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THE USE OF ELASTIC OSCILLATIONS OF DIFFERENT WAVELENGTHS TO EVALUATE THE DYNAMIC PARAMETERS OF BUILDINGS AND STRUCTURES AND ASSESS THE STRENGTH OF MATERIALS OF THE BUILDING CONSTRUCTION

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Abstract. *The presented work discusses the potential use of elastic oscillations of different wavelengths to determine the dynamic parameters of the investigated buildings and structures. Furthermore, the use of acoustic methods is examined as nondestructive testing methods to assess the strength and composition of the building construction. Finally, the results of the research are presented, for example, to evaluate the earthquake resistance of buildings, the velocity sections of constructions and soils, as well as the options and measuring systems for research. The presented methods in this work are used in the survey of reinforced concrete, brick and wood structures.*

The monitoring of the building structures state presents on the example of The Naval Cathedral of Saint Nicholas in Kronstadt during the period between 2005 and 2010.

Data on the surface waves velocities is obtained in the soil along the length of the tunnel during the survey behind the subway oblique course linear space.

Data presented on the creation and adaptation of precast concrete structures finite element models with large spans of their actual dynamic parameters. Calculation of carrying capacity using the model is confirmed by the analysis of the initial design decisions of the investigated structures.

The pass-through sensing method is used for the survey, as a rule, of large-scale structures with access to a variety of surfaces, such as foundations of buildings and structures, as well as arrays between underground excavations. The method was also used for cross-borehole sensing.

1 INTRODUCTION

The main objectives of the existing buildings and structures structural design under seismic actions taking into account the survey results are:

- identification of the reserves (or deficit) of the buildings or structures earthquake resistance generally and of its structural elements taking into account the data on their real state which was obtained by results of survey abiding the requirements of the applicable regulatory documents;
- identification of the causes which led to the appearance of building and structural elements' defects and damages, detected in the survey;
- based on the results calculation analysis of earthquake resistance of the buildings or structures, taking into account the survey results to develop proposals for engineering and technical measures that must be performed on an object to restore and maintain its functional stability, as under operational loads and as seismic action at a given intensity, and their design feasibility.

2 DYNAMIC TESTING OF BUILDINGS WITH DIFFERENT STRUCTURAL SYSTEMS EXPOITING THE METHOD OF FREE OSCILLATIONS

The earthquake resistance evaluation requires the use of test methods and means to obtain objective information about the main properties of materials, as well as building and structural elements.

The amount and type of information received by the requirements of the synthesis and identification of the design models.

The initial data for the design models identification uses the following structures and buildings dynamic characteristics, obtained in the free oscillations analysis recorded during the tests:

- Periods and forms of oscillations;
- Logarithmic decrement of oscillations.

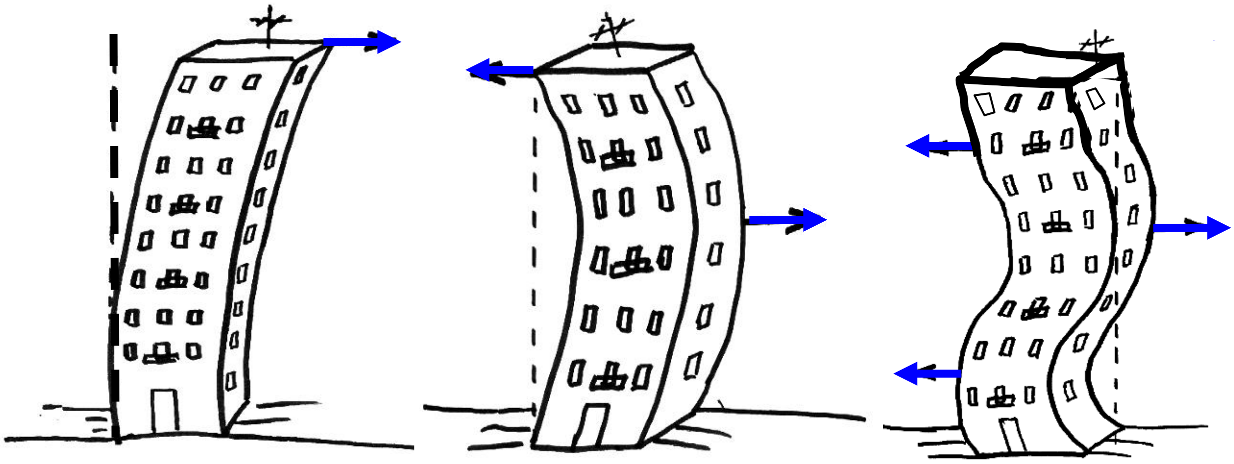
The main free oscillations forms of buildings and structures are presented in figure 1.

For buildings with complex structural system with unevenly distributed weight or stiffness characteristics can exist at different frequencies of higher tones which bending With oscillations height, and sometimes of the first tone, for different parts of the building. In this case, for these forms of oscillations build also diagrams along the length of the building.

In this case the foundation of the building may remain stationary or to some extent involve in oscillations.

