Modeling and Analysis of a Spar Platform
CE 410: Introduction to Offshore Engineering
Prof. Manasa R. Behera, IIT Bombay

PREPARED BY
Sunandinee Mehra
Govind
Vivek Kumar Singhal
Shameem Ahmed
Kishan Kashyap
Priyanshu Meena

COURSE TA
Nasma Noor N V
Anjali Choudhary

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INDIVIDUAL CONTRIBUTIONS

Priyanshu Meena - Experimental setup, testing procedure, data and methodology, frequency calculation

Sunandinee Mehra - Model Setup, Experimental procedure, Model schematic and images, Hydrodynamic Analysis and Inferences, Sources of errors, Analysis of data

Vivek Kumar Singhal - Hydrostatic Analysis and Inferences, Data and Methodology

Govind Kumar - Results and Discussion, Abstract, calculation of data using software in lab

Kishan Kashyap - Data and Methodology, Source of Errors and results

Shameem Ahmed - Results, Scale calculation, Introduction

ABSTRACT

Our project understands the behaviour of Spar platforms under wave-induced loads, combining numerical simulations with hands-on experiments. A meticulously crafted Spar platform prototype, ballasted to simulate real-world buoyancy factors, served as our primary test subject. Within a controlled wave flume environment, we subjected the prototype to diverse wave conditions, capturing its dynamics using the advanced Xsens 6-DOF motion sensor. This sensor's precision allowed us to unravel the platform's intricate responses to various wave intensities. Our dual approach yielded crucial insights into the Spar platforms' real-world performance, emphasizing the need for design and operational refinements in offshore engineering. The project's significance extends beyond academic interest: by bridging theoretical knowledge with practical observations, we aim to enhance the safety, efficiency, and reliability of future offshore structures. This research not only offers a deeper understanding of Spar platform dynamics but also sets the stage for more resilient offshore structural designs.

Introduction

Offshore structures are essential for resource extraction beneath the ocean's surface, with Spar platforms frequently utilized in deepwater oil and gas drilling operations. Ensuring the safety and efficiency of these platforms hinges on a comprehensive understanding of their dynamic response to wave loads. Our project is focused on modelling and analyzing the behaviour of a Spar platform under diverse wave conditions.

Objective:
Our primary goal is to investigate how a model spar platform dynamically responds to a range of wave patterns. Our specific objectives include:
1. Developing a Physical model for the spar platform.
2. Fabricating a model.
3. Incorporating ballast to simulate buoyancy.
4. Subjecting the model to controlled wave conditions in a wave flume.
5. Analyzing the response of the spar platform to varying wave scenarios.

Prototype Specifications:
Our spar platform prototype emulates the buoyant structure of a real spar platform and will be appropriately scaled to match the dimensions of typical offshore spar platforms. The introduction of ballast ensures that our prototype replicates the response of full-scale platforms to wave-induced loads and provides stability.

Relevance:
The significance of studying how spar platforms react to wave loading lies in the following areas:

1. Enhanced Safety: Insights gained will lead to improved safety features and contribute to the design of more robust offshore structures.
2. Cost Efficiency: Optimizing designs based on dynamic response data can result in cost savings during construction and maintenance.
3. Environmental Impact: Efficient spar platforms can reduce the environmental footprint of offshore drilling operations.
4. Advancements in Engineering: Our study can drive progress in offshore engineering and structural analysis.

Methodology Overview:
1. Numerical Analysis: We will create a physical model incorporating plastic material properties and buoyancy characteristics and numerically analyze it to find its natural frequency.

2. Prototype Construction: A scaled-down prototype of the spar platform will be fabricated.
3. Ballast Integration: Ballast will be added to replicate buoyancy characteristics.
4. Wave Flume Testing: The prototype will be exposed to controlled wave conditions in a wave flume.
5. Data Collection: We will collect data on the prototype's response to various wave scenarios.

