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An Experimental Methodology for Investigating Vertical Displacement and Acceleration of Offshore Barges Using Towing Tank Model Tests

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ABSTRACT
Wave causes floating offshore structures to move in six degrees of freedom (pitch, roll, yaw, sway, surge, and heave motions). Heave motion is the vertical movement of a vessel or offshore platforms. Wave induced heave motion is one of the major metocean condition with high effects on offshore operations. This study is aimed at introducing a novel, simple and inexpensive experimental method to demonstrate how vertical displacement (heave motion) and acceleration of barges in West African environmental conditions can be replicated in a towing tank test. Typical wave height of West African Offshore (Gulf of Guinea) is between 2.1m and 3.1m, while the wave periods are between 7s and 16s, scaled wave heights of 2.3cm - 3.3cm with wave periods of 0.7s - 1.7s will be generated. The experimental uncertainty will be measured by considering the accuracy and resolution of the vertical displacement sensor, wave height and wave period measurements, model dimensions. The experimental results will be validated against an analytical and numerical/CFD Methods.The study will be resourceful to researchers, ship builders, petroleum, marine and offshore engineers during offshore operations as well as shipbuilding.

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INTRODUCTION

Maritime industry undoubtedly plays a vital role in facilitating economic growth (Nwaogbe et al., 2024). This includes the use of vessels for oil and gas production, and the transportation of cargoes. Six degrees of freedom system are normally used to depict vessel movements in a three-dimensional space. These movements occurs as a result of wave, wind and current actions. These degrees of freedom comprises of the translation motion and the rotational motions. Rotational motions, on the other hand are defined as Pitch, roll and yaw motions. Translation motion are known as heave, surge, and sway motions of the vessel respectively (Aumtab & Wanichanon, 2022). Wave induced heave motion happens to be one of the major metocean condition with high effects on offshore operation. Heave motion can be described as the vertical oscillatory movement of a vessel or offshore platforms caused by ocean waves, vessel hydrodynamic characteristics and hull geometry among others as influenced by the environment (Adumene & Ikue-John, 2022).

Wave causes floating offshore structures to move in six degrees of freedom. This leads to increase in dynamic response and also affects their structural stability. Heaving is very significant due to the fact that heaving occurs in the vertical plane and at the same time interacts with the vortex effects in the horizontal plane due to wave actions. Non-linear mechanisms can induce heave resonance at certain conditions, and is capable of creating a critical operational state that can compromise vessel's performance and as well as safety. Offshore operations can be disturbed by extreme heaving (Adumene & Ikue-John, 2022).

MATERIALS AND METHODS

Operational Challenges during Vertical Displacement of Offshore Barges

Offshore lifting operations and offshore drilling are just some of the operations which can be affected by heaving. In the instance of an MPD operation, the heave disturbance can induce vertical motions of the rig. These motions can translate to pressure fluctuations in the wellbore. Uncontrolled vessel heaving can lead to surge/swab when making connections. This can lead to kicks, lost circulation, and well control difficulties (Pazoki et al., 2024). Motion from vessel heaving is also a leading cause of seasickness as the motion can cause stimulation of the human vestibular system. These vertical motions (heaving) do not only cause nausea and discomfort, it also increases physical energy demand required from passengers and crew. Extended duration of heaving may lead to crew fatigue and decreased vigilance on voyages which may cause degraded performance of crew members and decrease their capability to react properly when engaged in strenuous operations or in case of emergency (Arribas, & Piñeiro, 2007). Similarly, in lifting operations, the vertical (heaving) motion of a vessel greatly influence the stability of floating cranes. Large heave motions can also induce unpredictable cargo sway, cause excessive tension forces in hoisting ropes and increase the probability of collisions between surrounding structures and suspended loads. Large heaving motions illustrate the need for dynamic response and heaving stability analyses of offshore vessels/barges.

