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THE METHOD OF FULL-SCALE MODELLING OF ACOUSTIC COHERENT IMAGES IN HYDROACOUSTIC TANK

Abstract. The method to perform a full-scale modelling of acoustic coherent images in hydroacoustic tank is proposed in the paper. The method is based upon a direct measurement of parameters of the acoustic field which was reflected from the studied model. The model simulates to a preset scale the specific surface features of the whole class of actual objects. The proposed method makes it possible to minimize time and resources as well as improve repeatability of the measured results irrespective of the ambient conditions, which ensures high reliability of the obtained data.

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МЕТОД ПОВНОМАСШТАБНОГО МОДЕЛЮВАННЯ АКУСТИЧНИХ КОГЕРЕНТНИХ ЗОБРАЖЕНЬ В ГІДРОАКУСТИЧНОГО БАКА

Анотація. *Розглянуто метод натурного моделювання акустичних когерентних зображень в гідроакустичному басейні. Метод засновано на прямому вимірюванні характеристик акустичного поля, відбитого від досліджуваної моделі. Модель відтворює характерні особливості поверхні цілого класу об'єктів. При використанні пропонованого методу досягається мінімізація витрат часу і коштів, а також повторюваність результатів вимірювань незалежно від стану середовища, що забезпечує високу достовірність отримуваних даних*

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МЕТОД ПОЛНОМАСШТАБНОГО МОДЕЛИРОВАНИЯ АКУСТИЧЕСКИХ КОГЕРЕНТНЫХ ИЗОБРАЖЕНИЙ В ГИДРОАКУСТИЧЕСКОГО БАКА

Аннотация. *Рассмотрен метод натурного моделирования акустических когерентных изображений в гидроакустическом бассейне. Метод основан на прямом измерении характеристик акустического поля, отраженного от исследуемой модели. Модель воспроизводит характерные особенности поверхности целого класса объектов. При использовании предлагаемого метода достигается минимизация затрат времени и средств, а также повторяемость результатов измерений вне зависимости от состояния среды, что обеспечивает высокую достоверность получаемых данных*

1. Introduction. In sounding systems, the images of studied objects are formed by processing their secondary wave fields that are of diverse physical nature. In a number of application areas such as hydroacoustics, medical and technical diagnostics and seismic acoustics acoustic wave fields are most preferable.

A secondary acoustic field reflected from the studied object contains all necessary information about the object's surface. A peculiar feature of such fields is a high coherence of the individual spatial components which leads to an interferential character of the acoustic image formation, their spotted structure and low spatial and brightness contrasts. Complexity of the processes governing formation of the secondary acoustic fields of objects and the processes of their handling in acoustic sounding systems determines the necessity to make further theoretical and experimental investigations.

Acoustic wave dissipation and propagation processes are studied by theoretical and applied acoustics and a number of fundamental papers [1,9,10] have dealt with them. Of a self-consistent significance in terms of the general range of problems associated with a study of acoustic images are acoustic tomography and holography [5,6,8]. The papers [4,7] are devoted to mathematical and simulation modelling of acoustic waves dissipation on complex surfaces of objects.

A problem of adequate simulation of acoustic image formation and processing required for remote sounding of the objects having complex surfaces is far from being solved. Primarily it is due to an essential distinction of such images from their optical analogues which exists as a result of the differences in spatial-and-temporal scales and the mechanism which forms secondary fields. Acoustic images are mainly of a coherent and glare nature [4-7] which hinders their study and processing. The known theoretical models simulating acoustic coherent images (ACI) based on the Kirchoff's approximation [1,6,10] do not allow to adequately describe acoustic wave reflection on complex shape surfaces. Performance of experimental studies devoted to formation and processing of acoustic coherent images is very important in order to specify theoretical models and are of practical value for obtaining parameters of studied objects which have complex reflection surfaces.

The objective of this paper is a full-scale modelling of ACI formation in a specialized hydroacoustic tank and a development of the information technology required to obtain such images for further desktop simulation.

2. Full-scale modelling in the hydroacoustic tank. The method of full-scale modelling (FSM) of ACI in a specialized hydroacoustic tank [2,11] is based upon a direct measurement of parameters of the acoustic field which was reflected from the studied model. The model simulates to a preset scale the specific surface features of the whole class of actual objects. An advantage of the proposed method is a similarity of the physical processes governing the formation of the secondary acoustic field pertaining to an actual object and its scaled model. Accuracy of the obtained data is determined by the accuracy of the model reproducing the object and the measuring equipment accuracy. As compared with the field experiment conducted in real environment, the proposed method makes it possible to minimize time and resources as well as improve repeatability of the measured results irrespective of the ambient conditions, which ensures high reliability of the obtained data.

