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DETECTION OF FLOATING OBJECTS BASED ON HYDROACOUSTIC AND HYDRODYNAMIC PRESSURE MEASUREMENTS IN THE COASTAL ZONE

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ABSTRACT

The development of coastal infrastructure and related maritime transport necessitatesthe intensification of vessel traffic monitoring. Navigation systems used in this research are traditionally based on the information transmitted by radio waves. Marine traffic safety requires constant supervision carried out by dedicated systems, the operation of which may be limitedby difficult environmental conditions. The possibilities of supporting navigation systems with underwater observation systems are explored here. The research was carried out using an underwater measurement system. Local disturbances of the hydroacoustic and hydrodynamic field from the moving vessels were analysed. The potential for identifying a moving vessel, for example for offshore infrastructure security purposes, is demonstrated.

Keywords: marine safety, coastal zone, marine traffic, underwater pressure research

INTRODUCTION

The economic development of coastal zones in recent years has led to increased coastal infrastructure. This in turn requires appropriate security measures and environmental monitoring to carry out a long-term assessment of the impact of investments on the marine environment [1, 2]. Economic development in the coastal area is associatedwith the development of ports and the increase in the volume of goods sent by the sea, thus affecting the dynamics of the transport.

The Vessel Traffic Service (VTS) aggregates data from on-boardreporting systems such as the Automatic Identification System (AIS). The International Convention for the Safety of Life at Sea (SOLAS) obliges the implementation of AIS on all passenger vessels, and on all vessels of 300 gt and upwards [3].Data received from AIS are one of the main sources of information on the trajectory ofvessel movements. The main disadvantage of this system is its susceptibility to manipulation, in that, for example, reports can be intentionally fakedor jammed. Moreover, data entered manually by the crew can contain errors, and systems can be switched off to cover illicit operations [4, 5].

Maritime transport is considered to beone of the most ecologically friendly, with a high level of safety, but any accident in maritime traffic can have serious environmental consequences [6, 7]. The development of VTS systems with underwater modules will enable the detection of anomalies related to avessel's reported movement and position data, and as such contribute to the improvement of safety in the offshore zone. Validation of data received from AIS and other VTS systems by data from an underwater stationary measurement system will increase VTS reliability.

In the context of the impact on offshore coastal development, observations of shipping tend to focus on such aspects as traffic safety [8], the impact of vessels on the coastal zone [9, 10], and the impact of fixed infrastructure in the area of increased traffic [10, 11]. When examining the impact of vessels on the coastal zone, one should also take into account the fact that each object moving on the water surface is a source of disturbances of the local pressure fields. In the literature, the pressure perturbations are separated into hydroacoustic pressure [12, 13] and hydrodynamic pressure [14, 15] signals. These might be used synergisticallyto improve the detection and identification opportunities for objects floating on the water surface, compared to the capability provided by each signal individually. Concurrent analysis of two different physical fields in realtime will allow observation of the environment and detection of objects based on the perturbations in those fields. Information thus acquired on a potential object may be transferred to the master system in realtime. The main target of the solution described is to support the decision-making process of marine navigation in severe environmental conditions.

This article will present the possibility of detecting a moving object in a specific water body using a passive underwater multi-sensor measuring system. The research was conducted using information acquired about sources of disturbances to assess the possibilities for detecting unknown floating objects. The collected data can be used to simulate and build a mathematical model of the observed phenomena [16, 17].

EXPERIMENT

CHARACTERISTICS OF THE MEASURED SIGNAL

Disturbances of the local pressure field caused by the motion of the vessel have the character of vibrations with frequencies ranging from Hz to several kHz [18, 19]. In the case of a hydroacoustic field, disturbances in the form of noise are caused by the operation ofvessel devices [20], propeller rotation and to a lesser extent by the flow of water around the hull [21, 22]. The noise source components listed above give an overall picture of the disturbance of the hydroacoustic field by the moving object.

