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# The Assessment of ADIS 16364 for the Examination of Ship Motions in the Free-Running Model

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**ABSTRACT**

The ADIS 16364 instrument is frequently employed for direct measurement of ship motion on ships. However, the validation process for ADIS 16364, to assure its reliability in monitoring ship motion, has not yet been completed. The ship motion model test conducted at the hydrodynamics laboratory utilizes the free-running test technique in conjunction with the QUALISYS motion capture system and the ADIS 16364 device. The purpose of this assessment is to ascertain the instrument's appropriateness for performing ship motion testing. The ADIS device is composed of two components: an accelerometer and a gyroscope. These components are employed to quantify the acceleration of the ship's heave motion and the rotational velocity of its pitch and roll motions, respectively. Utilizing a motion capture system, the QUALISYS Motion Capture System records the motion of a ship model. The examination evaluates two discrete waves produced, comprising two cases of regular waves measuring 10 centimetres in height and 1.5 seconds in period and two cases of irregular waves measuring 16 centimetres in height and 1.75 seconds in period. The elevation motion data in the time domain is acquired from the measurements of the instrument via a wireless system. Following this, various numerical processing methods are implemented, including the moving average filter and cumulative trapezoidal numerical integration. As a result, the root mean square percentage error (RMSPE) discrepancies between the two measuring instruments for regular waves are restricted to a maximum of 5.7% for roll motion and fall below 4% for heave and pitch motions. In the results of the model test response, every movement in both the regular wave and irregular wave scenarios is the same because it does not have an RMSPE of more than 5%.

## 1. Introduction

The study of ship motion encompasses the many behaviours and features shown by ships when subjected to wave conditions. These phenomena have a significant impact on both the vessel itself and its passengers, thereby necessitating their careful consideration during the ship design process [1]. The investigation of ship movements was effectively conducted through the utilization of

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numerical simulation [2]. However, the experimental model conducted in a laboratory setting yielded even more precise results [3]. The accuracy of ship model motion testing in a laboratory basin is largely determined by a number of factors, one of the most important being the precision of the equipment used to measure the six degrees of freedom of the ship model motion caused by wave forces. Ship motion testing methods are modified according to the type of testing basin, such as in a towing tank, where the test model is held and towed by a speed-adjustable carriage, and in a large basin, where the test model is allowed to freely drive with remotely controlled direction and speed [4]. Likewise, the measurement devices and data collection procedures used in the two types of basins also differ from each other.

Currently, the ADIS 16364 device is becoming popular for measuring ship motion directly on ships. This device is equipped with two sensors, namely an accelerometer and a gyroscope. The accelerometer is used to measure heave motion, while the gyroscope is used to measure angular motion, namely roll and pitch motion. ADIS 16364 device is often used in naval architecture, such as to detect changes in ice shift under an ice-breaking station on a ship [5,6], simulate floe-ice fractures that occur from ship motions [7], and be used as a ship motion measurement tool on an Offshore Supply Vessel (OSV) directly in Norwegian waters [8]. ADIS 16364 belongs to the Inertial Measurement Unit (IMU) which is in great demand by scientists because it is more practical, excellent at measuring lateral motion [9], and economical. However, there is a weakness of this tool, namely that the data generated by the sensor has quite complex noise [10,11], thus data processing is needed, such as filtering data [10,12,13], calibrating, and validating tools [14] such as validated IMU misalignment estimates [9,15], validated accelerometer sensors [16,17], and gyroscope sensors [18]. Ship motion position data from measurements is carried out by converting acceleration data to motions with double integration [17-19], and validation of compensation simulations [18,19].

This research is possible; it is based on several previous studies that compared the ADIS 16364 instrument with several reliable measuring devices, such as optical 3D motion capture system devices [13] to capture human movement and using GPS (Global Positioning System) sensors to measure ship motion [20]. The ADIS 16364 instrument is frequently employed on ships to directly measure their motions, and several relevant studies have been referenced [10-19]. However, the validation process for ADIS 16364, to assure its reliability in monitoring ship motion, has not yet been completed. Therefore, this entails a comparison between the ADIS 16364 and the QUALISYS motion capture system, which is a commercially available tool used for conducting seakeeping tests in basin laboratories. This research is also a continuation of previous research that examined the measurement methodology and processing methods for ship motion data using ADIS 16364 [21]. Furthermore, this tool is used to directly measure ship movements in the Malacca-Indonesia Strait [22].

The ADIS 16364, manufactured by analogue devices, is a tri-axis inertial sensor known for its excellent accuracy. This sensor incorporates a 24-bit analogue-to-digital converter (ADC) [23]. The ADIS 16364 sensor is comprised of two distinct sensors, namely a gyroscope and an accelerometer. The gyroscope sensor has the capability to monitor three rotational motions in XYZ dimensions, specifically roll, pitch, and yaw. The data is expressed in terms of angular velocity, specifically measured in degrees per second (°/s). The accelerometer sensor quantifies the ship's translational motion acceleration in XYZ dimensions, encompassing surge, sway, and heave. The unit of measurement for recording acceleration is commonly expressed as meters per second squared ($m/s^2$). The microcontroller of the IMU-Evaluation board incorporates all sensors and facilitates their integration. This board can be easily installed and connected to a personal computer using a USB cable. Furthermore, it should be noted that the parameters of the ADIS 16364 sensor instrument have been meticulously engineered to achieve a high level of accuracy and precision, with a specific emphasis on motion measurement capabilities [23].

The QUALISYS motion capture system, another prevalent equipment, is very appropriate for implementation within ship model testing facilities as well. The aforementioned instrument has demonstrated extensive usage as a validator for devices utilized in the measurement of motions [24]. The QUALISYS Motion Capture System is a motion capture system utilized for capturing the motion of things. It employs a motion capture camera to record object motion as analogue input. This system enables the tracking of objects inside expansive volumes in real-time, operating at a high frequency [25]. The system has the capability to monitor the object's location and orientation in six degrees of freedom (6DOF). The QUALISYS Track Manager (QTM) software is capable of real-time automated identification of rigid bodies, facilitated by its seamless integration with peripheral devices.

Both ADIS 16363 and QUALISYS are suitable measuring equipment options for assessing ship motion performances during free-running operations in an open basin laboratory. In this experimental configuration, the ship model's velocity is propelled in a forward direction, but its orientation is controlled by an operator via a remote-control system. The free-running test is a widely employed methodology within the marine model testing for evaluating the manoeuvring and the seakeeping of ship [26]. The experiment is conducted via a scaled-down model capable of unrestricted movement within a test tank, which is accurately recreated to simulate real-world environmental conditions. The QUALISYS motion capture system employed in this study serves as a validation tool due to its exceptional precision in capturing motion-related parameters [15,16]. In order to ascertain the accuracy and reliability of the ADIS 16364 measuring equipment, it is important to conduct a systematic evaluation to verify the precision and dependability of the acquired data. The aim of this paper is to conduct a comparative analysis of measurement data obtained from two different systems, namely the ADIS 16364 and the QUALISYS Motion capture system. The data will be acquired under identical testing conditions, including the ship, its operation, and the waves.

The objective of this study is to assess the reliability of the ADIS 16364 instrument. The innovation implemented involves assessing the efficacy of ADIS 16364 by conducting a comparative analysis with the QUALISYS motion capture system, which is a globally recognized commercial benchmark for ship design. While the research flows are to gather measurement data, to determine the best way to aggregate it to reduce noise from the ADIS 16364 measurement apparatus, and to calculate the percentage difference in measurement outcomes between the ADIS 16364 and QUALISYS systems. The percentage difference is utilized as a metric to assess the precision of a measurement. Once all the necessary tests have been successfully conducted and satisfactory results achieved, the ADIS 16364 equipment will be deemed prepared for subsequent utilization. This will entail the direct onboard measurement of the ship's motion while it is navigating in open waters.

## 2. Experimental Methodology

### *2.1 The Basin Laboratory and the Ship Model*

Ship motion experiments are conducted at the Manoeuvring and Ocean Engineering Basin (MOB) facility of the Indonesian Hydrodynamics Laboratory (IHL) [27], which is a division of the National Research and Innovation Agency (BRIN) of Indonesia. The principal MOB dimensions are as follows: 60 meters in length, 35 meters in width, and 1.25 meters in depth. It is possible that the basin facilities could evaluate a model with a length of 2 to 3 meters and the capability to travel at high velocities. The pool's dimensions enable the measurement of ship motions along the entire length of the test path in accordance with the following wave directions: 25 meters in the direction of headseas ($180^0$), 35 meters in the direction of quartering seas ($135^0$), and 25 meters in the direction of beam seas

($90^0$). Furthermore, MOB has a facility for creating waves that can be used to test the seaworthiness of model ships. An electric motor drive with 72 blades is used as the wave generator to produce both regular and irregular waves. It can produce waves with amplitudes and periods ranging from 0.05 to 0.45 meters and 3 seconds, respectively.

