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Development of acoustic methods and production of modern digital devices and technologies for ultrasonic non-destructive testing

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Abstract

Acoustic fields, formed in solid half-space by small aperture sources of normal and tangent forces are investigated. Methods of ultrasonic testing, using transducers with dry point contact and electro-magnetic acoustic transducers are proposed. Results of investigated of multi-elements antenna are presented the examples of solving the specific tasks for testing the concrete structures, rails, welds and others a given. The information about the new up-to-date digital equipment, developed basing on information technologies is presented.

Keywords: acoustic method, developed basing on information technologies.

Introduction

The significant role in effective production and safe exploitation of structures play technologies and means of Nondestructive Testing and Technical Diagnostics, based on different principles of materials and fields interaction [1]. The most widely applicable method is ultrasonic testing, based on excitation of ultrasound in the object under a test with piezoelectric or electromagnetic transducers.

Among the problems, limiting implementation of ultrasonic methods, is the necessity of creation and holding the stabile acoustic contact, therefore the researchers pay serious attention to methods of ultrasound excitation of different types in wide frequency range, using transducers with a dry point contact (DPC) and electromagnetic-acoustic transducers (EMATs) [1-3].

Another direction of development and improvement of methods, equipment and testing technology is implementation of multi-element antenna arrays with small-aperture transducers and digital data processing. The multi-element transducers and antenna arrays (both linear and two dimensional) – are the new stage in development of transducers with a liquid contact type. The main advantage of these multi-channel transducers is the possibility of electronic control over the input angle, position of focus point and wave type due to independent delay for every element when sending and receiving acoustic signals.

Investigations of the use of phased antenna arrays and EMATs were made by specialists of Research Institute of Introscopy of MSIA “SPECTRUM”, Moscow. As a result, these types of transducers allow avoid the influence of unstable acoustic contact on testing and allow implementation of new methods of ultrasound excitation and signal processing (such as pulsing with phase-manipulated signals, SAFT, correlation data processing and other).

Basing on the results of investigation, the specialists developed the number of devices and equipment for ultrasonic nondestructive testing of concrete with echo technique, for thickness measurement in a wide range using piezoelectric and EMA transducers, for guided wave testing of rails, for tomographic testing of welds. These devices and equipment simplify the testing procedures and technologies, improve the metrological characteristics of equipment, reduce the influence of human factor and improve the objectivity of ultrasonic testing results [1, 3-11].

Acoustic fields of small-aperture piezoelectric transducers (SAT).

To determine conditions for effective excitation of shear and longitudinal waves the investigations of acoustic fields, formed in a solid half-space by small-aperture sources of normal and tangential forces, and experimental researches of echo-signals characteristics for ultrasonic waves sent by SAT in different materials, were made [4-11].

The tangential force creates on the boundary of a solid isotropic half-space in elastic body oscillations, due to two mechanisms: compression and shear deformation. This causes excitation and propagation of different wave types: longitudinal, shear, surface waves.

When analyzing the fields of piezoelectric transducers with a dry point contact, which are the elements of antenna array, with aperture equal or smaller then the wavelength (SAT), was described the multi-mode 3D field of elastic tensions, excited by the normal or tangential force, acting on the boundary of half-space.

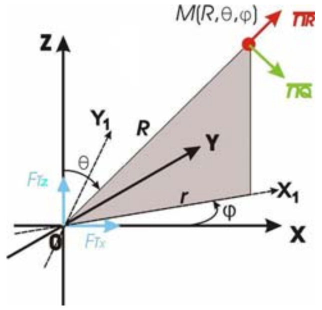


Fig. 1. **Calculation scheme for field of normal F_{Tz} or tangential F_{Tx} harmonic force source**

According to the superposition principle each liquid type transducer can be represented as a number of normal force point sources, acting in limits of transducer's aperture on the surface of half-space. The different types of transducers (straight beam, angle, focused and other) are modeled by the corresponding amplitude and phase distribution of forces in aperture limits.

For DPC transducers and EMATs the force can have tangential or normal vector with regard to the surface of half-space.

The paper [4] represents the theoretical calculation of longitudinal and shear wave shift (Fig. 1), excited at an arbitrary point of a half-space, for SATs of different types: DPC transducer with perpendicular vibration of type, DPC transducer with tangential vibration of wear tip and for rectangular piezoelement acting with normal force. The calculations are made for 2D model, and then using Smirnov-Sobolev method were transformed to 3D model.

For a point source of a **normal force** the following equations of longitudinal l and shear τ shift components were obtained:

$$U_r^l \approx \frac{F_{Tz}}{\mu 2\pi}\,\frac{k_l^2 \sin\theta\cos\theta}{W(k_l \sin\theta)}\,(k_\tau^2 - 2k_l^2 \sin^2\theta)\,\frac{\mathbf{e}^{i k_l R}}{R},$$

$$U_z^l = U_r^l \frac{\cos\theta}{\sin\theta};$$

$$U_r^\tau \approx -\frac{F_{Tz}}{\mu 2\pi}\,\frac{k_\tau^3 2\sin\theta\cos^2\theta}{W(k_\tau \sin\theta)}\,\sqrt{k_l^2 - k_\tau^2 \sin^2\theta}\cdot\frac{\mathbf{e}^{i k_\tau R}}{R}, \tag{1}$$

$$U_z^\tau = -U_r^\tau \frac{\sin\theta}{\cos\theta}.$$

In spherical coordinates the displacement in radial direction $\vec{n}_R$ (longitudinal waves) is given by

$$U^l = U_R^l = U_r^l \sin\theta + U_z^l \cos\theta \approx$$

$$\approx \frac{F_{Tz}}{\mu 2\pi}\,\frac{k_l^2 \cos\theta}{W(k_l \sin\theta)}\,(k_\tau^2 - 2k_l^2 \sin^2\theta)\,\frac{\mathrm{e}^{i k_l R}}{R}. \tag{2}$$

