Investigation of Sonar Stabilisation Method for Improved Seafloor Image Quality

Arūnas Andziulis, Tomas Lenkauskas, Tomas Eglynas, Miroslav Vozňák and Sergej Jakovlev

Abstract Constant monitoring of sea floor in harbours is an essential part of economy development of every sea country. Exact estimation of the sea floor relief parameters is very important not only for port development but also for scientists. Sonar image corrections are constantly made with a high margin of error, using GIS. New correction methods are developed. They include: mechanical correction of the cables of the side-scan sonar, programmable correction of the ship navigation and steering system, other software tolls with developed correction and control algorithms. Most commonly sea floor images are made using side scan sonar. It is used for rapid seafloor imaging. The quality of the captured images is strongly influenced by the sonar towing consistency. Even small sonar disturbances caused by the vessels' towing motion can affect the quality of the images. Therefore, to reduce the influence of the ship motion new methods are being developed. In some cases heave motion compensation can prove to be effective. In this paper an efficient heave motion detecting system was proposed and briefly analysed. Sonar and the ship motion were taken into account during the development and testing of the heave motion compensation system prototype.

Keywords Side scan sonar · Heave motion compensation · Ship movement · GIS

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1 Introduction

In 2012–2020 the Republic of Lithuania will build two major sea transport objects. These objects are: the liquefied natural gas terminal in the Klaipeda seaport and the outer deep seaport near Butinge. Examination of the seabed in the waterfront of Klaipeda and Butinge seaports and under the major sea lanes is very important (CORPI data funds, www.portofklaipeda.lt). Sea floor exploration is important topic in Baltic region and globally. Kuchler et al. [1, 2] are working on sea crane stabilization. This system reduces motions caused by rough sea waters. Wenlin et al. [3] created system that reduces ship motion influence to remotely operated vehicles. Sarker et al. [4] made comparison of several systems for heave motion compensation on ocean drilling ship. Adamson [5] created efficient heave motion compensation. Huster et al. [6] designed and tested passive heave compensation for ROV. Other scientists work with software solutions, such as Trucco and Garofalo [7], with their image merging from twin sonar system solution and Teixeira et al. [8] with their nonlinear adaptive control of an underwater towed vehicle. Yet–Chung et al. [9] presented side scan sonar image correction algorithms, for correcting brightness variation and patching gaps. New, improved methods are developed, how to produce the best quality sea floor maps and extract objects of interest, using GIS applications [10, 11]. Also our team was working on object detection in images produced by side scan sonar [12].

In the coming years the Republic of Lithuania will build two major sea transport objects. These objects are liquefied natural gas terminal in Klaipeda seaport, and outer deep-sea port near Būtingė. Both projects require good preparation. One of most important preparation part is to explore big areas of Baltic Sea and Curonian Bay floor in great detail. Lithuanian territorial waters in Baltic Sea are shallow, deepest places in sea are just over 100 m deep, in Curonian Bay, where the Klaipeda sea port is and liquefied natural gas terminal will be located, waters are just 1–16.5 m deep. For sea-floor imaging in shallow waters Klaipeda University Coastal Research and Planning Institute use ship with small draught and side scan sonar system. This system performs well only at perfect or nearly perfect sea conditions. Image quality produced by side scan sonar depends on how smoothly the side scan sonar is towed. Most of towed device distortions come from uneven towing vessel movement. At rough waters small ship heaves a lot, and images generated by towed sonar are disturbed and not usable. Using current system, seafloor images produced by side scan sonar are good quality when sea waves are up to 0.5 m high. When height of waves is between 0.5 and 1 m, images produced by side sonar system are distorted, but still usable quality. In Figs. 1 and 2 are samples of such images with objects on sea floor. It is much harder to use automatic object detection using distorted messages, because wavy pattern and big colour variations. If waves are over 1 m high, sonar images are very distorted and unusable. Few methods were designed to improve image captured by the side scan sonar quality. To reduce vessel heave motion effect to seafloor images we designed system that can detect and mechanically reduce motions of side scan sonar.