Vessel's Vertical Displacement Approaches

There are different approaches that can be employed to obtain a vessel's vertical acceleration. Studies such as Augustine et al. (2018), Tang et al. (2022), Reis et al. (2023), Begovic et al. (2020), and Chen et al. (2023), Li et al. (2025), show examples in which these researchers utilized analytical approaches to determine a vessel' s vertical acceleration. There are other studies that used numerical approaches which numerically simulates the ship motion by directly applying computational fluid dynamics (CFD) or hydrodynamic solvers to obtain coupled responses such as Hu et al. (2025), Zeng et al. (2025), Jeon et al. (2023), Liu et al. (2025), Yu et al. (2025), Mathioudakis et al. (2025), Bourkaib et al. (2025), Han et al. (2025), a study by Somayajula and Falzarano (2015), and Other studies used data driven approaches which is based on deep learning, machine learning and hybrid statistical methods to predict the heave motion based on previous or generated data. This method uses CFD-generated dataset or motion time series Such as Yan et al. (2025), Hou et al. (2025), Sun et al. (2025), Lee and Ahn (2025), Meng et al. (2025), Guo et al. (2025), Ding et al. (2023), Guo et al. (2022), and Chen et al. (2024). This research will work towards creating an experimental methodology that displays how we can obtain vertical acceleration of barges in a towing tank.

Experimental Hydrodynamic Towing Tank Studies

Many experimental studies have been carried out using hydrodynamic towing tanks. Pacuraru et al. (2020), carried out experiments to research resistance reduction caused by an interceptor on a fast displacement ship. Authors used a towing tank to validate their theory at Froude numbers ranging from 0.23 to 0.69. Authors measured resistance, roll, and heave data. Jentzsch et al. (2022), performed a towing tank study to research flow field around a 2D submerged foil near a free surface. The researchers examined steady state and unsteady state flow around different depths and angles of attack. The authors also took measurements of the model facing upside down. Authors recorded surface deflection and free surface effect. Data collected allowed them to confirm their prediction model of showing wake pattern at arbitrary model velocity. Zhang et al. (2020), designed an experiment with a water tank to predict both drag of a fish cage and deformation of attached mooring system. Scale model of an actual cage was created to be tested in the water tank. Validation of this experiment was done with an analytical model for predicting position and attitude of the cage as well as tensions on the mooring which is based on force balances of individual components of the model. Experimental result was able to be compared to the water tank to confirm that as speed increased, the cage and floats tended to move in a downstream direction. Portillo-Juan et al. (2026), conducted research using acoustic measurements of atmospheric and acoustic testing facility at Technical University of Madrid. Researchers characterize facility's background noise and how it propagates through facility. It was concluded there were acceptable acoustic measurements taken even with high amounts of reverberation inside of the facility. Measurements proved to accurately predict weak signals at rated speed of five blade propeller when either zero thrust or ventilation was applied, allowing this facility to be used during certain situations. Ye et al. (2025), investigated the effect of sword-support structure on resistance characteristics of axisymmetrical rotary body underwater vehicle (ARBUV) and blended-wing-body underwater vehicle (BWBUV) with numerical simulations and tank experiment. Results from numerical simulations were verified by conducting tank experiment with differences between them below 5%. Yu et al. (2020), took a different approach and decided to use experimental methodologies along with computational prediction methods to predict where a freely falling model rocket would land in the towing tank depending on the initial angle it was dropped at. Researchers took approach by using the bottom of the towing tank as if it were the ocean bottom where you would want your model to land. Depending on situation if the rocket lands in desired area can be critical to know where it will land if you want to launch another rocket or retrieve rocket that fallen. Falcon 9 first stage was manufactured and dropped into the towing tank at University of New Orleans' Towing Tank facility at initial angles between 0 and 90 degrees separated by 15- degree intervals.

Gutirrez-Romero et al. (2020), came to similar conclusions of positive results when experimenting with how artificial blocks on the free surface to simulate ice would affect the interactions of propeller and block within CEHINAV towing tank. Tests took place using towed ship model tests to measure thrust and torque while it was being propelled by two different set combinations of broken ice sizes. Main break ice simulated throughout research was paraffin wax. While experimenting with different speeds and concentration of paraffin ice blocks three different models were used and recorded.