The modelling scale M is chosen on the basis of the wave equation applied for an acoustic field potential [9,11] without taking attenuation into consideration

$$\frac{\partial^2\Phi(t,x)}{\partial x^2}=\frac{\partial^2\Phi(t,x)}{\partial^2(ct)}, \qquad (1)$$

where $\Phi(t,x)$ is an acoustic field potential, x is a grid coordinate of the space,
c is an acoustic wave propagation velocity.

Equation (1) will not change when shifting to new variables

$$x_m = x/M, \qquad c_m t_m = ct/M, \qquad (2)$$

which correspond to the modelling conditions made to scale 1:M ("m" index indicates that the variables refer to the physically simulated conditions in the hydroacoustic tank).

In accordance with (2), the criteria equation is

$$M = x/x_m = ct/c_m t_m. \qquad (3)$$

Should the scale modelling conditions (3) are observed, it can be guaranteed that the processes of reflection from actual objects as well as their scaled models are similar within the frame of the linear dissipation theory. In case signal pulses having a constant carrier frequency are used, the criteria equation takes the form of

$$\mathrm{M} = x/x_m = \lambda/\lambda_m = c\tau/c_m\tau_m, \qquad (4)$$

where λ is a wavelength of the coherent sounding signal, and τ is its duration.

Two necessary conditions for scale modelling follow from expression (4):

– if the actual object model is made to scale 1:M, then the scale for the acoustic waves length should be the same when conducting physical experiments (condition of equality of wave dimensions of the studied objects);

– if the propagation velocities under actual conditions and when full-scale modelling are the same, a duration of the simulated signal should be reduced M times as compared to the signal duration under actual conditions (condition of equality of the sounding field spatial and wave scales).

Hydroacoustic tank is a rectangular reservoir which contains special equipment and measuring instruments. The tank walls are provided with a special coating which ensures the minimum level of secondary reflection.

Standard equipment of the hydroacoustic tank (HT) should include a rotating coordinate device, an electric drive and a control panel for these components. The rotating coordinate device ensures positioning of the model in three planes, rotation of the model at a preset speed and its displacement in the preset direction. The model can be set to various angles at preset increments and its depth can be changed in longitudinal and transverse directions from the initial position. HT standard equipment allows of simulating changes of the observation angles of the object in three planes as well as its own angle position relative to the line of axis.

A standard set of the HT measuring instrumentation (Fig.1) should include: simulators 1 of the receiving antennas; simulators 2 of the radiating antennas; electric motors 3 of the rotating coordinate device; power amplifier 4; preamplifiers 5; amplifiers 6 incorporating an automatic gain control; master generator 7; frequency converter 8; quadrature component former 9; phase detector 10; amplitude detector 11; frequency detector 12; analogue-to-digital converter 13; digital data and control processor 14; and means of visualization and recording 15.

Simulators 1 and 2 of the antennas are designed as piezoelectric transducers. A set of antenna simulators is used for radiating the studied model and reception of the signals reflected from it. Piezoelectric cell sizes are selected within the range which provides for obtaining various widths of the sounding field direction diagram.

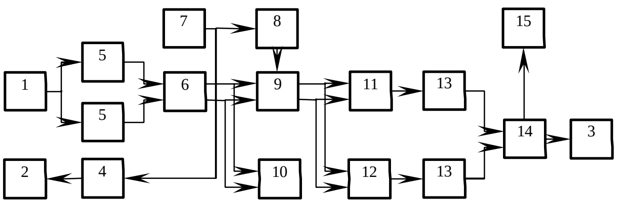

Fig. 1. Measuring instrumentation set

The HT standard equipment maintains three measuring modes:

1. Combined "reception-radiation mode".

In this mode an antenna simulator is used wherein the radiator and the receiver are arranged either in one case or separately, i.e. simulators 1 and 2 are fixed together and are secured as a block. The object model is displaced and/or rotates along coordinate axes.

2. Separate "reception-radiation mode I".

In this mode two simulators of the receiving 1 and radiating 2 antennas are used as minimum. These antennas are spaced apart by the required angle (distance) and are permanently fixed in the position necessary for the experiments. The object model is caused to rotate and/or move along the entire length and width of the HT.

3. Separate "reception-radiation mode II".

In this mode two simulators of the receiving 1 and radiating 2 antennas are used as minimum. Simulator 2 of the radiating antenna is permanently fixed and simulator 1 is caused to move around the permanently fixed model so that it describes a circle of the intended radius.