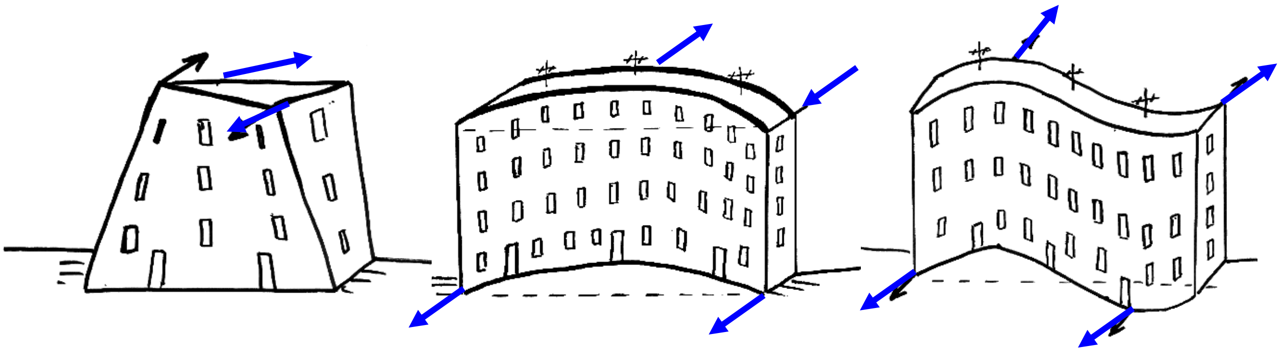
Method of the construction dynamic characteristics' determination according to their free oscillations [1-2] excited by shock impulse load, includes the following steps:

- excitation and recording of oscillations;
- calculation of their Fourier spectra;
- analysis of the Fourier spectra aiming to allocate the resonance peaks corresponding to the various forms of free oscillations;
- obtain the allocated resonance peaks impulse implementation for each form of free oscillations performing the inverse Fourier transform;
- diagram creation of various forms of free oscillations.



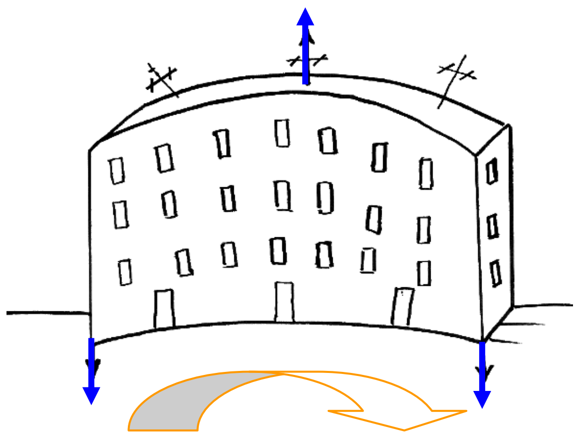
First form building oscillation *Second form building oscillation* *Third form building oscillation*

1a. Bending oscillation about the vertical axis of the building



Building torsional oscillation *Building second form torsional oscillation* *Building third form torsional oscillation*

1b. Bending oscillation about the horizontal axis of the building



1c. Bending oscillation on soil foundation

Figure 1. Main forms of oscillations of rectangular buildings

To register oscillations recommend the use of equipment, technical characteristics of which is given in Table 1.

№	Name	Technical Characteristics
1.	Accelerometer	Sensitivity 300 mV / m / s^2, frequency range 1-300 Hz.
2.	Accelerometer	Sensitivity 10 mV / m / s^2, resonant frequency 15 kHz.
3.	Amplifier	Measurement modes: acceleration, velocity, displacement; amplification from 1 to 10000 with a step increments of 10 dB; frequency range from 1 Hz to 20 kHz; number of measuring channels not less than 8; power supply 220 V or direct current battery.
4.	Analog to digital converter, ADC	Number of channels – not less than 8, resolution – not less than 12 bits, ranges of measured signals – ± 5.12 V, 2.56 V, 1.024 V, conversion maximum frequency – 300 kHz /channel.
5.	Personal Computer, PC	Must be equipped with the measurement information input and processing software. Parallel port availability.
6	Mean for excitation of oscillations, container filled with bulk material, tamper, hammer	Container (sack) weight up to 50 kg, equipped with cushion liner ; Tamper weight up to 12 kg, equipped with cushion liner; Hummer weight up to 2 kg, equipped with cushion liner and threaded hole for fixing an accelerometer

Table 1. Technical characteristics of equipment included in the measurement system

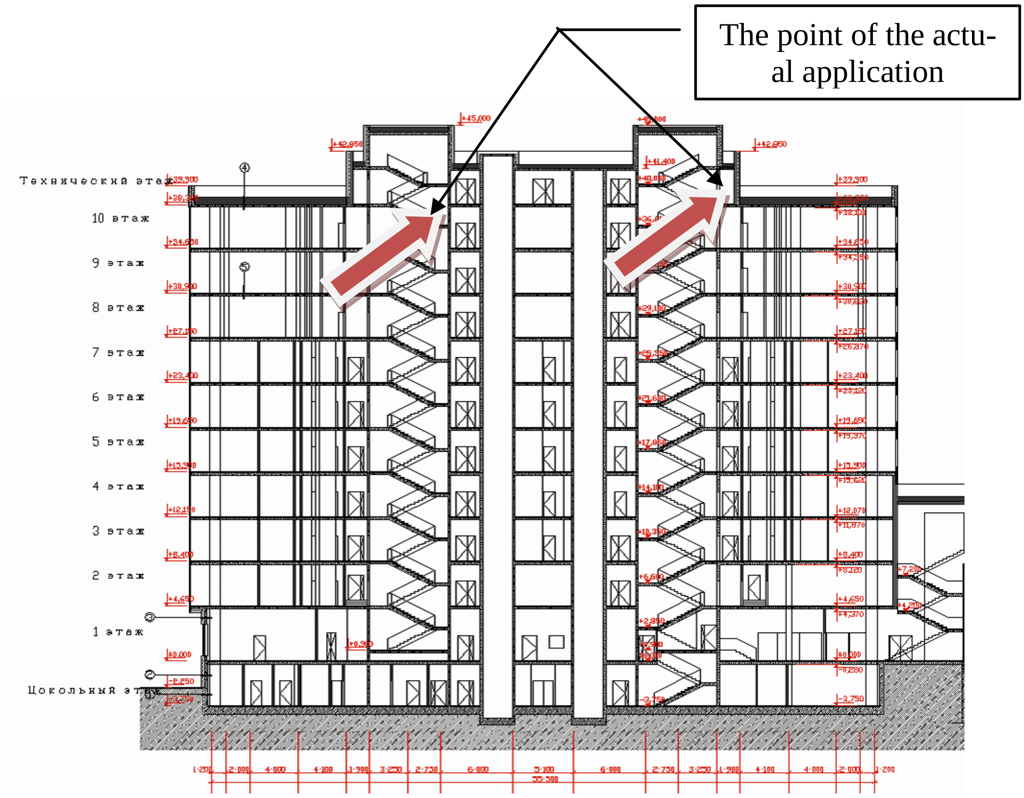
To improve the frequency detection accuracy and for diagram generation of higher forms oscillations from initial implementations which recorded under applied load at different points, use the ***superposition principle***.