Movement of the underwater part of the hull is responsible for changing the hydrostatic pressure at a specific measuring point located at the bottom of the water body. The pressure change of the water column caused by the movement of the object is a feature of thehydrodynamics of this object [23], which is characteristic for a given type of object.

MEASURING SYSTEM

For the investigation of the described signals, a measuring system based on three sensors was used: a hydrophone for measuring the hydroacoustic field, a pressure sensor for measuring the hydrodynamic field and a sound speed sensor with a built-in hydrostatic pressure sensor as an additional element of hydroacoustic measurements [24].

The measurements of the hydroacoustic field were made using the RESON TC4032 hydrophone. The hydrophone is equipped with a preamplifier with 10 dB gain of high sensitivity, which enablesthe detection ofa low-level signal, below the sea level. The main parameters of the sensor used in the measuring platform are presented in the table below (Table 1).

Tab 1. Main parameters of the hydrophone

Hydrophone – RESON TC4032	
Useful frequency band	5 Hz – 120 kHz
Sensitivity	–170 dB re 1V/ μPa
Horizontal directional characteristic	Omnidirectional
Vertical directional characteristic	270°

Disturbances in the hydrodynamic field were recorded using a Honeywell high-precision pressure sensor. It is used to measure the dynamic pressure changes associated with a moving object near the measuring platform. The Precision Pressure Transducer Ruggedized (PPTR)is a deep-sea sensor for use in difficult environmental conditions. The sensor has a digital data output through the RS-485 serial interface, which additionally provides the possibility of full sensor configuration in the field of changes in operating parameters. The main parameters of the sensor used at the measuring platform arepresented in the table below (Table 2).

Tab 2. Main parameters of the hydrodynamic pressure sensor

Hydrodynamic pressure sensor – Honeywell PPTR0100AP5VN-R120	
Measurement range	0 MPa – 0,68947 MPa (100 PSI)
Resolution	6.89 Pa
Accuracy	±0.02% full scale

Ameasurement of the velocity of sound in water wasan additional source of metadata about the measurement conditions. If the results of research were inconsistent with expectations, information about detailed environmental conditions would be relevant. A ValeportminiSVS probe was used for measurements. The sensor calculatesthe velocity of sound based on the measurement of the pulse travel time between the transmitter and the receiver at a known, fixed distance. Communication with the probe was carried out through the RS-485 serial interface due to the requirements of the low frequency of measurement. The main parameters of the sensor used in the measuring platform arepresented in Table 3.

Tab 3. Main parameters of sound velocity with the hydrostatic pressure sensor

Sound velocity with hydrostatic pressure sensor – ValeportminiSVS	
Measurement range	1375 m/s – 1900 m/s
Resolution	0.001 m/s
Accuracy	±0.02 m/s

This configuration does notallow the measurement of the vertical profile of sound velocity in water. It does, however, provide information on the sound velocity in water at the measuring platform's location near the seabed. This additional information was included in metadata for each measurement and may be used in future modelling. Furthermore, the integrated hydrostatic pressure sensor acquires information on the measuring platform's current depth.

The measurement system was built around an industrial computer with a real-time system and an FPGA processing unit. This approach enabled the implementation of the algorithms used directly on the logic system, thus shortening the processing time of the signals. The computer had several input and output interfaces adapted individually to the needs of the measurement platform. The recording and processing of analog signals required A/D converters. The 24-bit dynamic range enabled the recording of signals with a large variation in voltage levels, and the internal clock synchronised the operation of the transducers, resulting in signals starting at the same time and being recorded for the same duration. The serial communication in the RS-232 and RS-485 standard has been used for the measurement of the hydrodynamic field and the sound velocity probe. The schematic of the measurement system is shown in Fig. 1. The land and underwater stations were connected with a hybrid underwater cable.

