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PHASED ANTENNA ARRAY RESOLUTION ENHANCEMENT FOR INSPECTION OF UNDERWATER CROSSINGS OF PIPELINES

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Abstract – It is shown that available methods and devices for testing leakage of underwater pipelines do not allow to determine a defect location to high accuracy. In this view, it is suggested to receive the signals coming from acoustic emission by transducers of two-dimensional phased antenna array (PAA). It is demonstrated that an optimal way of PAA signal processing is the combination of pair multiplication with the subsequent algebraic summation of signals from several transducers. On the basis of the suggested method, the device PAL-121 was developed, which allows to determine a location of defects by means of two-dimensional representation of acoustic field of the inspection space.

Keywords: acoustic emission, phased antenna array signal processing, underwater pipeline, ultrasonoscopy

1. INTRODUCTION

In huge extent, continuous oil delivery to users depends on no-failure operation of such complicated pipeline sections as underwater crossings through rivers, lakes, marshes and conservation reservoirs. One of the reasons of failures of underwater pipelines is their loss of containment and steady defects precipitation (leaks). Before-the-fact prevention of the defects results in a decrement of fatal ecological consequences and irreplaceable losses of liquids transported.

At present, techniques used for the leakage test of trunk pipelines can be divided into two classes [1, 2]:

- methods of the direct inspection during a pipeline operation. They are as follows: linear balance, pressure decline, negative air-blasts, comparison of fluid consumptions, and comparison of changes of fluid consumptions speed;
- methods of the indirect inspection by physical symptoms appearing due to leaks precipitation. The methods are, for example: visual inspection of a pipeline and environment, and periodic acoustical surveillance of the pipeline.

Methods of the first class are mainly applied for detection of major accidents (leakage) affecting a process of pipeline transportation. They are characterized by too low leakage sensitivity. Additional deficiency of the methods is null information on a defect location. Methods of the second class [2, 3] are used for detection of small breaks, in particular, in underwater pipelines. The most perspective among them technique is the acoustical passive method which is based on a registration of audible signal emerging under the outflow of a liquid through the defect in the presence of an overpressure in the pipeline [3-6]. In comparison with others, the method has the following advantages: it is applied for both small and large leakage in underwater crossings of oil and gas pipelines under construction and/or during their use; it is safe for the environment and maintenance staff; it provides the real time information processing with high confidence.

2. PROBLEM STATEMENT

The acoustical effect under the outflow of gaseous and liquid media through the defect has been widely used for industrial and field inspection of a linear part of the trunk pipelines, heat exchangers of power reactor facilities, high-pressure vessels, water turbines, etc. [2, 7-9].

The acoustical method has been intensively developed in connection with working out means for leakage test of underwater pipelines which are based on noncontact registration of acoustical radiation from a face of the pipe.

Generally, the problem of pipeline defect detection can be solved in two stages.

First, one has to ascertain the fact of a defect existence. If there is a visual easy access to a defect location then it appears quite enough to fix the defect. In case of underwater pipeline sections, this method is inapplicable. There are several ways to ascertain the fact of a defect.

One of them can be implemented by means of the leak detector AET-1 which is developed in Research Institute of Introscopy at the Tomsk Polytechnic University and produced commercially [9, 10]. The device is intended for detection of location and character of through defects in underwater pipelines during their hydraulic test in processes of construction and operation. The leak detector has the following specifications: accuracy of position finding of defect is not worse than ± 0.1% of a reservoir depth; threshold sensitivity (on a water discharge) is 8 l/h; setting depth of the pipeline is up to 30 m.

Other approach is implemented in the developed in USA [11] equipment. It includes a magnetostrictive transducer which is hermetically enclosed and towed by boat with a cable along a line parallel to the pipeline axis at a height of 36 m from a bottom and at a distance of 75 m from the pipeline. The pipeline with an interior diameter of 178 mm, located on a sea-bottom at a depth of 40 m, was prefilled under pressure 12.2 MPa. A directional diagram of the transducer had horizontal angle of 2 degree and vertical angle of 10 degree. Speed of the boat was 7.4 km/h. Acoustical radiation was recorded in the frequency range (50±2.5) кHz. Sensitivity of the method by a water discharge under a test pressure was 9 l/h.

