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Multibeam Sonar with a Hexagonal Array

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The paper presents a multi-beam digital sonar that was designed for monitoring and fish stock assessment in inland waters. The sonar can also be used as a bottom profiler in lakes, rivers and shallow sea areas. The hexagonal piezoelectric transducer array co-operates with a commutator set. The 32 –channel digital beamformer creates 30 narrow receiving beams in every 60^0 sector of simultaneous observation. The six sectors cover the whole 360^0 angle range of the sonar. The beamformer digital signal processing is based on second order sampling of echo signals and the phase-shifting principle of beam deflection. The sonar block diagram, beamformer algorithms, as well as transducers designs are discussed.

1. Introduction

The sonar presented here is designed for fish observation and determination of the location of various objects in shallow inland waters. It is also fit for profiling the configuration of the bottom of water reservoirs. The operating parameters of the sonar have been specifically selected to allow the observation of single fish and fish shoals.

Work on the sonar was funded by the Polish Committee of Research under Grant No. 710/T10/96/11. As the work progressed, the configuration of the sonar changed. The successive versions of the sonar are presented in papers [1], [2], [3]. Below is presented the final solution for the sonar. Its characteristic feature is the use of a hexagonal receiving array, which helped to significantly reduce the number of the receiver channels [2].

2. Basic Parameters of the Sonar

Operating frequency	150 kHz
Total observation sector	360° x 7°
Number of receiving beams	180
Width of single beam	2,8° x 7°
Sector of simultaneous observation	60° x 7°
Ranges of distances	25, 50, 100, 200, 400, 800 m
Duration of sounding pulse	$^1/_8$; $^1/_4$; $^1/_2$ ms
Transmitter power in pulse	6 x 500W
Source level	88dB re 1m, 1Pa
Type of beamforming:	digital with second order sampling, serial, phase
Sampling frequency	600 kHz
Effective envelope sampling frequency	18,75 kHz
Display type:	panoramic, semi-panoramic, sectoral, A, AT.
Angular resolution of display	1°

3. The Operation of the Sonar

The sonar is a multibeam system with round observation in a round angle, equipped with a fixed, cylindrical, multi-element transmitting array and a fixed hexagonal receiving array [2]. The area is scanned in sectors within six sectors, which cover a round angle in a horizontal plane. In each sector, the observation is happening simultaneously, with a high angular resolution on a horizontal plane. In the vertical plane, the observation is done within a narrow beam of a constant width.

Fig. 1a gives an overview of round sounding, performed horizontally. The area being searched is divided into sectors that you will find marked with symbols. In each of the sectors, 30 narrow receiving beams are generated simultaneously.

a) b)

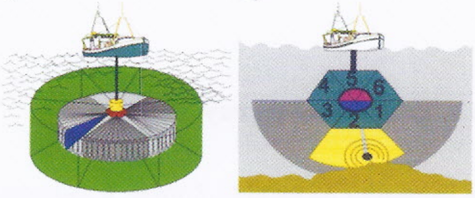

Fig. 1. a) Round sounding performed horizontally; b) sounding done on multibeam echo sounder basis.

A full picture of the area being searched is received after every six soundings. It is then presented in a panoramic view on the screen of a colour computer monitor. Fig. 2 shows the actual display on the screen. Apart from the recorded echo signals, it also includes a set of icons to present the status of the sonar's setting. Detected underwater objects are displayed as spots with the colour denoting the target strength while the on-screen location represents the location of the objects in the space.

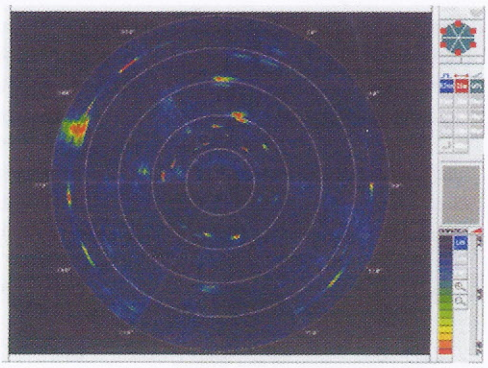

Fig. 2. Display on the monitor's screen during a round sounding.

Rotating the array in a vertical plane by 90^0, changes the function of the sonar from round observation in a horizontal plane to a multibeam echo sounder with observation performed in a vertical plane. In this option the system performs observation in a straight angle with its median directed at the bottom. At this point, only three sections of the receiving array are used, which reduces the observation time twice.