Fig. 1 Fragment of old and rotten ship wreck
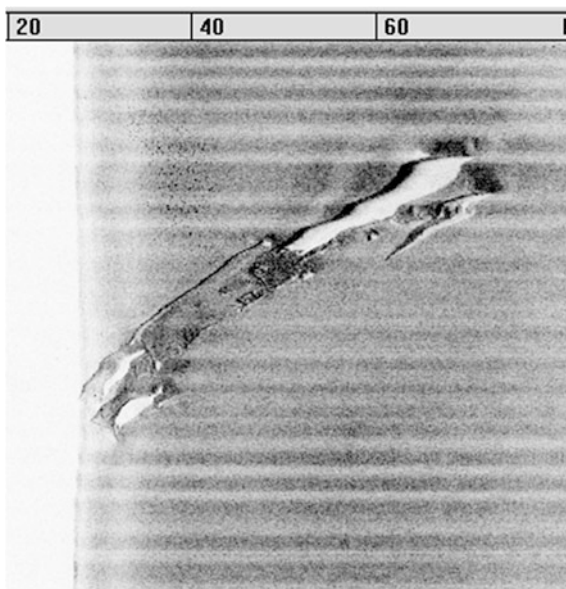
Fig. 2 Recent small ship wreck
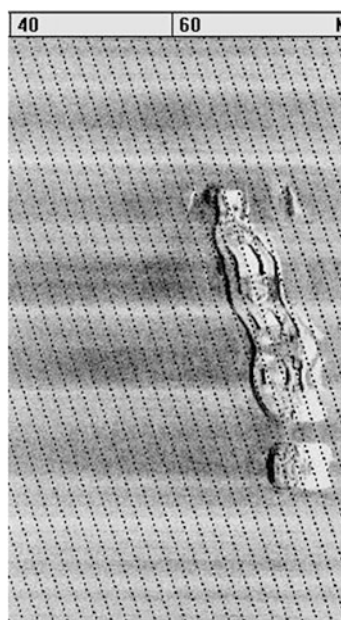
2 Heave Compensation Method

The essence of the mechanical side scan sonar stabilization is to physically remove intrusive sonar and towing vessel movements and imaging noises that cause poor quality sonar image [13]. These movements are mostly caused by the sea waves, sudden manoeuvring of the towing vessel sonar and underwater currents. The biggest and the most common issue addressed on side scan sonar systems is the poor quality of the seafloor images, obtained by the side scan sonars, due to heaving of the ship caused by the rough sea waves. There are several methods to cope with this problem. The easiest way to avoid the swinging of the ship is to plan the seafloor-scanning expeditions at the time when sea waves at their minimum. Even though this method is effective, it limits the number of days per year for expeditions. Another method is to choose the preferable swimming route. When the ship swims lengthwise but not perpendicular to the waves to reduce the impact of rebounding waves.

The depth of the Baltic Sea in Lithuania's territorial waters is up to 100 m. However there are shallow areas, which also need to be researched. The optimum operating height of the sonar is about 12 m above the seabed. But when scanning shallow areas near coast, the sonar has to be towed just 3–4 m above the seabed. It can be done by using a short cable (from 2 to 5 m) which connects the ship and the sonar. Because of the turbulence caused by the ship, the sonar towed with a short cable is more disturbed. It happens because a short cable does not absorb the imbalances of tension. Exploring seabed in the deeper waters long cable is used and the sonar is towed far from the ship. This reduces the impact of the turbulence caused by the ship. Also Long cables absorb shock caused by the ship. Scanning the seabed in deeper waters it is faced with a problem of maintaining the sonar in a constant depth. Towed sonar tends to rise to the surface. It moves away from the optimal 12 m height above the seabed. As a result, the quality of images is worse than needed.

3 Current System Parameters

The standard Current system uses Side Scan Sonar. Its main parameters are presented in Table 1. For our tests we used standard a typical side scan sonar system (see Figs. 3 and 4). It consists of dual frequency (100/500 kHz) sonar "Edgetech 272–TD", "Edgetech 560P" controller and a portable computer with sonar and GIS software, for real time map producing.

This system is mounted on Klaipeda University ship. Sonar cable is mounted on the cable drum, which helps to adjust sonar immersion depth. At end of ship sonar cable goes through pulley, it is the last point in ship where sonar and ship are connected. All further measurements of ship movement will be captured at this point.