The model ship is a vessel characterized by its planning hull design, known for its high-speed capabilities (see Figure 1). The model ship is constructed at a scale ratio of 1:18.75.

**Fig. 1.** Ship models

Table 1 presents the primary dimensions, wherein the model ship has a length of 3.43 meters. The vertical centre of gravity (VCG) of the model ship is positioned at 155.80 cm ahead of the after perpendicular (AP) and is elevated 22.30 cm above the base line, with the keel distance to the length centre of gravity (LCG). Experimental seakeeping procedures involve the use of a model vessel propelled by a direct current (DC) motor, which is fitted in accordance with the power specifications of the model. The DC motor that has been installed is furnished with a remote-control mechanism for the purpose of manoeuvring the model. The remote control restricts the voltage supplied to the motor based on the predetermined revolutions per minute (rpm) being examined. Consequently, the model ship operates at the intended motor rpm or in line with the model's vessel speed (Vs).

**Table 1**
Principal dimensions of ship models

| Principal Dimensions of Ship Models | |
|---|---|
| Length Between Perpendicular (LBP) | 343.00 cm |
| Breadth (B) | 54.30 cm |
| Depth (H) | 41.30 cm |
| Draft (T) | 16.80 cm |
| Length of Centre Gravity (LCG) | 155.80 cm from AP |
| Vertical of Centre Gravity (VCG) | 22.30 cm |
| Ship model speed (Vs) | 2.4 m/s |
| Displacement (Δ) | 126 kg |

### *2.2 ADIS 16364 and QUALISYS Devices*

The process of installing the ADIS 16364 device on a model ship for the purpose of measuring ship motion involves many sequential phases. The ADIS 16364 and its supporting equipment are to be prepared and arranged in accordance with Figure 2.

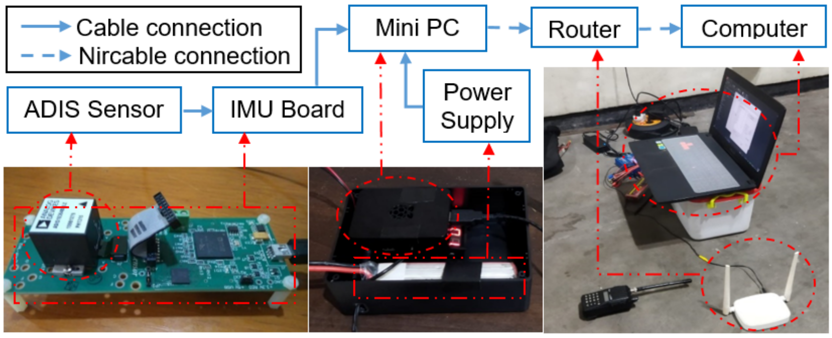



**Fig. 2.** ADIS 16364 devices and their supporting and working principles

Subsequently, they are installed on the ship deck, as depicted in Figure 3. In order to minimize the effects of vibration during seakeeping testing, the ADIS devices must be firmly placed inside the navigation room, namely at a distance of 42 cm in front of the length centre of gravity (LCG) and 25 cm above the LCG. The device's placement does not coincide with the centre of gravity, necessitating a transformation of the measurement findings to align with the centre of gravity.

The model ship is outfitted with an ADIS 16364 device that incorporates a micro-PC, namely a Raspberry Pi 3, for its operations. The Advanced Dynamic Information System (ADIS) is utilized to document the vessel's movements during seakeeping experiments, with the resulting data being compiled into a structured data sheet. A Mini PC is employed for the purpose of storing and transmitting data obtained from the ADIS 16364 to the computer operator. The ADIS data, presented in the format of data sheets, is transmitted by wireless means to the small PC by utilizing the Universal Serial Bus (USB) interface. Subsequently, the data is wirelessly transferred to the computer over the local network. According to Figure 2, computers and mini-PCs are linked to the local network through the router. The characteristics of ADIS 16364 employ a pair of sensors, specifically the accelerometer and gyroscope. The accelerometer sensor accuracy employed is specified as +5 g, where g represents the standard acceleration due to gravity at 9.806 m/s$^2$. Additionally, the gyroscope sensor utilized exhibits an accuracy of less than 0.050 deg/s. Based on the provided specs, it may be inferred that the ADIS 16364 is suitable for application within the transportation industry, including for the purpose of quantifying ship motions [23].

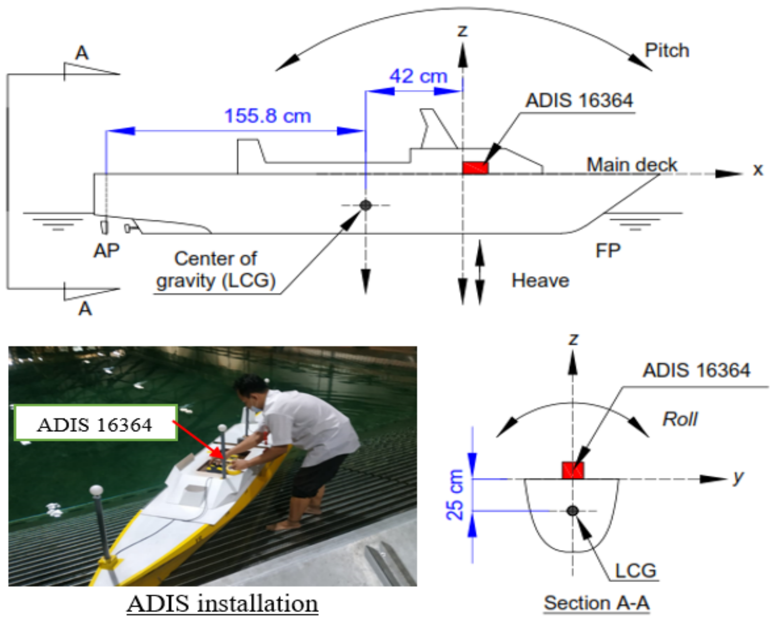



**Fig. 3**. Installation of the ADIS 16364 device on the ship models

In this experimental setup, a total of seven QUALISYS cameras are strategically positioned along the periphery of the basin. Each camera is spaced at a uniform distance of 3.9 meters from one another and is elevated at a height of 3 meters above the free surface of the water, as seen in Figure 4. The camera's field of view encompasses a 625-square-meter area, allowing for the recording of basin tests throughout its range. The gadget is outfitted with the Long-Range Active Marker, which serves as a mechanism for controlling the active marker in remote scenarios. The QUALISYS Long Range Active Marker has a high level of precision, with an accuracy of +0.01 mm (2σ), as verified by calibration conducted by Exova Metech [25].