The use the superposition principle applied to the impulse method of free oscillations building construction excitation lies in:

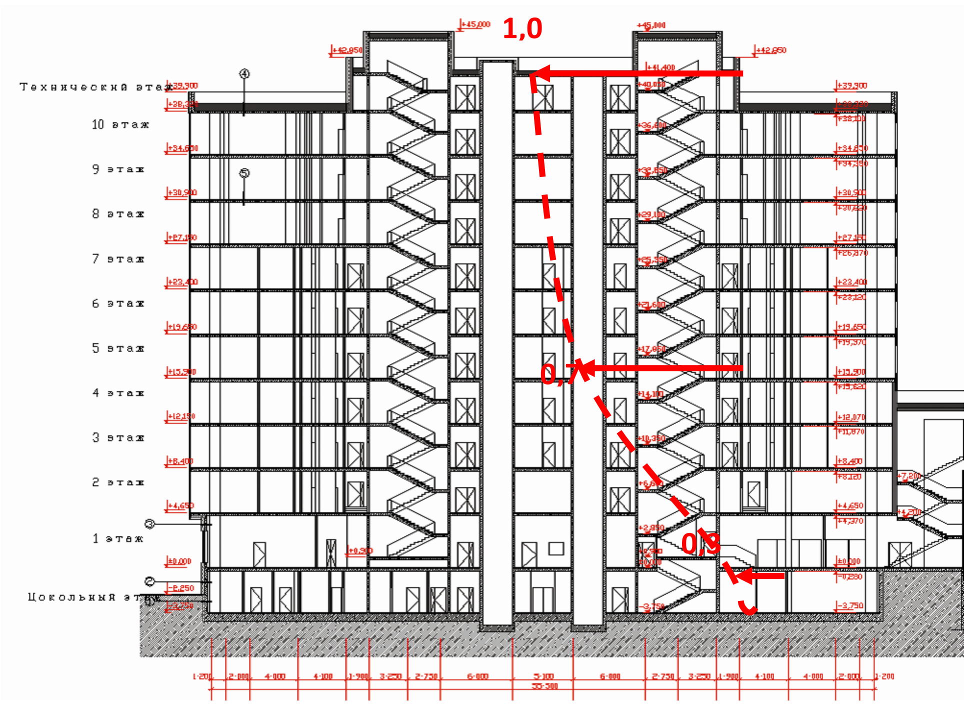
- excitation and recording of oscillations under action of impulse point load application at different points of the structure;
- addition (taking into account the action of the load) of oscillations recorded under applied load at different points of the structure (simulating the simultaneous application of the load in several points).

Processing of the obtained oscillations from the result of addition ***(combined implementations)*** in order to determine the resonance peaks corresponding to the analysed forms of oscillations is performed for each measurement point by adding or subtracting implementations obtained by separate crashes. The inclusion of the implementation in the combination with minus sign means that by the preparation of the combination modelled the action in the opposite direction. Implementations included in the combination, and the corresponding sign are selected in such a way as to amplify the oscillations in the direction of the applied load.

The following are examples of creating combined implementations for the horizontal alignment measurements according to the scheme of sensors arrangement (figure 2).



2a. Scheme of load application



2b. Scheme of sensors arrangement and form of oscillations

Figure 2. Creating combined implementations for the horizontal alignment measurements

The obtained combined implementation treated the same way as any initial implementation. Diagrams of torsional oscillations and bending oscillations along the front of the building showed in figure 3 and 4, respectively.

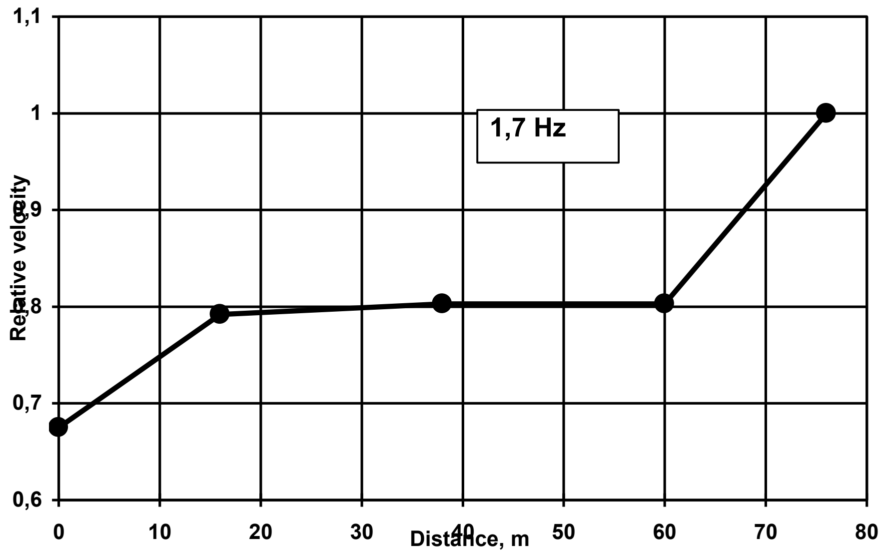


Figure 3. The diagram of oscillations (horizontal alignment, transverse direction, first tone)

