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# APPLICATION OF "FOCUSING TO POINT" ALGORITHM FOR STANDARD-EXCLUSION MEASUREMENT OF ULTRASOUND VELOCITY IN THE PROCESS OF TOMOGRAPHY OF CONCRETE PRODUCTS

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**ABSTRACT**

It is shown that the imaging algorithm, that is widely used in ultrasonic tomography of concrete building structures and based on the sequential focusing of the probing signal to each point of an object under monitoring and subsequent formation of tomographic image of the product, is focused on the visualization of point reflectors, while it relatively poor displays planar ones. At that, the tomographic image formation accuracy depends on adequate choice of value of ultrasound velocity in concrete. In addition, it is shown that basing on the application of “focusing to point” algorithm it is possible to implement standard-exclusion method for simultaneous determination of ultrasound velocity and failure location in non-extended products made of homogeneous materials.

**Keywords:** ultrasound, concrete, phased antenna arrays, velocity of ultrasonic vibrations, focusing to point algorithm.

## INTRODUCTION

### Distinctive features of visualization of reflectors of various shapes with the help of "focusing to point" algorithm

Nowadays, in the process of ultrasound (US) non-destructive testing of large-sized building structures (BS) of concrete there are widely used low-frequency tomographic scanners that allow obtaining an image of the internal structure of the object being under monitoring. The operation of such tomographic scanners is based on the use of phased antenna arrays (AA), known from the radio detection and ranging, with the help of which there is sequentially performed, in the echo-location mode, beam focusing to each point of the BS (Figure-1) with following formation of the product image in a computing device (CD). The principle of focusing the US beam to the *j*-th point of the BS is illustrated in Figure-1, which for the sake of simplicity shows the ultrasonic AA consisting of *N*=4 elements. The US signal propagates from the emitting transducer (ИП) to the reflector (product failure) and, diffusely reflecting, reaches the receiving transducers $ПП_1$-$ПП_3$.

The focusing is carried out in the CD by means of using a delay for the time period $T_{зад1}$-$T_{зад3}$ of the signals reflected from the *j*-th point of the product, so that the echo pulses that arrive at all the receiving antenna elements to be summed coherently. Time delay $T_{зад.j}$ for the signals for each *j*-th point of the product is determined by the time of passage of the US pulse from the radiating element ИП to the failure and further on to each receiving element ($ПП_1$-$ПП_3$ in Figure-1:

$$T_{зад.j} = L_{\Sigma j}/C_L = (L_{изл}+L_{отр.j})/C_L \quad (1)$$

- At that $C_L$ - velocity of longitudinal ultrasonic vibrations.

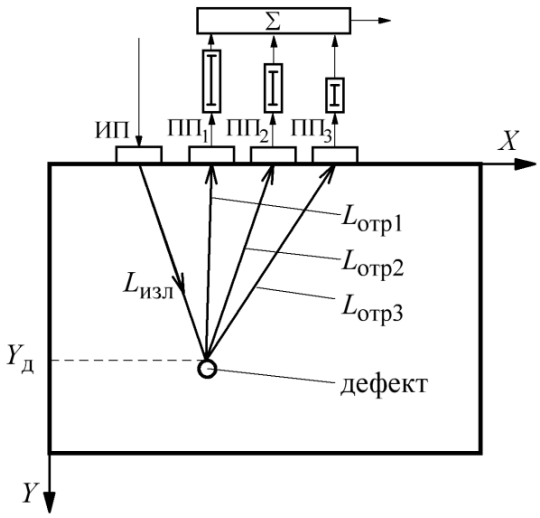


**Figure-1.** Explanation of the "focusing to point" algorithm.
*At that: «дефект» means “failure”*

As it can be seen in Figure-1, the path that the US signals pass from the ИП to the failure and back is composed of distance $L_{изл}$ from the sending transducer to the failure, and distance $L_{отр}$ from the failure to the receiving transducer ПП. Generally, the total path for each transducer comes to:

$$L_{\Sigma j} = L_{изл} + L_{отр \cdot j} \quad (2)$$

In case of presence in a *j*-th point of any reflector (a failure, an acoustic heterogeneity), after the coherent summation of signals an impulse with amplitude $U_{\Sigma j}$ is formed in *N*-1 channels. In the event of absence of such

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reflector, the amplitude in the *j*-th point comes to zero. After that there is carried out sequential focusing of the US signals to each point of the object under monitoring, and then the image (tomogram) of the object under monitoring is formed in the CD in conjunction with the echo-signals reflected from all points of the product being monitored [1-4].