Table 1 Side scan sonar parameters

Parameter		Value
Frequency kHz		100/500
Horizontal beam width, °	100 kHz	1.2
	500 kHz	0.5
Maximal imaging area width, m	100 kHz	500
	500 kHz	200
Diameter, cm		11.4
Length, cm		140
Weight, kg		25
Submerged weight, kg		12
Maximum operating depth, m		1,000

Fig. 3 Side scan sonar system Edgetech 4100

Fig. 4 Sonar connection scheme
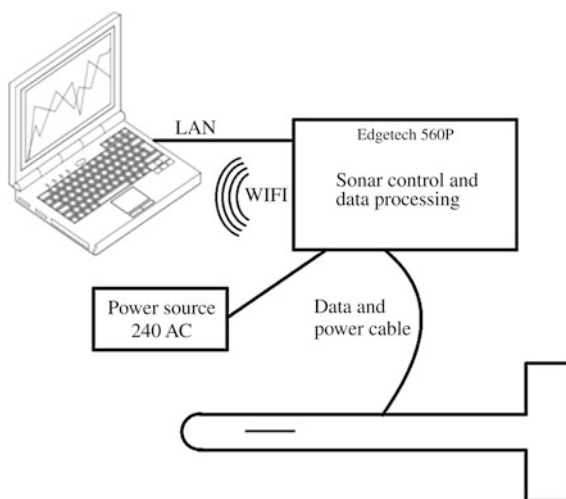
3.1 Operating Conditions

In the Baltic Sea there are no strong underwater currents. Image disturbances occur due to uneven movement of the vessel that tows the sonar. While scanning in the rough sea, sonar heaves together with the vessel. If the sonar rises higher above the sea floor, the scanned sea floor path widens. If the sonar goes down, the image captured by sonar becomes narrower and distorted. The fluctuations of the ship and the sonar are not completely identical due to the flexible cable that connects the sonar and the ship [14, 15]. Using current vessel without any additional stabilization system, the seafloor scanning surveys can be done only when the sea waves are not higher than 0.5 m. In order to ensure stable side scan sonar towing, a system that could accurately capture heave motions of the towing vessel and the side scan sonar was designed (Figs. 5 and 6). The initial system operating conditions have to be determined in order to calculate the engine parameters that ensure the minimization of sonar fluctuation in the sea waters [1]. According to the ship crew, the maximum height of the waves that still enables the ship to maintain constant speed and trajectory is 2 m. We have calculated the maximum speed of the vertical (axis Z) movement of the starting point, while ship is swimming on h = 1 m waves.

It is assumed that the ship runs perpendicularly to the direction of waves. The vertical fluctuation of the ship coincides with the wave's fluctuation in the axis Z. Fluctuation of the keel aboard is not taken into account. The simplified equation of the wave motion is presented as (1):

Fig. 5 Chosen start point
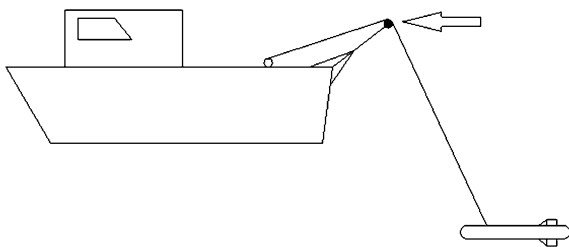
Fig. 6 System with a gravitic depressor

Gravitic depressor
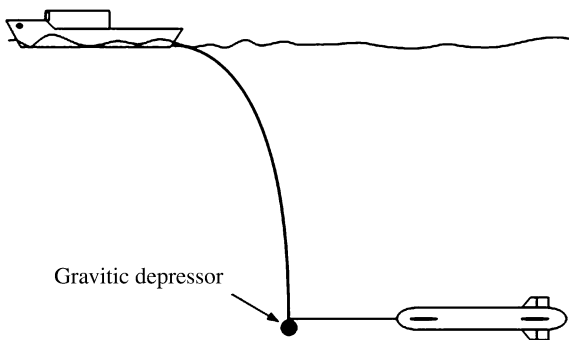
$$Z_b = r_0 \cos \frac{2\pi t}{\tau} \tag{1}$$

The equation: of ship vertical velocity while swimming on wave (2):

$$v_z = -\frac{2\pi}{\tau} r_0 \sin \frac{2\pi t}{\tau} \tag{2}$$

here, v_z—speed, m/s, τ—the wave length, m, r_0—wave radius, m, The radius r_0 is equal to the half of the wave height (3):

$$r_0 = \frac{h_b}{2} = 1\,m \tag{3}$$

Here h_b—the wave height, m, then:

$$\upsilon_{max} = \left| \frac{2\pi}{\tau} r_0 \right| = 1.52\,m/s \tag{4}$$

v_{max}—maximum velocity on vertical axis, m/s.

