ASSESSING THE IMPACT OF THE STRUCTURAL ELEMENTS ON THE ACOUSTIC PARAMETERS OF A TWO-LAYER SONAR ARRAY, THE OPTIMIZATION OF ITS DIRECTIVITY PATTERNS

Gorelov Andrey
JSC «Concern «Oceanpribor», St. Petersburg, Russia 197376
e-mail: Gorelovacoustics@mail.ru

In this paper has shown the two-layer antenna array. Such antennas are useful in terms of the possibility of forming various kinds of directivity patterns, including cardioid pattern. Cardioid directivity pattern is used in acoustics to reduce the level of the signal coming from the back side. The principle of this formation is that, the signal from one layer of the signal prior to subtraction of the second layer on the delayed time equal to the transit time of the acoustic wave the distance between the layers of the antenna. This forms a fairly low level in the rear half.

In this paper we consider the two-layer sonar array based on the flexural transducers of finite size. The antenna consists of two filled with polyurethane hose located one above the other. In connection with its non-zero geometric dimensions pressure receivers shades each other. This leads to the need to adapt the directivity pattern. In this paper, both theoretically and experimentally investigated peculiarities of cardioid directivity patterns for a two-layer structure of the antenna. It is shown that the "path" of the sound wave between the individual receiving channels forming the cardioid directivity pattern in the actual antenna is greater than the hypothetical antenna consisting of dot elements. Just shows that a significant contribution to the increase in time "path" makes waves transverse elasticity of the material aggregate. In the experiment and in the calculation used polyurethane with the known properties and the speed of propagation of longitudinal waves equal to the speed of sound in water. Experiments were carried out using National Instruments hardware in anechoic hydro-acoustic pool. Building a computer model implemented in the software environment ANSYS.

1. Introduction

Any speaker system certainly has in its composition receiving or transmitting device antenna exciting acoustic wave in a production environment or, on the contrary, its host of the environment. From the antenna depends on the quality of the whole sound system in general. Specialized antenna system can be installed in places with very harsh operating conditions, therefore, their designs are quite complex. A vivid example of antenna systems installed on underwater media and used for purposes of security, search and orientation. The design of these antennas are often complex, and their development is fraught with a number of technological problems. Step to creation of such systems is a preliminary calculation of their parameters using computer simulation.
Construction of hydroacoustic antennas can be various, including multilayer. Such antennas are useful for the formation of a various sort of directivity patterns, including cardioid characteristics. Cardioid directional used in acoustics to reduce the signal coming from the back side. The principle of this formation is that the signal from one layer before subtraction of the signal of the second layer is delayed for a time equal to the time of the mileage of a sound wave is the distance between the layers of the antenna. Thus forming a rather low level in the back of a half-space.

In this work, examples of real-double layer hydro acoustic antenna shown that in connection with its non-zero geometric sizes receivers of pressure shades each other. This entails problems in the formation of the directivity patterns.

2. The geometry of a real antenna

Based on bending piezoelectric converters, antenna consists of two filled with polyurethane rubber tubes placed one above the other. Tubes are located in the support structure, which has the possibility of suspension of the antenna in a vertical and horizontal position. Receiving channels of the first layer are opposite the corresponding channel in the second layer. The distance between the centers of the layers is equal 0.051m.

The antenna geometry shown in Fig. 1.

![Figure 1. Prototype of antenna](image1)

Intake of each hose module are two piezoelectric bending receiver of pressure diameter 0.066m. In the experiment and calculation used polyurethane with known properties and the velocity of propagation of longitudinal waves equal to the speed of sound in water.

3. The experiment and the problems

To estimate the parameters of the antenna was made a series of experiments in anechoic hydro-acoustic pool. The composition of the measuring bench and the geometry of the experiment is shown in Fig. 2.

![Figure 2. Measuring bench and the geometry of the experiment](image2)
On the Fig. 2, the following notation are used: A – researched antenna, B – emitter, C – measuring hydrophone, 1 – multichannel measurement system of National Instruments company PXIe-1075 with NI 8133 controller and DAQ 6368, 2 – PC, 3 – oscilloscope Fluke 225c, 4 – power amplifier CROWN 600 XTi, 5 – electrical transformer.

The distance from the measuring transducer to the receiving antenna was chosen based on their upper frequency working range and conditions of the far field. The distance was set 4.2m. Antenna was placed on supporting bars vertically at a depth of 14m. There was the opportunity of turn of a rod with the antenna in a horizontal plane with the purpose of research the directional characteristics.