Results:

The findings from our project will provide invaluable insights into the dynamic behaviour of Spar platforms under wave-induced loads. These insights can be used to refine design criteria and operational strategies, enhancing the safety and efficiency of offshore platforms. Thorough analysis of the data collected during wave flume testing will enable us to draw conclusions about the structural performance of Spar platforms in deepwater environments.

Data and Methodology

ASSUMPTIONS:

In our team project focusing on the analysis and testing of a spar platform in a wave flume, we've made several key assumptions.

- Firstly, we've assumed that the spar's structural material properties are homogeneous and isotropic. In reality, material properties can vary along the length of the structure.
- We're also operating under the assumption that the model spar platform used in the wave flume tests has a rigid structure, and structural deformations are negligible. The spar experiences rigid body motion,
- Water properties (e.g., density, viscosity) within the domain of interest, neglecting any variations due to temperature or salinity gradients.
- Additionally, we're neglecting any additional mass due to equipment, personnel, or other variables that may be present on the platform during operation.
- We concur that the scaling laws governing the model in the wave flume accurately represent the full-scale spar platform, involving geometric scaling, Froude and Reynolds number similarity.
- We collectively ensure that the boundary conditions within the wave flume faithfully replicate open-water conditions, paying particular attention to wave reflection and absorption.
- Furthermore, we presume that the wave generation system precisely reproduces the desired wave spectrum and sea states for testing. In terms of instrumentation, we agree that the tools employed to measure the spar platform's response, including accelerometers and strain gauges, are accurate and calibrated.

SCALE CALCULATION:

We need to determine an appropriate scale for our model. It is essential to ensure that the diameter of the model relative to the width of the wave flume falls within the range of 0.1 to 0.2 to prevent wave reflection.

Given that the width of the wave flume is 100 cm, the diameter of the model should be between 10 cm and 20 cm to meet this criterion.
We have chosen a 16 cm diameter pipe with a thickness of 0.2 cm because it is readily available in the lab.

Scale = Diameter of Model / Diameter of Prototype
Scale = 16 cm / 3500 cm (prototype diameter)
Scale = 1/218.75

Therefore, our chosen scale factor for the model in our group project is approximately 0.00457. This scale ensures that our model falls within the desired range relative to the wave flume width, meeting the criteria for our experiments.

Other parameters calculation:

Model Dimensions:
Height of model(h_model) = scale × height of prototype
Inner diameter(d) = Outer diameter(D) - 2 × thickness
Inner area = pi×d×d×0.25
Draft of model = scale*draft of prototype
Displaced volume of water by model = 0.25×D×D×pi×(draft of model)
Centre of mass of model(G_Z) = s×(Centre of mass of prototype)
IYY = (1/64)×pi×D^4
B_M = IYY/Displaced volume of water by model
k_B = Draft of model/ 2
G_M = k_B + B_M - G_Z

For the lid and closure:
Lid Dimensions: The lid should match the outer diameter of the model, which is 16 cm.
Closure Dimensions: The closure should match the inner diameter of the model, which is 15.6 cm.
We then shared these dimensions and calculations with our lab staff, who fabricated the model with the following specifications:

Fabricated Model Details:
Pipe Material: The pipe of the model is constructed from plastic.
Closure Material: The closure is made from an acrylic sheet.
Lid Material: The lid is composed of plastic, curved at the top and a nail has been affixed to it for easy lid opening.

Dimensions:
Pipe Diameter: The diameter of the pipe is 16 cm, and it has a thickness of 0.2 cm.
Closure Dimensions: The closure, which fits inside the pipe, has a thickness of 1 cm at the bottom.