In tangential direction $\vec{n}_\theta$ (shear waves):

$$U^\tau = U_\theta^\tau = U_r^\tau \cos\theta - U_z^\tau \sin\theta \approx$$

$$\approx -\frac{F_{Tz}}{\mu 2\pi}\,\frac{k_\tau^3 2\sin\theta\cos\theta}{W(k_\tau \sin\theta)}\,\sqrt{k_l^2 - k_\tau^2 \sin^2\theta}\cdot\frac{\mathbf{e}^{i k_\tau R}}{R}. \tag{3}$$

For a point source of **tangential force** the following displacement components equations are valid:

$$U_r^l \approx \frac{F_{Tx}}{\mu 2\pi}\cos\varphi\,\frac{k_l^3\, 2\sin^2\theta\cos\theta}{W(k_l \sin\theta)}\cdot$$

$$\cdot\sqrt{k_\tau^2 - k_l^2 \sin^2\theta}\cdot\frac{\mathbf{e}^{i k_l R}}{R},$$

$$U_z^l = U_r^l \frac{\cos\theta}{\sin\theta}; \tag{4}$$

$$U_r^\tau \approx \frac{F_{Tx}}{\mu 2\pi}\cos\varphi\,\frac{k_\tau^4 \cos(2\theta)\cos^2\theta}{W(k_\tau \sin\theta)}\,\frac{\mathrm{e}^{i k_\tau R}}{R},$$

$$U_z^\tau = -U_r^\tau \frac{\sin\theta}{\cos\theta}.$$

In spherical coordinates the longitudinal waves displacement in radial direction $\vec{n}_R$ is given by:

$$U^l = U_R^l = U_r^l \sin\theta + U_z^l \cos\theta \approx$$

$$\approx \frac{F_{Tx}}{\mu 2\pi}\cos\varphi\,\frac{k_l^3\, 2\sin\theta\cos\theta}{W(k_l \sin\theta)}\sqrt{k_\tau^2 - k_l^2 \sin^2\theta}\cdot\frac{\mathbf{e}^{i k_l R}}{R} \tag{5}$$

The shear waves in tangential direction $\vec{n}_\theta$ (not accounting SH polarization displacement):

$$U^\tau = U_\theta^\tau = U_r^\tau \cos\theta - U_z^\tau \sin\theta \approx$$

$$\approx \frac{F_{Tx}}{\mu 2\pi}\cos\varphi\,\frac{k_\tau^4 \cos(2\theta)\cos\theta}{W(k_\tau \sin\theta)}\,\frac{\mathbf{e}^{i k_\tau R}}{R}. \tag{6}$$

For 2D task with SH polarization the displacement amplitude of longitudinal wave (vector length, detected as a square root from squared projections sum) is determined by the value (received from Eq. 2 above) $U^l = U_R^l$. For a shear wave

$$U^\tau = \sqrt{U_\theta^{\tau\,2} + U_\varphi^{\tau\,2}} \cong$$

$$\frac{F_{Tx}}{2\pi\mu}\sqrt{\cos^2\theta\cos^2\varphi\,\frac{k_\tau^8 \cos^2(2\theta)}{W^2(k_\tau \sin\theta)} + \sin^2\varphi}\;\frac{\mathrm{e}^{i k_\tau R}}{R}. \tag{7}$$

For **square source of a normal force** on the half-wave surface were calculated the following equations of displacement components for longitudinal and shear waves in spherical coordinates:

$$U^l = U_R^l = U_r^l \sin\theta - U_z^l \cos\theta \approx$$

$$\approx \frac{P_0}{2\pi\mu} S_{np}\,\frac{k_l^2 (k_\tau^2 - 2k_l^2 \sin^2\theta)\cos\theta}{W(k_l \sin\theta)}\times \tag{8}$$

$$\times F_n(k_l a \sin\theta\cos\varphi) F_n(k_l b \sin\theta\sin\varphi)\frac{\mathbf{e}^{i k_l R}}{R};$$

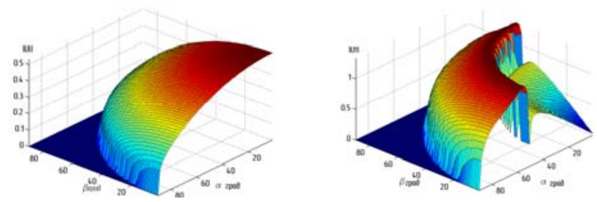
$$U_\theta^\tau = -U_r^\tau \cos\theta - U_z^\tau \sin\theta \approx$$

$$\approx \frac{P_0}{2\pi\mu} S_{np}\,\frac{k_\tau^3 \sqrt{k_l^2 - k_\tau^2 \sin^2\theta}\cdot 2\sin\theta\cos\theta}{W(k_\tau \sin\theta)}\times \tag{9}$$

$$\times F_n(k_\tau a \sin\theta\cos\varphi) F_n(k_\tau b \sin\theta\sin\varphi)\frac{\mathbf{e}^{i k_\tau R}}{R}.$$

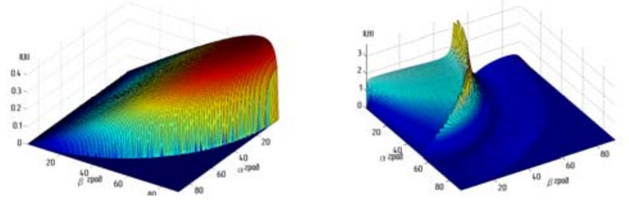
These equations allowed analyze characteristics of SAT and antenna arrays.