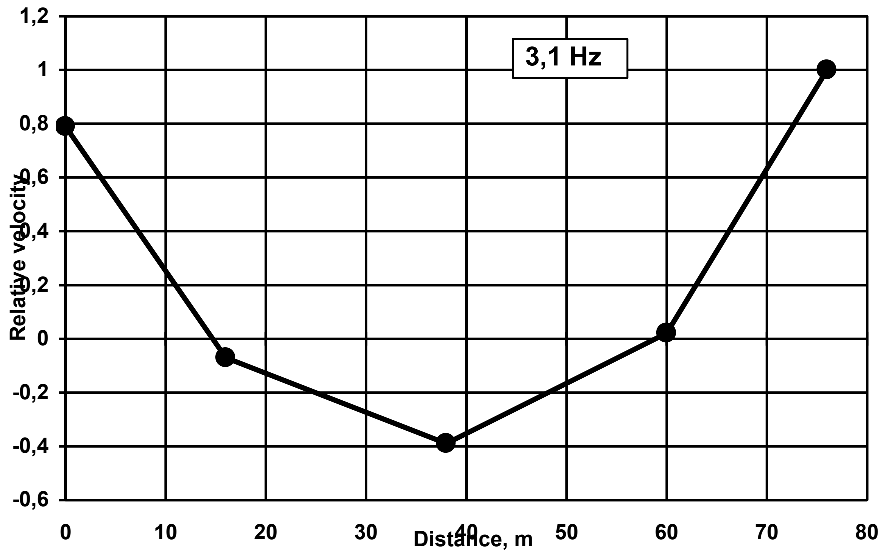


Figure 4. Diagrams of oscillations (horizontal alignment, bending along the front, first tone)

3 MATERIALS INTEGRATED CHARACTERISTICS EVALUATION WITH THE USE OF ELASTIC WAVES

For the evaluation of physic-mechanical material characteristics, the surface elastic waves method use is recommended.

The method of using elastic wave of acoustic frequency range [2] is intended to assess the state of materials of plane multilayer structures, which allow the installation of the measuring sensor on one of the surfaces. The length of the available structure surface for the surveys must be at least three depths of its sensing.

The material characteristics evaluation is executed in three stages:
- At the first stage the building construction surface reaction on the shock impulse action is determined;
- At the second stage the multilayer structures' reaction is theoretically modelled on the shock impulse action;
- At the third stage the measurement processing and results modelling as well as the comparative analysis of experimental and calculated dispersion curves (dependence of wave velocity on its length) of the surface waves and the adaptation of the acoustic model parameters to match criteria of the dispersion curves using the iteration method is performed.

By correlational dependence between the structure's material acoustic characteristics (usually the velocity of longitudinal waves) and its strength the actual strength characteristics of the structure materials and their compliance with the design values are assessed.

3.1 First stage – the surface waves measurement

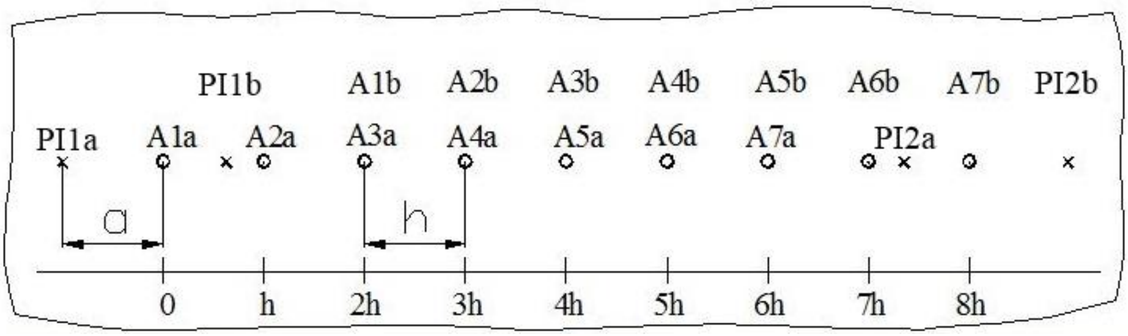
Building structure material acoustic characteristics are determined by oscillations, initiated by shock impulse load which is applied to the structure surface.

For the surface waves the velocity of spread at different wavelengths as well as the damping intensity and the presence of reflections are determined.

The absolute values of the elastic characteristics of the building construction material (elastic or shear modulus) or its different layers (for multilayer structures) are determined using the velocities values of longitudinal or transverse waves for the theoretical model, provided that the maximum coincidence is actually received and calculated dispersion curves of surface waves.

The strength of the structure's material or its individual layers is determined by the correlational dependence between the strength and velocity of longitudinal waves spread in it.

Typical measurement scheme is shown in figure 5.



A1-A7 – the points of installation of accelerometers
PI1, PI2 – the points of load application

Figure 5. The scheme of the surface wave measurements of the velocity in the structure

For generating the dispersion curves separate measuring rays are selected in different parts across structure surface and to build velocity hodograph measuring alignments are selected formed by several measurement rays (arrangement with the letters «a» and «b» in figure 5). In this case measuring rays are arranged in a straight line and shifted relative to each other along the measuring alignment by constant step.

The accelerometers installation locations surface is prepared for the installation of the sensors by cleaning the dust, loose paint, etc., if necessary, dried and coated with a thin layer of plasticine or special mastics.

The measuring layout represents a series connection of transducers (accelerometers), amplifiers, multi-channel analog-to-digital converter (ADC) and a personal computer (PC). One of the measuring channels is allocated to accelerometers installed on the shock loads to measure application moment and impulse value of shock load, and on structure surface.

To excite oscillations tamper (hammer) is prepared, on which the piezoaccelerometer is fitted. The duration of the shock impulse is regulated by cushion liner, which fixed to tamper.

Tamper is a wooden beam weighting of 10-12 kg, one of its end has hemispherical shape or is equipped with an elastic material spherical tip. The accelerometer for measuring the load is fitted to the second end of tamper. For excitation of low-frequency waves it is recommended to use a heavier tamper with soft tip (porolon, cellular rubber).

