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ULTRASONIC ECHO-PULSE TOMOGRAPHY OF CONCRETE USING SHEAR WAVES LOW-FREQUENCY PHASED ANTENNA ARRAYS

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Abstract

The paper gives the description of up-to-date method for concrete testing based on the dry-point contact ultrasonic transducers technology, advanced methods of computer tomography and new techniques of signal processing using SAFT algorithm.

The authors explain the operating principles of Low-frequency ultrasonic Tomograph for concrete A1040M MIRA, the main working element of which is 40 DPC shear wave transducers antenna array. The A1040M MIRA tomographer is applicable for concrete testing using the ultrasonic frequency range of 20-150 kHz. The main operation principle of the equipment is pulse-echo tomography based on the coherent accumulation of reflected signals, received by different elements of antenna array, with their further processing. The implemented SAFT algorithm allows building the 3D data massive of structure's reflected parameters in tested area and then reviewing it in different sections and images.

The practical trials on different objects confirmed the applicability of the Tomograph A1040M MIRA for the following testing tasks on reinforced concrete, monolith concrete and other concrete objects:

- Thickness measurements up to 2 m;
- Testing of structure integrity by presence and level of backwall signal;
- Searching for location and estimation of sizes of different reflectors inside the objects, localization of cable ducts, reinforcement bars, hollows, delaminations and other discontinuity flaws;
- Estimation of integrity between hidden sides of concrete or tunnel paneling with the solid grouting behind.

The paper also represents the signal processing methods, operation techniques and methodic, allowing successful and efficient testing of objects from concrete with imaging the internal structure of the objects in different areas and depths.

Key words: echo-pulse tomography**,** phased antenna array, shear wave, low frequency, concrete inspection

Introduction

The wide application of concrete as the main building material as well as great number of concrete newly built or requiring repair objects demand development of new equipment and techniques for reliable and effective testing.

Among the available nondestructive testing techniques, including the Ground-penetrating radar (GPR), X-rays, the Ultrasonic Tomographic Imaging based on shear wave pulse-echo technique becomes more and more demanding due to its feasibility to more accurate and

effective detection of different defect types, higher resolution of testing and applicability for deeper thicknesses of testing object at one-side access testing.

A1040M MIRA tomograph for concrete testing

The company Acoustic Control Systems Ltd., Moscow[1] is well-known for researching the pulse-echo technique for concrete testing and developing different types of equipment, based on this technique. The latest development of the company, combining all the recent researches and up-to-date technologies in this area, is the low-frequency ultrasonic tomograph for concrete A1040M POLYGON (name on the Russian market), also known MIRA (which is an International name), hereafter called the Tomograph. The Tomograph is based of pulse-echo testing technique and provides almost in real-time imaging of the internal structure of testing object on-site and without the delays.

The Tomograph is applicable for the following testing tasks:

- Thickness measurements of the objects up to 2 m;
- Testing of structure's integrity by presence and level of backwall signal;
- Searching for location and estimation of sizes of different reflectors inside the objects, localization of cable ducts, reinforcement bars, hollows, stratifications and other discontinuity flaws;
- Estimation of integrity between hidden sides of concrete or tunnel paneling with the solid filling behind.

The Tomograph utilizes a patented phased matrix array of 40 shear wave transducers, organized in 10 units by 4 elements each and controlling unit of Laptop type for data accumulation and processing. The Dry-Point Contact elements with individual spring loading to the testing surface are used as elements of the antenna array. The frequency spectrum of signals is from 30 to 120 kHz with the central operation frequency of 50 kHz. Sending and reception of signals is made in combinations between the units. The space-time processing is based on SAFT-C method [1, 2]. The photo of the Tomograph is represented on the fig. 1.



Fig. 1. Low-frequency ultrasonic tomograph for concrete testing A1040M MIRA (MIRA).

[1] http://www.acsys.ru/

The testing with the Tomograph is proceeded as a step-by-step scanning of the testing object, at that data from each position is accumulated and processed without the delays on-site. The final result of testing is obtained on the display as a combination of several scans (B-, C- and D-scans) of the tested area.