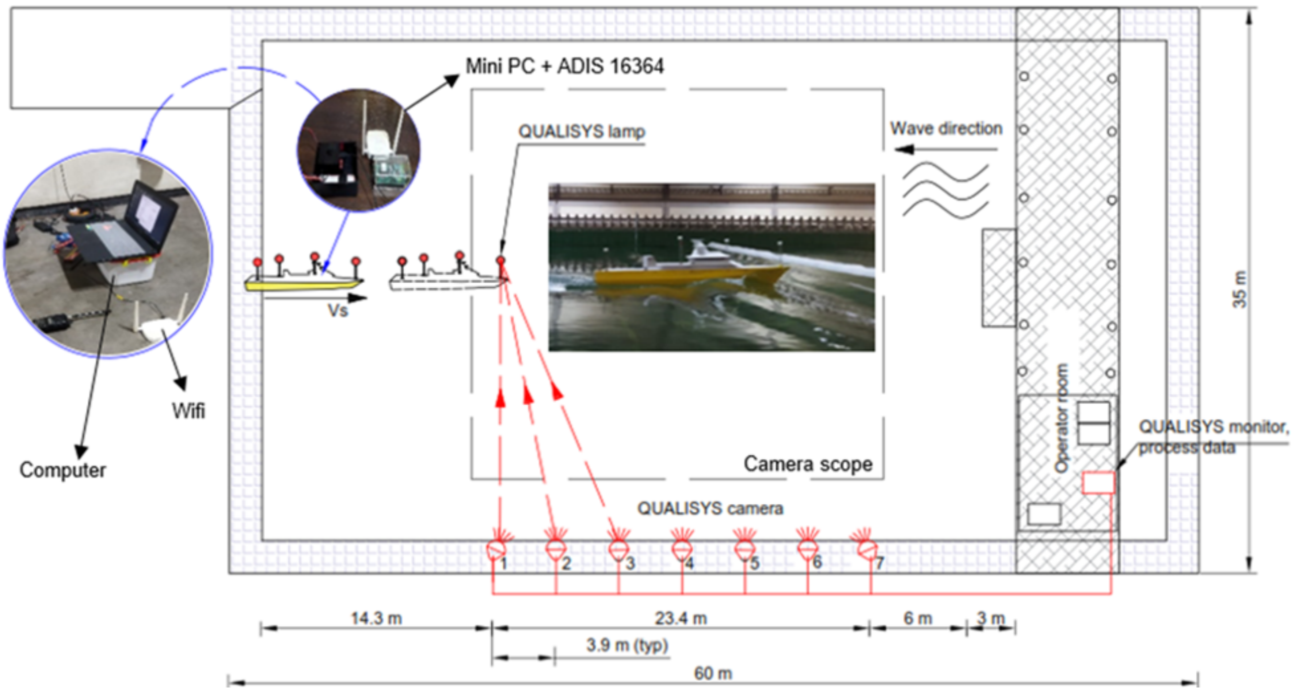



**Fig. 4.** Seakeeping testing facilities and techniques at MOB

### *2.3 Experiments Arrangements*
#### *2.3.1 Calibration instrument*

The calibration of the QUALISYS motion capture system is an integral component of the preparatory phase for testing. Calibration is a fundamental process that ensures the accuracy and precision of measurement devices by verifying their correctness and evaluating the associated error margins. The determination of instrument error can be achieved by calibrating the measuring instrument to conform which the precision specified by national and international standards. Experimental calibration of the QUALISYS equipment is performed, which involves the utilization of a light validator. This calibration process is executed in accordance with the camera's coverage scope, as seen in Figure 4. The research used the rigid body calibration approach, which may be understood as being analogous to the triangulation method. The step method involves several key components.

Firstly, the QUALISYS lights are affixed to the ship hull model, treating it as a rigid body. Secondly, the ship motions are modelled using the QUALISYS Track Manager (QTM) software, accounting for all six degrees of freedom (6DoF). Thirdly, the reservoirs are designated as the designated testing area for the rigid body. Lastly, the motion data is captured by recording the movement of the QUALISYS models' lights. The calibration procedure is conducted in advance to verify that the measured data pertaining to movements is accurately aligned with the Cartesian coordinate system. The QUALISYS system is utilized for the measurement and documentation of the ship's rigid body motion in six degrees of freedom (6DoF), including translational movements (surge, sway, and heave) as well as rotational movements (roll, pitch, and yaw).

The motion optical tracking system manufactured by QUALISYS is used to validate ADIS 16364 in this study of ship motion measurement. The system consists of a QUALISYS camera and a motion tracking captured data manager. Four marker sensor balls are attached to the model, each with a diameter of 5 cm, which will be recognized by the camera as a rigid body which will later obtain 6-dof motion after calibration. The data obtained from the measurement system is in the form of surge, sway, heave, roll, pitch, and yaw movements with a sampling frequency of 50 Hz. Meanwhile, the measurement results from QUALISYS did not undergo data filtering. Apart from that, the QUALISYS manufacturer recommends that the placement of marker sensors should be random, and should not overlap or cover each other's markers.

#### *2.3.2 Ship motions test*

Simultaneous ship motion measurements are made on model ships with the ADIS 16364 and QUALISYS sensors. The wave generator initiates both regular and irregular waves within the MOB. The arrow depicted in Figure 4 signifies that the waves in question conform to the characteristics of a scaled sea state 5, making them appropriate for use in the forward ship model when considering scenarios involving two directions. The ship model is operated in such a manner that it aligns itself with the direction of the waves that are approaching, namely at an angle of incidence of 180 degrees (when the waves are directly in front of the ship) or an angle of arrival of 135 degrees (when the waves are approaching from a diagonal direction towards the bow of the ship). The duration allocated for data recording from both measuring devices has been established with a consistent time interval ranging from 15 to 25 seconds. The running model test is conducted subsequent to verifying that the measuring instrument has undergone calibration or validation in accordance with the steps defined in the preceding section.

### *2.4 Data Processing*
#### *2.4.1 Filtering process*

The data format being considered is the motion elevation format to compare both measurement devices. The QUALISYS measurements device output is already in that format, but the ADIS 16364 device outputs are translational acceleration and angular velocity. Consequently, it is imperative to employ data conversion techniques in order to derive the elevation of motion through data processing, utilizing the Matlab R2018b program. To mitigate or minimize data noise, the ADIS sensor employs an initial filtration process on the delivered acceleration and velocity data. The employed filter is the Moving Average Filter (MAF), which is defined by Eq. (1) and Eq. (2) as stated in reference [28]. According to a study conducted by Redhyka *et al.,* [29] the MAF filter has been determined to be the best appropriate filter among five others, including the Kalman filter and complementing filter. The acceleration data is subsequently integrated in order to obtain the value of the speed data. The method employed for integration is the Cumulative Trapezoidal Numerical Integration (Cumtrapz) method. In a broad sense, the formula for the Cumtrapz method may be described as Eq. (3) to Eq. (7). The outcome of this double integral is utilized as data for measuring motion.

$$y(i) = \frac{1}{M}\sum_{j=0}^{M-1} x\,(i+j) \tag{1}$$

$$y(n) = \frac{1}{windowSize}\left(x(n) + x(n-1) + \cdots \quad + x\big(n - (windowSize - 1)\big)\right) \quad (2)$$

The MAF, or Moving Average Filter, is a filter utilized to process the random series included in the original signal. In this context, x(n) represents the input vector x, while y(i) or y(n) denotes the output value of the MAF. The parameter M, or windowSize, corresponds to the length of the MAF. The trapezoidal method can be obtained by replacing f(x) with a 1st order Lagrange function, i.e. [30]:

$$P_1(x)\frac{(x-x_1)}{(x_0-x_1)}f(x_0) + \frac{(x-x_0)}{(x_1-x_0)}f(x_1) \quad (3)$$

Therefore:

$$I = \int_a^b f\,(x)dx = \int_{x_0}^{x_1} P_1\,(x)dx + R \quad (4)$$

Where R denotes the term that contains the computational error 0($h^3$). As a result, we get the trapezoidal integral formula, which is:

$$I = \int_a^b f\,(x)dx = \frac{h}{2}\,[f(a) - f(b)] + 0(h^3) \quad (5)$$

$$I = \int_a^b f\,(x)dx = \sum_{i=0}^{N-1}\frac{h}{2}\,(f_i + f_{i+1}) \quad = \frac{h}{2}\,(f_0 + 2f_1 + 2f_2 + \cdots + 2f_{N-1} + f_N) \quad (6)$$

$$I = \int_a^b f\,(x)dx = \frac{h}{2}(f_0 + (2\,\sum_{i=1}^{N-1} f_i) + f_N) \quad (7)$$

*2.4.2 Comparison of measurement*

The subsequent stage in the study of motion measurement involves the comparison of measurement outcomes obtained from the ADIS and QUALISYS systems. The difference in measurement results between ADIS and QUALISYS is called error. This large difference is a consideration for the effectiveness of the ADIS device compared to the QUALISYS device. The root mean square percentage error (RMSPE) is used to show the difference indicator with the formula shown in Eq. (7). We can compare measurements from two instruments by finding the percentage difference between the measured data sets using the Root Mean Square Percentage Error (RMSPE) formula, which can be found in Eq. (8) [31].

$$RMSPE = \sqrt{\frac{\sum_{i=1}^{N}\left(\frac{E|A-Q|}{Q_i}\right)^2}{N}}\, x\; 100 \quad [\%] \quad (8)$$

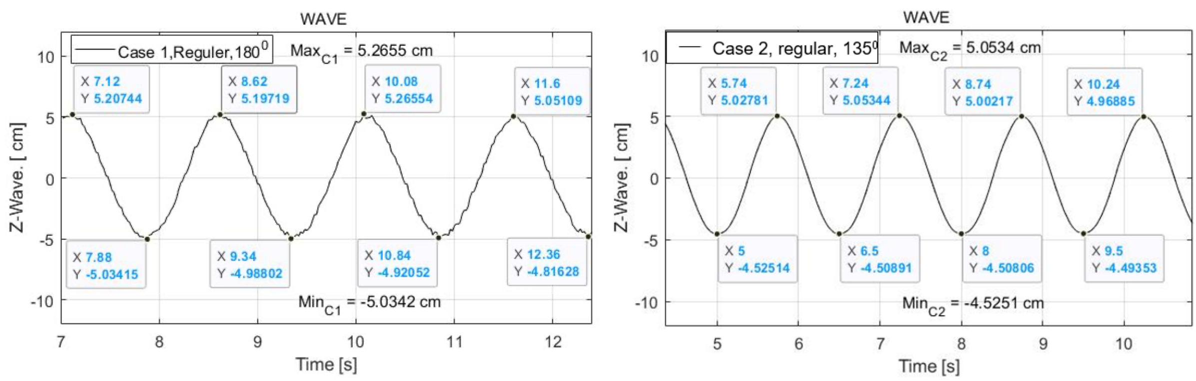
Let N represent the total number of samples in the given data set. The variable i denotes the value of each individual sample in the data set, ranging from the first sample (i = 1) to the Nth sample (i = N). E(A-Q) refers to the discrepancy between the first and second samples in the data set, where A represents the first sample and Q represents the second sample. The equation Ei = Ai – Qi represents the relationship between the ADIS 16364 data (Ai) and the QUALISYS data (Qi).

