Concretes have an initially inhomogeneous composition due to their technology and structure; their acoustic properties are mainly defined by its aggregate [1]. The basic parameters that influence these properties are the shape and size of the grains, the origins of the solids and their water sorption, and adhesion between concrete and steel reinforcement, if any is used, as well as the elastic properties of these steel bars. In this case, the ultrasound velocity variance in the solid aggregate is approximately ±20 and sometimes even ±35%. The ultrasound attenuation coefficient $\delta$ and its strong dependence on the frequency determine the operational frequency and bandwidth that are optimal for concrete testing. The possible variation of the attenuation coefficient in most common concretes is quite substantial. The rapid increase of attenuation with frequency places an upper limit on the operational frequency of the signals.

If significant distortion of the signal spectrum in the region of the rapid attenuation increase does not occur, the upper boundary of the frequency band is taken as 150–200 kHz. One feature of concrete is a much greater attenuation coefficient $\delta_\lambda = \delta \lambda$, which is reduced to the wavelength $\lambda$, than that of other materials. The coefficient shows a decrease of the amplitude of ultrasound that propagates at a distance of one wavelength; for example, $\delta_\lambda$ is approximately 0.024 dB/$\lambda$ in steel, 0.5 dB/$\lambda$ in plexiglass, and approximately 2 dB/$\lambda$ in concretes. The lower limit of the operational frequency band could be determined from the demanded depth resolution of the echo-pulse hardware, which could be estimated as $\Delta_d = 0.66c\tau_p$, where $c$ is the velocity of ultrasound in concrete and $\tau_p$ is the sounding pulse duration.

For an estimate, one should take the value $\Delta_d = 50$ mm with a longitudinal velocity of approximately $v = 4000$ m/s; then, the required pulse duration is approximately 20 $\mu$s. A short half-period pulse of 20 $\mu$s duration occupies approximately 100% of the bandwidth with respect to the frequency that corresponds to the spectrum maximum which is approximately 50 kHz. Consequently, the lowest frequency in this idealized case would be close to 20 kHz. Thus, it is reasonable to use the frequency band between 20 and 150 kHz for ultrasonic evaluation of concrete products. At an ultrasound velocity of 4000 m/s the wavelength $\lambda$ would be between 200 and 27 mm. It should be noted that the stated requirements for the measuring hardware for ultrasonic evaluation of concrete due to high practical priority were formulated at the beginning of the development of ultrasonic methods of material evaluation [2–7]. Conventional ultrasonic transducers with a 30–40 mm aperture at the selected wavelengths have insufficient acoustic field directivity to support the necessary transverse resolution. The length of the transducer’s near field is defined as $z_n \approx D^2/(4\lambda)$, where $D$ is the aperture diameter and for $D \approx \lambda$ the near field is quite short. In this case, the sizes of controllable concrete constructions in most cases are not greater than (20–30) $\lambda$ and the

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**ACOUSTIC METHODS**

**The Development and Current State of Methods for the Nondestructive Testing and Acoustic Tomography of Concrete**

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Abstract—The development of acoustic methods for the nondestructive testing of concrete during the recent decades is described. The main characteristic problems and tasks of acoustic tomography of concrete are outlined and the evolution of the methods of their solution is analyzed. The advantages and disadvantages of the synthetic-aperture focusing method as a tool for the visualization of the internal structure of concrete are discussed. Possible directions of further progress in theory, as well as practical acoustic tomography methods, including those using phase information, are indicated.

Keywords: acoustic tomography of concrete, synthetic aperture focusing method (SAFT)

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depth of the detectable defects is not more than a few $\lambda$, while the possible size of the defects could be approximately $\lambda$. Nevertheless, despite these disadvantages, the discussed methods, which can be nominally called classical ultrasound methods of concrete evaluation, have developed quite intensively [8–24].