Kouklakis et al. (2025) decided to build their own ship model by taking an RC model and outfitting it completely before towing it in NTUA's towing tank. Their main goal was to get data they could reproduce later and try to scale up their system and test in open water. Their RC high speed model would act as the body of their ship model and two DC brushed motors were mounted with shafts and propellers connected to them to allow thrust to propel the autonomous ship model forward. There were two battery packs that needed to be built in order to house either the motors or controllers system. They decided Optical Real Time System was best to obtain positional data of model while it traveled through the tank. All data was recorded through external USB data logger while testing was being conducted. Gutirrez-Romero et al. (2024) conducted tests that went through similar procedures. The main difference was they tested ship motion through broken ice. Towing tank was different they called it an Ice basin. Ice blocks were obviously not usable so when funds allowed for it paraffin blocks were used. Tests were then conducted by towing RC modeled ship hull through different concentrations of ice blocks. Blocks were able to record photogrammetric analysis while moving to allow for a mean of ice-block initial configuration. Ice block initial configuration becomes important parameter to consider when you are developing/validating numerical simulation codes that have applications in ship motion resistance in drift ice. Takyi, and Beem (2024) designed and constructed a towing tank that was less than $1,000 dollars to build and simple enough for anyone to reproduce with listed materials. Tank itself was 1,000mm x 200mm x 200mm. Movement of the tank was decided by a very simple controller chip named Arduino. Arduino used its open source GRBL(G-Code, Ruler, Bridge) firmware to translate movement information to the tank's the two axes using two stepping motors. Those motors would then dictate velocity and movement for whatever experiment was being conducted. They proved this system to have a margin of error up to 1%. Long et al. (2020), Lasers were also used in a towing tank during the same year. Researchers created and used Laser-Doppler Velocimetry to map propeller wake flow inside the towing tank. Device used a high precision 3D computer controllable frame that was connected to an optical fp50 shift probe. There was a range of power (50-500mW) emitted from the Nd: YAG-laser head which was screwed directly on to the probe. Velocities of the carriage used during the experiment were taken using the 2D probe. Carriage velocities were found to agree very well with similar CFD models. The data was compared to uncertainty values approved by standard methods.

Alamian et al. (2020), attempted to improve efficiency and performance using a towing tank to test example of three-blade horizontal axis tidal turbine under varying conditions pitching angle and electrical load showed. When the data collected was near the surface of the water there was not as much variation between the different speed data. Liu et al. (2025), used two different models with two varying condition parameters (calm water and different waves) with various amounts of towing speed to measure current impacts on gravity cages. Ma et. Al. (2026), derived an experimental protocol and experimental data processing protocol for towing tank drag tests of rotating underwater vehicle. This paper introduced there test model, towing tank model,drag measurement platform and then the two experimental conditions. Varied depth and repeatability runs. And then focus on the towing tank experimental data processing method: eliminate the instrument measurement errors based on the analysis of uncertainties sources and improve the accuracy of the drag coefficient measurement. Finally, the experimental data of the two kind's models are compared with CFD simulation results. To verify the accuracy of the CFD simulation method. Simonet et al. (2024), presented an overview of research concerning the hydrodynamics of rigid and flexible hydrofoils, subjected to pitching actuation in dynamic stall regime. An original experimental facility was designed and built at the towing tank facility of Centrale Nantes, France, to perform hydrodynamic tests on innovative and large scale floating appendages. Innovative, the main feature of this towing tank setup is that it can apply dynamically pitching motions to the appendages while recording their deformation simultaneously. To do so, arrays of optical fiber sensors with fiber bragg gratings are employed to provide in-situ real-time strains measurements. Forces and moments are retrieved with a 6DOF hydrodynamic balance. Validation measurements performed with the facility uncovered its capability to capture subtle flow phenomena such as the translation of the center of pressure or the stall onset delay. Results also showed good agreement between lift coefficient measurements and strains acquired on the flexible hydrofoil.