3.2 Second stage – the mathematical modeling

For cases where the investigated structure can be considered as a homogeneous half-space or homogeneous plate, the acoustic characteristics of the structure material are defined as follows:

- the surface wave velocity for the half-space is equal to the velocity of Rayleigh waves;
- the dispersion curve of the surface (bending) waves in the plate at a predetermined velocity of the Rayleigh wave in its material V_R and thickness of the plate is built by solving the analytical equation of the form:

$$\frac{\sqrt{1-\frac{V_u^2(0.87+1.12\mu)^2}{V_R^2(1+\mu)^2}}\sqrt{1-\frac{V_u^2(0.87+1.12\mu)^2(1-2\mu)}{2V_R^2(1+\mu)^2(1-\mu)}}}{\left(1-\frac{V_u^2(0.87+1.12\mu)^2}{2V_R^2(1+\mu)^2}\right)^2}= \tag{1}$$

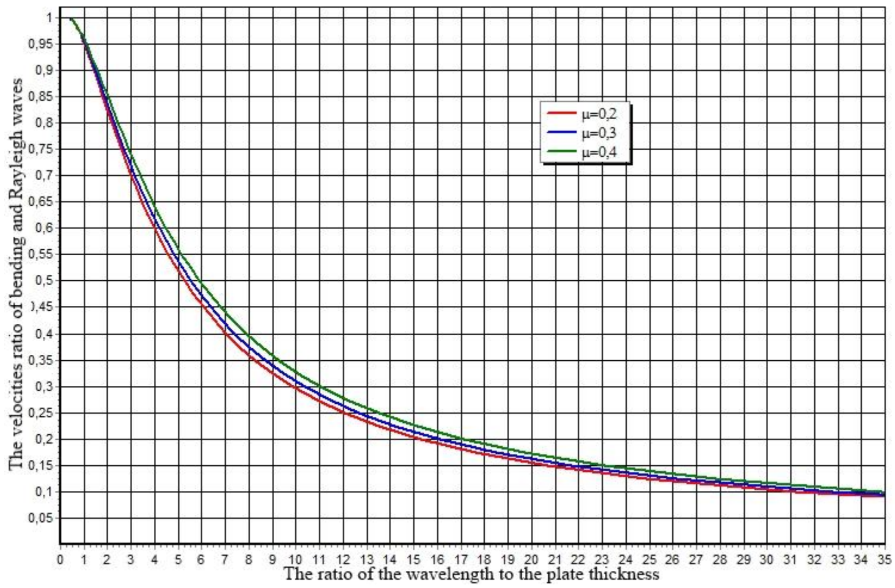
$$=\frac{th\left(\frac{H}{\lambda}\cdot\pi\sqrt{1-\frac{V_u^2(0.87+1.12\mu)^2(1-2\mu)}{2V_R^2(1+\mu)^2(1-\mu)}}\right)}{th\left(\frac{H}{\lambda}\cdot\pi\sqrt{1-\frac{V_u^2(0.87+1.12\mu)^2}{V_R^2(1+\mu)^2}}\right)}$$

where: H – thickness of the plate;
λ – bending wavelength;
μ – Poisson ratio;
V_u – phase velocity of the bending waves.

Mathematical modeling of multilayer structure reaction on the shock impulse action is based on the integration of the equations system with using numerical methods in the plane statement.

The transcendental equation solution results using the iteration method yielded text files containing the value λ / H in first column, in second - – V_U / V_R for values of Poisson's ratio of

0.1 to 0.5 through 0,1, which are used for the theoretical calculation of the dispersion curves for given values V_R, H и μ. Dispersion curves diagrams of homogeneous plate for different values of Poisson's ratio shown figure 6 (a – section λ / H from 0 to 30, b – to 10).



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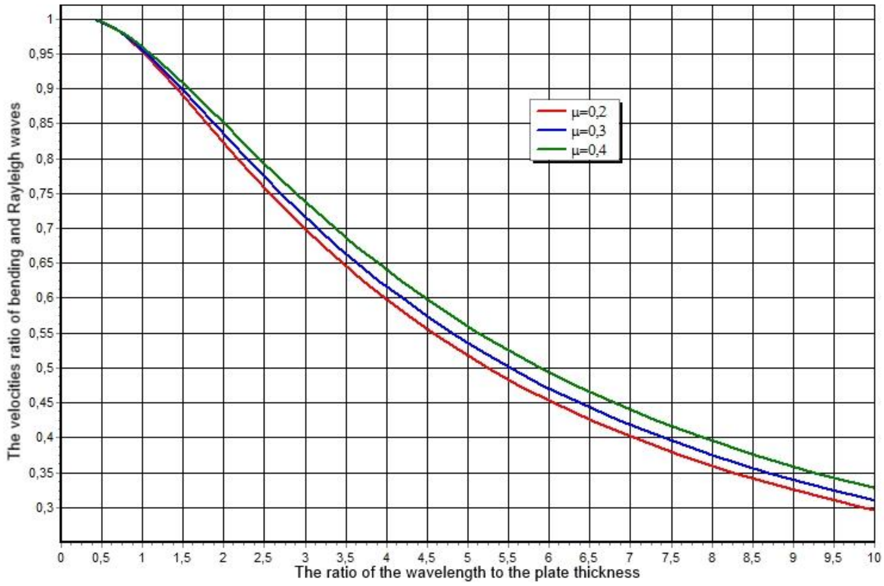

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Figure 6. Graphics of dispersion curves for different values of Poisson's ratio

3.3 Third stage – the processing of tests measurement

The initial realisations of wave processes are divided into monochromatic beams with a group of band-pass filters. For the selected monochromatic wave beams the time of wave spread successively for all measurement points are determined. The time is determined by the wave peaks or by intersection of the oscillations curve with the zero line.

