High Accuracy Multisensor Hydroacoustic System for Models of Trawl Geometry Measurements

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The new high accuracy multisensor hydroacoustic system for models of codend geometry measurements was designed for developing the construction of cod codend for the Baltic fishery. The system consists of 20 miniature hydrophones attached by the light-gauge cables to the measuring microprocessor device and notebook computer. The pulse excitation at high frequency and correlation digital signal processing make it possible to obtain high resolution of measurements. Additionally each of hydrophones is equipped with the thermistor, which is used to calculate the local sound velocity and enable precision calibration of obtained measuring data. This method of calibration is particularly important for measurements investigated in the surface water layer with the high temperature gradient. The construction details, the measuring digital signal processing algorithms as well as examples of obtained data and the accuracy verification are presented in the paper.

1 Introduction

With the rapid development of fishing gear and electronic support equipment over the recent decades, fishing is becoming increasingly more effective. Sadly, the growing efficiency of fishing gear coupled with a lack of a fishing quota policy has badly affected many fish species and caused serious environmental threats [1]. The Baltic's dwindling cod stocks are an example. To curb any further cod stock decreases the European Union has imposed very strict fishing quotas on the member states. An important cause of the drop in cod stocks is the fishing gear, which catches both mature specimen and young fish which have not reached reproductive age.

An important task of fishing gear designers is to develop effective selective fishing gears, especially trawls' codends to ensure that only the right size fish are caught leaving young specimen unharmed. The Department of Fishing Technique from University of Agriculture in Szczecin has been developing new fishing gear for many years [2]. Models of new fishing gear are tested and verified at the Model Research Station on Ińsko Lake [3].

To obtain reliable trawl data the Department of Fishing Technique from University of Agriculture in Szczecin contracted the Department of Marine Electronic Systems from Gdańsk University of Technology to develop a prototype of a measuring device for precision measurements of codend geometry and distribution of forces while towing. Below is the design of the measuring apparatus.

2 System parameters

The client identified the required technical parameters for the measuring system. The objective of the system is to measure the geometry of the cod codend as it is being towed by the measuring catamaran at the Model Research Station on Ińsko Lake.

The measurements should be able to identify minimum 10 distances between pairs of hydrophones located on the model. The system measures the distance by recording the time it takes for the acoustic signal to propagate from the sending hydrophone to the receiving hydrophone. There is only one measurement at a time between specific pairs of hydrophones and the subsequent measurements occur in a series. The distances were identified from 0.1 m to 10 m. The accuracy of the measurements should not be less than 1 cm, with resolution equal to 1 mm. The series of measurements should be once every second.

The system should consist of small size measuring sensors connected with the on-board computer using 15 m light-gauge cables. A notebook computer should be used to control the measurement process and record measurement data.

The system should allow further development, especially to include force and towing speed measurement.

3 Problems to be solved

Because of the high expectations for measurement accuracy, there were a number of technical problems that needed solving.

3.1 The effects of sound velocity

Sound velocity in water depends greatly on water temperature and salinity. The measurement system is designed to operate in inland waters with no salinity. In this case the sound velocity depends only on the water temperature. Fig. 1 shows the relation between sound velocity in water and temperature varying from 0 to 30°C.

If a constant sound velocity were to be used for calculating the distances, an error of ± 3.7% would occur, which is significantly above the assumed measurement accuracy for the maximal scope. This is why sound velocity or temperatures have to be taken constantly to ensure that measurement results can be calibrated.