For matrix antenna arrays built from SAT with DPC in the frequency range 10-100 kHz (which are applicable for concrete and composites testing) were analysed the 3D images of directivity patterns for longitudinal and transversal waves using SATs with DPC of tangential (Fig.2) and normal (Fig. 3) wear tip vibration.



a) b)

Fig. 2. **3D directivity pattern for SAT with DPC with a normal vibration of wear tip: a – for longitudinal wave; b – for shear wave**



a) b)

Fig. 3. **3D directivity pattern for SAT with DPC with a tangential vibration of wear tip: a – for longitudinal wave; b – for shear wave**

Using SATs with DPC with a tangential type of vibration gives new possibilities for NDT, providing sending and reception of shear waves in non-metallic testing objects without couplants (dry contact).

The total number of elements and configuration of the antenna array depend on the necessary lateral resolution and relation of signals to non-correlated noises with correlation radius γ_{cor}. The lateral resolution of antenna array, focused in a point, does not depend on the way of focus creation and is defined by the angle θ, under which the aperture A is seen from the point of geometrical focus:

$$d_f \approx \frac{\lambda}{2\sin\frac{\theta}{2}} = \lambda\frac{z_0}{A}. \qquad (10)$$

For the aperture A with the focal point diameter d_f and the distance to the aperture side from focus point z_0 the number of elements in the antenna array will be given by the following equation:

$$n = \left(\frac{A}{r_{cor}}\right)^2 = \left(\lambda\frac{z_0}{d_f r_{cor}}\right)^2. \qquad (11)$$

For non-destructive testing of long objects, such as pipelines, rails, rolling plates and other, antenna arrays from SATs with DPC, phased along the surface, are applicable (Fig. 4). For SATs with DPC with a tangential vibration of the wear tip for θ=90° Eq.7 will transform to the function of directivity versus the angle φ:

$$U^{\tau} = \frac{F_{Tx}}{2\pi\mu}\sin\varphi\,\frac{\mathbf{e}^{ik_\tau R}}{R}. \qquad (12)$$

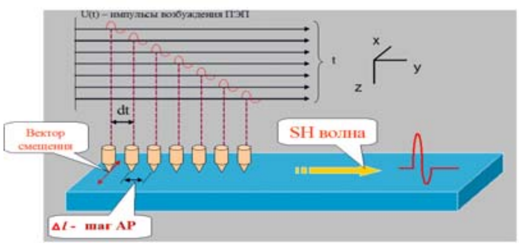


Fig. 4. **SH-wave for guided wave testing**

At $\varphi = 90°$, that means in the direction of y axis, is the maximal excitation of SH-wave, when the angle φ changes from 90 to 0º the level of SH-wave falls according to the sinusoidal law.

The linear equidistant chain from n elements forms the additive antenna. The phase condition of such antenna array for pulse signals is the providing of the signal time delay dt when sending and receiving by one element:

$$dt = \frac{\Delta l}{C_\tau},$$

where C_τ – is the velocity of shear waves.

The directivity pattern equation for linear continuous antenna arrays with the base length B in far zone will be the following:

$$U(\varphi) = \frac{\sin\left[\left(\frac{\pi B}{\lambda_\tau}\right)\sin(\varphi)\right]}{\frac{\pi B}{\lambda_\tau}\sin(\varphi)}, \qquad (13)$$

where λ_τ is the shear wave length; φ is the angle between the antenna axis and the required direction on the surface of a halfspace.

Further we shall analyze the possibilities of optimization of linear arrays parameters for metal testing (Fig 5), built as a linear set of similar rectangular SATs.

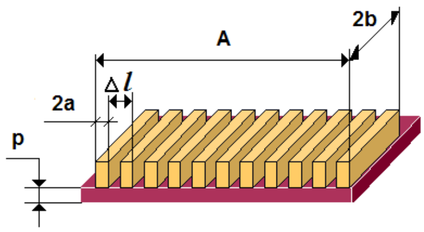


Fig. 5. **Linear antenna array**

Basing on Eq. 8 and .9 were obtained the field characteristics for elastic parameters, corresponding to steel, and for element size 2a=0,2 mm and 2b=15mm at main frequency f=2,5 MHz.

Let us determine the optimal size of element a in area of focusing according to Eq.9. Fig. 6 represents 2D dependence graph of the normalized module of shear wave as a function of two variables: a and propagation direction angle - θ at φ=0.

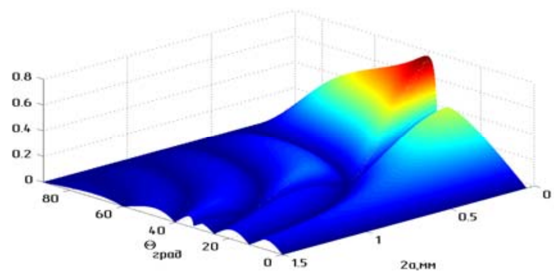


Fig. 6. **Dependence of shear wave normal value module as a function of two variables - width of the element 2a and angle θ at φ = 0**

It is found that at value of 2a less then 0,6 mm the shear wave level reduction will not be more then 6 dB. The wear plate will worsen the relation of longitudinal and shear waves levels, its optimal thickness p should be found experimentally.

Fig. 7 represents the graphical image of dependence of shear vibrations modules as a function of parameters b and φ at $\theta = 50^o$, corresponding to the direction of the pattern maximum. Basing on this dependence and on methodological aspects the parameter $2b$ for element of antenna array can be 15 mm. Estimation of resolution parameters can be made using Eq.10 for a near field zone and Eq.13 for a far field zone.