For each monochromatic wave beam spread time instance ***the phase velocity of the wave spread*** (equation 2) and ***the length of its wave*** (equation 3) are determined:

$$V = L/t, \ (m/sec) \tag{2}$$

where: L – the length of the interval between the measuring points, on which the velocity is determined, m;

t – run time of the surface wave on this interval, sec.

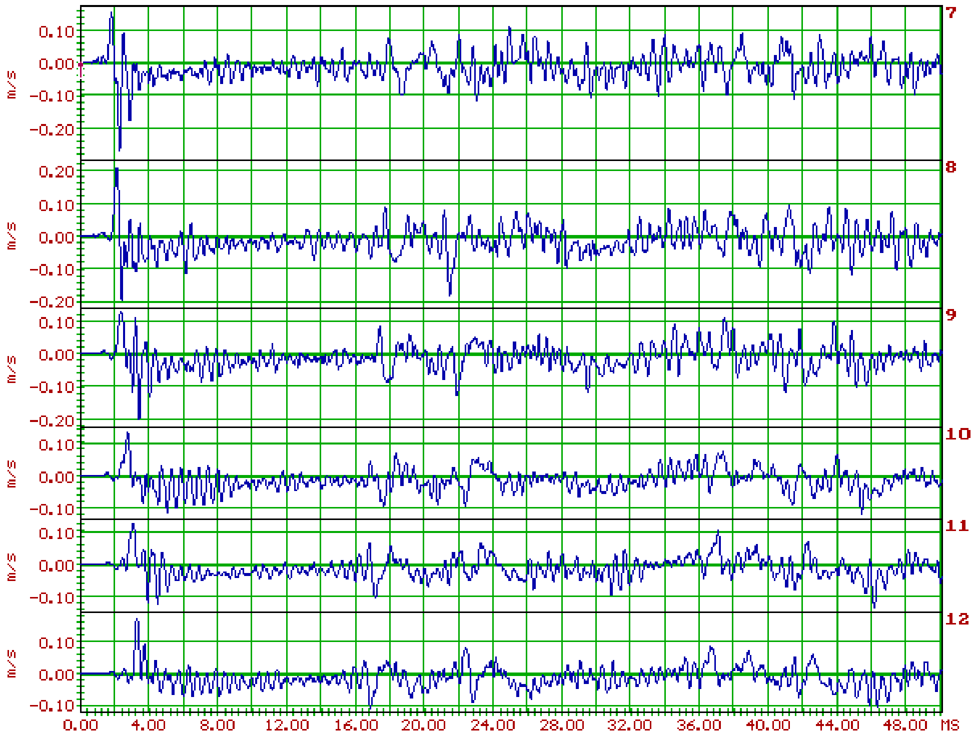
$$\lambda = T \bullet V, \ (m) \tag{3}$$

where: T – period of oscillations in the beam of monochromatic waves, sec.

For the dispersion curves generation along the section of the measuring ray by length not less than 4 steps accelerometers placement, each monochromatic beam of wave are processed to yield several instances of wave run time from the beginning to the end of the section. Then, in each case the velocity and the wavelength is calculated. Thus the obtained data "speed - wavelength" is filtered to obtain a smooth dispersion curve.

The velocity section along the length of the measuring alignment is determined by the average run time of the distance between each pair of measurement points in the measurement ray for all placements in both directions of wave spread, which enables the calculation of the wave velocity and its length. The entire range of obtained wavelengths is divided into 2-3 sections where the average velocity of the wave is calculated and the produced graph of wave velocity changes along the length of the alignment.

Figure 7 shows an example of the initial implementation and the selected beam of monochromatic waves with applied lines of wave run time hodograph.



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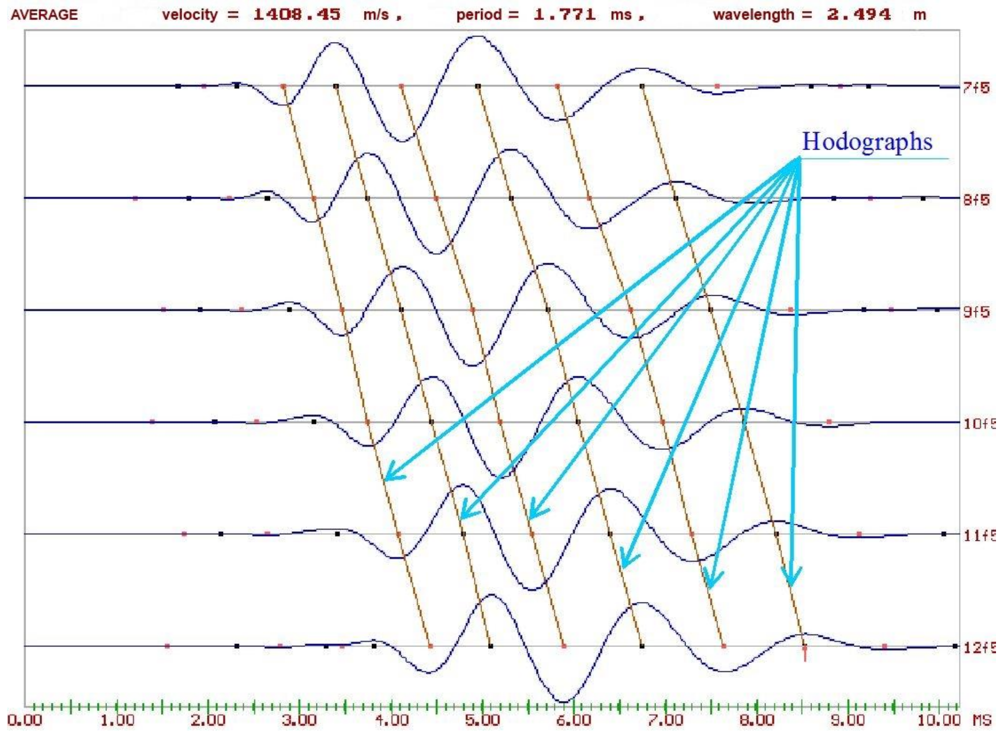

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Figure 7. Example of the initial implementation (a) and of selected monochromatic wave beam (b)

Manipulation results of wave processes of structural response by shock impulse action used to determine the acoustic characteristics of building construction materials by comparing the dispersion curves of surface waves, which obtained from the experimental and calculated theoretical responses to the shock impulse action.