In the capacity of the acoustic transducer in both of the leak detectors a near-omnidirectional antenna was used. This enables to detect easily pipeline leakage, but does not allow to determine a defect location to a high accuracy that is so necessary for quick and high-quality repair of the defective section.

Thus, the second stage of the given problem solving consists in application of the equipment having sufficiently large resolving power. The remainder of the paper is devoted to a way of the stage implementation.

3. PHASED ANTENNA ARRAY RESOLUTION ENHANCEMENT

The resolution of a leak detector can be increased by means of applying a multi-channel equipment which enables to carry out not only the inspection in a single point, but spaced sensor measurements. A perspective trend in development of such devices is the application of the phased antenna arrays (PAA). In spite of rather high complexity of acoustical and electronic chains, its defect-measuring and service characteristics provide high accuracy, efficiency of the inspection and serviceability.

Traditionally, resolving power of PAA is increased by extension of number of antenna elements. Clearly, it results in essential complication of the block diagram, decrease of reliability, grow in cost of the equipment development and manufacturing. Other way consists in use of the special distribution law of partial signals amplitudes and phases of the antenna elements. Usually, in the capacity of the distribution law one uses various kinds of polynomials, for example, Chebyshev polynomials [12]. It allows to lower some number of PAA elements and to reduce a level of the directional diagram side lobes. One of obvious deficiencies of the solution is too difficult ensuring of high accuracy of the polynomial factors. Besides, such the distribution can be hardly implemented.

Authors of the paper have proposed a method of PAA resolving power enhancement that consists in a combination of multiplication partial signals and addition of results of this multiplication. Let us show that, in this way of the signal processing, the width of principal lobe of the directional diagram becomes less than in simple summation of the partial signals. For linear equispaced antenna array in a zone of Fraunhofer diffraction the following formulae can be written

$$A_p(t,F) = \prod_{n=1}^{N} \sin(\omega \cdot t + n \cdot F)\,, \tag{1}$$

$$A_s(t,F) = \sum_{n=1}^{N} \sin(\omega \cdot t + n \cdot F)\,, \tag{2}$$

where $A_p(t, F)$ and $A_s(t, F)$ are input signals of PAA under multiplication and summation accordingly; N is number of elements in antenna array; F is the signal phase, n is the current number of antenna elements; t is current time; ω is the frequency of acoustical radiation.

The amplitude ratio is conditionally accepted to be equal to 1. Equations (1) and (2) are valid if PAA elements are much less than wave-length of the acoustical radiation.

It is obvious that in order to estimate the spatial resolution it is necessary to obtain explicit analytical dependence of the signal amplitudes $A_p(t, F)$ and $A_s(t, F)$ on phase F which, in turn, is defined by location of the inspection point. For (2), corresponding expressions are derived in a general form, and in the normalized form are called the antenna array multiplier [12].

Analytic representation of (1) in a form of finite product does not exist. Therefore, it seems to be expedient to carry out the numerical computer analysis of equations (1) and (2) in graphical form. Fourier transform was applied to implement these calculations. It is interesting to note that (2) includes only linear operators with regard to the acoustical radiation frequency ω. Therefore, for its analysis, it is enough to define an amplitude multiplier for a first harmonic of frequency.

As a result of PAA signal processing by suggested algorithm, intermodulation components of various orders frequencies ω are generated depending upon n. Besides, a final signal certainly includes a constant component which is considered to be useful information one.

For a greater convenience, let us express the phase of signals accepted by PAA elements via a direction deflection angle to the inspection point. Zero phase corresponds to the PAA line of symmetry.