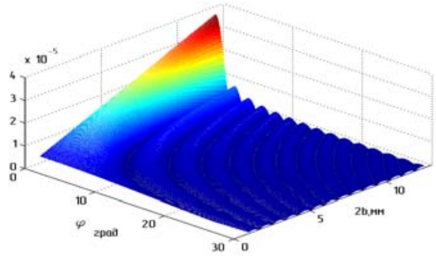


Fig. 7. **Dependence of shear oscillations asa function of parameters 2*b* and φ at θ = 50°**

For reconstruction of internal structure of the object under a test with antenna arrays SAFT-C algorithm is implemented. The idea of this algorithm is in coherent accumulation of signals, corresponding to the definite areas, at the condition of existence of non-correlated echo-signals.

In case of two-dimensional matrix antenna array for the point F in a halfspace x_f, y_f, z_f the normalized reflection coefficient will be calculated by the following equation:

$$I_F = \frac{1}{M}\left|\sum_{j=0}^{j_m}\sum_{i=0}^{i_m} A(\bar{r}_i, \bar{r}_j) U_{i,j}\left(t_0 + \frac{|\bar{r}_i| + |\bar{r}_j|}{c}\right)\right|, \quad (14)$$

where i – the number of the sending element; j is the number of the receiving element; $A(\bar{r}_i, \bar{r}_j)$ – weight coefficient, showing the influence of the directivity pattern for sending and receiving elements; $U_{i,j}(t)$ – time pulse-echo realization for the corresponding pair of elements; t_0 – time of constant hardware delay; $\bar{r}_i$, $\bar{r}_j$ – distance from sending and receiving elements to the focus point F; c – ultrasonic wave velocity; $M = i_m j_m$ – total number of used echo-signals realizations.

For 3D reconstruction of a half-space area, limited by x_m, y_m, z_m, the general equation for calculation of reflection coefficient set (3D image) will be the following:

$$I_F(x,y,z) = \\ = \frac{1}{M}\left|\sum_{j=0}^{j_m}\sum_{i=0}^{i_m}\sum_{y=0}^{y_m}\sum_{x=0}^{x_m}\sum_{z=0}^{z_m} A(\bar{r}_i, \bar{r}_j) U_{i,j}\cdot\left(t_0 + \frac{|\bar{r}_i| + |\bar{r}_j|}{c}\right)\right|. \quad (15)$$

The reconstruction step should not exceed $\lambda/4$ to avoid loosing the defects, therefore the number of operations for realization of this algorithm will be the following:

$$N_{op} = M\frac{64 x_m y_m z_m}{\chi^3} = 64MV\left(\frac{f}{c}\right)^3, \quad (16)$$

where V – the volume of testing area.

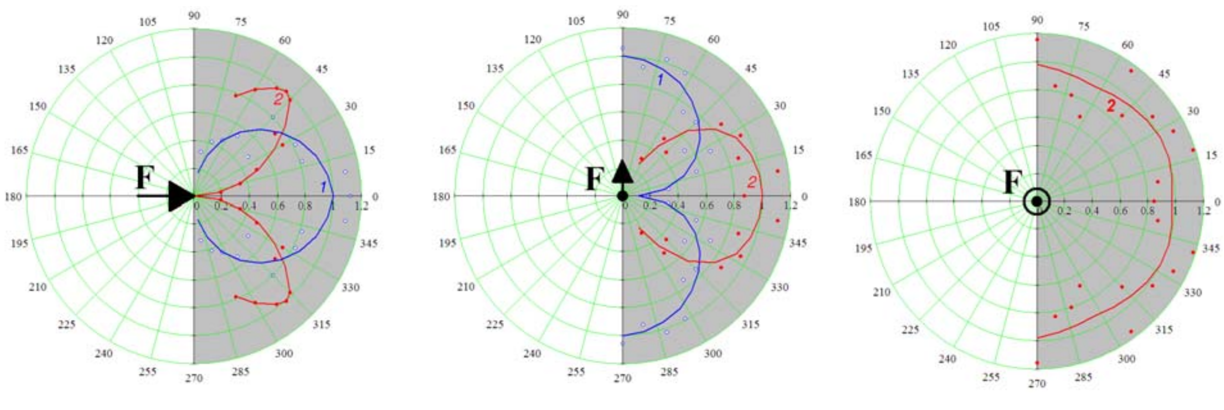
The number of operations is the group of calculations for one point in the space and from one realization. For concrete testing with the antenna array, consisting of 36 SAT shear wave elements ($i_m = 36$; $j_m = 36$), with operation frequency $f = 50$ kHz, and at a reconstruction area of 1 m^3, (ultrasound velocity in concrete 2700 m/sec) the number of operations will be $N_{op} = 526 \cdot 10^6$.

For testing of steel welds the one-dimensional antenna array is applicable and the reconstruction of one B-scan (cross-section) is made. In this case the equation for efficiency will have the following view:

$$N_{op} = 16MS\left(\frac{f}{c}\right)^2, \quad (17)$$

where S is the area of crossection of reconstruction.

The number of elements in the antenna array is 32 ($i_m = 32$; $j_m = 32$); operating frequency f = 2,5 MHz, reconstructed area 1000 mm^2, shear wave velocity 3250m/sec. The number of operations will be



a b c

Fig. 8. **Directivity patterns of transducers with DPC: a – with normal vibration of the wear tip; b – with tangential vibration of the type, section along the vibration vector; c – with tangential vibration of the type, section perpendicular to oscillation vector; 1 – longitudinal waves; 2 – shear waves**

$N_{op}=9{,}7{\cdot}10^6$. For welds a real-time tomography it is necessary to form not less then 5 images pro 1 sec, which is due to a small size and low power consumption of handheld means is possible with the use of specialized processors.

To estimate the real characteristics of transducers with DPC the measurements of parameters and directivities patterns of transducers in a pulse mode were made. Analysis of the echo-signal shape and spectrum characteristic for TD20 transducers type with tangential vibration of wear tip (manufactured by Acoustic Control Systems, Russia) showed spectrum maximum at the frequency of 55 kHz and width of the spectrum 65 kHz at the level –6dB, which is corresponding to the relative bandwidth of 118%.