Real waves can mismatch the waves being described with the equations of the motion. That is why we will use the maximum speed $\upsilon_{max} = 2\,m/s$, which is higher than counted value. The maintenance of height above the seabed that is required by the side view sonar is also a very important aspect to be addressed. If sonar is towed not in optimal depth, image quality drops drastically. It is complicated to reach the necessary depth. The scientists of CORPI cope with this issue by running the ship slower than is required by the manufacturer. Decreasing the speed means that the quality of the images would be worse. Avoiding sonar hitting the seabed is also very important, as sonar can be damaged. Several scientists like Teixeira et al. [8] proposed a standard system of seabed scanning. This system includes a ship and a side scan sonar with the stabilizer of weight. Their system is used to explore the seabed of the deep ocean. The length of the cable used in the system reached 900 m. The mass of the stabilizing weight reached 200 kg and the weight of the sonar was 113 kg. To implement this method the following components are proposed to be used: ship's motion sensors, data processing system and the weight of the stabilization of the sonar. Similar system was used by Teixeira et al. [8].

The purpose of weight is the stabilisation of sonar depth and steady movement of the sonar. In our system case we are planning to use gravitic depressor that will be scaled down to 50 kg weight, but system will operate on same basic method. The total weight of modified sonar system with gravitic depressor is 90 kg, it consists of the sonar, 50 kg of stabilization weight and connecting cables. This does not include cable drum motor and its controllers weight, because they are considered as a part of ship, not sonar, weight. For modifying our system we will leave same basic sonar lifting mechanism, only motor and its controller will be changed. Cable

connecting ship and sonar is wrapped around the drum, whose maximum angular velocity ω is calculated according to this formula described by [14]:

$$\omega = \frac{v}{r_b} = \frac{2}{0.15} = 13.33\frac{1}{s} \tag{5}$$

ω—the cable drum angular velocity, 1/s, r_b — radius of the cable drum, m. The rpm of the drum is calculated according to this formula:

$$n = \frac{30\omega}{\pi} = 127.36\,aps/min \tag{6}$$

The moment of the inertia of the load:

$$J_m = m\left(\frac{v_{max}^2}{\omega^2}\right) = 90\left(\frac{2^2}{13.33^2}\right) = 2.02\,kg\,m^2. \tag{7}$$

The coefficient of reduction for cable drum is described (8):

$$i = \frac{n_{mot}}{n} \approx 20 \tag{8}$$

i—the reduction coefficient, n_{mot}—the cable drum motor rpm. The torque that is needed to lift the weight (9):

$$M_s = mgr = 90 \cdot 9.81 \cdot 0.15 = 132.44Nm \tag{9}$$

M_s—the system torque, Nm. The angular velocity of the engine rotor:

$$\omega_{mot} = \frac{n_{mot}\pi}{30} = \frac{2400\pi}{30} = 251.2\frac{1}{s} \tag{10}$$

ω_{mot}—angular velocity of cable drum motor, 1/s. The engine reach the maximum speed during the time period $\Delta t = 0.5\,s$. We assumed that the moment of the engine inertia is equal to the reduced moment of the inertia of the load is described as:

$$J = J_{mot} + \frac{J_m}{i^2} = 0.01\,kgm^2 \tag{11}$$

J_{mot}—the motor inertia moment, kgm^2, The general moment of inertia of the motor rotor is (12):

$$J = J_{mot} + \frac{J_m}{i^2} = 0.01\,kgm^2 \tag{12}$$

Resistance to the axis of the engine torque presented as (12):

$$M_{sv} = \frac{M_s}{i\eta} = \frac{132.44}{20 \cdot 0.95} = 6.97\,\text{Nm} \tag{13}$$

M_{sv}— the resistance moment, Nm, η—the reducer efficiency coefficient. The torque which is required to start the engine is (14):

$$M = M_{sv} + J\frac{\omega_{mot}}{\Delta t} = 11.99\,\text{Nm} \tag{14}$$

The power of the engine is (15):

$$P = \omega_{mot}M = 3011.88\,\text{W} \tag{15}$$

The reserve coefficient of 1.25 is applied to the engine power PR is calculated as follows (16).

$$P_R = P \cdot 1.25 \approx 4000\,\text{W} \tag{16}$$

Therefore, the parameters of the engine are obtained:

- Power P = 4000 W;
- The maximum speed is 2400 rpm;
- Gear box ratio 1:20.