However, as practice shows, the application of the "focusing to point" algorithm does not always adequately reflect the structure of the products. Particularly, failures and planar reflectors in plane-parallel building structures are visualized differently. The foregoing is illustrated by the example of simulation of the US tomographic image for a concrete block 400 mm thick with an artificial failure in the form of an aperture with diameter D = 50 mm located at a depth of 200 mm (Figure-2). In the calculation there was used a short harmonic US signal with a frequency $f_0$=100 kHz and with a relative bandwidth $\Delta f/f_0 \approx 80\%$. At that, it has been assumed that there is no signal attenuation and therefore the form of the echo-signals reflected from the plane and from the failure is the same echo-signals (Figure-3). It has been assumed that the value of ultrasound velocity in concrete comes to $C_L$ = 4000 m/s and the length of the US wave in concrete comes to $\lambda \approx 4$ sm. In the simulation process there has been also assumed that the signal from the bottom of the product is reflected in specular way, and reflection from the failure is of diffuse nature because the aperture size is commensurable with the length of the US wave in concrete ($D \approx \lambda$), and this fact allows considering it as a "point" reflector. In the process of simulation there was used AA consisting of 12 elements, and pitch distance between the transducers came to $d$ = 30 mm ($d > \lambda/2$).

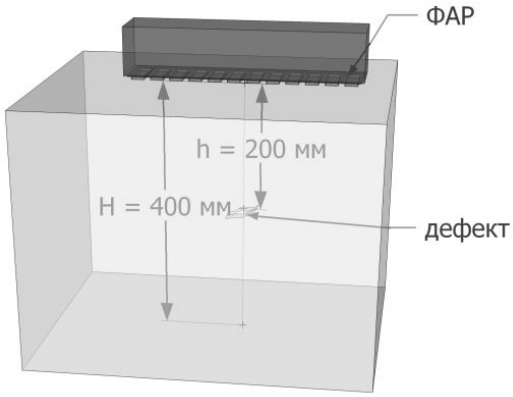



**Figure-2.** Object under monitoring.
At that:
"ФАР" means "phased antenna array"
"дефект" means "failure"

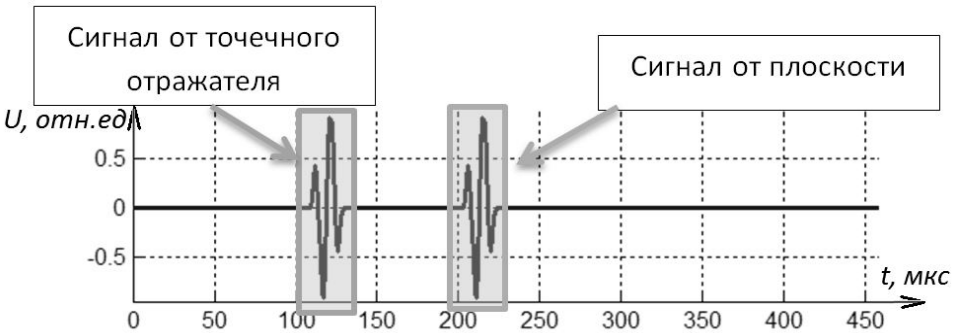



**Figure-3.** Echo-signals from plane and from point reflector.
At that: "Сигнал от точечного отражателя"» means "signal from point reflector"
"Сигнал от плоскости" means "signal from plane".