The similar characteristics have SATs with DPC with a normal vibration of the wear tip (LD20 type), due to similar construction and high damping.

The coefficient of double electro-acoustic conversion for SATs with DPC of TD20 type is 70 dB. This parameter is 30-50 dB less then for the transducers with a liquid contact type.

Fig. 12 represents the measurements results of directivity patterns for SAT with DPC of TD20 and LD20 type transducers with tangential and normal vibrations of the wear tip correspondingly. Measurements were made on the concrete half-space 0.32 m in radius made from cement 400 and granite filling (size does not exceed 8 mm). The experimentally obtained results fully correspond to theoretical models with accuracy up to 25%.

The analysis of absolute signal levels, obtained with SATs with DPC of two types in a solid body shows that the efficiency of sending and reception of shear waves is by 10 dB higher in comparison with longitudinal waves, if the SATs with tangential vibration of the wear tip are used.

To estimate the relation of informative signals to noise for pulse-echomethod of concrete testing the levels of the backwall signals and structure noise, surface waves of R, L and SH types on the concrete mark 400 with granite filling (15 mm sized) were measured for SATs with DPC of TD20 and LD20 types. The signals of surface waves were registered directly after placing SATs on the testing object surface at different distances.

The level of backwall signals was estimated by signal amplitude, received with using through-transmission method on different thicknesses. The effective value of structural noise σ_n was calculated from the statistical processing of large massive of non-correlated realizations.

Comparing the obtained results the following conclusions can be made: the level of the backwall signal is 10-12 dB higher than the structural noise level for shear wave than for longitudinal waves. As the theoretical investigation of SATs with DPC and experiments showed the shear wave is excited more efficiently than the longitudinal and the structure noise level does not depend on the direction of the excitation force, because it is appearing due to multiple re-reflections and transformations of ultrasonic oscillations.

Basing on the obtained results we can conclude that for pulse-echomethod of concrete testing the shear waves, formed by SATs with DPC with tangential vibration of the wear tip are more effective. At that the average backwall signal-to-noise ratio can be from 0 to –10dB for shear wave, and for longitudinal waves this ratio is 10-12 dB worse.

For quantitative estimation of structure noise parameters the "correlation radius" was used. The "correlation radius" is the size of minimal circle area on the surface of half-space inside of which the cross-correlation coefficient between echo-realization of structural noise received from any point inside the area and echo-realization in the center of the area is not less then 0,25.

Basing on the investigation results the following requirements for antenna arrays applicable for thickness gauging and tomography of concrete were formulated:

- For thickness measurements of widely-spread concretes (marks 200-400) the sufficient is the antenna array from 24 elements of SATs with DPC with tangential vibration of the wear tip (similar to TD20 by electro-acoustic parameters).
- These transducers are arranged in groups of 12 elements for sending and receiving and are placed in one housing.
- The step between SATs is 20 mm. The view of such antenna array and backwall signals, received with the antenna array on the concrete block 400 mm thick are represented on Fig. 9. The upper backwall signal was received in the area of monolith concrete and the lower signal – received in the area with the hole 30 mm in diameter. The concrete thickness measurement error on is 7% at the error probability of 0,97.

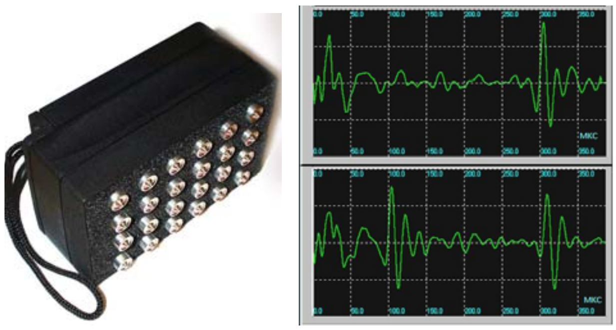


Fig. 9. **24-element antenna array built from SATs with DPC for concrete thickness measurement and received echo-signals**

For the tomography of concrete structures the antenna array consisting of 36 SATs with DPC arranged in a square matrix 6 x 6 was developed. As elements the SATs with tangential vibration of the wear tips with the operating frequency 55 kHz were used. Each element has own amplifier and generator and has an independent spring load to the testing surface. The controlling board allows independent use of every element both in sending and receiving mode.

Simultaneously can operate only a pair of elements. The received signals are digitized and sent to a PC.

Using the antenna array and data processing with the SAFT-C algorithm we can reconstruct tomograms of B-type, representing the possibilities of the pulse-echomethod for concrete testing. For trials we used a concrete block (concrete mark 400) with a middle size filling (15 mm). The thickness of the block is 400 mm. Fig. 10 represents the results: 1 – image of the sphere 100 mm in diameter inside the block; 2 – image of the sphere 50 mm in diameter inside the block; 3 – the backwall image. Fig 17 b represents the reconstruction of the cross section of channels inside the block: 1 – a channel 30 mm in diameter at the depth 250 mm; 2 – a channel 12 mm in diameter at the depth 230 mm; 3 - a channel 30 mm in diameter at the depth 350 mm behind the channel 2; 4 – backwall. For the case 3 (Fig. 17b) the signal / noise ratio is less then 10 dB.

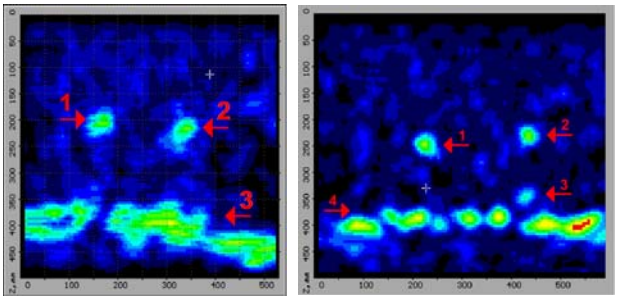


Fig. 10. **Tomograms of a concrete block with internal artificial defects, obtained after testing with 36 element antenna array**

The experiments made allowed to confirm the applicability and efficiency of the antenna array from SATs with DPC for solving different tasks of concrete testing in range of thickness 50-500 mm. At that the operation using shear waves is more sensitive and gives a higher resolution. Basing on ultrasonic the transducers with DPC and shear vibration of wear tip the following equipment was developed: the low-frequency flaw detector for concrete A1220 MONOLITH and the tester UK1401 [7].