Height of model = 38.6 cm

The inner diameter of pipe = 15.6cm
Weight of pipe = 912 g
Total weight of closure and weight of pipe = 1138 g
Weight of closure = Total weight of closure and weight of pipe - weight of pipe = 226 g

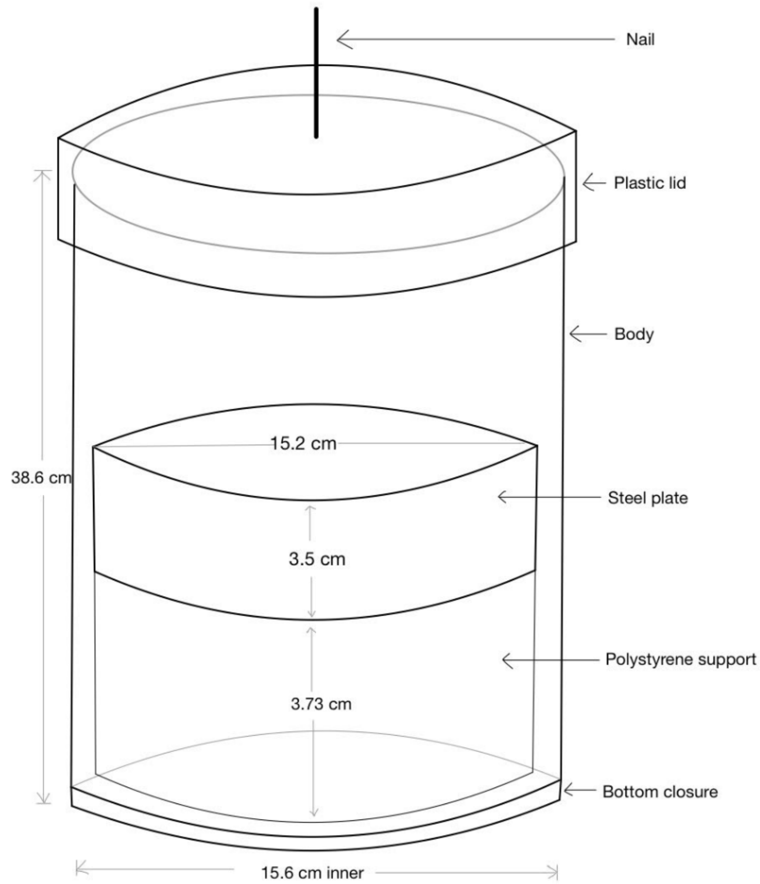


Fig 2.0 Schematic diagram of spar model

Weight of lid = 192 g
Centre of gravity of pipe from bottom = Height of model/2
Centre of gravity of closure sheet from bottom = Thickness / 2= 0.5 cm
Centre of gravity of lid from bottom = 41.8 cm

Ballast Calculations:
Weight of ballast = (Displaced volume of water by model×density of water - Weight of pipe, closure and lid) = 5106.57g
Center of gravity of ballast from bottom =[Weight of model × center of gravity of model from bottom- (Weight of pipe × Center of gravity of pipe from bottom + weight of closure × Center of gravity of closure from bottom + weight of lid × center of gravity of lid from bottom)]/ Weight of ballast = 6.4835 cm

Height of ballast = 2×(Center of gravity of ballast from bottom - Thickness of closure) = 10.964 cm
Density of ballast = Weight of ballast / (Inner area × Height of ballast) = 2.435 g/cc

Image 2.1: Steel plate ballast atop polystyrene support, together inserted within pipe

We have the option to select a material for ballast with a density of 2.435 g/cc and a weight of 5106.57 g, assuming the ballast would be touching the bottom of the pipe and be homogenous, and uniformly distributed in mass and density.

Table 2.1: Model Dimensions and Ballast Calculations

Parameters	**Data with initial assumption**	**Data with corrected assumption**
Diameter of prototype	3500 cm	3500 cm
Diameter of Model	16 cm	16 cm
Thickness of pipe	0.2 cm	0.2 cm
Scale	0.00457	0.00457
1/scale	218.75	218.75
Height of prototype	8350 cm	8350 cm
Height of model	38.17 cm	38.6 cm
Inner diameter	15.6 cm	15.6 cm
Inner area	191.21 cm^2	191.21cm^2
Draft of model	32 cm	32 cm
Displacement of water	6436.57cc	6436.57 cc
Gravity centre from bottom	9.14 cm	9.14 cm
Moment of inertia about y-axis Iyy	3218.28 cm^4	3218.28 cm^4