Generally, in the majority of the US tomography scanners there is formed two-dimensional image of a product under monitoring (B-scan). On the concrete block B-scan obtained as a result of simulation (Figure-4), signal with amplitude $U_\Sigma$ corresponds to the "point" failure. Voltage on the two-dimensional B-scan is visualized with the help of using a color scale; in this particular case, the normalized amplitude of the echo-signal from the "point" failure has a maximum value, which is visualized in the form of a bright red point. The image of the concrete block bottom is represented in the tomographic image in the form of a narrow light green segment.

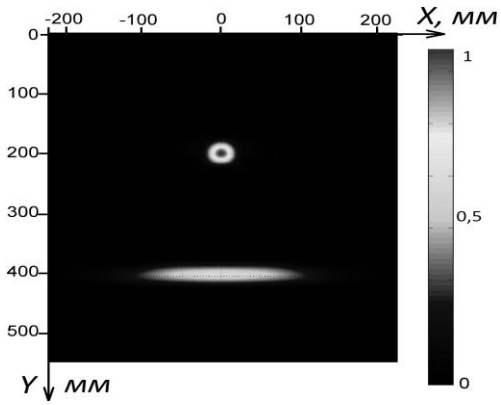


**Figure-4.** Two-dimensional image of object being studied with the help of "focusing to point" algorithm.

Comparison of images of the failure and plane with the real reflectors indicates to the fact that "point" reflector (this could be a failure or an acoustic heterogeneity) on the tomographic image is visualized adequately, while the bottom image is represented as a segment having a length that is substantially smaller than the actual size of the bottom. The difference in quality of imaging of reflectors having different configurations can be explained by the difference in the mechanism of formation of a signal reflected from a plane and from a point reflector.

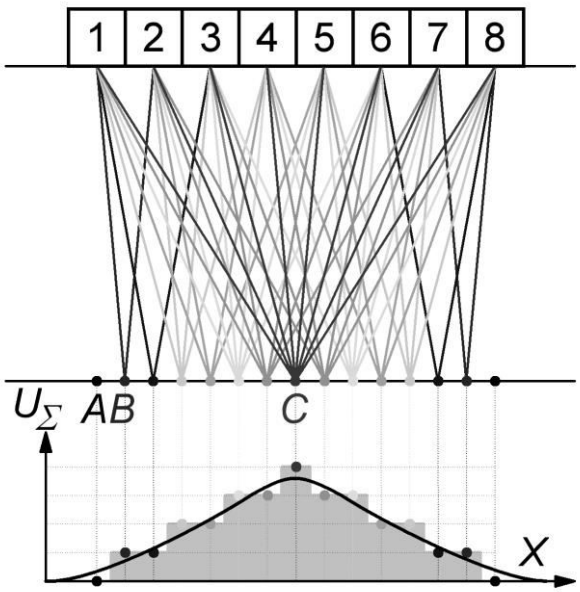



**Figure-5.** Formation of image of plane using the "focusing to point" algorithm.

In case of "mirror" reflection of a signal from a plane, there is no any single reflecting point, and therefore the receiving transducers receive those echo-signals that are reflected from various points of the bottom. At that, the AA receives different number of signals reflected from various points on the surface, and as a result the bottom image turns out to be "blurred". This effect is illustrated in Figure-5, showing paths for the emitted and received signals [5] for an AA consisting of 8 transducers. From point C, located under the center of the antenna, four signals are reflected and then summed-up. From point B, only one reflected signal is reflected and arrives at the antenna, and those signals that are reflected from point A do not arrive to the AA at all. As a result, on the image of plane visualization of point C has the maximum amplitude, because it corresponds to the sum of four echo-signals. Point B will correspond to the amplitude of one reflected signal, and point A is not visualized on the tomographic image. As a result, the image of the extended bottom on the B-scan in Figure-4 is represented in the form of a short segment having amplitude continuously decreasing at the edges.

Figure-4 also shows the difference in the amplitudes of images of the bottom and the failure: the amplitude for the point reflector (it corresponds to a bright red color) significantly exceeds the amplitude of the bottom image (it corresponds to a light green color). This difference is explained by the fact that for the "point" failure the reflection goes diffusely, and the signal reflected from it arrives to all elements of the AA (Figure-1, b).