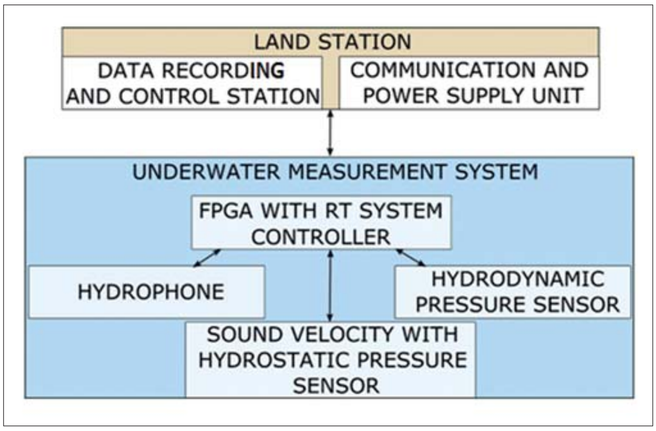

Fig.1. Diagram of the measurement system divided into underwater and land parts

The sensors of the measuring platform were carefully selected from those adapted to the requirements and assumptions of the system. The ranges of measured quantities were adjusted to the marine environment of the Baltic Sea and other waters with the operational depth not exceeding 100 m. The transmission losses mainly related to water salinity in the examined water area were analysed in [25].

METHODOLOGY OF MEASUREMENTS

The research was carried out in the Gulf of Gdansk, where the measurement system was placed at depth of 10 m at a distance of 700 m from the land-based measurement control station. The measurements were planned for specific hydrometeorological conditions and subject to the assumption that there is no other disturbance source within a 1 nautical mile radius. The layout of the measurement system is shown in Fig. 2.

The measurements of the impact of the object's movement on changes in the local pressure fields were preceded by background measurement of 7 days in the target measurement position. Every day, attempts were made to provide information on weather conditions in the area of the conducted tests. The hydroacoustic background level was determined based on the sound pressure level (SPL) dependence (1):

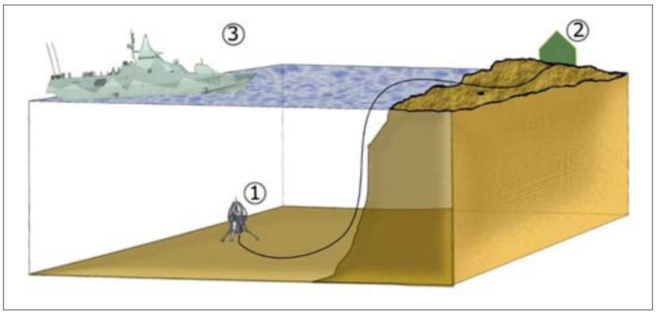

Fig. 2. The arrangement of the measurement system. 1 – underwater measurement system,2 – land control station, 3 – object measured

$$SPL = 20log\,\frac{p_{RMS}}{p_{0RMS}}\,, \tag{1}$$

where:

$$p_{RMS} = \sqrt{\tfrac{1}{N}\Sigma_{n=1}^{N}\left|X_n\right|^2} \tag{2}$$

p_{RMS} – sound pressure level of 1s signal duration,
N – number of samples corresponding to 1s of signal,
X_n – signal sample discrete values.

The analysis was performed in the range from 5 Hz to 25 kHz. The high frequency limit of the band was determined by the sampling frequency of the A/D converter (so that an anti-aliasing built-in filter was used). The low frequency limit was determined by the type of hydrophone used.

The noise level of the hydrodynamic pressure was calculated using Eq. (3),where the average value of the signal (measured for 60 s) was subtracted from the current pressure value as follows:

$$p_{HD} = p - \bar{p}, \tag{3}$$

where:

$$\bar{p} = \sqrt{\tfrac{1}{K}\Sigma_{k=1}^{K} p_k}\,. \tag{4}$$

Vessel measurements were carried out for meteorological conditions corresponding to sea state conditions of 1–2. A chosen vessel with a length of 60 m passed over the measuring system. The unit had a GPS satellite navigation system installed on board, supported by ASG-EUPOS reference stations [26, 27]. This system allowed precise determination of the trajectory of the vessel's movement with respect to the underwater measurement module. The vessel was moving along a given course and counter-course, setting the motion parameters from the position 400 m before the module to the position 400 m behind the module (Fig. 3). For each recoding, the speed of the vessel was fixed.