The HT measuring instrumentation can function in the modes allowing of emitting continuous and pulse acoustic signals. The sounding signal duration can be varied within the required limits at preset increments. The receiving channel sensitivity should provide for a required signal/noise ratio.

After being amplified in blocks 5 and 6, the received signals, enter either the input of quadrature component former 9 and/or phase detector 10, depending on the measurement task. Digital representation of the received signals is ensured by analogue-to-digital converter 13. Reflected signals in the digital form are processed by processor 14 in accordance with the preset algorithms. After processing the obtained results are controlled visually and are recorded in block 15. Mathematical support and software of digital processor 14 make it possible to statistically process the obtained signals – angular sections of the ACI in various operational modes and for various spatial configurations of the model and measuring instrumentation.

3. Methodology of measurements. The methodology of experimental studies in the HT consists of the methodology referring to calibration of the measuring instruments and of the measurement program developed to meet the preset task.

The measurement instrumentation is calibrated with the aid of an acoustically stiff calibration sphere of a preset diameter which is positioned in that point of the HT internal space where the studied model is supposed to be placed. The measurement instrumentation set includes a number of calibration spheres and cylinders of various dimensions. A specific type of the calibration sphere or cylinder is selected depending on the expected level of the reflected signals. The amplitude of the acoustic echo signals reflected from the calibration sphere is recorded together with the theoretical values of the effective reflection area (ERA) with due account of the assumed modelling scale, and then both are input into the computer memory.

The measured levels of signals reflected from the individual elements of the model surface are reduced to standard values in accordance with the interrelation:

$$\sigma = \sigma_0 \cdot \left(A/A_0 \right), \tag{5}$$

where σ_0 is the theoretical ERA of the calibration sphere with due account of the modelling scale, A – the measured level of an acoustic echo signal reflected from the studied model, A_0 – the measured level of an acoustic echo signal reflected from the calibration sphere, and σ is the model ERA with due account of the modelling scale.

The measurement methodology is chosen depending on the task to be solved. When performing full-scale modelling of the ACI formation processes, it is of the utmost importance to obtain the amplitude and spatial distributions of reflections from individual elements of the complex surface of the model which characterize its peculiar construction features. The method to measure such distributions is described below:

1. The measurement instruments are calibrated with the use of the calibration sphere which ERA corresponds to the expected ERAs of the elements of the actual object complex surface.

2. The studied model is positioned in the required place inside the HT with the aid of the rotating coordinate device where it is secured in the preset angular position and at the preset distance.

3. Simulators of the receiving and radiating antennas are positioned at the depth of the model, and the combined “reception-radiation mode” is activated.

4. The following parameters are preset with the aid of the computer: carrier frequency, minimum duration of the radiated pulse, receiver gate delay value which depends on the distance, sounding pulse repetition period, time sampling interval and averaging time.

5. The obtained averaged echo signal enveloping curves are entered in the database. Elementary reflections are selected and their relative amplitudes are determined in accordance with expression (5), same as the relative temporal (spatial) position in accordance with the maximum value coordinates.

6. The data to be indicated has the following format: the distance, model rotation angles, amplitude and spatial distribution of the individual reflections in relation to the chosen scale (5) and the reference point (geometric centre of the model or of the first glare reflection).

7. The measurements are repeated across all studied range of angles at the preset steps.

4. Measurement conditions and results. When conducting experimental measurements of the ACI angular sections, a scaled model was used which had a complex reflection surface which contained both the elements of spheres and cylinders, and the angular elements (edges, ribs, angles and jointed surfaces of various curvature). The model is acoustically stiff with the metal-coated reflection surface. The turning point of the model coincides with its geometric centre. The main measurements of the distributions pertaining to individual reflections versus the turn angle function have been made for the distance which corresponds to the spherical front zone of the signal. In the course of experiments additionally measured were the echo signal enveloping curves obtained with the use of the sounding pulses of various duration for all simulated angles of the model turn because the sounding signal pulse at the model position is not rectangular (Fig. 2). The actual shape of the sounding signal front is close to the Gaussian’s curve, which was taken into consideration when processing the measurement data.

The main results of the experimental study are represented as data arrays which contain, for each pair of the observation angles (bearing and elevation angles), the following ACI angular section parameters:

– number of glare reflections which level exceeded the HT noise level;

– amplitudes of glare reflections reduced to the reflection level of the equivalent calibration sphere;

– relative time delays taken in the absolute time scale between each fixed reflection and the model centre of the object (its rotation axis in the horizontal plane).