Receiving and emitting paths are checked for linearity and satisfy all the metrological requirements. Speed of rotation of the antenna was 1 degree per second. Time averaging of the signal in the third-octave band was chosen to be 0.5sec. The level of signal at this time averaging exceed the noise level 60 dB, as shown on the Fig. 3. The level 0 dB is equal 1volt RMS.

It is known\(^1\) that on the formation of cardioid directivity patterns, the delay between cardioid elements pair are chosen according to the formula: $\tau = k \cdot d \cdot \cos \theta / \omega = d \cdot \cos \theta / c$, where $c$ is the speed of sound, $k$ – wavenumber, $d$ – the distance between receivers. In work it is assumed that the speed of sound in water $c=1500$m/sec. It is known that the speed of longitudinal waves used in the polyurethane is equal the speed of sound in water. Based on the geometry of antennas required for formation of a cardioid directivity patterns with a “zero-level” in the back of a half-space $\theta=\pi$, the delay time is equal to 33.3$\mu$s. The shift of the signal of the second layer in the formation of the directivity pattern of the type carried out in the time domain.

Figure 4 presents the experimental normalized amplitude characteristics of the antenna.

\(\text{Figure 3. The spectrogram, signal 1.6kHz}\)

\(\text{Figure 4. Experimental peak directivity}\)
The blue line shows the amplitude directional characteristic layout when the formation time delay equal 33.3μs, black line-78μs. The green line shows directional dipole type.

From Fig. 4 we see that in the case of the dipole formation characteristics of direction does not occur features. The angular distance between zeros characteristics is given 180°, and the width of the directional characteristics equal to 90°. When forming cardioid characteristics over time shearing 33.3μs in the back of the half-space is observed maximum of a rather high level (-15dB). Zero in the back of the half-space is formed only by significant increase in the delay time to 78μs, the black line. The width of the directional characteristics with time shifting 33.3μs equal 116°, and at 78μs – 134°. In the case of classic cardioid characteristics width should be 120°.

To estimate the time of mileage acoustic waves between receivers of different layers was measured phase directional characteristic of one layer and the second. The phase difference of the directional characteristics on the corners, its normal drop wave permits at a specific frequency measurement to calculate the time of the passage of waves. Figures 5a,b) shows the amplitude and phase characteristics of direction.

![Figure 5. Amplitude and phase characteristics of channels antenna](image)

Figure 5a) green color shows the signal level measuring hydrophone for all time of carrying out of experiment; black and blue color shows the peak directivity single channels of the first and the second layers; red color shows cardioid directivity pattern characteristic. Time shift between the signals layers to produce cardioid was equal to t=33.3μs.

A reference signal for the construction of the phase characteristics of direction was the signal from the receiver of the first layer of the antenna. So on the Fig. 5b) phase characteristic of this signal to itself is straightforward. Blue color shows the phase response of the receiving channel of the second layer.

Figure 6 shows the frequency dependence of travelttime waves between receivers of different layers.

![Figure 6. The frequency dependence of travelttime](image)

Different color shows the results of measurements at the drop of a wave from the rear and the front face of the antenna. Figure 6 shows that the real running time is significantly longer than the
time at which the wave passed the distance between the geometric centres of receivers with the known speed of sound.

The coefficient of acoustic shadowing converters, calculated as the ratio of the voltage coming from the rear and the front of the receiver does not fall below 0.93. Experiments have shown that the attempt to equalize the levels of the signals in the back or front direction to compensate for shading, do not change the cardioid directional pattern characteristics.

4. Simulation models

In order to understand the discrepancy between the calculated and real time delays were considered two models in the ANSYS software that implements a finite element method for solving physical problems. Geometry models, represents a fragment of the investigated the two antenna of two elementary receiving channels in a layer, shown in Figs. 7a, b.

In model №1 is assumed that the receivers are located directly in water, and the model № 2 assumes a polyurethane core. In the models adopted the following options materials: housing material receivers, sound pressure is titanium, the density of $\rho=4500\text{kg/m}^3$, the Young’s modulus $E=1.1\cdot10^{12}$, Poisson’s ratio $\nu=0.3$; parameters casting of polyurethane - density $\rho=900\text{kg/m}^3$, the Young’s modulus $E = 1.694579\cdot10^7$, Poisson’s ratio $\nu = 0.4986$. The boundary conditions on the edges of the models correspond to the method of infinite antenna array.

![Figure 7. Geometry of finite-element models](image)

For a different radius (R = 10, 20, 30, 33mm) of receiving antenna elements on Fig. 8 shown cardioid directional characteristics obtained for the model №1 with a fixed delay time $t = 33.3\mu\text{s}$ and the distance between layers is $d = 0.050\text{m}$. Red color shows the cardioid type directional pattern, calculated for the case of a point receivers. It is seen that with increasing radius of the receiving element, increases the back maximum too.