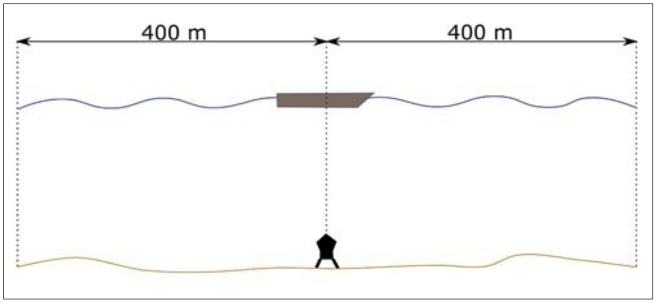

Fig. 3. Vessel trajectory movement during investigations

Tab 4. Meteorological conditions during measurements

Day	Sea condition	Wind speed [m/s]	Wind direction	Air temperature [°C]	Atmospheric pressure [hPa]	Rainfall rate [mm/h]
1	5-6	13.2	N	10	984	0
2	1-2	4.2	N	16	1017	0
3	4-5	11.5	N	12	1003	0

In addition, the changes in hydrodynamic and hydroacoustic pressure were recorded for two other vessels (of 170 m and 40 m length) to allow comparison ofthe disturbances made by different objects. The vessels were passing at a speed of 3.5 m/s and the distance between the vessel keel and sensors could not be greater than 10 m.

RESULTS

Monitoring changes in hydroacoustic and hydrodynamic pressure in real conditions requires knowledge of the current environmental conditions. The waters of the Gulf of Gdańsk are characterised by highly variable weather. Changes in weather conditions can directly affect the values of themeasured physical quantities. This fact was taken into consideration during the tests, so that recordings were made of the pressure disturbancesover a few days, duringwhich period significant differences in hydrometeorological conditions were noted. Three days with different conditions (sea conditions, wind speed, and atmospheric pressure) were selected (Table 4).

Fig. 4 shows selected segments (of 60 s duration, made in the absence of a vessel passage) to illustrate the effect of the changing weather conditions on the hydroacoustic background level during 3 consecutive days.

Based on the data of which Fig. 4 show a selected section, it can be concluded that the hydroacoustic background level increases with worsening weather conditions [28], presumably due to the associated increased eddy activity. Comparison of the hydrodynamic pressure background recorded (in the absence of a vessel passage) by the pressure sensor for the 3 different measurement days is shown in Fig. 5.

Just as Fig. 4 illustrated for the hydroacoustic background, Fig. 5 shows that when the weather conditions deteriorate and the waveforms increase, the level of the hydrodynamic background amplitude increases [29, 30, 31]. The determination of hydroacoustic and hydrodynamic background levels will be an important factor in determining the detection threshold for vessels from hydroacoustic and hydrodynamic signals under severe weather conditions.

Tests of changes in local pressure fields depending on moving objects were carried out under favourable weather conditions and sea conditions 1–2. Three different vessels were used as sources of perturbation, to see what effect the change of vessel had on the time history of the measuredacoustic pressure disturbances (Fig. 6). The dedicated vessel was measured at 3 different test speeds: 2.3 m/s, 3.5 m/s and 5 m/s (Fig. 7). Analogously for the hydrodynamic perturbation comparison, three different types of vessel were used (Fig. 8). The same