Thus, we can assume that the "focusing to point" algorithm adequately visualizes "point" heterogeneities and relatively poor visualizes planar failures: the size of a flat reflector does not correspond to the real value of the bottom of the product, and the plane image amplitude does not correspond to the area of the reflecting surface. Therefore, to visualize a bottom, in the US tomographic scanners the antenna array is moved along the product surface, synthesizing image of the plane "piece by piece".

## METHODOLOGY

### Standard-exclusion method of determination of ultrasound velocity in concrete

In the process of US monitoring of BS, on frequent occasions the main required parameter is velocity of propagation of US vibrations in concrete, because the strength of concrete is determined by longitudinal vibrations velocity $C_L$ [6-7]. In the event of one-sided access to the product, velocity $C_L$ is calculated by formula:

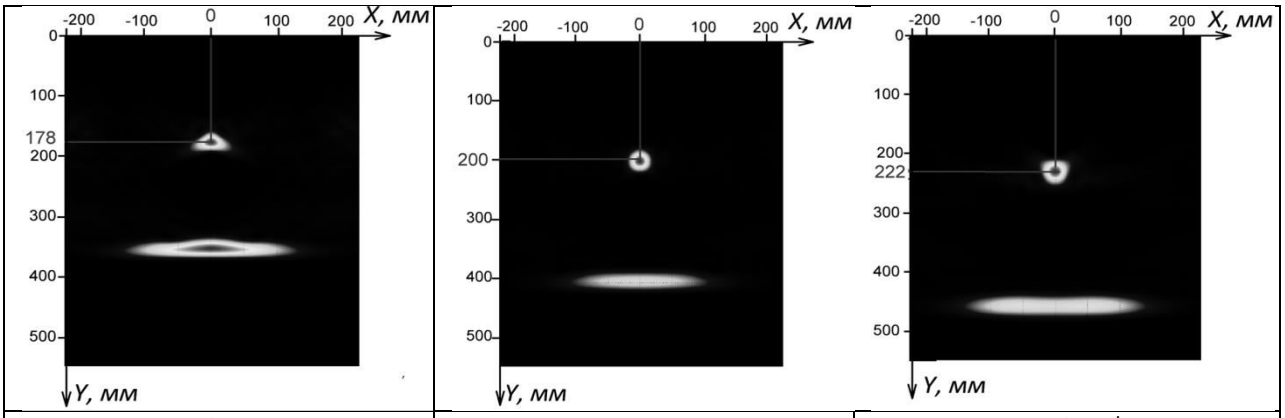
$$C_L=2H/T_c \quad (3)$$

- At that $T_c$ - time of passage of the US signal from the ИП to the BS bottom and back.

Information about the exact value of the US vibrations velocity is also required in the US tomography, because any incorrect value of velocity $C_L$ in (1) leads to an incorrect definition of distance $L_\Sigma$, and as a result the product image is distorted. It is appropriate to note here that determination of the exact value of velocity of vibrations when using phased antenna arrays is important just in the process of the US tomography. Indeed, in the radio detection and ranging velocity of electromagnetic waves is practically constant, and in hydrospace detection velocity of propagation of US vibrations in the water changes insignificantly. The situation is different in the process of US monitoring of concrete products, when in different products the US vibrations velocity can vary from 200 m/s to 4000 m/s.

The impact of velocity of US vibrations on the accuracy of visualization of concrete products is illustrated in Figure-6, a-b-c, which shows B-scans for different values of ultrasound velocity in concrete, formed as a result of simulation. Tomographic images in Figure-6-a were formed at value of the longitudinal velocity of US vibrations in concrete $C_{L1}$= 3500 m/s; in Figure-6-b at

$C_{L2}$=4000 m/s, and in Figure-6-c at $C_{L3}$=4500 m/s. Two-dimensional B-scans show that depending on the value of velocity, specified in the calculation, there are obtained different values of distance to the failure: from $h$ = 178 mm (a) to $h$ = 222 mm (c). Apart from that, the product bottom image is also displaced: thickness of the concrete block in Figure 6-a turns out to be equal to $H$ = 3500 mm, and in Figure 6-c to $H$ = 4500 mm.