Previous literature provided information on how vertical displacement of vessels could be achieved through different methods and also informed about towing tank applications for different hydrodynamics tests. However, no studies have been made on the determination of vertical displacement (heave motion) and acceleration using typical West African environmental conditions, thus this study aims to introduce a novel, simple and inexpensive experimental method that can demonstrate how vertical displacement and acceleration of barges in West African environmental conditions can be replicated in a towing tank test.

RESULTS AND DISCUSSION

Towing Tank Dimensions

The towing tank referred in this study is at the NNPC/RENAISSANCE JV Center of Excellence in Marine and Offshore Engineering, Rivers State University. The dimensions of the tank are as follows:

i. Length Overall = 60m
ii. Length of Carriage = 50m
iii. Breadth = 2m
iv. Depth = 2m

Figure 1 and 2 shows pictures of the towing tank.

Figure 1: The Towing Tank

Figure 2: Towing Tank Filled with Water

The towing tank facility is used for scaled ship model tests; ship's appendage and marine equipment tests, and as well as testing of offshore and subsea structures. The principal features of this facility comprise: tank basin, towing carriage, wave maker at one end of the towing tank, data receiver and acquisition system, instruments for model based measuring and also, water treatment and circulations system. Figure 3 shows the towing tank wave generating device.

Figure 3: Towing Tank Wave Generating Mechanism

Waves are produced by the wave maker as either regular or irregular waves, the absorbing beach located at the other end of the tank reduces the wave reflection. Figure 4 shows the towing tank measurement and data collection devices.

Figure 4: Towing Tank Measurement and Data Collection Device

The instrumentation component used to perform measurements is attached to the carriage. The values measured are transmitted to the two computer device where readings can be obtained. Figure 5 shows towing tank carriage and rail.

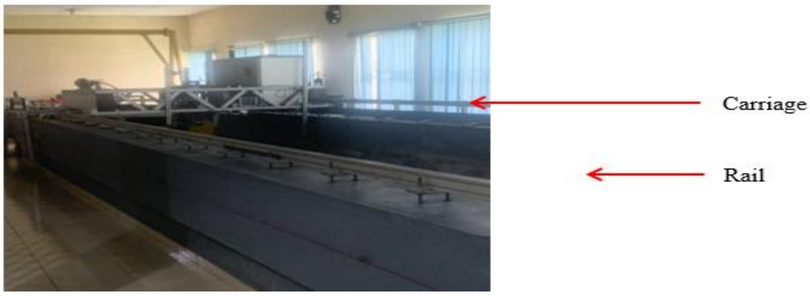

Figure 5: Towing Tank Carriage and Rail.

Models are towed through the water by the towing carriage that runs along the rail on top of the towing tank. The system for water treatment and circulation maintains a stable test environment.

Experimental Setup

The scale model barge will be placed in the towing tank using spud poles attached to the sea bed by means of gravity anchor. This will also allow for pitch and roll motions, since these motions can be coupled with heave motion. The wave maker will be positioned to create periodic waves with a certain height and frequency. A water resistance (displacement) sensor will be placed on the scale model barge, this will be used to measure the vertical displacement of the scale model barge throughout the waves' cycle. The sensors will be calibrated according to the manufacturer's instructions before usage in order to ensure accurate readings of the vertical displacement. A stopwatch to measure the time it takes for the up and down movement of the vessel should be kept as part of the experimental apparatus. The barge model is shown in Figure 6.

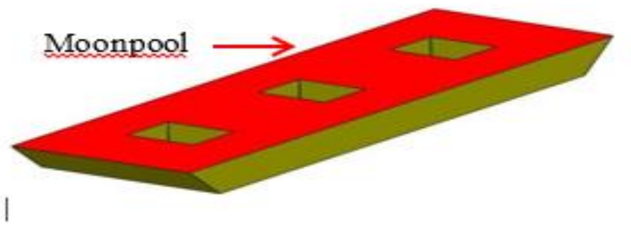

Figure 6: The barge model in Solidworks

Create regular waves with varied heights between 2.3cm - 3.3cm. When the measurement is ready to start, the wave maker should continue making waves until the generated waves forms a pattern that becomes steady. Table 1 shows the principal dimensions of the considered barge as evidenced in Karana (2016), and the scaled values with scale ratio 1:93.