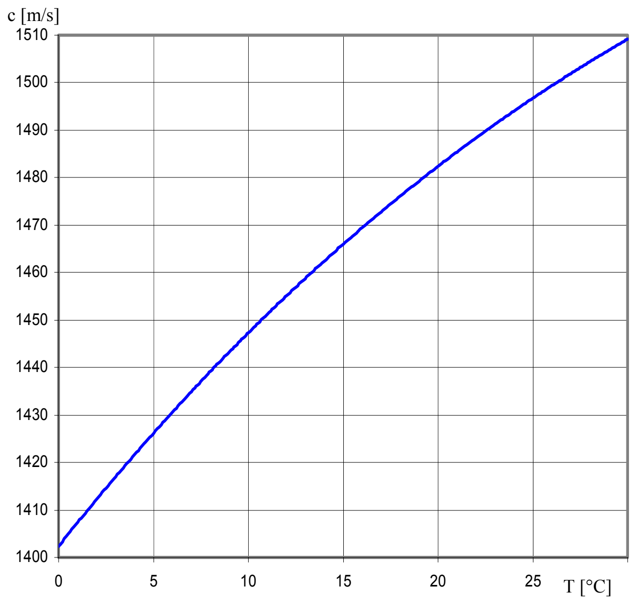

Fig.1 Change in sound velocity depending on water temperature.

3.2 Doppler effect

There may be an error in the measurement results when sound velocity and motion velocity of the model are summed up. The worst situation will be when measuring distances in the direction consistent with the model's motion. The relative measurement error Δ caused by Doppler effect can be described in this relation:

$$\Delta = \pm \frac{v}{c} \cos \Theta \,, \qquad (1)$$

where:

- v - the velocity of the model,
- c - sound velocity in water,
- Θ - angle between direction of motion and direction of measurement.

The error will be negative if the sending hydrophone will be more to the front of the receiving hydrophone and positive if situated the other way round. For a towing speed equal to 1.5 m/s the error will be equal to 1‰. Measurements perpendicular to the direction of the motion, i.e. for $\Theta = \pi/2$, will not be affected by error caused by Doppler effect. For the majority of the measurements Doppler effect will have a negligible effect on the results.

3.3 Size and shape of hydrophones

Measuring hydrophones and the cables connecting them should be small enough not to obstruct the motion and shape of the trawl codend. On the other hand, the size of the hydrophone in the direction of distance measurement should be less than the assumed measurement accuracy. The hydrophone should maintain a uniform level of the beam pattern, especially within the distance measurements plane. Where the measurements will be transverse to the model's towing direction, the hydrophone may take the shape of an elongated cylinder with a diameter smaller than the distance measurement accuracy and with the light-gauge cable output towards the rear end of the model.

3.4 Measurement signal and its detection

For high accuracy and resolution of the measurements, it is advisable to use measuring signals with a wavelength significantly below the assumed accuracy and a short duration. Because the length of an acoustic wave in water equal to 1 cm equals a frequency of 150 kHz, the measurement system should use a much higher frequency of operation. This will also help with keeping the measuring hydrophones small. Because very short distances are to be measured (from 10 cm), to ensure a sufficiently small dead zone, it is advisable to use signals with a duration less than 50 µs. Short measuring signals are also good for reducing the effects of multi-channel propagation on measurement results.

Measurement accuracy and resolution are also affected by how the measuring signal is detected, and especially by how precise the receiving time is identified. In case of interferences, to ensure that false alarm levels are kept to the minimum, we are forced to raise the detection threshold. On the other hand, a high detection threshold increases the measuring error of the signal transmission time.