a -3500m/s | b – 4000m/s | c – 4500m|s

**Figure-6.** Tomograms of a concrete product at different values of ultrasound velocity in concrete (simulation).

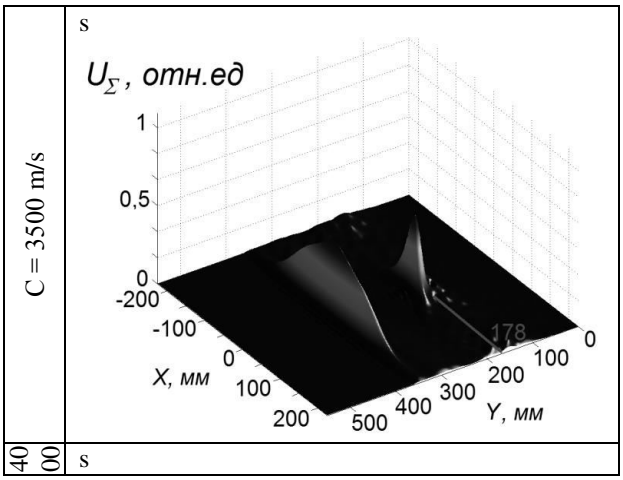
Determination of velocity in accordance with formula (3) assumes that the product thickness $H$ is known. Unfortunately, in some cases it is not possible to measure the BS length with a line (e.g., building foundation or inter-floor overlapping). In this case there are used standard-exclusion methods for the velocity determining, among which the most common is the method of determining the velocity of longitudinal vibrations $C_L$ by easily measured velocity of the US surface vibrations $C_s$ with due consideration of known ratio of velocities $C_L = \gamma C_s$ [8-10]. However, this standard-exclusion method allows accurate measuring velocity $C_L$ in the product volume only in the event that the concrete BS's are not subject to climatic, radiation or other impacts. Otherwise, the characteristics of concrete on the surface and in the depth can vary greatly, and this fact leads to an error in determining the ultrasound velocity (strength of concrete).

In this research paper, we propose a different, standard-exclusion method of determining the US vibrations velocity in concrete, based on the use of the US phased antenna arrays.

It should be noted here that the tomographic images in Figure-6 are also formed with the help of using the US PAA, however it is quite difficult to make any conclusion about the true value of the US vibrations velocity and the true failure location on the basis of a point failure on a two-dimensional tomographic image.

However, it can be conveniently done with the help of three-dimensional tomographic images (Figure-7, a-c), which represent a projection of a three-dimensional image on plane $XY$ and are more informative than the two-dimensional B-scans. In the three-dimensional tomographic images, a point failure corresponds to a peak, by height of which it is easy to determine the amplitude of total signal $U_\Sigma$. The length of the bottom image, same as on the two-dimensional B-scans, is much shorter than the actual size of the bottom surface, and the amplitude of the bottom surface image is less than amplitude of the peak visualizing "point" failure.

Analysis of the three-dimensional images shows that with changes in values of velocity $C_L$, used to calculate tomograms, the peak amplitude changes due to the change in the time delay of signals arriving at the AA elements (1) and due to changes in the coherence conditions during summing-up of signals.