## 3. Results and Discussion

The ship motion is experimentally evaluated in four distinct cases at the Indonesian Hydrodynamics Laboratory. There are two cases of ship model testing conducted in regular waves, while an additional two cases include testing in irregular waves. The four test cases consist of the following scenarios: Case 1 involves conducting seakeeping tests on model ships in regular waves, with the incoming wave direction aligned directly with the forward model ship (at a heading angle of 180 degrees, also known as head seas). Case 2 entails seakeeping tests in regular waves, with the model ship's heading angle set at 135 degrees (referred to as bow quartering). Case 3 involves seakeeping tests in irregular waves, with the model ship's heading angle set at 180 degrees. Lastly, Case 4 entails seakeeping tests in irregular waves, with the model ship's heading angle set at 135 degrees (bow quartering).

### *3.1 Wave Measurement*

A wave height sensor (WHS) of the Waling Ford type is used here in order to capture the test waves that are created by the wave generator. Waves of two distinct types—namely, regular waves and irregular waves—are created and examined as part of the model experiment. The wave generator results are set in the same way for each scenario, namely with a wave height of 10 cm and a period of 1.5 seconds for regular waves and a wave height of 16 cm and a period of 1.75 seconds for irregular waves. The regular waves between those generated and those produced through measurements are similar. Figure 5(a) and Figure 5(b) show that the results of regular wave measurements carried out by WHS during testing in the Basin test for cases 1 and 2 are similar, with differences of around 5%. The wave in case 1 has an average wave height ($H_{1/2}$) of 10.12 cm, while the wave in case 2 has an average wave height of 9.52 cm. The average wave peak period (Tc) for the two cases also has the same period, namely 1.5 seconds.

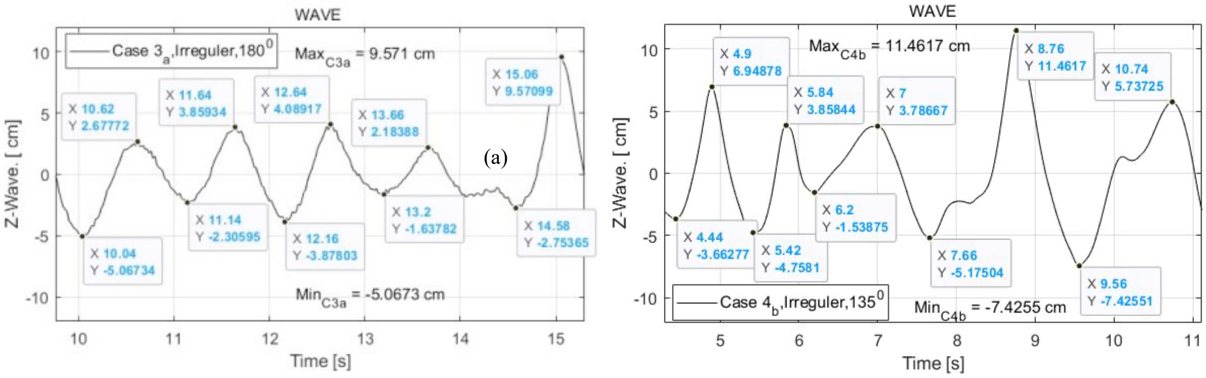



(a) (b)

**Fig. 5.** Regular wave chart on (a) Case 1 (b) Case 2 of model test

The measurement results of irregular waves for Case 3 and Case 4 are presented in Figure 6(a) and Figure 6(b), respectively, illustrating two experimental trials. The variability in wave height occurs in all observations as the presence of random wave characteristics. A statistical analysis is conducted to examine the final results of the irregular wave data in the time domain for Case 3. Based on the presented data, it can be observed that the average wave height ($H_{1/2}$) is measured at 11.28 cm. Additionally, the average wave peak period (Tc) is shown to be 1.89 seconds. The measurements made for Case 4 about irregular waves produced the following findings: an average wave height ($H_{1/2}$) of 11.43 cm, and a wave peak period (Tc) of 1.46 second. The observed disparity between the test of

Case 3 and 4 in the average wave heights is around 1.3% and the average wave peak period (Tc) is around 2.3%. The wave data shown in Figure 6 is cut data from one test. The following is irregular wave data in actual test cases 3 and 4. The data was acquired from the Indonesian Hydrodynamics Laboratory-National Research and Innovation Agency (LHI-BRIN Surabaya: Indonesia) [27].




(a) (b)

**Fig. 6.** Irregular wave chart on (a) Case 3 (b) Case 4 of model test

The wave generator produces waves with a random wave input and a significant wave height ($H_{1/3}$) of 16 cm and a period (Tc) of 1.75 s. Outcome the wave spectrum generated in this experiment is graphed in Figure 7. The wave spectrum conforms to the wave spectrum obtained using the Pierson-Moscovitz approach (shown by the dotted line in Figure 7), with a variation of less than 5% [27].

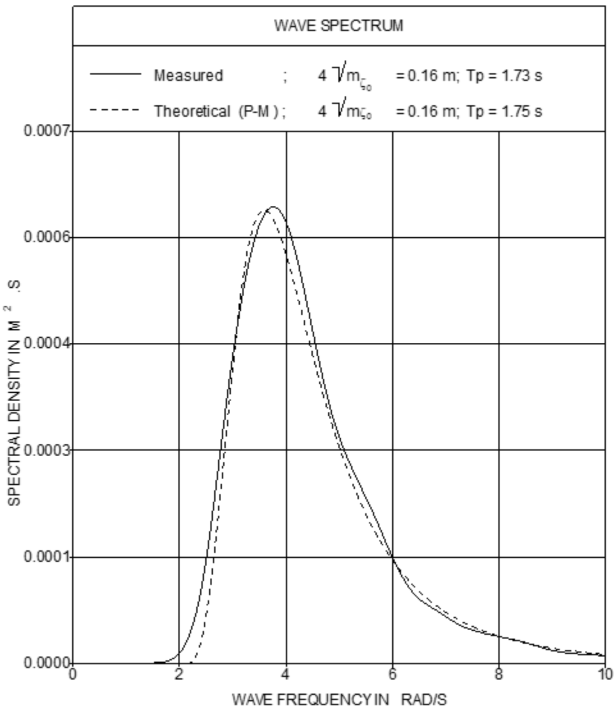



**Fig. 7.** Irregular wave spectrum in testing at MOB [27]

### *3.2 Data Processing of ADIS 16364*

The seakeeping test results of the ship model under regular and irregular wave conditions are collected using the ADIS 16364 instrument. The data collection period ranged from 14.76 seconds to 22.63 seconds, and the data is sampled at a frequency of 833 Hz. The data collection is in accordance with the measurement time matching between ADIS and QUALISYS. During this time, about 12,300 data points are gathered. The dataset comprises three motion measurements of heave acceleration as well as angular velocities for roll and pitch motion. This section only delineates the data processing methodology for heave motion, while noting that the identical procedure may be employed for the data processing of roll and pitch motion. Figure 8 represents the results of the heave acceleration measurements obtained during the Case 1 test. The grey line in the figure corresponds to the raw output of the ADIS 16364 sensor. To mitigate the effects of data noise, the MAF approach, as described by Eq. (2), is applied to the raw data. The black line in Figure 8 depicts the processed results. The figure has successfully shown the amplitude deviation between the signal before and after the application of Moving Average Filter (MAF). Regarding the acceleration in the heave motion, the initial unfiltered data has a peak value of 4.8363 m/s$^2$. However, with the filtering technique, the resulting acceleration is reduced to 3.5513 m/s$^2$.