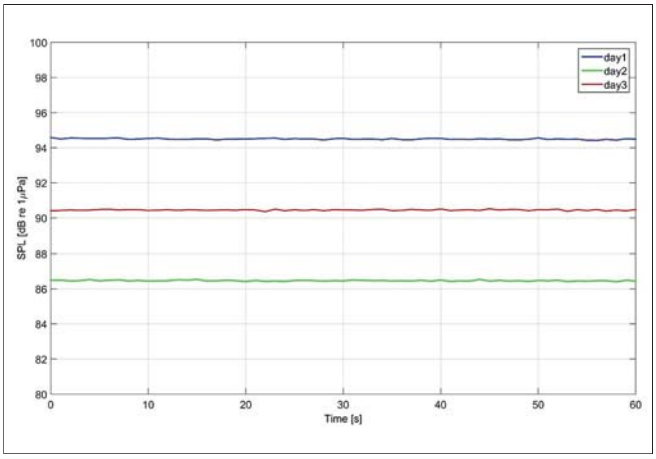

Fig. 4. Comparison of hydroacoustic background levels during 3 measurement days according to Table 4

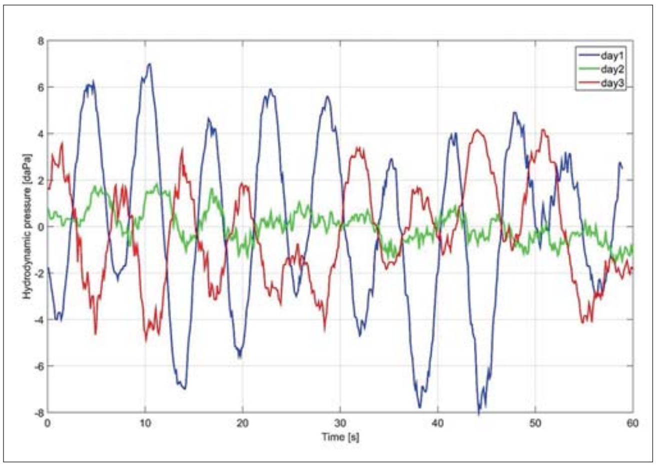

Fig. 5. Comparison of hydrodynamic background levels during 3 measurement days according to Table 4

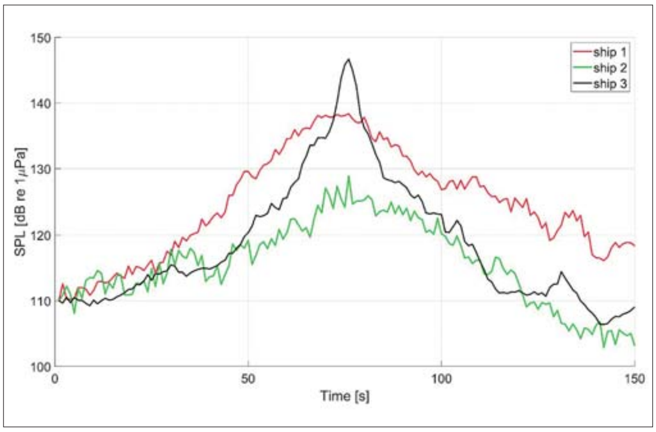

Fig. 6. Sound pressure levels for objects of diverse typesat speed 3.5 m/s (vessel 1 with length 170 m, vessel 2 withlength 40 m, vessel 3 with length 60 m) for sea condition 1-2

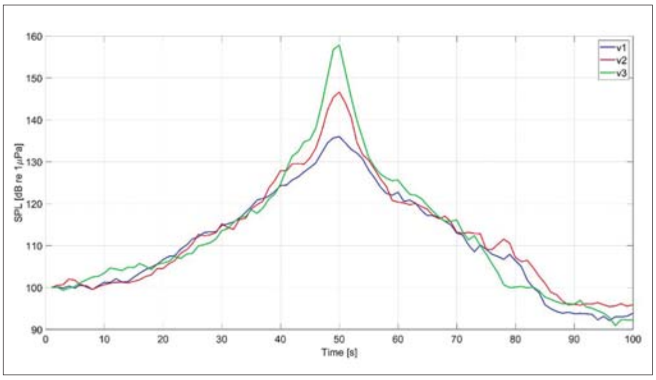

Fig. 7. Hydroacoustic pressure values for different speeds of the same vessel (v1 – 2.5 m/s,v2 – 3.5 m/s and v3 – 5 m/s)for sea condition 1–2