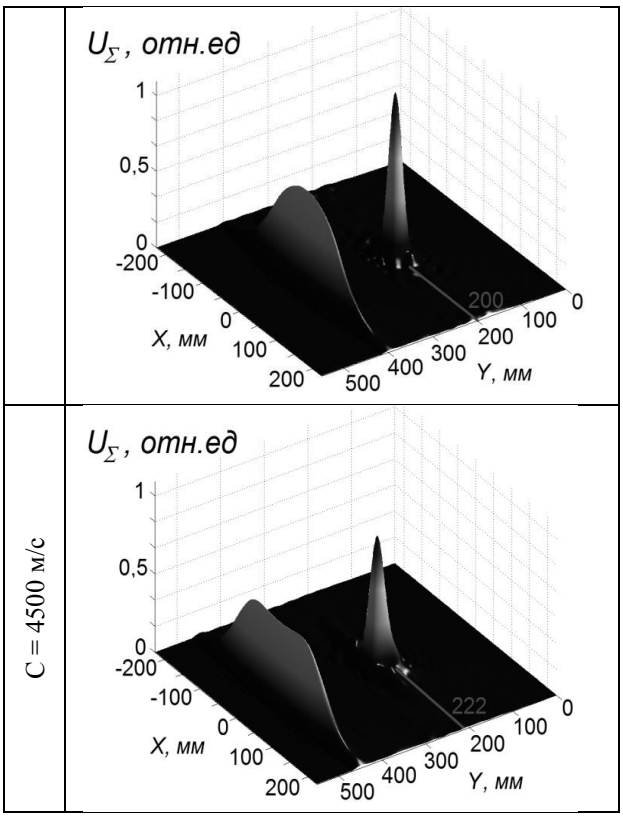



**Figure-7.** Two-dimensional and three-dimensional B-scans, formed at different values of velocity of acoustic vibrations.

At that, the peak, visualizing the "point" failure, has the greatest height at the rated parameter of velocity corresponding to the real value of $C_L = 4000$ m/s.

So, in accordance with (1), $L_{\Sigma j}=C_L T_{зад.j}$; with changing of velocity $C_L$ the peak coordinates are also changing, and this fact leads to errors in determining the failure location (Figure-6; d, e, f). Thus, the peak reaches a maximum at the moment when its location strictly corresponds to the failure location.

Such pattern of changing of peak amplitude from the specified design velocity has allowed us to offer standard-exclusion method for measuring velocity of US vibrations by the analysis of the amplitude of signal reflected from the "point" reflector. The same method simultaneously determines the true values of the failure location. Our proposed method consists in formation of several three-dimensional tomographic images for different values of design velocity, in comparing the amplitudes of the peaks in the different B-scans, and in subsequent determination of the true value of ultrasound velocity by the maximum of dependence of the peak amplitude on the ultrasound velocity. At the same time there is determined the true location of failure.

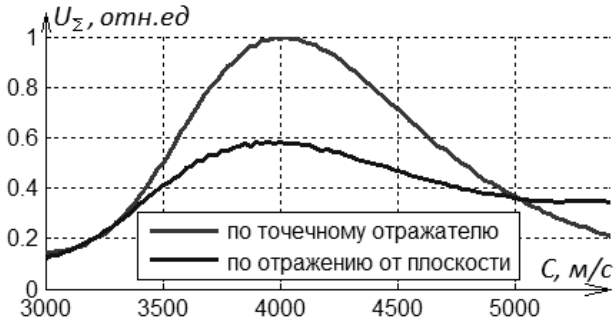



**Figure-8.** Dependence of amplitude of echo-signals on the US vibrations velocity for a "point" reflector (red color) and for a planar reflector (blue color).
*At that*:
"По точечному отражению" - "By point reflection"
"По отражению от плоскости" - "By reflection from plane"

Such dependence of changing of the peak amplitude on the values of the US vibrations design velocity is represented in Figure-8 (red color), where basing on the maximum peak amplitude it is easy to determine the true value of ultrasound velocity in the given concrete $C_L$= 4000 m/s.

The proposed standard-exclusion method for measuring ultrasound velocity in concrete allows to carry out monitoring of changes in the strength of concrete in the course of operation of the object and to predict the period of trouble-free service of buildings and structures. However, this method can be used only in such structures, in which the existence of a "point" reflector (for example, a service opening) is known beforehand. In the case where such a "point" reflector is absent, standard-exclusion determination of ultrasound velocity is possible also by the reflection from the bottom of the product.

Indeed, during changing of velocity $C_L$, image amplitude of the bottom surface and its location are changing in a similar manner, which also leads to inaccuracies in the measurement of the BS thickness. However, it should be noted here that the "focusing to point" algorithm is focused on the detection of just point reflectors, while planar reflectors are fixed none too well. This fact is illustrated by dependence of the product bottom image amplitude on the ultrasound velocity (blue color in Figure-8), which has a less pronounced maximum in comparison with the analogous dependence of amplitude of the "point" failure image (red curve).