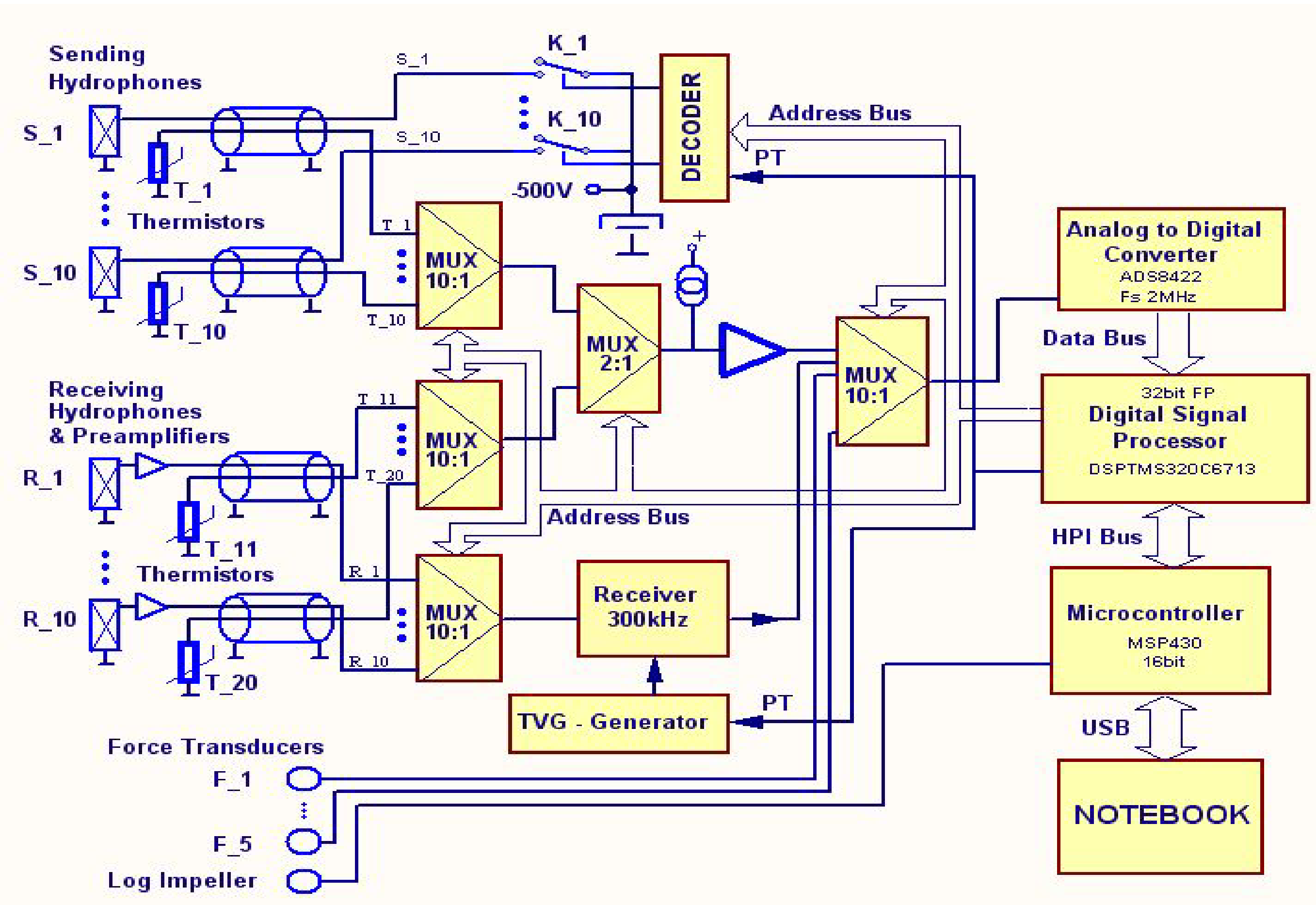

Fig. 2 The block diagram of the system.

The required high measuring accuracy can only be obtained by using a short measuring signal with a narrow auto-correlation function and matched filtration in the receiver.

4 System description

The system comprises three segments:

- sensors segment,
- electronic circuits segment responsible for sending, receiving and signal processing,
- control and data storage segment in the notebook computer.

Fig. 2 shows the block diagram of the system. The measuring sensors segment has 10 pairs of hydrophones for measuring distances. This segment will soon be extended to include tensometric transducers for measuring the forces in the models' structural elements and a precision impeller log for measuring towing speed.

The electronic sending and receiving and signal processing segment is responsible for generating, transmitting and receiving sequences of measuring pulses, and when they are processed to a digital form, for making the calculations in the Digital Signal Processor.

Using a specialist software the notebook selects the parameters measured and records the results.