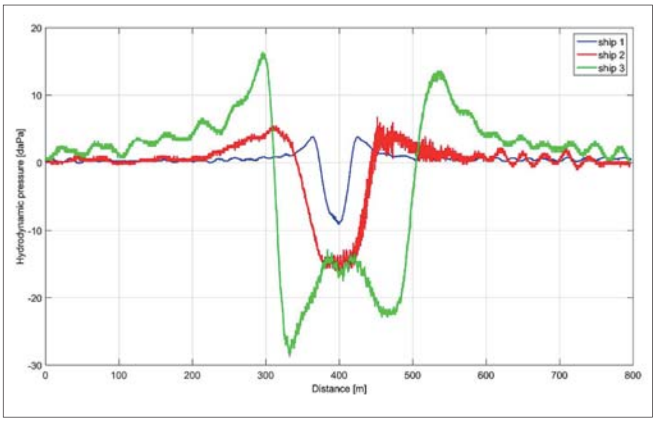

Fig. 8. Hydrodynamic pressure changes for three floating objectsat speed 3.5 m/s (vessel 1 with length 60 m, vessel 2 with length 150 m, vessel 3 with length 230 m) for sea condition 1–2.

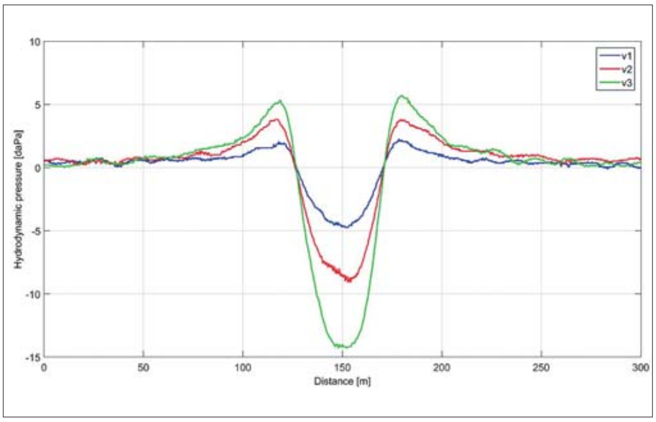

Fig. 9. Hydrodynamic pressure values for different speeds of the same vessel (v1 – 2.5 m/s, v2 – 3.5 m/s and v3 – 5 m/s) for sea condition 1-2

dedicated vessel runs were used for the hydrodynamic analysis as for acoustic pressure, when the vessel was passing at 3 test speeds: 2.3 m/s, 3.5 m/s and 5 m/s (Fig. 9).

For the hydroacoustic field, the level of noise generated by vessels significantly exceeded the level of background noise. The increased noise level was noticeable for every passage before the point located 400 m from the measuring system. Although at first sight the SPL recorded (when the vessel is above the sensor in sea states 1–2) exceeds the background in the absence of the vessel at sea states 5–6, it cannot simply be assumed that this system could detect a vessel passage in the higher sea states without taking the actual measurement, because the coupling between the vessel and the water column can change at a higher sea state (e.g. more bubbly water can better absorb the pressure perturbations, preventing them from propagating to range).

Fig. 8 above shows disturbances of the hydrodynamic field of three objects with various hull sizes and shapes in the vicinity of the measurement system. The vessel with the largest length and draught caused the largest disturbances of hydrodynamic overpressure and underpressure alike. The dedicated vessel caused the smallest disturbance. For this vessel only, the disturbances could have been measured for various velocities, as shown in Fig. 9.