**Results of the experiment on standard-exclusion determination of ultrasound velocity in a concrete product**

The results regarding standard-exclusion determination of ultrasound velocity, obtained with the help of simulation, were confirmed experimentally during monitoring an extended product ($H$ = 800 mm) made of fine-grained concrete (grain size of gravel has not exceeded 5 mm), inside which, at a distance of 180 mm, there was a failure in the form of a hollow cylinder having

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diameter of 40 mm. In the process of the experiment there was used US phased antenna array, the elements of which were manufactured by AXIS LTD and represented broadband transducers with dry point contact and with cross-type excited wave [11]. In the capacity of probing element there was used a signal with linear frequency modulation (LFM-signal) having average frequency $f_0$ = 50 kHz and relative bandwidth $\Delta f/f_0$=80%. Generation of probing pulses and subsequent optimal filtration of echo-signals was performed in a multifunctional measuring complex [12].

Ultrasound velocity in concrete was considered to be unknown beforehand and was subject to be determined, for the purpose of which, basing on results of one probing, there was carried out computer calculation of nine two-dimensional "B-scans", shown in Figure-9, at different values of velocity of transverse vibrations $C_t$, lying within the range of 1900 - 2700 m/s. The pitch of changing of the velocity preset for the calculation came to 100 m/s. Since the definition of ultrasound velocity was performed by reflection from the "point" failure, there was formed image of not the entire product, but only of a part of it within the limits of 400 mm.

Figure-8 shows the two-dimensional tomographic images, similar to those that are used in the US tomographic scanners for the representation of monitoring results. However, two-dimensional images allow determining only the fact of displacement of failure image (spots with maximum brightness) at different values of design velocity, but it is quite difficult to determine the true ultrasound velocity and real location of the failure basing on this displacement.

In addition, the foregoing method of determination of ultrasound velocity has allowed sufficiently accurately measuring the true value of velocity basing on changing of the peak amplitude at the three-dimensional B-scan with the help of using the dependence shown in Figure-7. However, such a measurement can be carried out only by using an additional operation, which in our case has been implemented with the help of a multifunctional measuring complex (MC), which calculated the peak amplitude at the 3-dimensional B-scan for each design velocity value. With the help of the MC there was formed experimental