4.1 Measuring hydrophones

The measuring hydrophones are built of Ø 5 mm x 3 mm cylindrical piezoelectric ceramic profiles. To obtain the desired beam pattern, the circular planes of the profiles were acoustically isolated using layers of cork. This ensured that the ceramics' dominant mode of operation is radial resonance at about 300 kHz. As a consequence, the length of the acoustic wave in water is equal to 5 mm. Fig. 3 presents the cross-section of the sending and receiving hydrophone.

The ceramic profiles and structural elements were covered with polyurethane to form a Ø 9 mm x 90 mm cylinder externally. To ensure that noise level at the input of the receiver is low, an FET transistor preamplifier was placed inside the receiving hydrophone. The casing of the hydrophones also includes thermistors for measuring local water temperature.

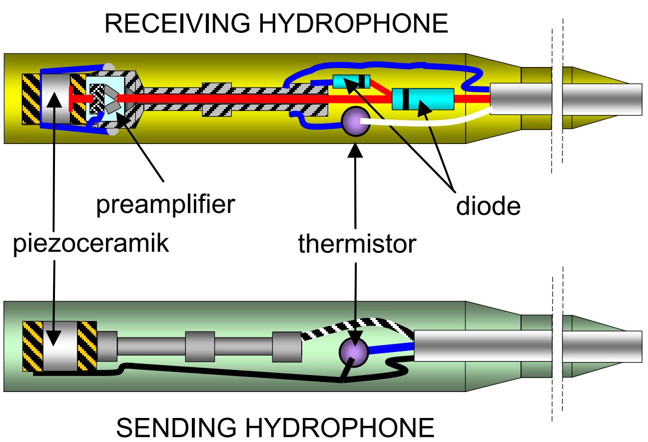

Fig. 3 The cross-section of measuring hydrophones.

4.2 Generating the measurement pulse

Ultrasonic defectoscopy provided the solution for generating a short duration measuring acoustic pulse. The sending hydrophone is excited with a minus 500 V amplitude voltage change. The short duration acoustic pulse is the hydrophone's response to the excitation. The mid-frequency of the measuring pulse in the system is equal to the resonance frequency of the piezoelectric profile about 300 kHz. The resulting duration of the measuring pulse is equal to 20 µs, which is consistent with 6 periods of mid-frequency.

The transmitter comprises the following elements shown in the block diagram: source of high voltage -500 V, set of 10 analogue high voltage keys and a decoder. In the next cycle the measuring pulse is generated by short-circuiting one of the keys and exciting the sending hydrophone. A Digital Signal Processor, which manages the measurements, controls the selection of the key's address and its switching with a PT start pulse.

4.3 Signal receiving and matched filtering

The system's receiving section comprises a set of analogue multiplexers, band-bass analogue amplifier, source of power supply for the thermistors, analogue to digital converter, digital signal processor and microcontroller.

Floating-Point 32-Bit Digital Signal Processor DSP **TMS320C6713** is the main element of the measuring system. It controls the measuring cycle, carries out digital filtration of the acoustic signals received and all the necessary calculations involved in the measurements and results calibration.

Using an address bus and multiplexer, a receiving hydrophone is connected to the input of the band-pass amplifier with mid frequency at 300 kHz. For a fixed signal level, the receiver uses Time Variable Gain TVG. The receiver's output is connected via another multiplexer to an Analogue to Digital Converter ADC. In keeping with the measuring cycle the ADC converts also the voltages from thermistors placed on sending and receiving hydrophones. The analogue to digital converter **ADS8422** ensures that the processing has a 2 MHz sampling frequency and a 16 bit resolution.

Microcontroller **MSP430** via the Universal Serial Bus USB acts as an interface between the DSP and the notebook computer. The microcontroller is also responsible for controlling the measurements and counting the log impeller pulses.