Fig. 11 represents the process of testing the contact line support at the Moscow Railway using the ultrasonic tester UK1401. The instrument has two built-in transducers fixed on the base 150 mm. The UK1401 tester allows measuring time or velocity of ultrasound propagation in a material using surface sounding method with an error of not more then 1%. It can be used for estimation of concrete strength by changes in ultrasound velocity in material. Also, it allows to estimate the crack depth for the cracks coming to the surface, in the range of depths 10-50 mm.

Fig. 11. **UT tester UK1401. Testing of contact line support**

The transducers with a longitudinal vibration of the wear tip can be used for measuring of the Rayleigh wave velocity in materials at surface sounding of materials.

The short signals of these transducers allow using them for estimation of integrity of materials and presence of defects inside, located along one coordinate axis.

If the wavelength is more then the lateral size of the object, then this object can act as a wave guide and different types of core waves are propagating on the long distances.

The example of such application of the transducers is pulse-echomethod of testing the state and length of steel anchor bolts built in concrete. Fig. 12 represents two oscillograms, received with a pair of transducers with shear vibration of the wear tip on the models of anchor bolts 1 m long and 30 mm in diameter. The transducers were set near each other on the side of the bolt near one end and the vibration vectors were oriented across the bolts axis. The upper signals in Fig. 12 a were received on a free lying bolt, showing absence of a contact between the bolt and concrete. The signals in Fig. 12 b were obtained on the bolt built in concrete, when only 50 mm of bolt were left above the concrete. The significant difference of signals character gives information about the quality of the contact between the bolt and the concrete. The delay time between the signals gives information about the bolt length or length of its non-damaged part.

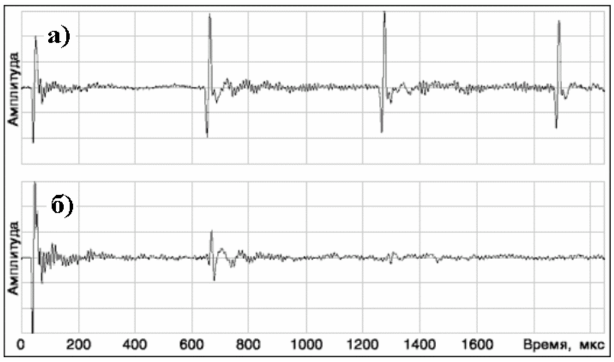


Fig. 12. **Echo-signal oscillograms received on anchor bolt end: (a) free lying bolt; (b) built-in concrete bolt**

Guided wave flaw detection of rails

The guided wave flaw detection of rails at low-frequencies can be applicable for testing without the necessity of scanning the whole surface of the object. The rails head, web and foot in this case are acting as separate independent waves guided. The longitudinal (symmetric), flexural by thickness (asymmetric) and SH-waves are propagating in them.

The ultrasound velocity propagation was measured by the through-transmission method using a pair of SATs with DPC (TD20 type) perpendicular to the rails axis. For sounding the rails on the base of 1500 mm and more the velocity is (3090 ± 10) m/sec, which is lower then the shear wave velocity and can be explained by the guided wave propagation of ultrasonic signal in a rail. The results of signal spectrum measurements showed that the time delay interval of about 200 μs from the moment of the signal reception is characterized with a dominated spectrum in the range of 15-50 kHz.

To estimate the possibilities of the guided wave method we carried out the physical modeling of 8 element linear phased antenna array (elements of TD20 types) [8].

The experiments were made of a rail 2590 mm long with an artificial defect of a gash type (25 x 25 mm), which is 15% of the cross section of the rail, at the distance of 1000 mm from the rail's end. The distance from the end of antenna array to the rails butt-end is 200 mm. The results of experiments showed that the signal peak amplitude from the defect (maximum at 720 μs) exceeds the of noise level of 15 dB and in comparison to the amplitude from the butt end is 5-7 times lower. The guided wave method allows detecting defects like cross cracks in rails head with a size of about 15% area of the rail head cross section and more.

To estimate the maximal possible testing distance the special phased antenna array from 12 elements with DPC for guided wave testing was developed and tested on the rails up to 25 meters long. The informative signals spectrum lies in the range 10-25 kHz.

The relation between peak signals from the butt-end of rail to the noise level exceeds 30 dB. The equivalent ultrasound velocities are 2924, 2933, 2912 and 2907 m/sec for distances 5, 10, 15 and 20 m correspondingly. The difference in velocities is not significant so the average velocity 2920 m/sec was used for testing.

The signal levels from the rail's butt-end were measured versus the distance. The results are presented in Fig. 13 as interpolated dependence of the signal versus the distance to the butt-end.

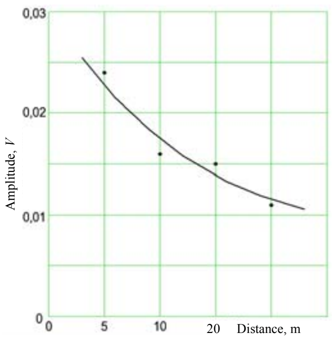


Fig. **13 Echo-signal amplitude from the rail's butt-end versus the distance between the antenna array and the butt-end**

From the results of the experiments it can be concluded that the guided wave method can be realized with linear antenna arrays, built from SATs with DPC with tangential vibration of wear tip. The number of elements in antenna array can vary from 8 to 12. The operation frequencies are in the range 15-40 kHz. The optimal oscillation mode propagation velocity is 2920 m-sec. The dead zone is not more then 500 mm. Such antenna array allows detecting defects with cross section area less the 15% of section area of guided wave at the distance up to 20 m with the signal/noise ratio not worse then 10 dB. Due to use of synthetic focusing it is possible to control the testing direction. It provides two directional scanning from the place of antenna array and therefore increasing efficiency of rails testing.