The Tomograph has four operating modes:

1. «Calibration». This more is used for calibration of the Tomograph to the concrete characteristics of testing object: automatic measurement of average ultrasound velocity in the concrete, necessary gain adjustment and setup of other parameters for clearer imaging of internal structure.

2. «Explore». In this mode the data is reconstructed as B-Scan image from one position of the array. It is used for quick estimation of the internal structure of testing object in random positions. The operator places the antenna array in the point subjected to testing and receives the B-Scan image of the structure under the antenna array. The depth of B-Scan can be 0.5, 1 or 2,5 m (as preset by the operator), the width of the scan reconstructed on the display is 0,5 m according to the width of the array. This mode allows estimation of the concrete structure under the array, measurement of the object's thickness.

3. «Scan». This mode is for data acquisition from large areas of testing object and automatic saving of results with all the current parameters, setups and calibration. It is used for data collection from several positions of antenna arrays (line) when testing step-by-step moving the antenna along the object with the preset step (for ex. 50 mm). At that the operator receives the B-scans image of testing object in every position almost in real-time mode (the time for processing and reconstruction is about 3 sec) on the display. The length of the scanning line is not limited. The width of the scanned area is corresponding to the width of the antenna array and is about 0,5 m. At that the operator can make several lines, the data from each line will be saved in separate file, containing raw data, available for further analysis by the operator.

4. «Review». This mode allows detailed analysis of the received in Scan mode testing results. On the display the operator obtains the reconstructed image of the scanned area in three sections: B-, C- and D-scans. The operator can review and explore in details the received images not necessarily on site, but also in laboratory, as this mode is for analysis only and doesnot require the connection of the antenna array.

Application examples

Fig. 2 shows the example of B-scan image (tomogram), received with the Tomograph A1040M MIRA on the concrete block 400 mm thick with three drillings, running parallel to the testing surface. The visualized image is perpendicular to the drillings, imitating the long inclusions or defects inside the concrete structure. The large image corresponds to the larger drilling 30 mm in diameter on the depth of 140 mm from the surface; the two drillings are 13 mm in diameters on depths 80 and 180 mm depths (images on the right). In the bottom is the backwall image.

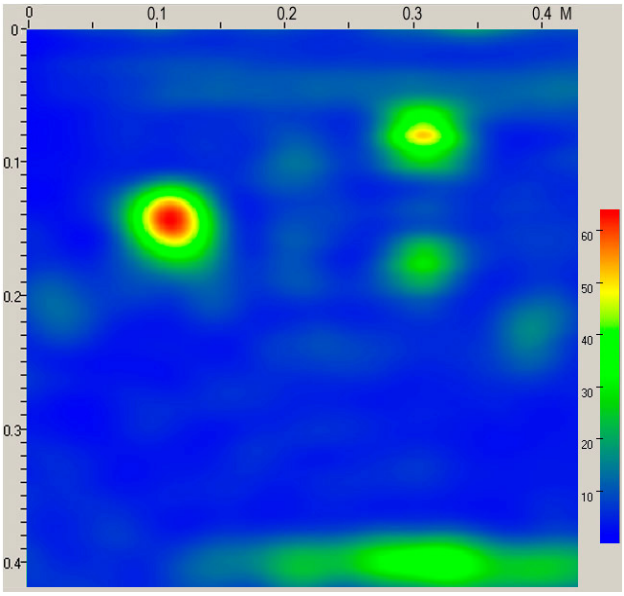


Fig. 2 The cross section image (B-scan) received with the Tomograph A1040M MIRA on the concrete block 400 mm thick.

The given example shows high sensitivity and resolution of the Tomograph. The sizes of the artificial reflectors – drillings are smaller then the wavelength and not more then 50 mm.

Another application example for the Tomograph A1040M MIRA is its application for testing of paneling in tunnels. The important quality parameter for tunnels paneling is the quality of concrete grouting between the panels and soils, influencing the reliability and durability of the construction in general. According to tunnels building technology the area behind the concrete paneling of tunnels (which is a load-carrying structure) is grouted with sand-cement mixture, providing hermetic encapsulation of the tunnel. The presence of non-grouted areas is not allowed, as the outer side of the panels is in free impact by the ground waters, destroying the panels and the grouting quality.