## 4 The New Software Creation of the Measurement System

The designed motion measuring system prototype consists of a laptop, controller and some sensors. Accelerometers and gyroscopes that are used in the system make the appropriate measurements, calculate the difference in the motion of towing vessel and sonar. Sensors are connected to the Arduino Duemilanove controller. This controller performs collects data. We used paired sensors in the prototype. Pair consists of accelerometer and gyroscope. Both sensors are mounted on the same chip. The developed system data reliability is estimated as high, because the angles between the sensors axis are fixed. Due to the low number of the connecting wires, this system is more compact and easier to use than the conventional systems with one-sensor-per-chip. For capturing vessel motions the sensor unit is mounted to the vessel (Fig. 5).

The main system works with the SerialChart and Arduino 1.0 software. Such interconnection between SerialChart and the Arduino's functions of data scanning allows not only to see the digital values of sensors in real time, but also depict data in real time with updated diagrams. The maximum operating frequency of the accelerometer ADXL 345 is 200 Hz, ITG-3200—400 Hz. System sensors frequency can be up to 150 Hz only if just accelerometers are connected. If the

gyroscope is connected to the system, frequency drops to 20 Hz. The differences between the maximum operating frequency of sensors and the frequency of the measurement systems occur since the system performance is limited by the controller Arduino Duemilanove computing power. The gyroscope "ITG-3200" sends the data to the controller which converts signals into degrees, additional processing of the signal is not required. The data from the accelerometer is sent by signals in which 1 g (9.81 m/s^2) is 256 bytes. If the accelerometer is not moved, the value of axis Z is—256 bites. That is because the accelerometer senses earth gravitation pull. In order to properly provide the axis Z accelerations it adds 256 to the value of the received signal. The result is to be divided by 256 and multiplied by 9.81. The resulting units of acceleration are m/s^2. Accelerometer data is converted in the same way.

The main parts of the algorithm that were used/programmed within the controller are shown in Fig. 7. The first step was to integrate drivers for all sensors, including calibration. Reading the data from the sensors is the first part of the actual program. Here it is very important to get 'smooth' data. The first part is to combine the data form the g-sensor and the accelerometer. The second part is to use a virtual filter proposed by Koseeyaporn and Koseeyaporn [16]. For system testing we used the mentioned virtual filter with some simple adjustment modifications for our case study. Vessel heave motion was calculated using the acquired raw data. Calculations were done to determine how the speed of the electric motor and the direction of spinning affected the heave motion compensation. Finally, we examined the sending signal to the electric motor. On our small scale testing model we used a low power stepper motor. Our model was functioning properly and efficiently compensated the heave motion. Also alternative data collection system is now being prepared, using the same sensors and the new National Instruments (NI) software and hardware components in Klaipeda University research laboratories.

Fig. 7 Algorithm scheme
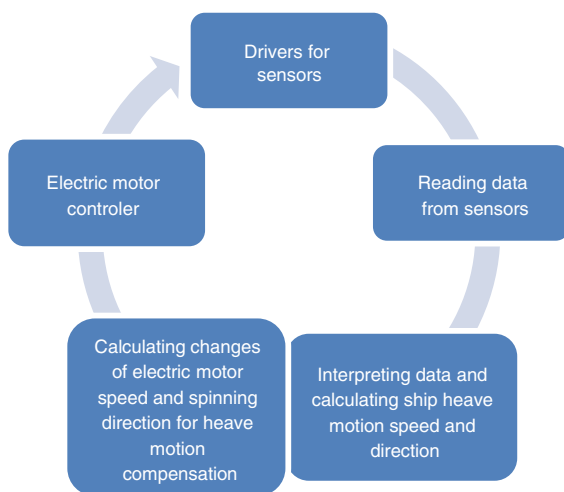
5 Experimental Research

The designed system prototype was installed and used in the Klaipeda university ship. The measurement was carried out when the weather conditions were favourable for working at sea. The direction of wind was variable from 1 to 2 m/s, the height of the waves was from 0.3 to 0.5 m and the sip used an "Edgetech 4100" side view sonar system. For a proper research of the seabed the ship movement has to be at least 4 knots (about 2.06 m/s) (the data foundation of CORPI). During the research, the speed of the ship was 10 knots (about 5.14 m/s).