Metacentric radius BM	0.5 cm	0.5 cm
Buoyancy center of model from keel	16 cm	16 cm
Metacentric Height	7.36 cm	7.35 cm
thickness of closure		1 cm
Weight of pipe		912 g
Gravity center of pipe from bottom		19.3 cm
Weight Of closure		226 g
Gravity center of closure from bottom		0.5 cm
Weight of lid		192 g
Gravity center of lid from bottom		41.8 cm
Weight of ballast		5106.56 g
Gravity center of ballast from bottom		6.48 cm
Height of ballast		10.96g
Density of ballast		2.44g/cc

MODEL IMAGES:-

Image 2.2: Complete model set up from outside, showing body and lid (with nail handle), and draft height marked in red

Image 2.3: Model successfully floating in water with the required draft height

Experimental set-up and Procedure

EQUIPMENT

Wave Flume:
The wave flume is a controlled environment designed to simulate wave conditions to test the response and behaviour of offshore structures such as the spar platform. It's an integral part of experimental testing in offshore engineering. In this case, the wave flume's dimensions are 50 meters in length, 1 meter in width, and 1 meter in height, providing a confined space to generate and observe waves while conducting experiments.

Components of the Wave Flume: Water Circulation System: The flume is equipped with a water circulation system that ensures a continuous flow of water. This system maintains the water level and flow required to generate the waves and simulate real offshore conditions.

- Adjustable Floor and Walls: The flume is designed with an adjustable floor and walls to replicate different water depths and wave conditions. This adjustability allows for varying experimental setups to imitate diverse offshore scenarios.
- Wave Generating Machine: Within the wave flume, a wave generator machine is installed to produce controlled waves for the experiments.

Wave Generating Machine:
The machine employed to generate waves in the wave flume is typically a paddle system, capable of creating a range of wave patterns and amplitudes. It works by simulating the motion and force of waves through the following mechanisms:

- Paddle Mechanism: The wave generator uses a paddle or a series of paddles that move back and forth or up and down in a controlled manner. This motion creates disturbances in the water, generating waves.
- Control System: The machine is equipped with a control system that regulates the speed, frequency, and amplitude of the paddle's movement. This control allows for the precise generation of different types of waves, from regular to irregular patterns.
- Wave Monitoring Instruments: Additionally, sensors and instruments are integrated to measure and monitor the characteristics of the generated waves. These instruments capture wave heights, periods, and other wave properties, providing crucial data for analysis.

Image 2.4: Wave generator in the ocean engineering lab, IIT Bombay

6-DOF Motion Sensor (Xsens): The Xsens sensor is a sophisticated device used to precisely measure and record the full 6 Degrees of Freedom (6-DOF) of movement, which includes three linear (translational) and three angular (rotational) degrees of freedom.

Features and Capabilities:

- Measurement of Linear Movement: The Xsens sensor accurately captures the translation of the structure in three-dimensional space. It records movements along the x, y, and z axes, offering detailed data on how the structure shifts in response to wave-induced motion.

- Measurement of Angular Movement: In addition to linear movement, the Xsens sensor precisely measures the rotational movements of the structure. It records rotations about the x, y, and z axes, providing insights into the roll, pitch, and yaw of the model.
- Real-time Data Collection: The sensor typically operates in real-time, allowing for immediate data collection and analysis, which is invaluable for understanding the dynamic response of the structure to different wave conditions.
- High Precision and Accuracy: The Xsens sensor is known for its high precision and accuracy, ensuring reliable data on the structural behaviour in the wave flume.
- Data Analysis: The data collected by the Xsens sensor is crucial for post-experiment analysis. It provides researchers and engineers with a comprehensive understanding of how the structure oscillates, sways, and reacts to waves, aiding in the assessment of its stability, structural integrity, and performance in offshore conditions.