These results were used when developing the guided wave flaw detector for rails AKR1224, presented in Fig.14. In comparison with the known equipment for flaw detection this flaw detector solves more efficiently the problem of localization of defects at the distance 0.5 to 30 meters from one set of antenna array with accuracy 0,1 m. The device was tested and implemented in rail welding factories and departments of Russian Railways.

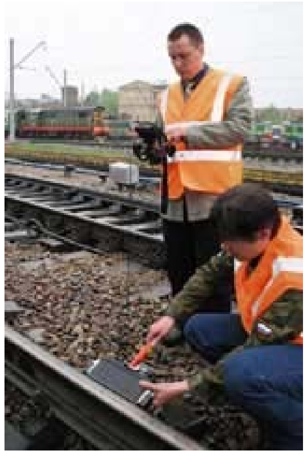


Fig. 14**. Rails testing process with the guided wave flaw detector AKR 1224**

Ultrasonic thickness gauges for testing of metals

One of the most widely spread non-destructive testing procedures of metals is thickness measurements of the objects, providing correspondence of the required sizes at production and finding of deviations from thicknesses during exploitation in critical conditions like high temperature or high pressure, in a corrosive environment.

Using the algorithm of autocorrelation data processing it is possible to avoid the influence of thermal and reverberation noises and to determine the period of multiple signals repetition and therefore calculate the thickness of the object under a test.

In order to investigate the metrological characteristics of this measuring method the data set was created using the set of standard blocks from AMG-6 alloy (KMT 92p-2571-00) with the highly damped straight beam single crystal transducer S3567 (produced by Acoustic Control Systems, Ltd., Russia) [8].

The absolute error of measurements in this case with autocorrelation function algorithm in the thickness range 0,8 – 20 mm is not more then 13 μm, which is 3,8 time better then in comparison with measurements made by the double crystal transducer П112-10,0-6/2 and V-correction in the thickness gauge type A1209.

The main advantage of the proposed method of acoustic signals processing is the possibility of solving the problems of thickness measurements using non-couplant method of EMA transduction. The investigation carried out showed the efficiency of processing signals from EMAT, which allows the measurements of smaller thicknesses up to 0,5 mm.

For the tasks of thickness measurements the following instruments were developed: **A1207** and **A1207C** small size portable ultrasonic thickness gauges with an easy, user-friendly interface, high sensitivity for express measurements of thickness on steel; **A1208** – universal thickness gauge of wide application for wide thickness range and wearproof transducer for operation on rough surfaces at operating temperatures from –30 up to +55ºC, **A1209** – universal thickness gauge for a big number of measurements with possibility of data storing (Fig. 15).

Fig. 15. **Digital ultrasonic thickness gauges A1207, A1208, A1209**

All thickness gauges have Certificates of Type Approval [5, 8].

EMA thickness gauge **A1270** [6, 11] is applicable for thickness measurement of rolling plates, cylindrical and spherical objects after stamping, milling and etching in thickness range 0,5 -100 mm, the minimal possible curvature radius at that is 30 mm and the allowed error of measurement is not higher then 0,01 mm (Fig. 16). The EMA transducer is made using the nonvolatile constant magnets from Nd-Fe-B alloy, which made it possible to create small, portable, low power consuming thickness gauge.

Fig.16**. Process of thickness measurement**

The algorithm of data processing allows searching mode and indication of the smallest thickness value for the testing object or of its part. The results of measurements can be saved in a nonvolatile memory of the device and transferred to the external PC through USB port for further processing, printing and storing.

The development of the portable EMA device for acoustic measurements with one-side access allows estimation of anisotropy of material and estimation of deformation mode of units and parts of structures [11].

Ultrasonic detection of flaws in welds using digital technologies

For optimization of a high-frequency antenna array parameters for welds testing the experiments of the test model of the antenna array with the following parameters were made (Fig 5): $2a$ = 0,6 mm, Δl = 1,25 mm, $2b$ = 15 mm, the number of elements – 18 with a ceramic wear plate (type 22XC) 0.8 mm thick. All elements are damped [10]. The parameters of all the elements are identical. The investigations have showed that the spectrum has maximum at the frequency of 1,8 MHz and the spectrum width 1,0 MHz at the level 6 dB, which corresponds to the relative bandwidth of 55%.

Measurement of directivity pattern for a single high-frequency SAT of the antenna array for longitudinal and shear waves was made on the specially made steel samples with side holes 6 mm in diameter, located at the same distance but under different angles with respect to the placing of SAT.

The results are presented in Fig. 17, where 1 – directivity pattern of longitudinal wave SAT, 2 - directivity pattern of shear wave SAT.