![Figure 8. The calculation of amplitude directional characteristics (model №1)．](image)
The search is necessary for the formation of zero in the back half-space, time delays lead to the need to calculate the phase of the directional characteristics of the receivers of each layer. When calculating with ANSYS simulation software in harmonic mode phase characteristics of channels of the individual layers are calculated sequentially. First receiver of one layer, then to the second. The characteristics obtained shifted relative to each other. This can be corrected by combining the values of phase characteristics of the angles ±90 degrees, since the model is symmetric in the fall wave of these areas. For example, the phase characteristics of direction at a frequency of \( f = 0.8 \text{kHz} \), when radius of receiving element \( R = 33\text{mm} \), shown in Fig. 9.

![Figure 9. The estimated phase directional characteristics (model №1)](image)

Due to the symmetry of the model Fig. 9 shows the phase directional characteristics of antenna layers for angles 0-180 degrees. Specifications are typical symmetrical appearance and intersect at point 90°, indicating that the simultaneous arrival of a signal at both layers in direction 90 degrees from the main peak. The difference sound waves between layers is proportional to the difference of the values of phase voltages of each layer.

Table 1 shows the values of traveltime waves for different radius at a frequency of \( f=0.8\text{kHz} \) to model №1.

<table>
<thead>
<tr>
<th>Radius, mm</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traveltime ( \Delta t ), ( \mu s )</td>
<td>35.646</td>
<td>36.5</td>
<td>37.177</td>
<td>38.37</td>
</tr>
<tr>
<td>( (\Delta t/33,3-1)*100% )</td>
<td>7.04</td>
<td>9.61</td>
<td>11.64</td>
<td>15.22</td>
</tr>
</tbody>
</table>

As seen from table 1, the mismatch between the estimated and actual time of mileage waves between layers reaches 15%.

Green color on the Fig. 10 shows the frequency dependence of the time of mileage for model №1, with a radius of receiving element \( R=33\text{mm} \).

![Figure 10. The frequency dependence of traveltime](image)
Similar calculations have been made to model №2. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Radius, mm</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traveltime $\Delta t$, $\mu$s</td>
<td>50.132</td>
<td>51.45</td>
<td>52.78</td>
<td>54.5</td>
</tr>
<tr>
<td>$(\Delta t/33.3-1)\times100%$</td>
<td>50.54</td>
<td>54.50</td>
<td>58.49</td>
<td>63.66</td>
</tr>
</tbody>
</table>

Table 2. Values of traveltime.

Figure 11 pink line shows the traveltime of acoustic waves between phase centres of different layers receivers in the model №2. The solid curve shows the result obtained by the introduction of the ratio of losses in material placeholder $\eta=5\cdot10^{-6}$, the result is shown as a dashed line obtained when the value of loss factor is equal to $\eta=5\cdot10^{-5}$.

![Figure 11](image1)

**Figure 11.** The frequency dependence of traveltime

On the Fig. 12 blue lines indicate cardioid directional characteristics obtained with the help of computer model №1 of radius $R = 33$mm. The solid curve shows the characteristic formed when the time delay equal $33.3\mu$s, bar - delay time taken from Table 1 for the appropriate radius. It is seen that the adjusted delay time nearer the form of cardioid characteristics.

![Figure 12](image2)

**Figure 12.** Amplitude characteristics of direction.

Black color shows directional characteristics obtained with the model №2. It is noticeable that, as in the case of the model №1, when using the estimated time $t = 33.3\mu$s in the back of a half-
space there is more level maximum, than for the model №1. When using found traveltime create a minimal level in the back direction. Compared with the model №1 of this minimum is significantly higher (-27 dB, against-50dB). Green color on Fig. 7 shows the directional characteristics obtained in the experiment.

5. Conclusions

• Solved the problem of search of the optimal time shift in the channels of the two-antenna located in a free field for the formation of a cardioid characteristics of direction.
• Main contribution to the increase in the duration of the sound waves between layers makes the presence of a rubber-like filler around the receiving antenna elements.
• This contribution is seen as more significant when compared to the contribution due to the shading of receiving elements of the first layer, adopted elements of the second layer.
• The presence of transverse waves in the material placeholder significantly complicates the analysis of wave processes inside the antenna.
• The lack of precise data about parameters used at the moment of potting compounds is the main problem for solution of such tasks.
• The introduction of traveltime the waves when forming cardioid characteristics of direction leads to the increase of width of the directional characteristics.

REFERENCES

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