The measuring signal sent by the sending hydrophone and then received by the receiving hydrophone and recorded by the digital oscilloscope is presented in Fig. 4 a). The shapes of the pulses depending on the hydrophone pair differ only slightly. The differences are in the amplitude but the shape, phase and pulse duration are the same. Figure 4 b) shows the autocorrelation function computed numerically

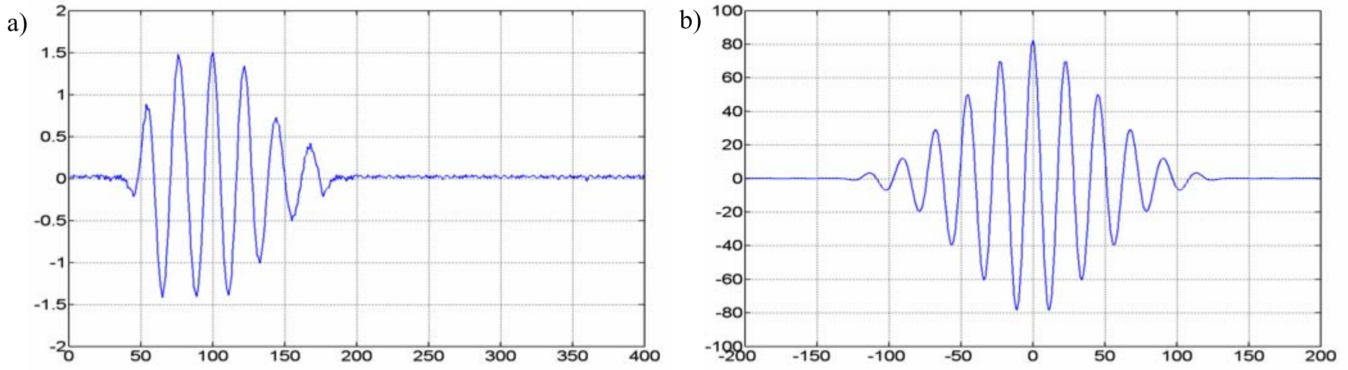

Fig. 4 a) Measuring signal. b) Its autocorrelation function.

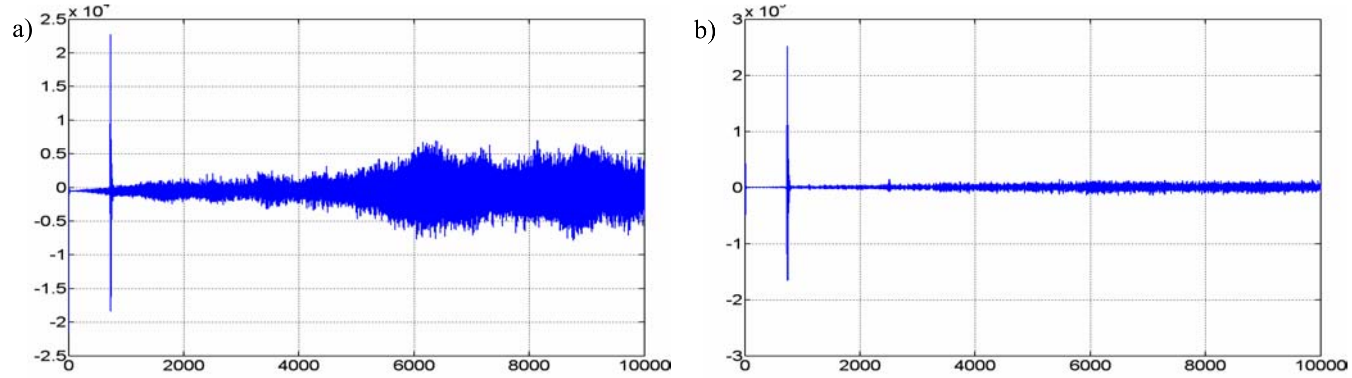

Fig. 5 Receiving signal: a) before, b) after matched filtering.

of a measuring signal. The autocorrelation function has a clear single maximum for time equal to zero. The curve in Fig. 4 a) was recorded in the DSP memory and is used as a template measure signal for digital matched filtration. The objective of the DSP is to compute the reciprocal correlation function [4] of the signal received and the template recorded as in the formula:

$$\varphi_{xy}(m) = \sum_{n=-\infty}^{\infty} x(n) y^*(n-m), \qquad (2)$$

where:

$\varphi_{xy}(m)$ – value of m sample of reciprocal correlation function,

$x(n)$ – value of n sample of signal received,

$y^*(k)$ – conjugated value of k sample of the template.