MODEL SETUP

- The last step to set up the model employed in this study, after determining the model parameters, was to select an appropriate ballast material that would give the centre of gravity at the required height. We tried various materials such as lead shots, mineral aggregates, and cement clinkers and have tabulated the results as shown in table 4.1
- Using a heterogenous ballast material with a combination of, say, lead shots and sand, was also considered and partially tested, but not pursued due to complications in finding the centre of gravity of this hybrid material (hybrid in density and mass distribution)
- While materials such as sand and lime were initially strongly considered for ballast due to their average density being close to the required density, we ultimately decided upon using conventional steel as the ballast material due to the difficulty in obtaining clean lime or soil with the exact density as needed.
- Even though the density of steel is three times more than the density needed, we maintained the same total weight of ballast by reducing the height of ballast used (hence reducing the total volume of ballast), and in order to still obtain the centre of gravity of this steel plate at the desired height of 6.4835cm from the base, we elevated our steel plate using thermocol or polystyrene.

  Polystyrene was chosen because of its low density, and hence it could be neglected in further calculations.
- We fabricated a steel plate of dimensions appropriate for the cylinder with a 4mm clearance and height of steel according to the required mass.

  This gave us the final steel ballast dimensions of:

  Diameter: 15.2 cm

  Height: 3.5 cm
- Care was taken to choose a final ballast that would be uniform in order to obtain a centre of gravity on the vertical axis of the cylinder and for ease of calculation
- Final model parameters with ballast are shown in table 3.2

EXPERIMENTAL PROCEDURE

1. A particular ballast material was chosen based on the availability of materials in the lab, and an exact weight of 5106g of this material was taken. This ensured that the draft obtained for the final model would be correct (as marked on the model and shown in image 4.1 attached)
2. In the above table 3.1, values in rows 3 to 10 were constant irrespective of the ballast used. The exercise was to measure the height of the ballast from the base closure (mentioned in row 2). This was done by subtracting h_diff, which is the height from the top of the cylinder to the top of the ballast once placed inside, from the total internal height of the cylinder,
   i.e., height of ballast = total height of cylinder - height of bottom closure - distance between the top of the cylinder and top of ballast once placed (or h_diff)
3. Once values in rows 1 to 10 were known or calculated, the G_Z value in row 11 was calculated using the formula
   Center of gravity of model from bottom = Weight of ballast* Center of gravity of ballast from bottom + Weight of pipe* Center of gravity of pipe from bottom + Weight of closure * Center of gravity of closure from bottom + Weight of lid * Center of gravity of lid from bottom)/Total weight of model
4. Trials were conducted on different materials with the intent to obtain a material that gave a centre of gravity value as close as possible to the required value for the entire model, i.e., 9.1428cm
5. Ultimately steel was chosen due to the above-mentioned reasons and elevated to obtain the final center of gravity at the desired location

Table 3.1: Comparison of different ballast materials to obtain the desired centre of gravity

Sr. No.	**Item**	**Lead shots**	**Aggregates**	**Cement Clinkers**	**Soil**	**Steel Plate** (not elevated)
1	h_diff (cm)	33	21.5	19	37.6	34.2
2	Height of ballast (cm)	4.6	16.1	18.6	19.8	3.4
3	Centre of gravity of ballast from the bottom (cm)	3.3	9.05	10.3	10.9	2.7
4	Centre of gravity of lid from the bottom (cm)	38.7	38.7	38.7	38.7	38.7
5	Centre of gravity of pipe from the bottom (cm)	19.3	19.3	19.3	19.3	19.3
6	Centre of gravity of closure from the bottom (cm)	0.5	0.5	0.5	0.5	0.5
7	Weight of ballast (g)	5106.57	5106.57	5106.57	5106.57	5106.57
8	Weight of lid (g)	192	192	192	192	192
9	Weight of pipe (g)	912	912	912	912	912
10	Weight of closure (g)	226	226	226	226	226
11	Centre of gravity of ballast from bottom (cm)	6.525	11.086	6.042	11.073	18.786