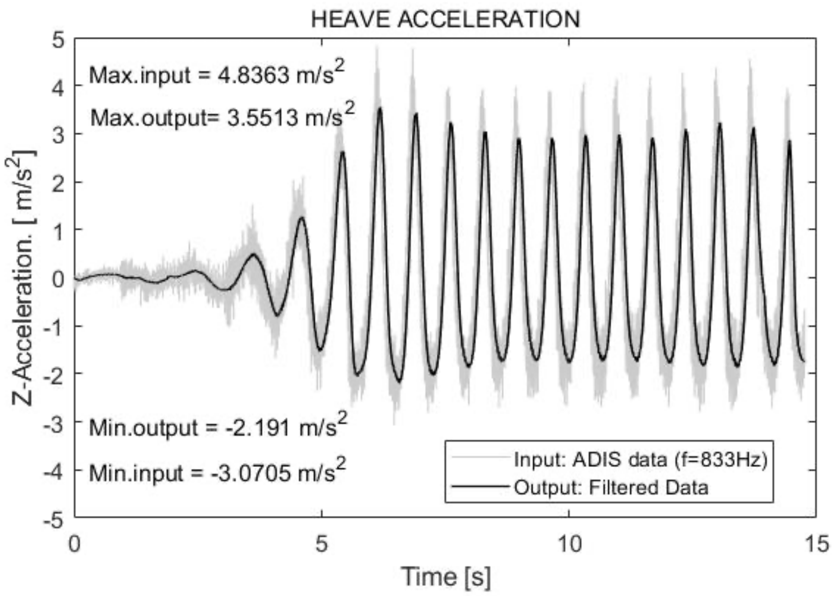



**Fig. 8.** Heave acceleration and filtering MAF at frequency of 833 Hz

The next stage in the data processing procedure involves the adjustment of the frequency of the measurement data obtained from ADIS and QUALISYS to ensure uniformity. After a Moving Average Filter (MAF) is applied to the first data from the Analog Devices Inertial Sensor (ADIS), the results are retrieved every 17-time step. The purpose of this screening is to reduce the frequency from the default value of 833 Hz to 50 Hz, and the outcomes of this process are depicted in Figure 9. Consequently, a marginal disparity is observed in the highest heave acceleration measurement, which amounts to 3.4982 m/s$^2$.

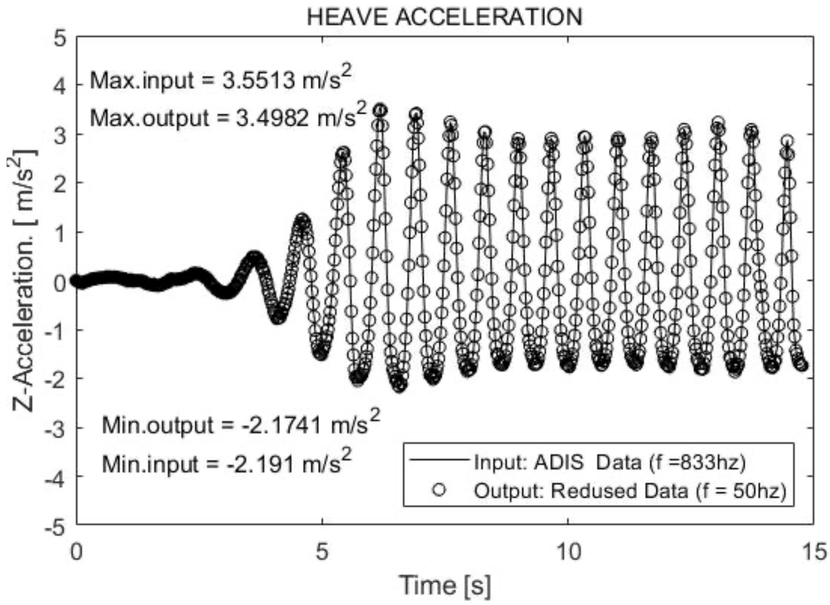



**Fig. 9.** Heave acceleration at frequency of 50 Hz

The process of converting heave acceleration data into heave motion velocity and elevation data may be accomplished by employing the Cumulative Trapezoid Numerical Integration (Cumtrapz) method, as explained in Eq. (3) to Eq. (7). The results of the first integration process provide the velocity data for heave, as seen in Figure 10.

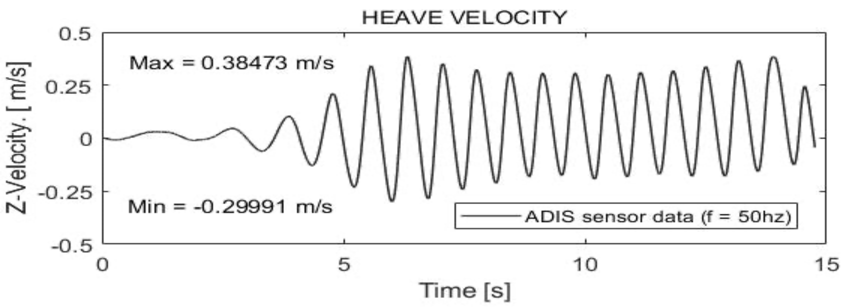



**Fig. 10.** Heave velocity in time domain at a frequency of 50 Hz

Following this, the subsequent integration process produces the elevation of heave motion, as seen in Figure 11.

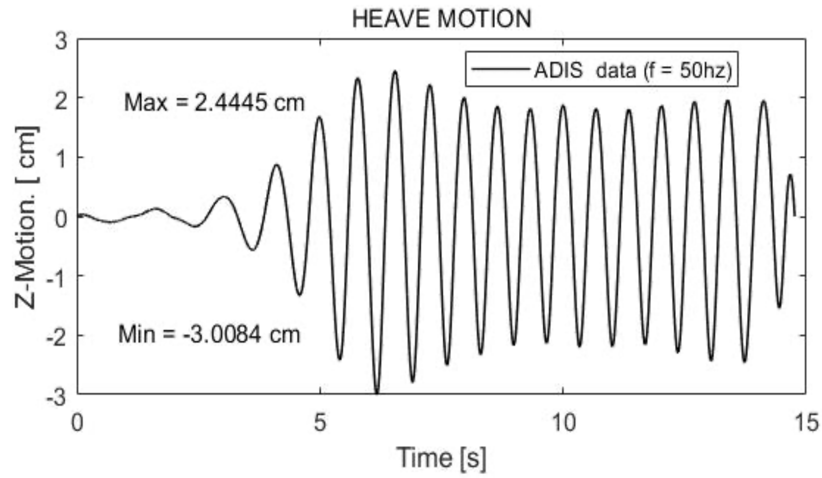



**Fig. 11.** Heave elevation in centimetres at a frequency of 50 Hz

The process of converting measuring units to centimetre is performed to facilitate the comparison of measurement results acquired from ADIS 16364 with those obtained from QUALISYS, as seen in Figure 12.