Fig. 1b presents the operation of the sonar with digital beamforming fulfilling the functions of a multibeam echo sounder with three 60-degree observation sectors.

The hydroacoustic array of the system in question consists of two independent parts: the transmitting array and receiving array.

The transmitting array has a cylindrical shape and contains six identical sections out of which three sections that neighbour on each other operate in a single cycle. A threefold extension of the illuminating sector in relation to the observation sector is introduced to make sure that the level of the transmitted signal within the observation angle is maximally equalised. After the transmitting pulse is emitted into a sector 180^0 wide, the extreme section gets disconnected while a new section gets connected to the remaining two. The three sections will then emit a pulse in the next sector. It is also 180^0 wide, but is deflected by 60^0 in relation to the previous one. Fig. 3a illustrates the sectoral operation of the transmitting transducer.

The receiving array is built out of six, separate, multi-element arrays, called blocks, which make the side walls of a parallelepiped on a base of a regular hexagon. Each block contains 32 sections, each of which has two elementary transducers (piezo-ceramic elements). The 32 sections of the block generate simultaneously 30 receiving beams each 2^0 wide in a horizontal plane and 7^0 wide in a vertical plane. Narrow beams ensure high resolution of the system. 30 beams of the block of the receiving transducer ensure observation of a 60^0 wide sector; the other five 60 degree sectors are handled by the remaining five blocks of the transducer set. The sectoral operation of the blocks of the receiving array is illustrated in Fig. 3b.

a) b)

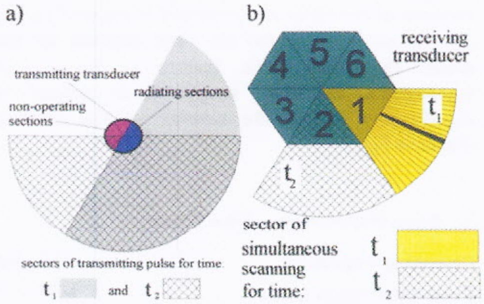

Fig. 3. Sectoral operation of the transmitting (a) and receiving (b) transducer.

4. Beamformer Algorithms

The generation of 30 receiving beams in each sector follows the same pattern in the 32 channel phase beamformer with second order sampling [1], [3]. The operation of the beamformer will be discussed on the basis of the geometry of one sector of the receiving array as shown in Fig. 4.

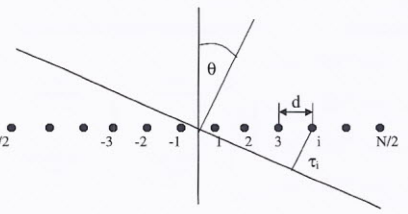

Fig. 4. Geometry of the sector of the receiving array.

Let us assume that a plane acoustic wave is incident to the exemplified sector at an angle of θ in relation to the adopted zero direction. If the elements of the transducer have the same sensitivity, then at the output of *i* section, voltage *u(t)* is created, having this form:

$$u_i(t) = A(t + \tau_i) \sin [\omega_0(t + \tau_i)]$$

where:

$$\tau_i^+ = \frac{d}{2c}(2i - 1)\sin\theta \quad \text{for } i=1,2,3,...,16$$

$$\tau_i^- = \frac{d}{2c}(2i + 1)\sin\theta \quad \text{for } i=-1,-2,-3,-16$$

and

i – number of section
$A(t)$ – envelope of echo signal,
$\omega_0 = 2\pi f_0$ - pulsation,
φ - phase shifting
d- spacing between the centres of the sections,
c- velocity of propagation of acoustic wave in water.

The voltage at the output in the same section, shifted in time scale by ¼ of the period of the carrier signal is equal to:

$$v_i(t) \cong A(t + \tau_i)\cos[\omega(t + \tau_i) + \varphi]$$

The voltages are treated as the actual and imaginary part of the complex signal $z_i(t)$, hence we have:

$$z_i(t) = v_i(t) + ju_i(t) \cong A(t + \tau_i)e^{j[\omega_0(t+\tau_i)+\varphi]}$$