The parameters (geometrical and acoustic) of multilayer building construction model selected by the iteration method and taking into account the results of the survey by other methods to achieve the best agreement between the theoretical and the experimental dispersion curves.

Elastic characteristics of the building structure materials are determined by the acoustic characteristics of its different layers obtained in the mathematical model as a result of its adaptation taking into account information about the properties of the structure material (density, Poisson's ratio, etc.) by the equations:

$$\mathbf{V_S} = \mathbf{V_R} \cdot \frac{\mu_d + 1}{0.87 + 1.12 \cdot \mu_d} \tag{4}$$

$$\mathbf{V_P} = \mathbf{V_S} \cdot \sqrt{\frac{2 \cdot (1-\mu_d)}{1 - 2 \cdot \mu_d}} = \mathbf{V_R} \cdot \sqrt{\frac{2(1-\mu_d)}{1-2\mu_d}} \cdot \frac{\mu_d + 1}{0.87 + 1.12\mu_d} \tag{5}$$

$$\mathbf{E_d} = \rho \cdot \mathbf{V_P^2} \cdot \frac{(1+\mu_d) \cdot (1-2\mu_d)}{1-\mu_d} \tag{6}$$

$$\mathbf{G_d} = \rho \cdot \mathbf{V_S^2} = \rho \mathbf{V_P} \sqrt{\frac{1-2\mu_d}{2(1-\mu_d)}} \quad (7)$$

where: V_S, V_R , V_P – the velocities of transverse, Rayleigh and longitudinal waves, m/sec;
E_d – elastic modulus of material, Pa;
G_d – shear modulus of material, Pa;
ρ – density of the concrete, kg/m^3;
μ_d – dynamic Poisson's ratio.

The strength of the structure material is determined by correlational dependence among the strength of the material and velocity spread of longitudinal elastic waves in it.

According to the test results using surface waves it is recommended to use the following data:

- the surface wave velocity hodograph of different types;
- the dispersion curves of waves on the most characteristic measuring rays;
- the main acoustic characteristics of the structure material:
  - the velocity of longitudinal and transverse waves in different sections of the structure surface;
  - respective to them elastic and shear modulus of the material;
  - the strength of the structure material in different sections of its surface.

To determine the concrete strength is recommended to use the calibration curve which shown in figure 8, and to determine the strength of brick masonry use data of Table 2 from [1].

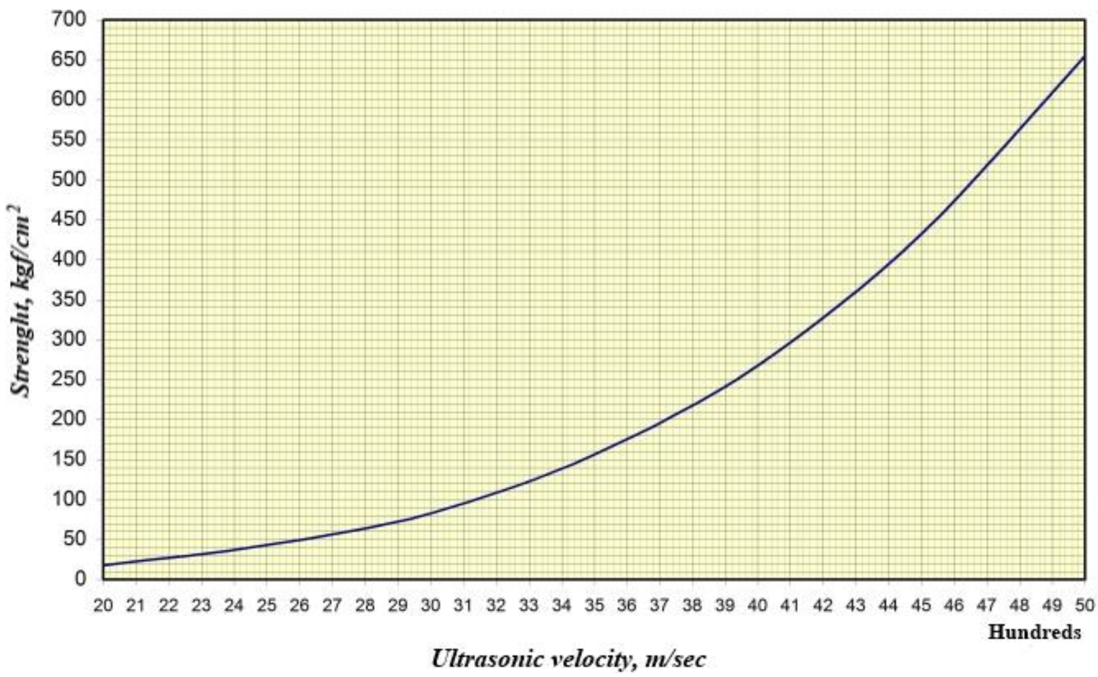

Figure 8. The calibration curve to evaluate the concrete strength

Characteristics of masonry	Rn, MPa	Vp, m/sec
High strength	4 ÷ 4.5	> 3000
Strength	3 ÷ 4	2000 ÷ 3000
Reduced strength	2 ÷ 3	1500 ÷ 2000
Low strength	1.5 ÷ 2	1000 ÷ 1500
Weak strength	1 ÷ 1.5	500 ÷ 1000
Very weak strength	0.5 ÷ 1	~ 500

$\boldsymbol{R_n}$ - the normative masonry compressive strength;
$\boldsymbol{V_p}$ - the longitudinal wave velocity of seismic-acoustic frequency range.