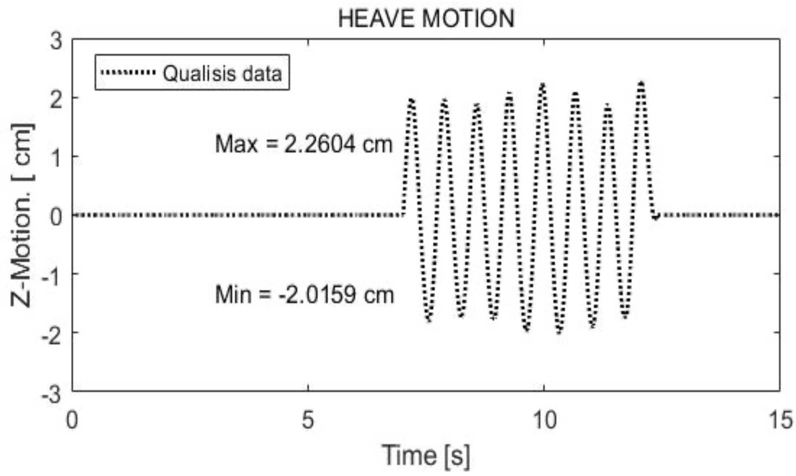


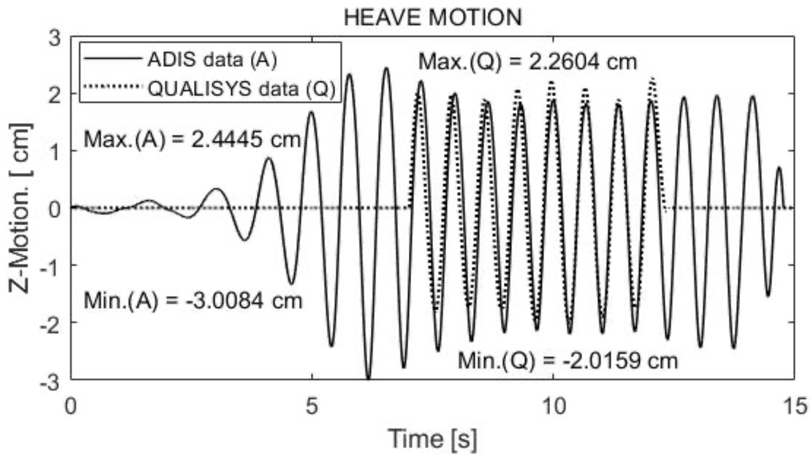

**Fig. 12.** Heave elevation in centimetres at a frequency of 50 Hz

*3.3 Comparison of the ADIS 16364 and QUALISYS Measurements*

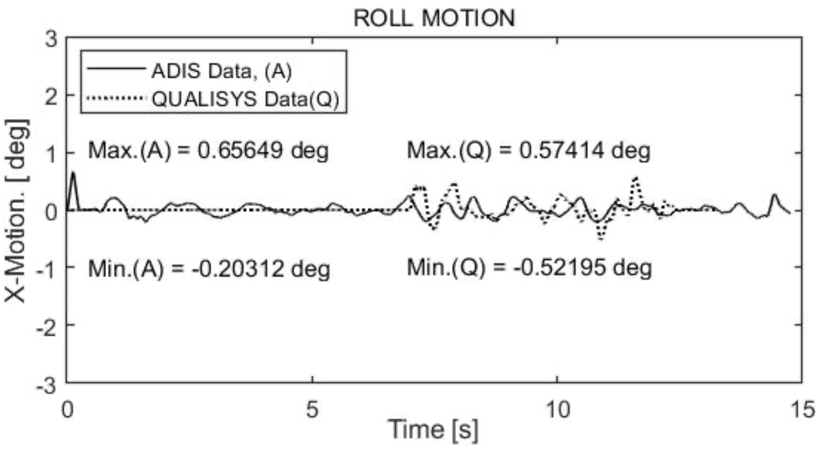
All the results of the ADIS 16364 and QUALISYS measurement data are compared to get the difference in the measurement error of the ADIS 16364 device. The 16 motions data sets with four experimental cases are processed to give results in the comparison of ship motions i.e. heave, roll, and pitch which are discussed in the following sections

*3.3.1 Case 1: Ship model test in regular wave and head seas (180$^0$)*

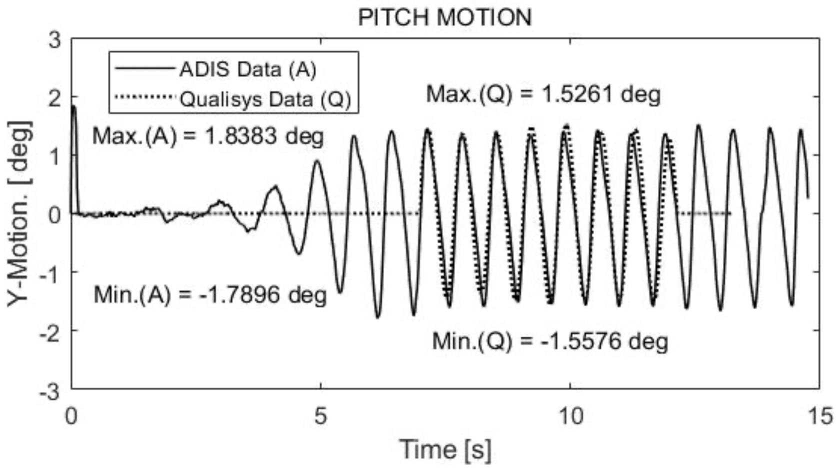
The seakeeping test of the ship model in Case 1 is performed for a duration of 15 seconds. During this test, the motion response of the ship model is measured using two devices concurrently, namely the ADIS 16364 and the QUALISYS camera. The measurement results for the heave motion obtained from the ADIS 16364 and QUALISYS cameras are presented in Figure 13(a) to Figure 13(c) A solid black line represents the ADIS 16364 data, while a dashed black line represents the QUALISYS camera data. The camera of the QUALISYS motion capture system only captures and records the seakeeping of the ship model throughout the temporal interval, spanning from 7.02 seconds to 12.40 seconds. The reason for this is that the ship model falls within the coverage region of the QUALISYS camera. According to the comparison results in the evaluation of pitch and heave motions, the ADIS 16364 device produces motion elevations that are nearly identical to those produced by the QUALYSIS device. In this case, the values generated by the ADIS 16364 device are marginally higher than those generated by the QUALYSIS device. In the roll motion evaluation, the difference between those devices is the largest. Specifically, the ADIS measurements indicate a maximum amplitude value response of 1.8383 degrees, surpassing the maximum value of 1.5576 degrees obtained from the QUALISYS measurements. Nevertheless, there is a significant disparity in the measurement outcomes of roll motion between the two devices, despite the fact that the magnitude of roll motion is minimal as a result of incoming waves from the bow (head sea).




(a)




(b)




(c)

**Fig. 13.** Comparison of ship motions measurement in Case 1 (a) heave (b) roll (c) pitch

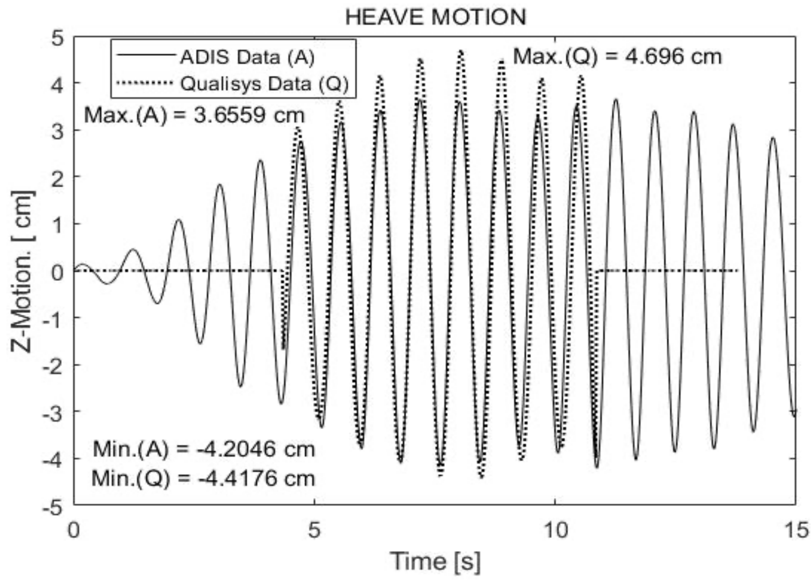
The Root Mean Square Percentage Error (RMSPE) calculation, shown in Eq. (8), can be used to calculate the difference between the results of ADIS 16364 and QUALISYS measurements. Since QUALISYS is a commercial product that numerous laboratories have used in various seakeeping model tests, QUALISYS sees itself as a validator of the measurement findings of ADIS 16364. The results of the model test on case 1 shows differences in the measurements for heave, roll, and pitch motions, with percentages of 2.15%, 6.39%, and 1.24%, respectively, as shown in Table 2. The most substantial disparity in measurements is seen in the roll motion measurement, exhibiting a difference of 6.39%. It is worth noting, however, that the roll motion during the test of the case 1 scenario is minimal. The data in Table 2 that show a minimal change in the mean value of 0.0376 degrees support this observation. Theoretically, the magnitude of roll motion in the head sea direction is rather minor when compared to heave and pitch motions. Consequently, variations in the precision of measuring devices can result in more pronounced discrepancies in size.