In the case of a hydrodynamic field, faultless detection of thededicated object was obtained at a distance of 50 m before the measurement system for sea condition 1–2. The value of the overpressures and hydrodynamic underpressure would not be distinguishable for the sea condition 5–6 for the same object. Noting the comment made above about the coupling between the vessel and water column changing with the sea state, necessitating actual measurements, it seems likely from these data at sea state 1–2 that only vessels with a length of more than 200 m and a draught of more than 7 m, travelling at these speeds, would be detectable through hydrodynamic pressure fluctuations in such unfavourable meteorological conditions [29, 30].

DISCUSSION

This paper conducted research and analysis on a passive detector that might be used to enhance the safety of maritime transport in the coastal zone. The development of offshore infrastructure is forcing the development of existing traffic monitoring systems fora given water body and the search for alternative solutions.

An object moving on the surface of the water is the source of changes in the local pressure field, notably the hydrodynamic and hydroacoustic fields. Analysis of hydrometeorological conditions is essential in the process of testing the ability of the system to detect vessels using such underwater pressure changes.

Nowadays existing and developing systems used for integrating navigational data from monitored reservoirs are responsible for information distribution and maritime traffic safety. The data collected continuously, together with historical data, allow the detection ofanomalies, which might occurfor various reasons. Such anomalies may refer to the movement of the vessel within the assumed trajectory, specified speed and course. In the case of any inconsistency between the reported geographical position and the actual vessel position, the incorrect determination of the destination and the appearance of a foreign vessel in the zone of interest may be included. Anomalies may also refer tothe type of vessel, cargo, and its quantity. Each of these situations is a threat to maritime traffic and should be prevented. The solution proposed here is based on the analysis of pressure field disturbances in the low-frequency range (hydrodynamics) and in the wider band (hydroacoustics). Data taken in sea states 1–2 showed that it can be used forthe detection of anomalies in realtime. The described method of measuring these quantities, and connecting results to a specific vessel and its movement parameters, could be used to supplement existing methods of monitoring maritime traffic. The use of an underwater stationary measurement system in a distributed configuration in a water body near critical infrastructure will also assist in providing data from an underwater environment. The safety of transport, and in this case sea transport, requires continuous development of existing systems, which is the basis for the implementation of new solutions.

CONCLUSIONS

The analysis of underwater pressure disturbances in respect of objects detection as reported in this article, and its results,have shown the need to develop monitoring systems not only in the airspace but also underwater. It should not be forgotten that suchresearch in real conditions requires consideration of the environmental conditions prevailing in the space covered by the research.

This research has indicated that, when there is an increased acoustic background resulting from the stronger sea conditions and increased wave activity, the detection of floating objects may be limited. Vessels with small hull dimensions and a small draught would be difficult to detect in large waves using hydrodynamic sensors only. This has been shown in Fig. 5 for day 1 and in Fig. 9 for velocities v1 and v2, where the object-generated disturbance is comparable to that generated by waves when the sea is in condition 5–6. However, as noted earlier, this only indicates that such large vessels might be detectable by this method in such high sea states: measurement will be needed to test this. The system would be enhanced, and potentially made more reliable in high sea states, with the use of a pair (or more) of sensors with a hydrophone, thus increasing the possibility, and range, of detection. False positives and false negatives will need to be considered. The different characteristics of the disturbances for the different units that were observed might also be used to separate out the vessel signature from that of the wave action. The results show not only the possibility of detecting the objects using the underwater measurement system but also their distinguishability in a certain range of vessel types, as shown in Figs. 6 and 8. In the future, a detailed analysis of the disturbance shape will enable not only detection but also identification of the source. The article points out the possibility of detecting various objects moving directly beyond the designed measurement system. Further research is planned with the use of the same measurement system configuration of objects moving with specific parameters at various distances from the measurement system. The data thus acquired will make it possible in the future to analyse the feasibility of detecting objects moving farther away from the measurement platform.

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