In the Fig. 1 one can see that the directivity of the system described by (1) is higher than one described by (2). Assume that PAA resolution is represented by an angle value of main maximum of a resulting signal on a level 0.5. Then, by results of the graphical analysis, it is possible to write:

$$\alpha_6^{\Pi} = 0.38\alpha_6^{\Sigma}\,, \tag{3}$$

where the subscript specifies number of the array elements. Their increase up to eight results in an essential decrease of the main maximum and increment of side levels to values where it is possible to speak about the system directivity loss. This phenomenon is observed, first of all, under mutual multiplication of the received signals. Therefore, it is expedient to exclude the antenna systems containing more six elements from the further consideration. This is also very important in practice as the processing algorithm assumes mathematical procedures which complexity essentially increases with increase in number of PAA elements.

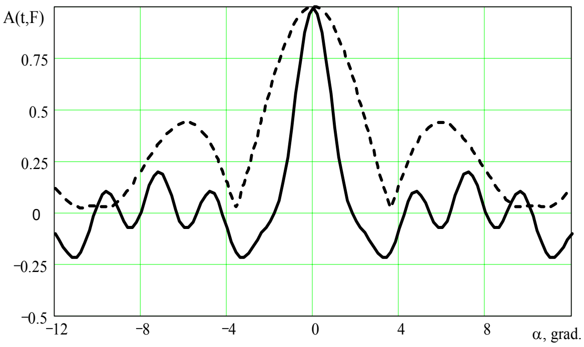

Fig. 1. Directional diagrams of the antenna array consisting of six receivers (PAA elements);
——— signal processing algorithm described by (1);
--------- signal processing algorithm described by (2).

Prominent feature of the array operation is presence of side lobes what is illustrated by Fig. 1. One can see that the amplitude of the signals received by an array from side directions is rather significant in any processing algorithms. It is necessary to emphasize prominent feature of the suggested algorithm. In contrast to the traditional method where the signal has only positive values, in our case the slowly varying both positive and negative voltage can be recorded. This allows to somewhat lower a level of side lobes of the directional diagram.

More cardinal solution to decrease the level of side lobes is attained by change of the processing algorithm. A combination of pair multiplication with the subsequent summation of the obtained results is offered. It is necessary to emphasize that just constants component of the products are summarized. The result of such solution is shown in Fig. 2, and an analytical form used for modeling is

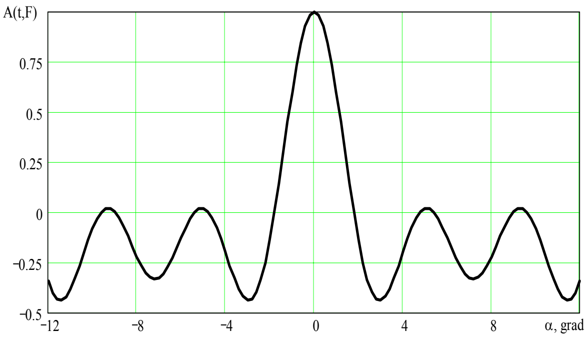

Fig. 2. Directional diagram of the antenna array consisting of 6 receivers with signals processing algorithm described by (4)

$$A(t,F)=\sum_{n=1}^{\frac{N}{2}}\left[\sin(\omega\cdot t+F(-n))\cdot\sin(\omega\cdot t+F(n))\right], \qquad (4)$$

where $F(-n)$ and $F(n)$ are signal phases of the elements located at the left and right of the PAA line of symmetry.

The decrease of side lobes level can be explained by the algebraic summation where positive and negative components are mutually compensated, and residual negative voltage is neglected. In this case, the resolving power is approximately twice more.

4. USE OF THE RESULTS ACHIEVED

The processing algorithm of audible signals is implemented by electronic units. They realize signal reception, amplification, conditioning, and also necessary mathematical operations. The electronic chain provides control functions of the whole equipment on the suggested algorithm.

Common structure of this kind of equipment assumes the three interdependent parts:

1. acoustic chain;
2. electronic chain; and
3. visual graphical indicator.

Based on this structure, there has been created the device of passive acoustical location PAL-121, which is connected to computer realizing formation of a visual image of the received acoustic emission signals. This provides a possibility for application of a lot of specific methods of information processing. For example, averaging by splines with the purpose of increase of signal-to-noise merit; taking a signal logarithm/antilogarithm or calculation of other functions. One more advantage of such complex consists in an opportunity of archiving sessions of the inspection for their subsequent analysis.