Matched filtration improves the SNR signal to noise ratio, which can be clearly seen in Fig. 5. The improvement in SNR depends on the shape of the signal autocorrelation function.

A higher SNR improves detection conditions, and the autocorrelation function with a single maximum makes an accurate measurement possible. The number of reciprocal correlation function sample with a maximal amplitude determines the duration of the measuring signal propagation time from the sending to receiving hydrophone.

4.4 Sound velocity adjustment

To ensure high measurement accuracy, the actual sound velocity should be measured or computed indirectly from water temperature. Placed in each hydrophone, the thermistors enable precision measurement of local temperature and when computing the distances for a given pair of hydrophones they take account of the average sound velocity computed using measurements at the sending and receiving hydrophone. To compute fresh water sound velocity Marczak's formula [5] was used:

$$c = 1.402385\text{x}10^3 + 5.038813T - 5.799136\text{x}10^{-2}T^2 + 3.287156\text{x}10^{-4}T^3$$
$$- 1.398845\text{x}10^{-6}T^4 + 2.787860\text{x}10^{-9}T^5, \qquad (3)$$

where:

c - sound velocity in m/s,

T - temperature in °C.

Fig. 6 shows the typical distribution of sound velocity in inland water. The chart shows a rapid decrease in sound velocity at thermocline depth. Measurements taken at thermocline boundary, when one of the measuring hydrophones is above and the other under the thermocline, measurement accuracy may deteriorate and this should be avoided when planning measurements.

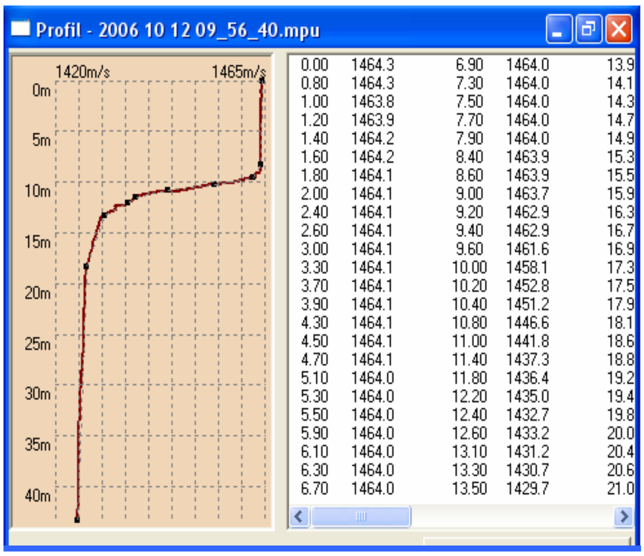

Fig. 6 Typical sound velocity profile in inland water.

