion

Note that, at this stage of investigation, the proposed RMM was used for large-size compact BCs of the most widespread standard shapes – parallelepipeds and disks (blocks, columns, supports, etc.). The developed algorithms for testing compact BCs, which involve construction of dispersion characteristics and determination of zones for optimal arrangement of transducers, allow adaptation of the proposed method to testing of arbitrarily shaped compact articles. However, in this case, it is necessary to construct an individual dispersion characteristic and identify particular optimal zones for positioning transducers for each new shape of an article.

Hence, as a result of studies performed at the Moscow Power Engineering Institute, a multichannel RMM for testing large-size compact concrete articles with unambiguous spectrum interpretation has been developed. This method allows determination of both the thickness of a tested article and the velocity of acoustic vibrations in it.

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5. References


In the recent decades, there has been a growing interest in micro- and nanotechnology. The advances in nanotechnology give rise to new applications and new types of materials with unique electromagnetic and mechanical properties. This book is devoted to the modern methods in electrodynamics and acoustics, which have been developed to describe wave propagation in these modern materials and nanodevices. The book consists of original works of leading scientists in the field of wave propagation who produced new theoretical and experimental methods in the research field and obtained new and important results. The first part of the book consists of chapters with general mathematical methods and approaches to the problem of wave propagation. A special attention is attracted to the advanced numerical methods fruitfully applied in the field of wave propagation. The second part of the book is devoted to the problems of wave propagation in newly developed metamaterials, micro- and nanostructures and porous media. In this part the interested reader will find important and fundamental results on electromagnetic wave propagation in media with negative refraction index and electromagnetic imaging in devices based on the materials. The third part of the book is devoted to the problems of wave propagation in elastic and piezoelectric media. In the fourth part, the works on the problems of wave propagation in plasma are collected. The fifth, sixth and seventh parts are devoted to the problems of wave propagation in media with chemical reactions, in nonlinear and disperse media, respectively. And finally, in the eighth part of the book some experimental methods in wave propagations are considered. It is necessary to emphasize that this book is not a textbook. It is important that the results combined in it are taken “from the desks of researchers”. Therefore, I am sure that in this book the interested and actively working readers (scientists, engineers and students) will find many interesting results and new ideas.

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