Fourier transform of the above function is equal to:

$$Z_i(j\omega) \cong e^{j\omega_0\tau_i} A[j(\omega - \omega_0)]e^{j\varphi}$$

If we multiply this function by $e^{-j\omega_0\tau_k}$, where

$$\tau_k = \frac{d}{2c}(2i \pm 1)\sin\theta_k$$

and sum up all the functions, we get:

$$|Z_k(j\omega)| = |A[j(\omega - \omega_0)]| \cdot |\sum_{i=-N/2}^{i=N/2} e^{j\omega_0(\tau_i - \tau_k)}|$$

The sum in the above formula is the sum of a geometrical series. By using the known formula for the sum of a series like this, we finally get:

$$\frac{|Z_k(j\omega)|}{|A[j(\omega - \omega_0)]|} = \left| \frac{\sin \frac{N\pi d}{\lambda}(\sin\theta - \sin\theta_k)}{\sin \frac{\pi d}{\lambda}(\sin\theta - \sin\theta_k)} \right|$$

The expression on the right hand side of the last formula describes the beam pattern deflected by angle θ_k. The calculations presented above are done for all θ_k angles which determine the axis of the beams. In this way what we get is a complex of beam patterns covering the sector of simultaneous observation, as shown in Fig. 5.

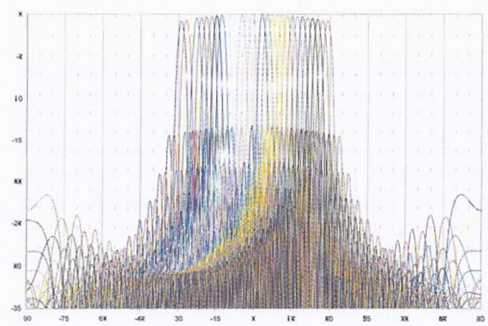

Fig. 5 . Complex of beams of one observation sector.

5. Block Diagram of the Sonar

The design of the multi-beam sonar with a digital beamformer is shown in the form of a block diagram in Fig. 6.

The diagram shows all the major functional blocks of the sonar and how they are interconnected. From the standpoint of external design, the sonar consists of a complex of the hydroacoustic array connected via a multi-core cable with the console of the operator of the sonar. The array unit also includes a commutation block and pre-amplifiers. Each of the 32 sections of piezoceramic transducers contained within the block of the receiving array is connected to one input of the

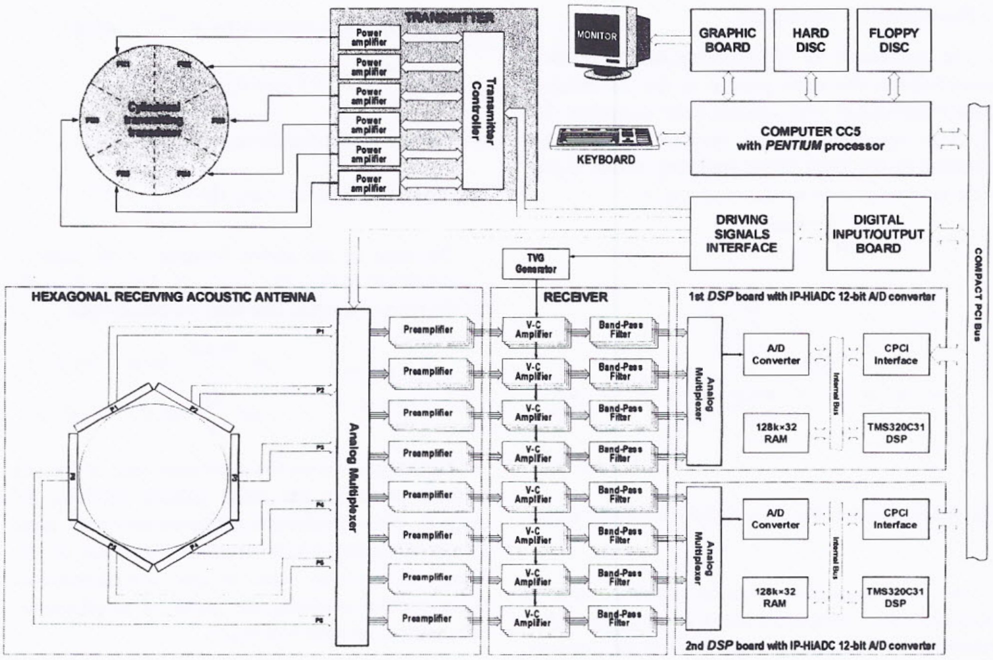

Fig.6. Block diagram of the sonar.