5.1 Experimental Results

The results of the first experimental measurements are presented in Figs. 8, 9, 10 and 11. Figure 8 provides the data collected with the three-axis gyroscope. It can be seen that parameters vary very slightly. The data collected with the three-axis accelerometer is presented in Fig. 9. There appear vibrations of the vessel engine
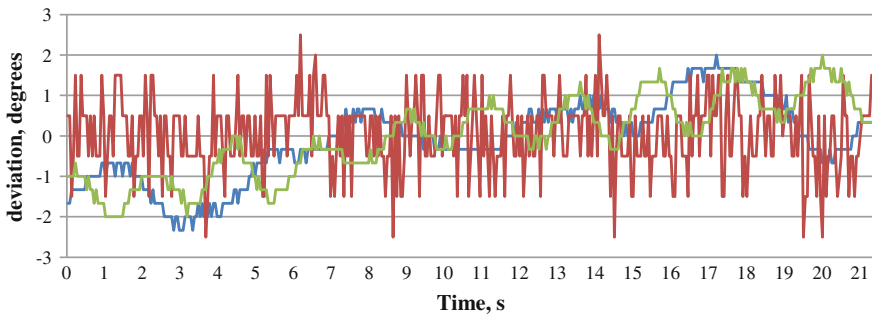
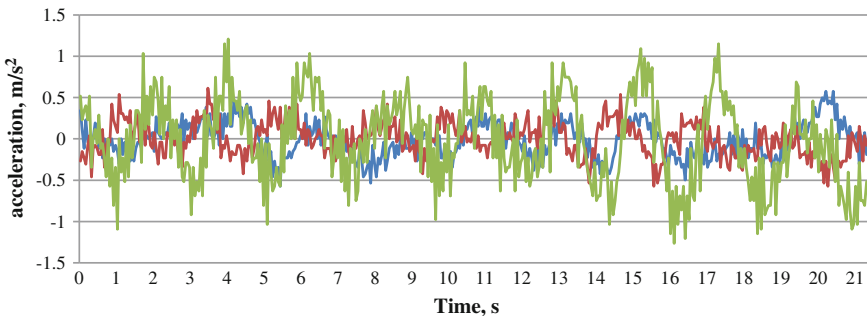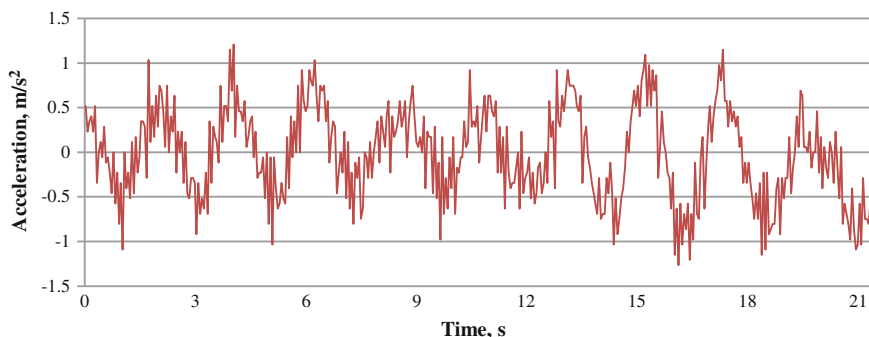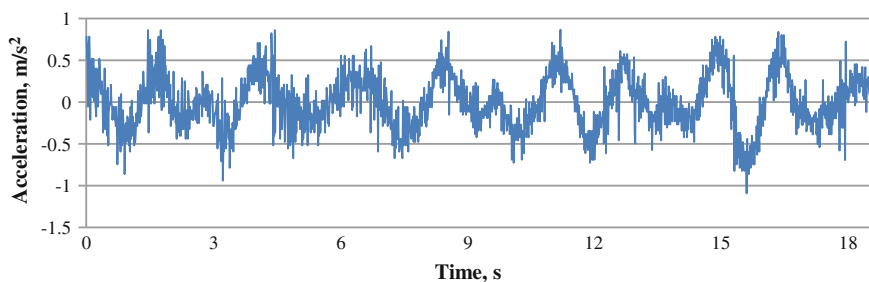**Fig. 8** First test results, data from the 3 axis gyroscope

Fig. 9 First test results, data from the 3 axis accelerometer

Fig. 10 First test results, data from the Z axis accelerometer

Fig. 11 Second test results, data from the Z axis accelerometer

and other disturbances the collected data of accelerometer. On the other hand, the parameters of ship movement can be clearly seen. The heaving motion of the ship rise when the ship swims through the waves is clearly visible. The acceleration of the ship fixed with axis Z is presented in Fig. 10.