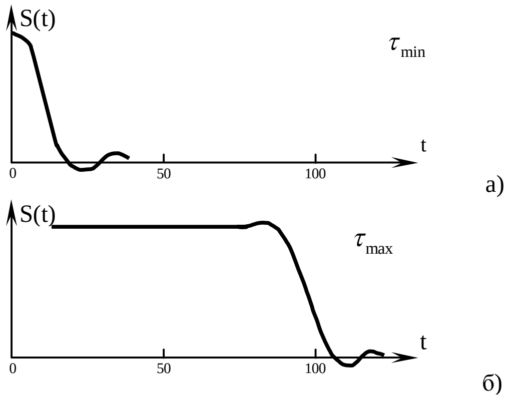

Fig. 2. Sounding signal shape

Measurements were taken within the ranges of the bearing angle variation from 0° to 180° at the preset steps for various inclination angles of the model.

Two-dimensional data arrays of the amplitude and spatial-and-temporal distributions of the individual reflections were used to simulate ACI at various spatial contrast [3]. In addition, the experimentally measured echo signal envelopes were recorded so as to be correlated later with the computer-simulated results.

The achieved measuring accuracy is conditioned by the reduced HT noise level and equals, in the calibration mode, $a = 4 \cdot 10^{-12} \cdot A_0$, where a is the average quadrature value of the HT noise level, A_0 – the measured level of the echo signal reflected from the calibration sphere. The reflections of the lower level were not recorded by the measuring instruments.

Time interval measurements were made with an error not exceeding 1 μs. To determine the instant reflecting centre position of each reflection, the maximum position of the echo signal enveloping curve was fixed. Obtained results were averaged on the basis of several thousands of realizations.

Measurements of the reflection distribution in the HT are shown in Fig. 3.

An important new feature of the full-scale modelling method is the additional measurement of the sounding signal at the place where the model is positioned which is required to establish the actual shape of the field coming to the model surface. Full-scale modelling in the HT was performed for a case typical for the acoustic sounding systems wherein the characteristic dimensions of the examined surface irregularities exceed the acoustic oscillation wavelength many times.

The model surface which ACI was studied in the HT is described as a determinate function, the source of the monochromatic sounding field and the receiving aperture coincided in space. Under described conditions the secondary field is a superposition of the fields of point sources located on the surface which amplitudes are proportionate to the main radii of the model curvature. Such point sources sequentially shape the reflected field when interacting with the sounding field. So, a theoretic assumption concerning the secondary field nature has been experimentally substantiated.

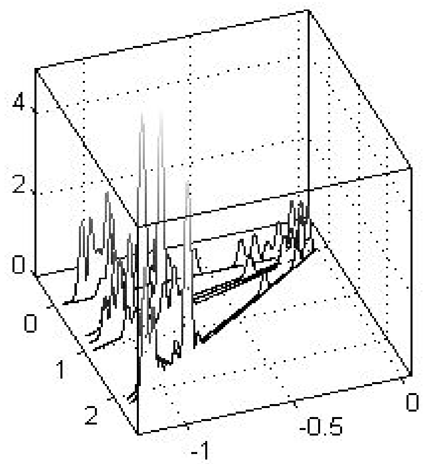

Fig. 3. Isometric view of angular sections of the reflection distribution of individual parts of the model surface

According to the experimental measurements and their statistical processing it can be concluded that distributions of the reflections relative to the changes in the angles of model observation and the changes of the distance between the model and the measuring instrumentation is highly stable. Relative position of such reflections correlates with characteristics of the model surface (Fig. 3) and the relations between the amplitudes of individual reflections correspond to the surface curvature radii. Thus, within the conditions of full-scale modelling in the HT, the theoretical concepts of the processes which form the secondary coherent field of the object having a complex reflection surface have found their experimental confirmation: the secondary acoustic field of the surface described by a determinate function is a coherent aggregate of individual reflections which interfere among themselves.

5. Conclusion. A method of full-scale modelling in the specialized hydroacoustic tank is an effective means to obtain the main attribute forming characteristics of the studied object acoustic images. The developed method makes it possible to obtain highly reliable amplitude and spatial-and-temporal distributions of the ACI angular sections required for computer simulation of secondary acoustic fields of the objects having complex reflection surfaces for various types of sounding signals and observation angles.

Prospects of further studies are linked to a computer simulation of ACI at various spatial resolutions based upon the obtained experimental data, and to a solution of the interpretation tasks.

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