Table1: Principal Dimensions of the Barge

Particulars	Actual Values (m)	Scaled Values (cm)
Length Overall	92.964	100
Length Between perpendicular	91.4	98.1
Breadth	24	25.8
Depth	6	6.46
Draft	4	4.3

Experimental Conditions

Typical wave height of West African Offshore (Gulf of Guinea) is between 2.1m and 3.1m, while the wave periods are between 7 and 16s (Kouadio et al.,2022). The wave heights will be scaled in the ratio 1:93 to obtain wave heights between 2.3cm - 3.3 cm that would be generated for the experiment with wave periods of 0.7s - 1.7s. The depth of water in the tank should be kept at 1.6m. The mass of load on the barge should vary from 250g, 500g, 750g and 1000g. The time span of each experiment should be 15 minutes, and the test should run 3 times in order to ensure accuracy.

Experimental Procedure

Install model barge using spud poles attached to a gravity anchor. Make sure that the barge allows free movement vertically. Attach the data acquisition system (water resistance sensor) to the barge and the wave should be generated. Wait for 20-30 seconds for the wave to stabilize and start data collection for the barge's vertical displacement. The stopwatch will be used to measure the heave period.

A vertical displacement sensor then records vertical positions of the barge, denoted by z_1, z_2, z_3… over successive intervals of time. This information is then used to derive the vertical velocity using the difference between subsequent recorded positions, as can be expressed by the Equation 1:

$$v = \frac{\Delta z}{\Delta t} \quad (1)$$

This then allows computation of the vertical acceleration by looking at changes in velocity with time:

$$a = \frac{\Delta v}{\Delta t} \quad (2)$$

After collections, determine the minimum vertical displacement, the maximum vertical displacement, the vertical acceleration, mean vertical displacement and peak-peak displacement of barge from collected data. Repeat the same load and wave condition for at least 3 trials to ensure higher accuracy of testing. Average all values to get correct value. The barge model showing installed spud poles and data acquisition device is shown in Figure 7.

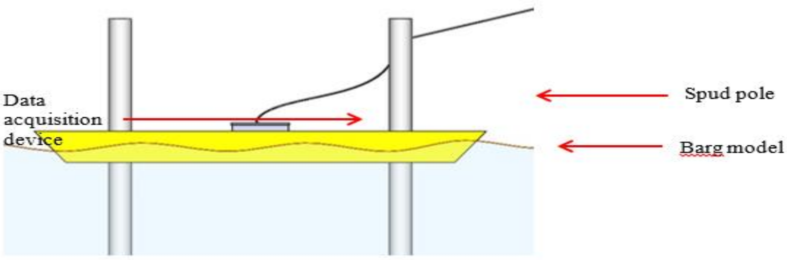

Figure 7: The barge model in Solidworks showing installed spud poles and data acquisition device

Data Processing

Measured displacement result could be exported into a spreadsheet program such as Microsoft Excel or MATLAB etc. to analyse or display in mobile phone (real time). From the collected data, we can attain several variables including: average vertical displacement value; maximum displacement value; standard deviation; average reading of repetitions measurement(s); relationship between wave height and displacement; relationship between applied loads and the displacement.

Experimental Uncertainty and Validation

Experimental uncertainties would be estimated by examining precision of the vertical displacement sensor, accuracy, resolution in wave height and wave period data and in model dimensions and sensor alignment. Repeated trials under identical conditions will be conduct-ed, the variation among the results of these repeated trials will determine repeatability.The experimental results will be validated against an analytical and numerical/CFD Methods.

CONCLUSION

In this study, a method of estimating vertical displacement and acceleration of a floating body (barge) when it is under wave induced loading was described in a systematic manner. This gives a reasonable method of predicting vessel heave motion and vertical acceleration under different seas states, detailing the experimental set ups and procedures. The study explained how wave conditions together with scaled barge model can be applied to the practical condition that can lead to an alternative method of predicting the vertical response of the barge. The study will provide good resource to researchers, shipbuilding, petroleum, marine and offshore engineers during ship building & offshore operations.

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