The second measurement was performed on the same day. The data acquisition system worked at 80 Hz frequency and only accelerometer was enables. In this case, the values scanned with Z axis accelerometer are only relevant. Collected data is presented in Fig. 11. It can be seen that the values between each measurement vary. The collected data was adjusted with a virtual filter proposed by Koseeyaporn and Koseeyaporn [16]. The processed data is presented in Fig. 12.

6 Calculations Using the Collected Data

Further calculations were made using the data from the second measurement. This data was not processed with any filters. Measurements started with the speed of the vertical fluctuation of the starting point when its value was 0. Then the modulus of acceleration was the biggest.
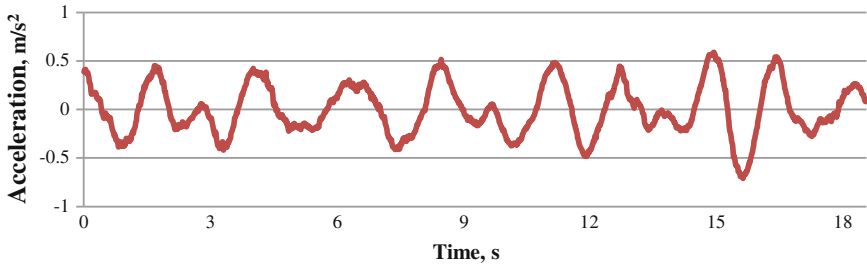
Fig. 12 Filtered accelerometer parameters. Second test, Z axis

To calculate the speed the following equation was used:

$$v_{n+1} = \frac{(a_n + a_{n+1})}{2} \Delta t + v_n \tag{17}$$

Here: v_{n+1}—is the current speed; a_{n+1}—is the current acceleration; a_n—is the acceleration, measured during the previous measurement; Δt—is the measurements frequency, 0.05 s; V_n—is the speed, during the previous measurement. Accelerations of the axis Z and the calculated speed of the heaving are presented in the Fig. 13.

The researcher operating the system, determines the required length of the cable h. Taking into account the heaving of the ship, the provided stabilization system can change the length of the cable. However, the length of the cable must remain at similar approximate value (±0.5–2 m). The operator can set the maximal allowable change of the cable's length. In the calculations the cable's length is marked as h_n. The starting settings of the system are: $\Delta t = 0.0125$ s; $h_n = 0$ m

To calculate the general change of the cable's length h_{n+1} the following equation was used (18):

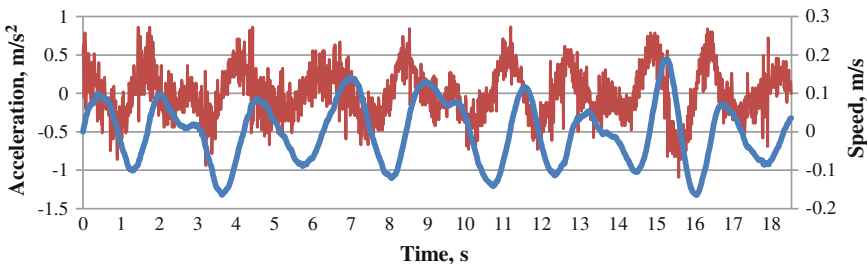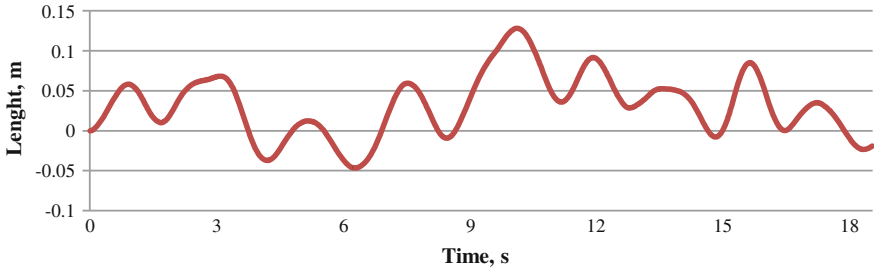$$h_{n+1} = h_n + \Delta t \cdot v_n + (a_n + a_{n+1})\Delta t^2 \tag{18}$$

Fig. 13 Ship accelerations and speed

Fig. 14 Calculated sonar cable length

Here: h_{n+1}—is the current difference of cable's length from the starting point, h_n—is the difference of cable's length from starting point that was fixed before the time period Δt. Results are shown in Fig. 14. The instant changes of the cable's length Δh are calculated according to this Eq. (19)

$$\Delta h = \Delta t \cdot v_n + (a_n + a_{n+1}) \cdot \Delta t^2 \tag{19}$$

For more accurate data collection we can use two or three identical sensors mounted in the same place. Then some average values can be calculated for a better accuracy. In order to get better results, different types of sensors could be combined as well. For constantly changing angle between the axis Z of accelerometer and g-sensor subtraction the accelerometers can be mounted on the stable sleeve.