The Tomograph A1040M MIRA was used for quality estimation of concrete paneling in abuilding railway tunnel (see fig.3).



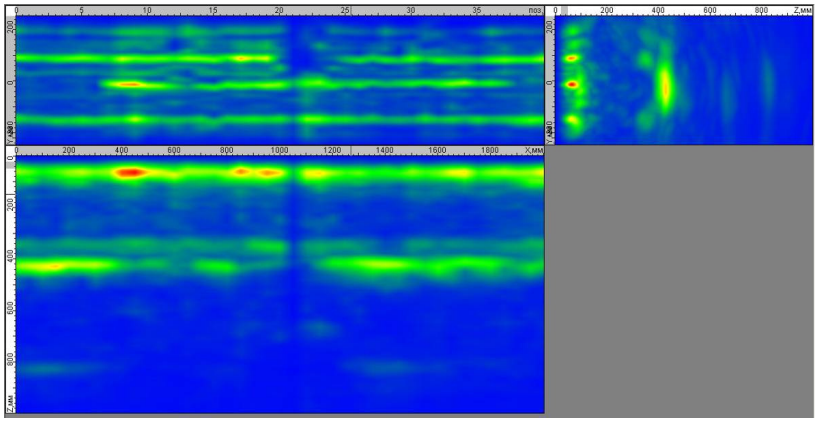
Fig.3 Application of the Tomograph A1040M MIRA for quality assessment of abuilding railway tunnel near Krasnoyarsk.

The area between the panels and soils when building the tunnel is grouted with concrete mixture. The solidity of this mixture is much lower then the solidity of the panels, therefore for estimation of grouting quality behind the paneling the presence of backwall signal and its intensity on the border between the panel and the grouting was chosen as an indicative parameter.

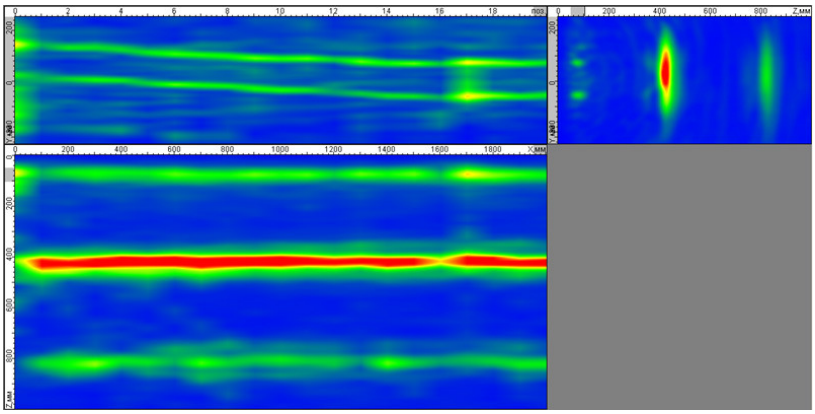
In the areas of good grouting there is a low backwall signal appearing on the border, as the main pulse energy is penetrating into the grouting mixture, at that the presence of the second or third backwall reflection is improbable. In the other case when there is air instead of grouting behind the paneling the operator receives the high-intensive backwall signal from the backside of the panel and the multiple reflections from backwall can also appear.

As a model of no-grouting behind the paneling the free elements of paneling, not installed yet, were accepted. As a model of well-grouted area was used an area in paneling where the grouting was checked with pull-out test.

Fig. 4 represents the results as B-, C- and D-scans for both cases: non-grouted area behind the paneling and well-grouted area behind the paneling.



a)



b)

Fig. 4. Images received with the Tomograph A1040M MIRA on the paneling: a) in case of well-grouted area and b) non-grouted area. The thickness of paneling is 400 mm, the shear waves ultrasound velocity is 2800 m/sec.