As preliminary researches have shown, the most informative form of a visual picture on the screen is a pseudo-3D graph representing an area of the simultaneous inspection, where the axes *X* and *Y* are spatial ones, and the axis *Z* represents the signal amplitude. This enables to estimate a location of a signal source in the scope of the inspection area.

With the purpose of check of formation of a visualized surface of equal phases, preproduction testing of the device PAL-121 has been carried out. Block-diagram of the test installation is shown in Fig. 3.

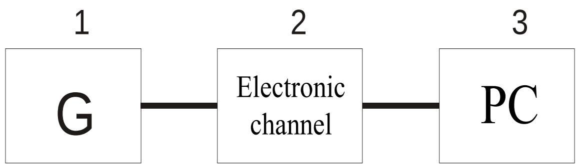

Fig. 3. Structure of the test installation: 1 – precision generator of low-frequency signals G3-110; 2 – electronic chain of PAL-121; 3 – computer.

Fig. 4 shows testing result as of a visual image of a surface of equal phases.

5. CONCLUSION

The results of the described above theoretical researches and laboratory tests allow to draw the following conclusions:

1. Multiplication of partial signals of PAA results in increase in its resolving power in comparison with a traditional way of signal processing.
2. The optimal way of the PAA signal processing is the combination of pair multiplication with the subsequent algebraic summation of slowly varying components of the product.
3. The surface of equal phases is placed in the center of a visualized inspection area on the computer monitor.
4. The size of the surface of equal phases on a level 0.5 of the maximum value is approximately 1.7 degree; the inspection area on the whole occupies 9.4 degree).
5. Magnitude of the side lobes does not exceed 8 %.

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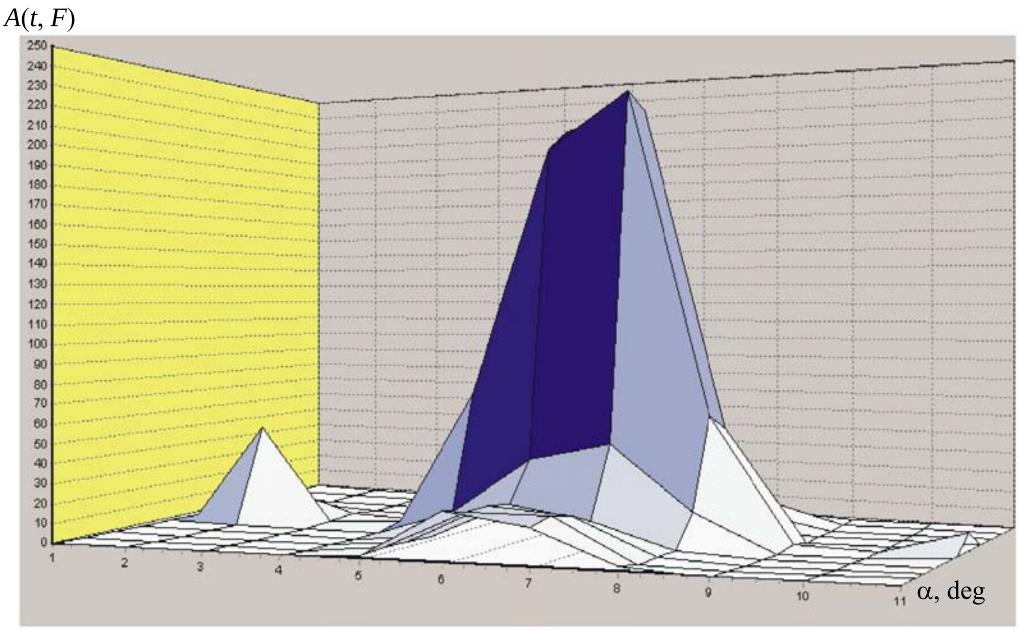

Fig. 4. A surface of equal phases