7 Conclusion

The biggest influence to the side scan sonar high quality images is done by towing vessel motion disturbances, caused by rough sea waves. Other less important factors are towing vessel turbulence, sonar distortions during U turns and underwater currents [17]. In this paper a successfully designed and manufactured motion detection measurement system that detects towing vessel and side scan sonar motions was tested in real life operations. The side scan sonar prototype control parameters were estimated and calculations were made. A side scan sonar system prototype that is suitable for seafloor imaging in shallow waters was designed. It uses mechanical stabilization using DC motor and the motion measurement system. In the future, more experimental data will be collected and additional research will be conducted to further improve the presented system. Also full a scale heave motion compensation system with gravitic depressor will be manufactured and mounted on the research ship. These improvements will increase number of days per year that sonar system can be used.

References

1. Kuchler S, Mahl T, Neupert J, Schneider K, Sawodny O (2010) Active control for an offshore crane using prediction of the vessel's motion. Trans Mechatron 16(2):297–309
2. Sawodny O, Kuchler S (2010) Nonlinear control of an active heave compensation system with time-delay. In: International conference on control applications, pp 1313–1318
3. Wenlin Y, Zhuying Z, Aiqun Z (2008) Research on an active heave compensation system for remotely operated vehicle. In: International conference on intelligent computation technology and automation, pp 407–410
4. Sarker G, Myers G, Williams T, Goldberg D (2006) Comparison of heave-motion compensation systems on scientific ocean drilling ship and their effects on wireline logging data. In: Proceeding of offshore technology conference
5. Adamson JE (2003) Efficient heave motion compensation for cable-suspended systems. In: Underwater Intervention
6. Huster A, Bergstrom H, Gosior J, White D (2009) Design and operational performance of a standalone passive heave compensation system for a work class ROV. In: Proceeding of oceans, MTS/IEEE Biloxi—Marine technology for our future global and local challenges
7. Trucco A, Garofalo M (2009) Processing and analysis of underwater acoustic images generated by mechanically scanned sonar systems. IEEE Trans Instrum Meas 58(7):2061–2071
8. Teixeira FC, Aguiar AP, Pascoal A (2010) Nonlinear adaptive control of an underwater towed vehicle. Ocean Eng 37:1193–1220
9. Chang Y-C, Hsu S-K, Tsai C-H (2010) Sidescan sonar image processing: correcting brightness variation and patching gaps. J Mar Sci Technol 18(6):785–789
10. Brown CJ, Sameoto JA, Smith SJ (2012) Multiple methods, maps, and management applications: purpose made seafloor maps in support of ocean management. J Sea Res 72:1–13
11. Masetti G, Calder B (2012) Remote identification of a shipwreck site from MBES backscatter. J Environ Manag 111:44–52
12. Andziulis A, Gaigals G, Lenkauskas T, Visakavičius E, Jakovlev S, Eglynas T, Beniušis V (2011) Comparison of two image processing techniques for objects detection on the sea floor. In: Proceedings of the 15th international conference. Transport means, pp. 62–64. ISSN:1822-296X
13. Peterson RS, Nguyen TC, Rodriguez RR (1994) Motion minimization of AUVs for improved imaging sensor performance beneath a seaway. In: Autonomous underwater vehicle technology, pp 247–254
14. Barrass B (2001) Ship stability notes and examples. Butterworth-Heinemann, London
15. Buckham B, Nahon M, Seto M, Zhao X, Lambert C (2003) Dynamics and control of a towed underwater vehicle system, part I: model development. Ocean Eng 30:453–470

16. Koseeyaporn J, Koseeyaporn P (2005) Kalman filtering adaptive stabilization of robot manipulator under sea wave interference. In: Proceedings of international symposium on intelligent signal processing and communication systems, pp 689–692
17. Lambert C, Nahon M, Buckham B, Seto M (2003) Dynamics and control of towed underwater vehicle system, part II: model validation and turn maneuver optimization. Ocean Eng 30:471–485