**Table 2**
Comparison of ADIS 16364 and QUALISYS data in Case 1

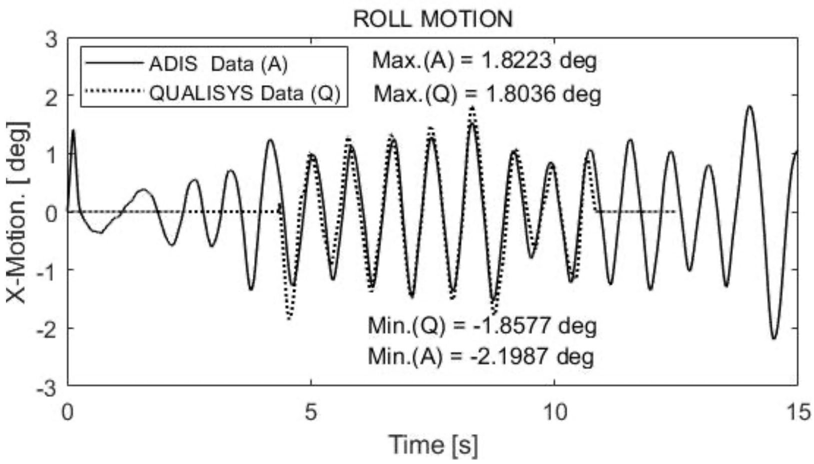
| No. | Motion type | RMSPE | |
|---|---|---|---|
| | | H (cm) | $T_c$ (seconds) |
| 1 | Heave | 2.15 % | 3.84 % |
| 2 | Roll | 6.39 % | 3.84 % |
| 3 | Pitch | 1.24 % | 3.85 % |

### *3.3.2 Case 2: Measurement of ship motion in regular wave and bow quartering directions (135$^0$)*

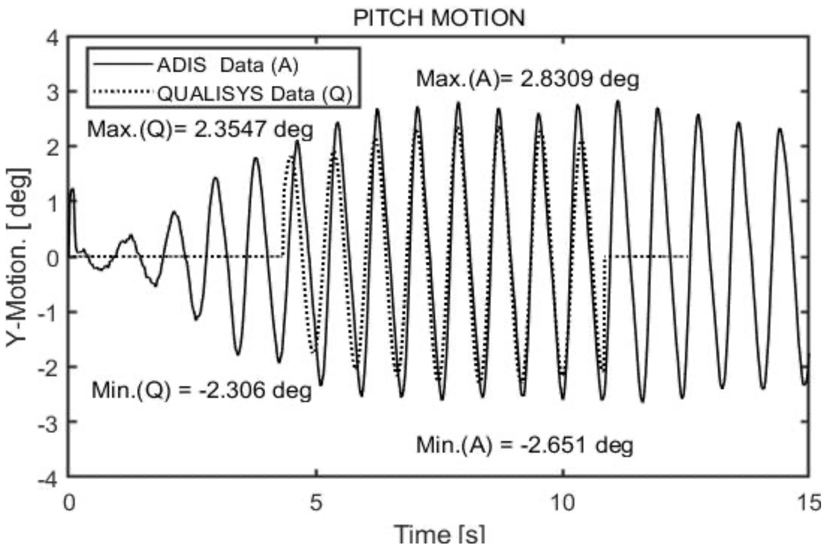
The experiment in the second case is done over a period of 15 seconds. In all results, the heave and roll motions captured by the ADIS device show smaller magnitudes than the QUALISYS device, as seen in Figure 14.




(a)




(b)




(c)

**Fig. 14.** Comparison of ship motion measurement in Case 2 (a) heave (b) roll (c) pitch

However, in terms of pitch motion measurement, the ADIS measurement value surpasses that of QUALISYS. The disparity in measurements obtained from the two-measuring equipment is minimal, specifically amounting to 2.27%, 1.98%, and 3.43% for heave, roll, and pitch motion, respectively, as indicated in Table 3.

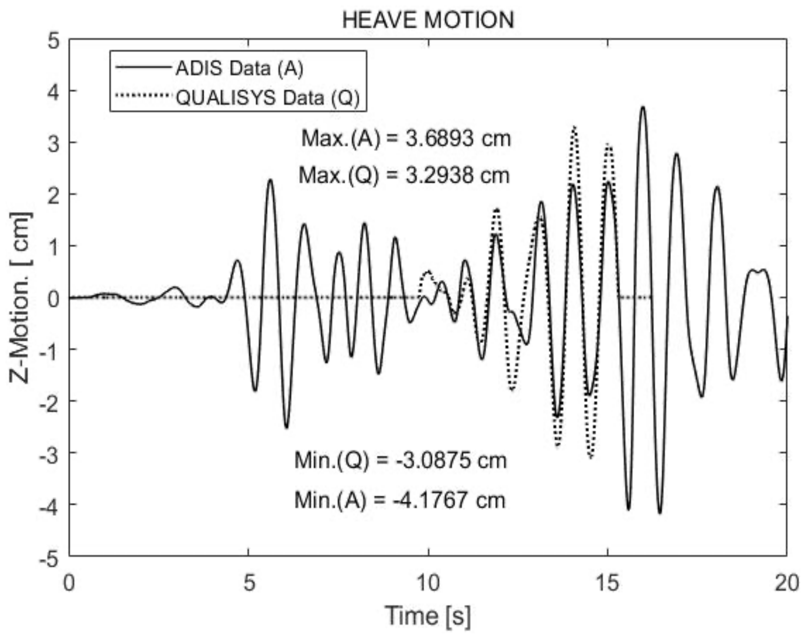
**Table 3**
Comparison of ADIS 16364 and QUALISYS data in Case 2

| No. | Motion type | RMSPE | |
|---|---|---|---|
| | | H (cm) | $T_c$ (seconds) |
| 1 | Heave | 2.27 % | 3.86 % |
| 2 | Roll | 1.98 % | 3.77 % |
| 3 | Pitch | 3.43 % | 4.23 % |

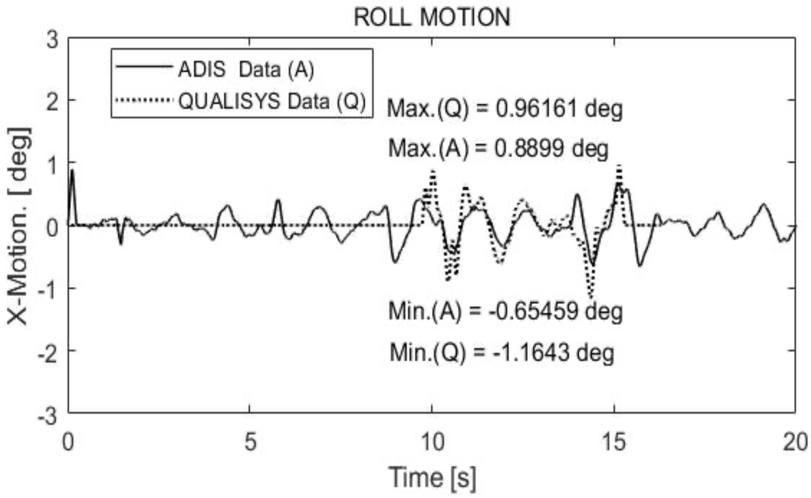
The observed disparity in roll motion between Cases 1 and 2, as seen in Figure 13 (b) and Figure 14(b), is evident. In contrast to the roll motion seen in Case 1, which exhibits a measurement discrepancy of 6.39%, Case 2 demonstrates a measurement discrepancy of 1.98% (refer to Table 3). This observation provides evidence supporting the validity of the explanation, attributing the significant disparity in roll motion measurement in Case 1 to the limited magnitude of the reaction. The roll motion measurements obtained in Case 2 exhibit greater magnitudes, but the disparity between the measurements is comparatively reduced.

### *3.3.3 Case 3: Measurement of ship motion in irregular wave and head seas directions ($180^0$)*

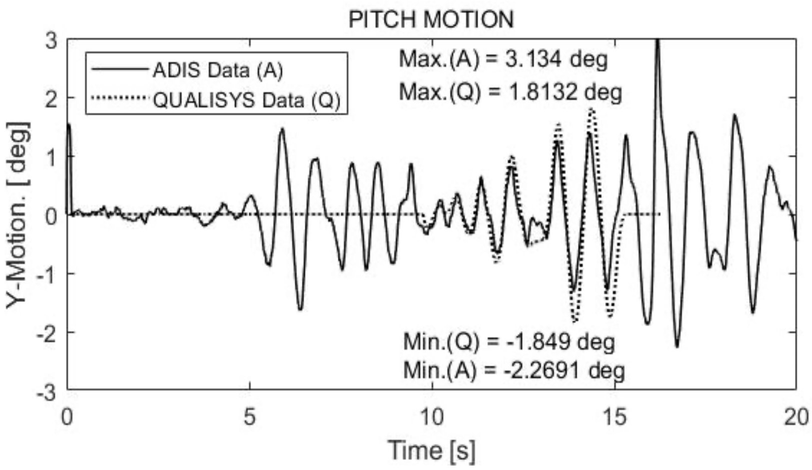
In the third case, the seakeeping test had a duration of 20 seconds, with the collection of measurement data from QUALISYS and ADIS occurring during the time interval of 9.76 seconds to 15.30 seconds. Figure 15 elucidates the disparities in heave, roll, and pitch motion measurements.