commutation block. The commutation block, in each operating cycle of the sonar, connects one block of the array to 32 pre-amplifiers. The choice of an active sector is done by the sonar control complex and changes along with the method of scanning which is selected by the operator from among the options available on the control desk of the sonar. The role of the pre-amplifiers is to pre-amplify the echo signals and to adjust the impedance of the piezoceramic transducer (relatively high) to the impedance of the cable (low). Each pre-amplifier at the input has an amplitude controller and does initial reduction of the spectrum of the acoustic signals received (acoustic noise). The operator's console includes the blocks of the transmitter, receiver, power supply, monitor, operator's desk and a computer block with 2 boards of signal processors TMS-320 C31 and a CC5 Pentium computer. The units of the operator's console are installed on boards, type Euro 3U.

The transmitter consists of the operating and control block which generates signals that excite 6 pulse power amplifiers built on transistors in the hexfet technology. Each of the amplifiers co-operates with one of the six sectors and ensures excitation of a 500W electrical power in sounding pulses. In each cycle, all sectors or three neighbouring ones – as an option - work simultaneously. Which three neighbouring sectors will be chosen depends on the method of searching; this choice is made like the choice of the sectors of the receiving array. The axis of the medium sector of the transmitting array always overlaps with the axis of the active sector of the receiving array.

The receiver block consists of 32 receiving channels. Each receiver channel consists of an amplifier with controlled gain (for range setting and manual gain control) and a band-pass filter which adjusts the spectrum of the signal to the requirements resulting from the theorem on second order sampling. Echo signals, after a reduction of the dynamics and filtration in the receiver, reach the inputs of analogue/digital converters via a multiplexer. We used two fast 12 bit analogue-digital converters by SBS Green Spring Modular IO with 16 input multiplexers and 4 sampling and hold sets of maximal sampling frequency of 800 kHz. The analogue-digital converters are installed directly on the boards of signal processors TMS-320 C31. The boards of signal processors, the Pentium computer and the boards of digital inputs and outputs communicate via a Compact PCI bus. The computer part of the sonar uses chips by OR Industrial Computers.

The signal processors perform operations on signal samples using algorithms, as described in the section "Beamformer algorithms". The calculated samples of signals from the particular beams are then sent to the Pentium computer for further signal processing. The result is a colour panoramic, semi-panoramic and auxiliary image type A and AT. The Pentium processor, apart from the graphic presentation of the results of sounding, is responsible for controlling the work of the entire sonar, co-operation with the operator's board, and recording of the results in the form of files on disks.

The receiver and transmitter are controlled via the digital input/output card and an interface, which generates the necessary levels and courses, needed to control analogue sets. Through a serial interface RS320 a meter of sound velocity distribution is hooked up to the computer. The measurement data it provides are used to determine the routes of the acoustic wave propagation and to estimate the current detection possibilities the sonar has.

6. Design of Ultrasonic Arrays

The array unit, presented in Fig. 7, consists of the following parts:

• six identical blocks of plane multi-element arrays, indicated with the letter A, which together make the receiving transducer;

• a single, multi-element cylindrical array of the transmitting transducer, indicated with the letter B;

• support and protection body, indicated with the letter C

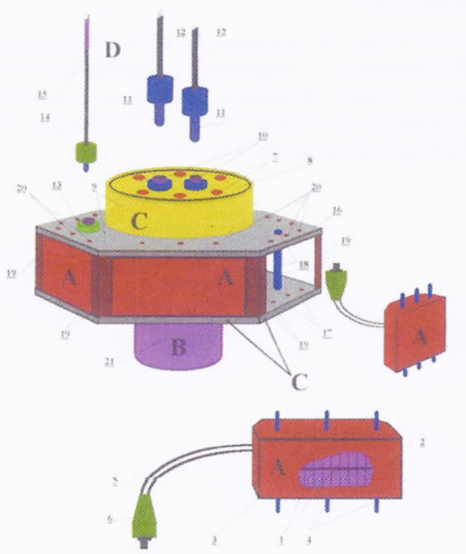

Fig. 7. Spatial presentation of the transmitting-receiving array of the round sonar.

• a set of signal cables and waterproof connectors of the transmitting and receiving channels, indicated with the letter D

The receiving array of the transducer part consists of six, independent, fully hermetic blocks (A), containing 64 pieces of piezoceramic elementary elements each. The design of a single block of the receiving array is presented in Fig. 8. The mechanical protection, hermetic layer and the layer, which couples the elementary transducers with the water – is made of a PU elastomer-filling compound. The blocks are laid in a regular hexagon and fixed in the assembly openings of the support boards of the array body.