Table 2. Qualitative classification of brick masonry strength by velocity of seismic-acoustic range

For rigid cement masonry the given in the table Rm values, are multiplied by a factor 0,85.

4 DEFECTIVE AREAS DETECTION IN BUILDING CONSTRUCTION MATERIAL USING THE METHOD OF ENSOUNDING

For the defective areas detection in building construction material the use of ***method of ensounding*** is recommended, which is based on measuring of the acoustic waves spread velocity in the material: longitudinal or transverse. Determination of these velocities values in different points of the structure allows to reveal the defective areas and to evaluate the elastic characteristics of structure.

For the wave spread velocity field generation in the building construction the ***tomographic measurement results processing*** of wave run time between its sources and receivers is used.

For the structure's velocity section a ***database*** is determined, which represents a group of tables containing source and receiver of wave coordinates and wave run time between them.

The excitation and detection of longitudinal and transverse elastic waves can be performed using any means allowing a reasonable precision to fix run time of wave:

- source should provide a short wave front (up to 1 msec);
- receivers (sensors) must be wideband (1 - 3000 Hz) to measure this wave without dynamic distortion.

Algorithm for calculating the velocity sections of structure is recommended to organize as follows:

- introduce the table of wave run times between all sources and receivers;
- introduce the initial model of structure in the form of layered medium: the relative thicknesses of the layers, the relative velocity at the boundaries of the layers and inclination angle of the layers plane to the coordinate axes, in this case the velocity along the left edge of the first layer V_o is taken equal to 1;
- calculate the run times of waves on all the specified rays for a given structure model at the wave velocity equal to the specified relative velocities;
- calculate the velocity Vo as the ratio of sum run time of wave on all rays;
- calculate the mean square deviation of the experimental and calculated run times of waves;
- calculate the velocity section of structure determined by iteration method, in which the mean square deviation of the experimental and run times of the wave reaches minimum value;

- for ***"optimal velocity section"*** calculate the absolute values of the velocities at the layer boundaries and build the graph in the coordinates "distance (along the axis perpendicular to the plane of the layers) - the velocity of wave spread ";
- calculate the ray paths and build situational plan, on which the ray paths and isolines of wave spread velocity are applied.

Figures 9 and 10 show an example of generation the structure velocity section made of concrete and brick masonry.

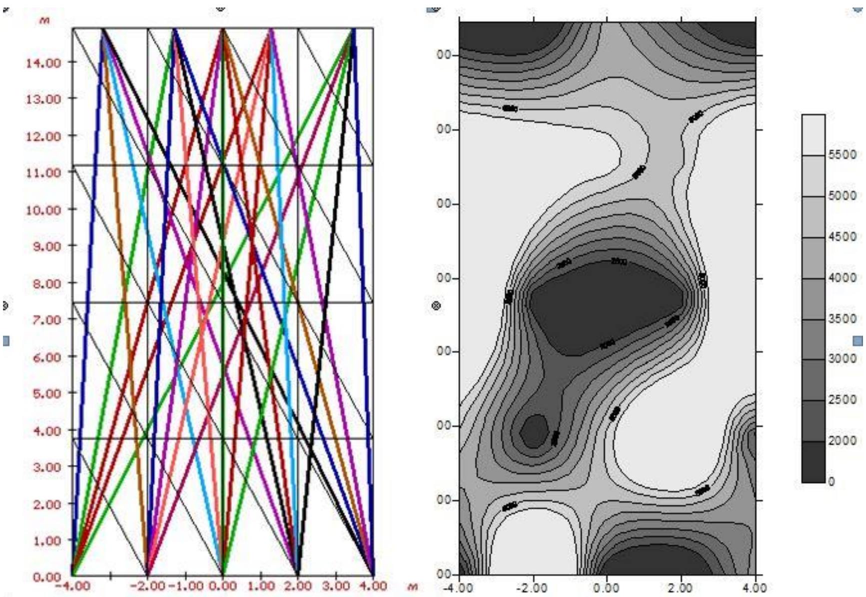

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Figure 9. The measurement ray paths (a) and velocity section (b) of concrete column

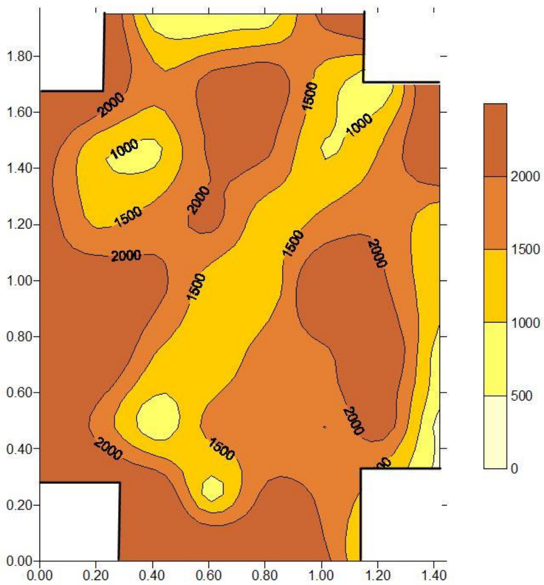

Figure10. The results of tomographic processing data of brick column by through ensounding

5 CONCLUSIONS

The presented methods above of nondestructive testing based on the use of free oscillations of buildings and building construction, as well waves of the acoustic frequency range initial data needed to determine the earthquake resistance and evaluation of technical condition of existing buildings and structures.

The results obtained during long-term practical research allow to recommend these methods to:

- evaluate the actual earthquake resistance of buildings and structures;
- determine of integral strength characteristics of building structures materials;
- evaluate the multilayer structures materials including the one-way access to its surface;
- evaluate the "structural strength" of building structure elements.

The proposed approach has been repeatedly used for mass surveys and certification of buildings and structure, monitoring the technical condition of particularly important objects, for research and practical purposes.

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