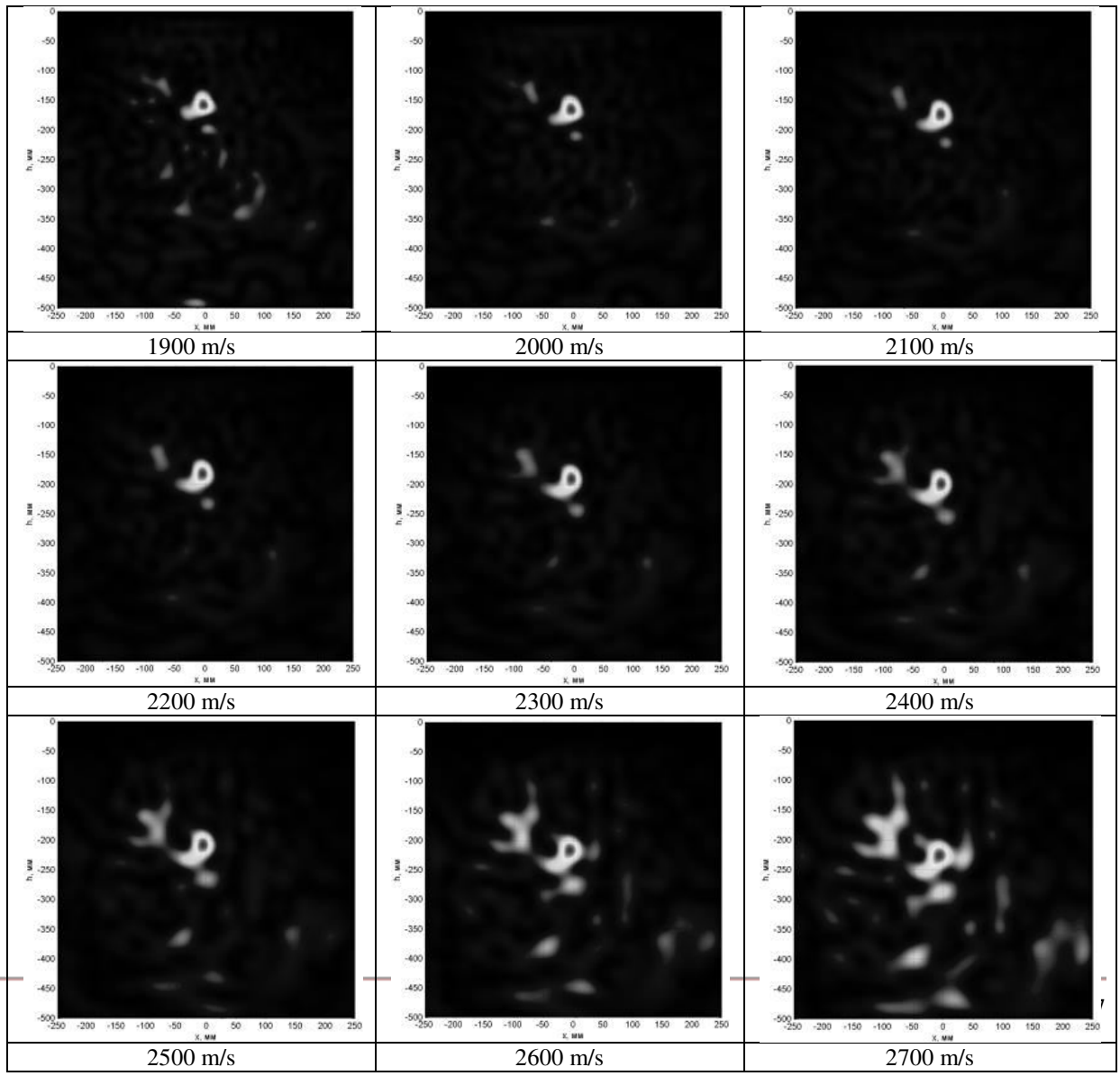


**Figure-9.** A set of two-dimensional "B-scans" formed for different values of ultrasound velocity in concrete products.

relationship between the maximum peak amplitude $U_\Sigma$ on the three-dimensional "B-scans" and ultrasound velocity in concrete (Figure-10).

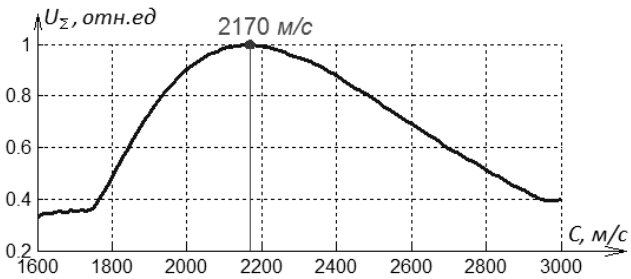


**Figure-10**. Dependence of amplitude $U_\Sigma$ of the maximum of three-dimensional "B-scan" on the US vibrations velocity in concrete.

Basing on the maximum of characteristic $U_\Sigma(C_t)$, formed with the help of multifunctional MC, it is easy to determine the true value of the US vibrations velocity: $C_t$ = 2170 m/s.

## CONCLUSIONS

The "focusing to point" algorithm is aimed to the visualization of point reflectors (failures and structural heterogeneities), and it visualizes planar reflectors (bottom of product) relatively poor.

The "focusing to point" algorithm allows implementing standard-exclusion simultaneous determination of both ultrasound velocity and location of "point" failure, but only when using relationship between the maximum peak amplitude of the three-dimensional "B-scan" and the ultrasound velocity. At that, a high-quality measurement is possible only in the products made of homogeneous materials not having any significant structural heterogeneities (for example, gravel in concrete) and characterized with relatively low level of structure-borne noise.

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