(a)




(b)




(c)

**Fig. 15.** Comparison of ship motions measurements in Case 3 (a) heave (b) roll (c) pitch

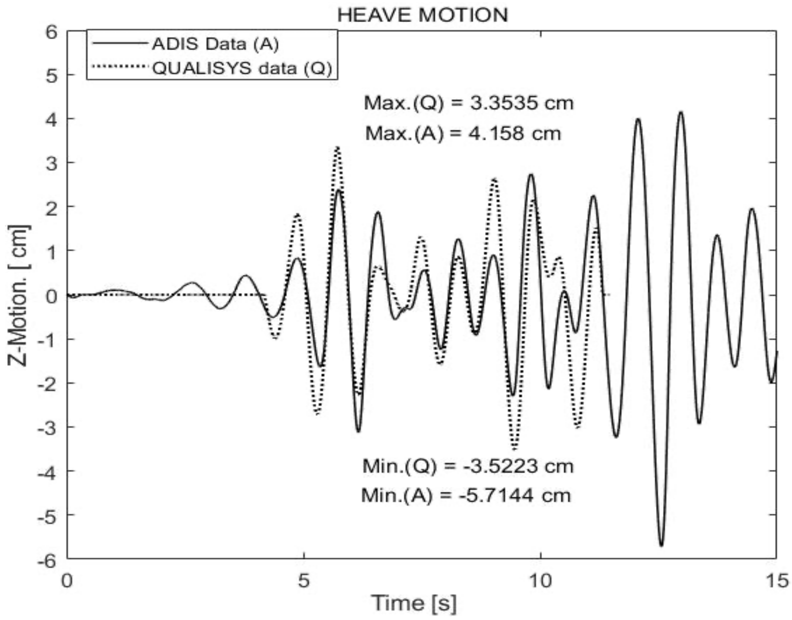
The ADIS 16364 measurement results are depicted by the black line, while the QUALISYS data is represented by the dashed black line. The discrepancy between the ADIS and QUALISYS measurement data for heave, roll, and pitch motion in case 3 is recorded as 3.72%, 5.12%, and 2.76%, respectively, as presented in Table 4. While the maximum disparity in roll motion amounts to 5.12%, it is noteworthy that the variation in movement is rather small, with an average of 0.0055 degrees.

**Table 4**
Comparison of ADIS 16364 and QUALISYS data in Case 3

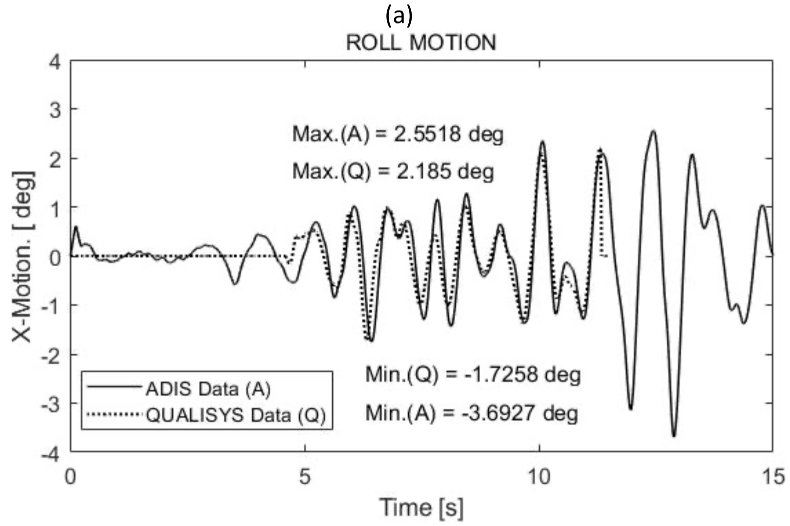
| No. | Motion type | RMSPE | |
|---|---|---|---|
| | | H (cm) | $T_c$ (seconds) |
| 1 | Heave | 3.72 % | 5.7 % |
| 2 | Roll | 5.12 % | 3.54 % |
| 3 | Pitch | 2.76 % | 4.16 % |

### *3.3.4 Case 4: Measurement of ship motion in irregular wave and bow quartering directions (135$^0$)*

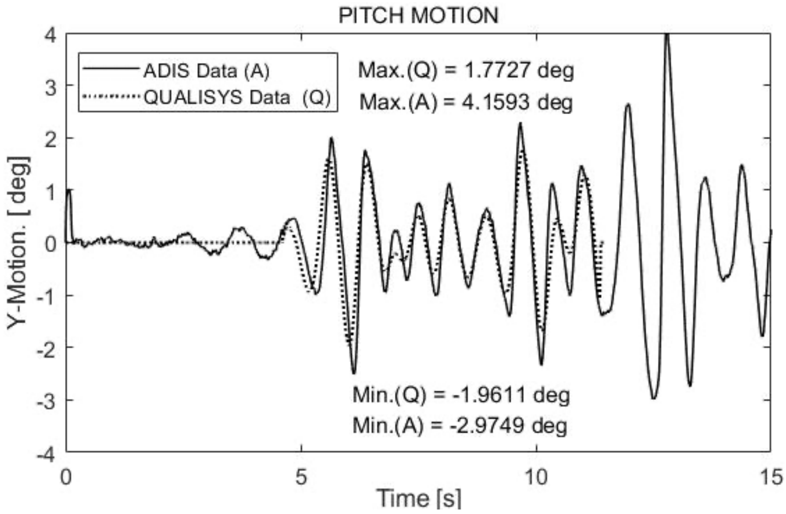
In the fourth case, the duration of the seakeeping test was 15 seconds. The discrepancy between the measurement outcomes obtained from the ADIS and QUALISYS methods is outlined in Figure 16.




(a)




(b)




(c)

**Fig. 16.** Comparison of ship motion measurements in Case 4, (a) heave (b) roll (c) pitch

The discrepancy is quantified by the root mean square error (RMSE) values of 2.75%, 3.78%, and 4.65% for heave, roll, and pitch movements, respectively, as presented in Table 5. The findings of the model test in Case 4 indicate that the disparities in motion measurements between ADIS and QUALISYS are all below 5%, indicating a confidence level above 95%.

**Table 5**
Comparison of ADIS 16364 and QUALISYS measurement motion data in Case 4

| No. | Motion type | RMSPE | |
|---|---|---|---|
| | | H (cm) | $T_c$ (seconds) |
| 1 | Heave | 2.75 % | 3.87 % |
| 2 | Roll | 3.78 % | 3.77 % |
| 3 | Pitch | 4.65 % | 3.88 % |

The results of this research are also relevant to several studies that compare the ADIS 16364 device with other reliable measuring devices. Seel *et al.,* [13] compared optical 3D motion capture system devices, which were used to measure human elbow and knee motions. The measurement results show that these two tools have a difference of $3^0$. ADIS 16364 has also been applied to ships with GPS (Global Positioning System) sensors, both of which are installed on the ship [20]. The measurement results show that a room temperature of 20°C has the best measuring power. This is in accordance with the measurements carried out in the experiments in this study, which were also carried out at room temperature. However, there are several limitations in this research, namely that seakeeping analysis is still used to measure oscillatory movements only, namely heave, roll, and pitch. Actually, ship motions have 6 degrees of freedom (6 DoF), so future research can be carried out on all motions (surge, sway, heave, roll, pitch, and yaw).

## 4. Conclusions

Seakeeping tests conducted on scaled-down ship models within the Manoeuvring and Ocean Engineering Basin (MOB) serve the purpose of validating the data obtained from ADIS 16364. The technology utilized for the purpose of validation is the QUALISYS motion capture system, which is widely recognized for its remarkable accuracy in measuring ship motion. The seakeeping performance of the ship model is assessed in two distinct wave conditions: regular waves and irregular waves, which are representative of sea state 5. The incoming waves have a head-sea ($180^0$) and a bow-quartering ($135^0$). The experimental results indicate that there is a minor difference in the measurement results of the two devices, as shown in the root mean square percentage error (RMSPE) value. RMSPE values for all test cases demonstrated results that are below 5% in heave, roll, and pitch motions. Except for case, which pertains to regular waves with the head seas incoming wave, RMSPE for roll motion is found to be 6.37%. In broad terms, the results acquired from ship motion measurement using the ADIS 16364 demonstrate similarities with those derived from the QUALISYS motion capture system device. Furthermore, the ADIS 16364 instrument possesses the capacity to be employed for seakeeping measurement carried out directly on deck of vessel in seaway.

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