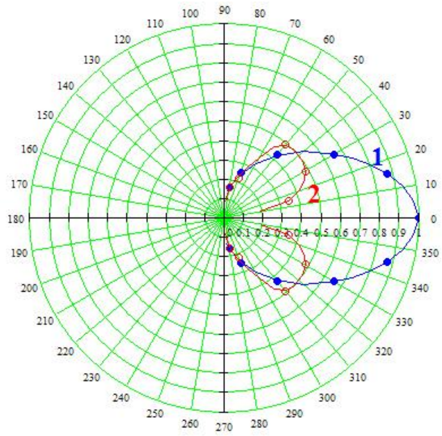


Fig. 17. **Directivity pattern of longitudinal and shear waves for a single high-frequency SAT of antenna array with a liquid contact**

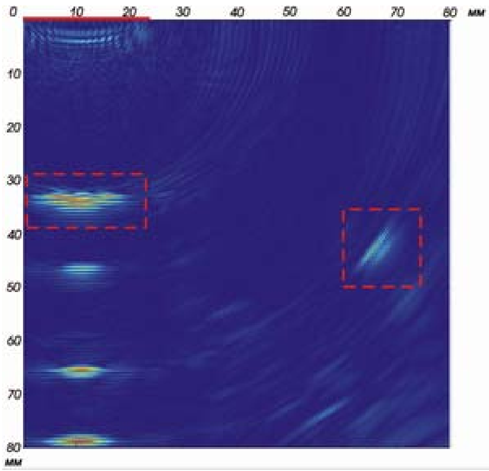
The results showed that the single SAT with the size 0,5 x 15 mm forms pulses of two wave types: longitudinal and shear, which confirms the possibility of excitation SH waves with an antenna array without angular prism. The correspondence of their level with the accuracy up to 30% is the same as obtained by calculations, which is 0,5 of the maximal amplitude of the longitudinal wave. The width of directivity pattern main lobe is the same as was calculated.

The experimental tests of the linear antenna array for tomography of metals using longitudinal and shear waves were performed with the model of the antenna array on the calibration block SO-2. After processing of the signals picked up on this block, the tomogram of the cross section area with a hole 6 mm in diameter lying at the depth 44 mm was reconstructed using the SAFT-C algorithm (Fig.18).

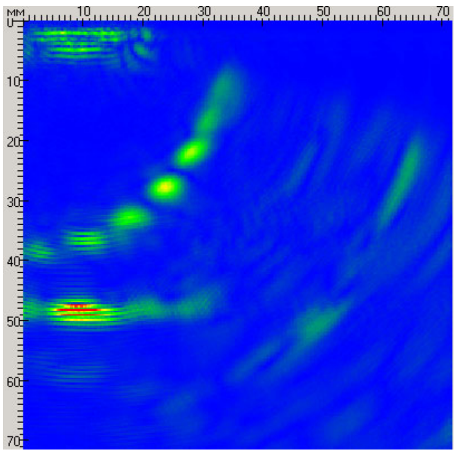
For reconstruction the term $A(\bar{r}_i, \bar{r}_j)$ of Eq.15 was taken as 1, at that on the tomogram (Fig. 18 a) it is clearly seen both the image of the hole formed by shear waves (on the right) and the image of the backwall formed by longitudinal waves (on the left).

Fig. 18b presents the tomogram of the internal structure of the aluminium block with several side holes 2 mm in diameter, located on the circle side 44 mm diameter. The antenna array was placed in the middle of this circle on the surface of the block. When using the correcting directivity pattern of elements on the tomogram (Fig. 18b), it is possible to see the maximal number of defects.

The experiments confirmed the suitability of the antenna array built from SAT with a liquid contact type for testing a metal structures and welds. For producing the array it is optimal to use piezo-composite ceramics with the step of elements 0,8 mm, thickness of elements not more then 0,4 mm and the wear plate thickness not more then 0,5 mm.



a



b

Fig. 18**. Reconstructed with SAFT-C tomograms, built on a test sample SO-2 and on sample from aluminium alloy**

90-95% of welds are tested with a portable handheld ultrasonic equipment. In most cases NDT of metals is performed in field conditions or hard-to-reach areas, therefore the small size, but most functional devices are more and more demanded.

The distinctive features of handheld ultrasonic flaw detectors and tomographic systems, produced by Scientific Research Institute of Introscopy "SPECTRUM" [6-11], is the fully digital channel, which enabled to unify the functional circuits and design solutions, speed up the new developments and widen the spectrum of ultrasonic transducers and antenna arrays, which can operate with the devices.

Among the devices of wide application the company produced the small and light ultrasonic flaw detector **A1212 Master** and the ultrasonic flaw detector **A1214 Expert**, which can operate in the temperature range starting from -30º C and the ultrasonic tomograph **A1250** with a linear antenna array (Fig19).

Fig. 19. **Digital ultrasonic flaw detectors A1212 MASTER, A1214 EXPERT**

All these instruments were specially designed for operation both in laboratories and in field conditions, using the conventional methods of ultrasonic non-destructive testing. All these instruments possess built in large configurations library for quick adjustment of the device under different transducers and different operating modes for easier data analysis.

Besides the development and production of modern equipment for non-destructive testing a great attention in the Scientific Research Institute of Introscopy "SPECTRUM" is devoted to raising the skill levels of specialists in NDT – customers and users of the equipment. There is a special study center in "SPECTRUM", providing studies and trainings in different fields of NDT and issuing certificates of I, II and III levels specialists of the international qualification.

There is also informational and technical support, consultancies on application of the equipment, upgrading of systems and repair and post-sales service provided.

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Akustinių neardomųjų bandymų metodų ir šiuolaikinės skaitinių įrenginių gamybos technologijos tobulinimas

Reziumė

Tiriamos akustinės sritys, suformuoti normuotieji kontrolės šaltiniai. Pasiūlyti ultragarsinės kontrolės metodai, panaudojant sausojo kontakto keitiklius. Tiriami ir elektromagnetiniai akustiniai keitikliai. Pateikti skleidimo multikeitiklių tyrimų rezultatai, įvertinti apibrėžtų uždavinių sprendimo pavyzdžiai, norint patikrinti konkrečias struktūras, pavyzdžiui, geležinkelio bėgius, suvirinimo vietas ir kt. Pateikta informacija apie naują šiuolaikinę skaitinę įrangą, kurioje informacinės technologijos dar labiau ištobulintos.

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