The given examples shows the applicability of the Tomograph both for thickness measurements on concrete objects and for imaging the internal structure, visualizing the positioning of reinforcement bars on different depths inside the panels. Both images are given in the same way as they are represented on the display of the Tomograph.

The upper image is the C-scan - the view from the top - of the tested area. On the C-scan image the positioning of reinforcements bars is clearly seen, the diameter of the reinforcement bars according to the specification of the panels is 20 mm.

To the right is the B-scan image in one (chosen by the operator) position of the antenna array. According to the scale on the top can be concluded that the top layer of reinforcement bars is on the depth of 70 mm from the surface, the backwall signal corresponding to the thickness of the panels is at 400 mm and above the backwall signal the light image of bottom layer of reinforcement bars can be detected. The image of the bottom reinforcement layer does not coincide with the upper reinforcement layer, which is confirmed by the construction drawings of the panels and allows concluding that the images close to the bottom are the image of the reinforcement bars and not the second reflection from the top reinforcement layer.

The lower section on the fig.4 is the D-scan – the section view from the side, the left scale at that shows the depth and the upper scales – united for C- and D-scans gives the coordinates along the scanning line. Both D-scans on the fig. 4 shows the top reinforcement bars layer and the backwall signal.

In case of bad grouting or absence of grouting mixture behind the paneling the intensity of the backwall signal is very high (shown with the red color on the image), at that the second backwall reflection is clearly seen. In case of good grouting behind the paneling the intensity of the backwall signals reduces significantly (the level of the backwall signal is not higher then the level of signals from the reinforcement bars). The second backwall appears only in two places, which can be the air holes behind the paneling.

The similar testing task was solved with the Tomograph A1040M MIRA in the underground tunnel of Moscow Metro, though in this case it was easier, due to the impedance difference of the paneling material and grouting mixture. There was no backwall signal in the areas of grouting behind the panels. The example images received on the paneling of Moscow Metro underground tunnel are given on the fig, 5. There are two B-scans represented: one with the air behind the paneling, another one with the grouting mixture.

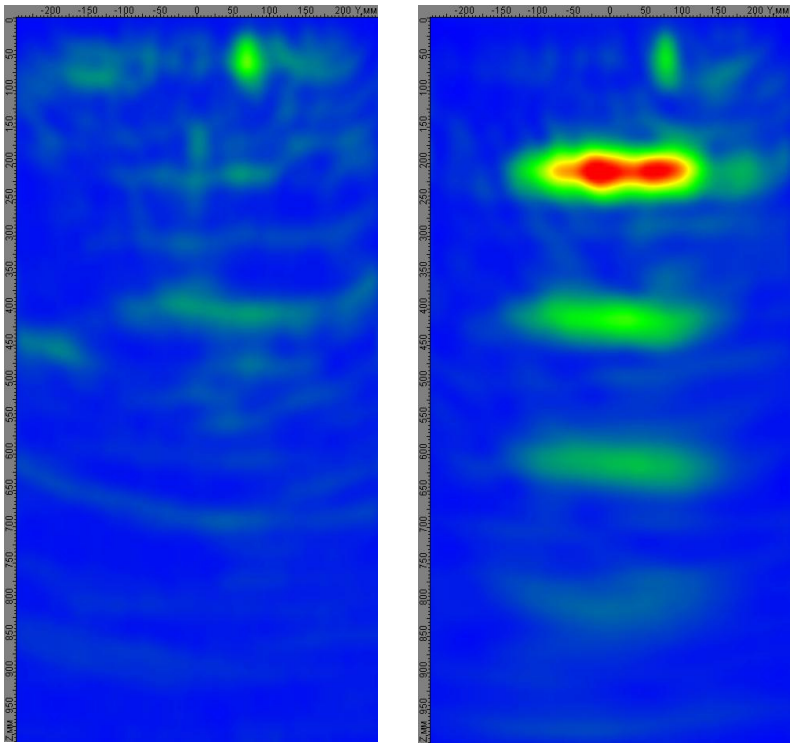


Fig. 5 Images received at testing the underground tunnel of Moscow Metro: left – with grouting behind the paneling and right – with air behind the paneling.