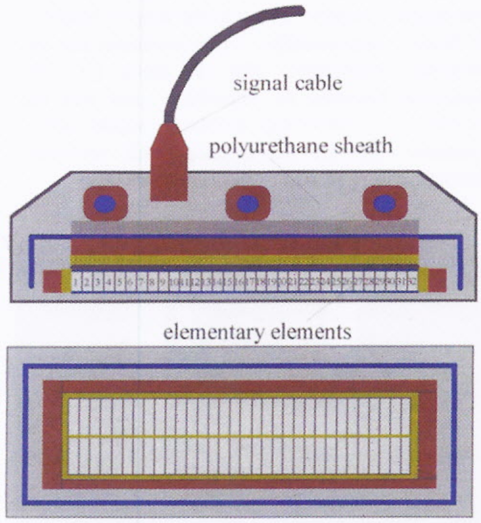

Fig. 8. Design of the array of the multi-element receiving transducer – a single block.

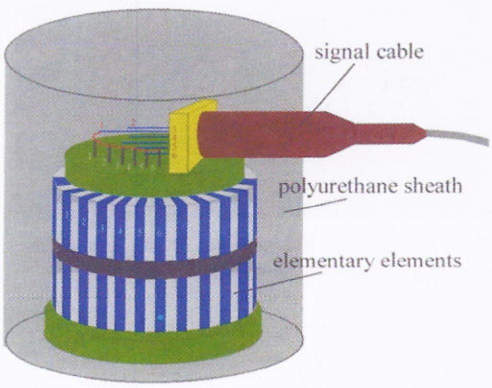

Fig. 9. Design of the array of the multi-element, cylindrical transmitting transducer.

The design of the transmitting array is shown in Fig. 9. The cylindrical transmitting transducer B that constitutes a single integrated and hermetic element of the structure, containing in it 72 piezoceramic elements, is fixed onto to the bottom support board in a way that makes a quick installation and disconnection possible. On the side wall of the cylinder are six array sectors, containing 6 elementary sections each. Each of the sections consists of two piezoceramic elements. All transducers in one sector are connected parallel.

The basic support elements of the protection body are made of two duralumin boards, in the shape of a regular hexagon, connected by six duralumin spacing brackets, with the corners between the blocks of the transmitting array filled with elastic "fenders". Fixed to the support board of the body – hermetically - is a container for the electronic components (Fig. 9, block C). The connection between the transducer unit and the console is ensured through multi-core signal cables, separately for the transmitting and receiving channels, equipped with watertight connectors.

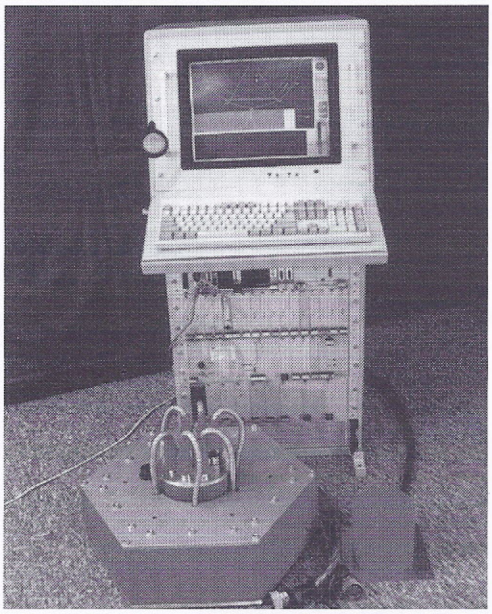

Fig. 10. View of the console of the sonar, the receiving and transmitting arrays.

The photograph in Fig. 10 shows the console of the sonar with its monitor, operator's desk and all electronic blocks of the on-board components. Below it is the receiving array with a container for electronic components and a transmitting array which prior to submerging it in water, is connected mechanically to the body of the receiving array.

7. Conclusion

The sonar was successfully tested both indoors and in the field. Further technical testing of the sonar will be resumed in the spring-summer season of 1999, and when it is finished, we plan to make the sonar available to research institutions dealing with inland fisheries. Joint operating testing will help to verify its usefulness or formulate conclusions to be used in modifying the design or introducing changes to the software.

References

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