Another significant feature of concrete evaluation is the structural reverberation of the ultrasound oscillations that propagate in the bulk, which is due to the large aggregate grain size being comparable to the wavelength, such that the grains effectively scatter ultrasonic waves. The speed of the decrease of the effective value of the structural noise, $\sigma_n$, with time after the sounding signal is usually 0.05–0.1 dB/μs, as has been shown in experiments [25–29]. This is much smaller than the value that was predicted using one-time ultrasound scattering approximation (0.25 dB/μs). This means that the structural noise contains a substantial component of inner multi-scattering. The absolute level of the structural noise is several orders greater than the self noise of the receiver hardware. A large number of scientific papers [30–35] have been devoted to the study of the structural noise in concrete, its suppression, and even gaining some positive information on the concrete properties from the noise characteristics. It should be noted in general that the ultrasound attenuation in materials with large structural elements depends heavily on the material composition and the sound frequency (this increases sharply at frequencies greater than 200 kHz [31]).

The ultrasonic control of concrete products and constructions is carried out by different methods. The resonance technique is applied to products of a simple regular shape [36, 37]. They allow one to determine the general state of a construction using the Eigen frequencies of its oscillations but do not provide any information on the locations of internal defects. The most widely used propagation methods use ultrasound waves that travel in one direction through a controlled object but these methods demand two-sided access to the object [38–41]. The exception is the use of surface acoustic-wave propagation along the object’s surface and corresponding internal structure reconstruction techniques [42–53]. Such methods allow one to determine the depths of mainly subsurface defects; this is the reason why the described peculiarities and problems of the ultrasonic control of concrete led to the development of combined methods of nondestructive testing of constructions [54].

As stated, one of the most important parameters of the state of concrete, which is relatively simple to estimate through ultrasonic measurements, is the presence of defects at the surface or near it. One of the first attempts at the quantitative evaluation of the state of concrete had the purpose of determining the total number of cracks or their statistical distribution over their size by means of direct ultrasound traveling methods using surface acoustic waves [55]. The principle of this method is based on prior knowledge of the ultrasound velocities in the material and simple geometric (ray) considerations on wave propagation and refraction on cracks. In contrast to another acoustic measurement, in which a pair of piezoelectric transducers is used, the impact-echo method involves an impact of a small metal ball that generates ultrasonic waves at the concrete surface while a wide-band piezo transducer is used as a receiver. The spectral analysis of the response from the concrete constructions that is obtained in such a way allows one to evaluate the presence of cracks and hollows near the surface, while a more detailed analysis using Rayleigh-wave dispersion curves and comparison with possible crack depths allows one to determine not only the presence but also the depths and sizes of cracks and other defects.

For enhancement of the method, the analysis of the phase information that is obtained from the received signals has also been performed [38], although only for model experiments with artificial simple singular defects and in theoretical studies. In this case, the necessity to have phase information is obvious from general mathematical considerations of diffraction and scattering theory and is constantly under discussion [56, 57]. It should be mentioned that solutions of the forward problems of ultrasound scattering were used initially for the development of the inverse problem methods. This approach enables one not only to connect the characteristics of the scattered acoustic field with sizes of the defects, but also to evaluate the feasibility of acoustic methods for the determination of these parameters. The philosophy of such approach of acoustic nondestructive testing methods was suggested in [58], which was the consequence of the expansion of the class of solved direct problems. For example, in [59] the issue of surface-wave scattering at a volumetric subsurface crack was considered. The problem was solved using ray theory and numerical calculations. Another aspect of the same crack problem was studied in [60], but for bulk wave scattering. In this case, some analytical results were obtained only through application of asymptotic diffraction theory in which the class of solutions was constrained to harmonic high-frequency waves. As a consequence of the issues and limitations that were stated above, harmonic waves appear to be obsolete in acoustic tomography of concrete; thus, further research in the field, although it is based on the described solutions to the problems of harmonic scattering in solids with simple defects, developed via the involvement of pulse wideband sources and receivers. One of these sources could be the impact impulse that is generated by a metal ball that falls from a fixed height on a concrete surface. In particular, the authors of [38, 39] determined the possibility in principle of determining the sizes and locations of cracks through