In case of air behind the paneling (fig. 5 right) there is a backwall signal of high intensity at the depth of 200 mm, as well as multiple backwall reflections at 400, 600 and 800 mm, herewith confirming that the panel contacts with the air or soft medium and the whole ultrasound energy is reflected from the bottom of the panel and not penetrating further.

In case of presence of grouting mixture behind the paneling (fig. 5 left) the backwall signal on the depth of 200 mm is of very low intensity, almost absent, the similar reflection appears at 400 mm. This allows concluding that the backside of the paneling is in good contact with the grouting mixture filling up to 400 mm depth then changed with the soil. There are no multiple reflections, confirming that the main ultrasound energy is penetrating to the soil due to the good contact between the paneling, grouting mixture and soil.

There are bright spots on the depth between 50 and 100 mm on both images on fig 5, which is the reinforcement, crossing the section in these positions of the antenna array.

The application area for the Tomograph A1040M MIRA is not only the concrete or reinforced concrete testing, it can be also successfully used for quality and integrity estimation of refractory blocks of different sizes.



Fig. 6 Refractory blocks from "BAKOR" material.

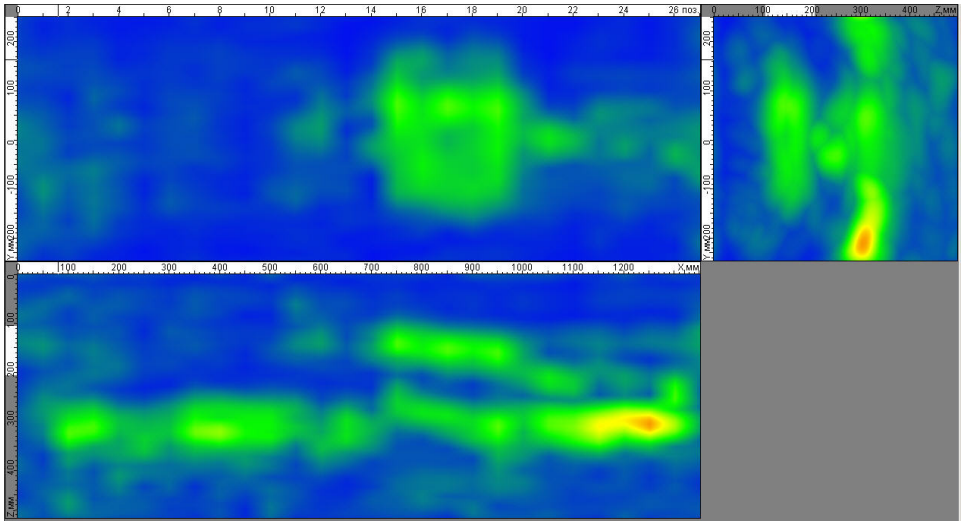


Fig. 7 Images received at testing the refractory block BK-37 from BAKOR material, the shear wave ultrasound velocity in the material 4073 m/sec.

Fig. 6 and fig 7 represents the refractory blocks and testing results correspondingly. The image (fig. 7) shows the example, received on the block with a defected integrity area at the depth of 100 mm from testing surface, which lays in the area 700-1125 mm from the zero scanning point. The area has a square form and resembles a kind of delamination.

The quality assessment of refractory blocks before dispatch to the customer and assembling them into the final product significantly reduces the costs of repair due to the bad quality of the blocks.

Conclusions

The given application examples for the Tomograph A1040M MIRA allows concluding its applicability for the following tasks of testing the objects from concrete, reinforced concrete and other similar materials:

(1) Estimation of adhesion between the dense medium to the hidden parts and surfaces of concrete walls or panels;

(2) Detection, location coordinates and size estimation of different reflectors inside the concrete objects, like ducts, reinforcement bars, honeycombing, delaminations, air hollows and other;

(3) Estimation of structure integrity by the presence or absence of backwall signal and its intensity;

(4) Thickness measurement (up to 2 m) of concrete objects at one-side access testing.

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