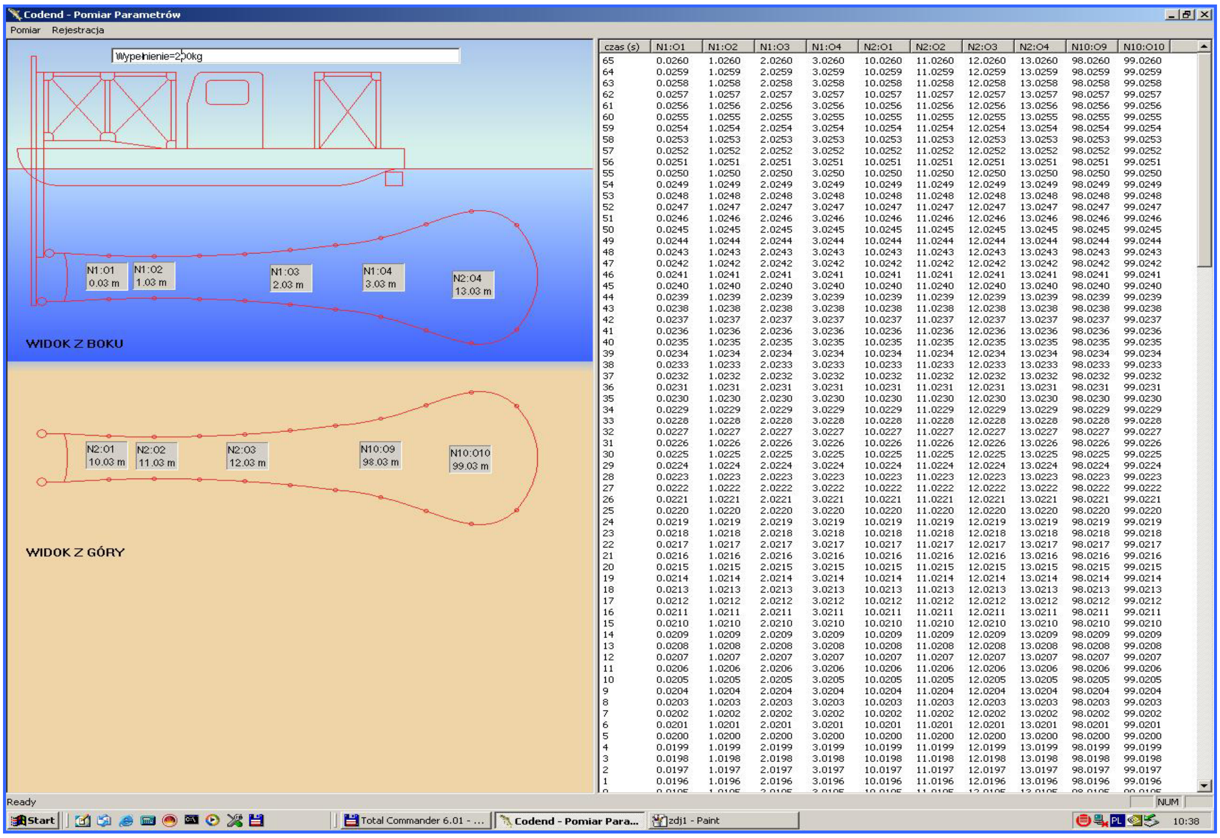

Fig. 7 Graphic user interface of application „Codend".

4.5 Application "Codend"

The "Codend" application was developed for the purpose of operating the measurement system using the notebook. It serves a Men Machine Interface MMI between the user and measurement system. The user can define his desired measurement configuration and visualise and record measurement results while operating the system.

The first step following the start of the application is to identify the number of measurements and define them. In the case of measuring the distances, the user is asked to complete a cross table with lines for the sending hydrophones and columns for receiving hydrophones. Because the number of sending and receiving hydrophones equals 10, the maximal possible number of distance measurements is equal to 100. "Codend" application starts, puts on, hold and terminates a measuring cycle. While the system is in measuring mode, the main application window is active, as seen in Fig. 7. It is a typical Graphic User Interface GUI. On the left-hand side is a window illustrating the selected measurements and on the right-hand side is the measurement results table.

The application automatically records the date and time of the measurements and supports user comments, which will be helpful later when processing the results.

5 Conclusion

The proposed system and software have helped to obtain the desired parameters of the measurement system. The system is now operational and serves as an important tool for verifying newly designed selective fishing gear developed by the Department of Fishing Technique from University of Agriculture in Szczecin.

Acknowledgments

The objective of the development work is to develop the design of a selective trawl for cod fishing in the Baltic, including the necessary measurement apparatus. The work is funded by the European Union under the Sectoral Operational Programme Fisheries and Fish Processing - Community Support Framework 2004-2006.

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