Table 3.2: Final model ballast parameters

Sr. No	**Item**	**Steel plate elevated with polystyrene**
1	h_diff (cm)	30.37
2	Height of ballast (cm)	3.5
3	Centre of gravity of ballast from the bottom (cm)	6.48
4	Centre of gravity of lid from the bottom (cm)	38.7
5	Centre of gravity of pipe from the bottom (cm)	19.3
6	Centre of gravity of closure from the bottom (cm)	0.5
7	Weight of ballast (g)	5106.57
8	Weight of lid (g)	192
9	Weight of pipe (g)	912
10	Weight of closure (g)	226
11	Centre of gravity of ballast from the bottom (cm)	**9.0476**
12	Height of polystyrene support (cm)	3.73

TESTING SETUP

Post fabrication, it is time to test the model. The following were the steps followed to test the model, basis each analysis type:

1. Hydrostatic Analysis
    - Initiate testing in a still water condition within the wave flume, known as the hydrostatic analysis phase.
    - Employ the 6-DOF motion sensor (Xsens) to measure and record displacements and accelerations in all six directions by giving slight manual disturbance: three linear (x, y, z axes) and three angular (roll, pitch, yaw) directions.
2. Hydrodynamic Analysis
    - Transition to the hydrodynamic analysis phase, where the Spar platform is subjected to various wave conditions created using the wave generator in the wave flume.

- Moor the Spar platform prototype using ropes to a steel frame within the flume to conduct the moored decay test. This mooring setup enables the study of the platform's response while restrained, simulating real-world moored conditions in offshore environments.
- Activate the Xsens 6-DOF motion sensor to continuously monitor and record the platform's movements and orientations during the wave-induced tests.
- Collect data on the platform's responses under diverse wave scenarios and moored conditions, measuring its motions, rotations, and accelerations in all six degrees of freedom.

3. Interpretation and Conclusion:
    - Interpret the results obtained from both the hydrostatic and hydrodynamic analyses, particularly focusing on the differences in behaviour between free-floating and moored conditions.
    - Draw conclusions regarding the Spar platform's performance and behaviour under varying wave conditions, considering the impact of mooring in offshore engineering scenarios.

Hydrostatic Analysis

FREE DECAY TEST

We did the Free heave decay experiment for the spar model in calm water conditions in the wave flume at the department of ocean engineering.

To obtain damping from the free decay tests, the linear damping equation of motion has been considered, which is given by
$(M+A)\ddot{z}+C\dot{z}+Kz=0$

Where M is the mass of the spar, A is the heave added mass, z is the heave displacement as a function of time t, C is the linear heave damping coefficient and K is the heave restoring stiffness.

The damping ratio is obtained from the heave decay curve, which is acceleration vs .time plot by using the procedures of the logarithmic decrement method.

The logarithmic decrement (δ), which is given by
$\delta=(1/n)\times\ln(Z0/Zn)$,
where z0 is the initial peak ampli-tude and zn is the peak amplitude after the nth cycle.
From the logar-ithmic decrement (δ), damping ratio (ζ) which is a dimensionless parameter is calculated using
$\zeta=1/\sqrt{(1+(2\pi/\delta)^2)}$

$\omega d=2\pi/Td$;
Where Td is the natural period obtained from the time difference between the successive peak acceleration.

$\omega n=\omega d/\sqrt{(1-(\delta)^2)}$

From the above procedure, the linear heave damping coefficient(C), which is related to damping ratio (z), is derived as below
$C=2(M+A)\omega n$
where the heave added mass (A) is given by $A=K/(\omega n)^2 - M$
The restoring stiffness coefficient (K) for heave motion is given by
$K=\rho\times g\times Awp$,
where ρ is the density of water, g is the acceleration due to gravity and Awp is the waterplane area

Calculations

Time period = 2.528- 1.34= 1.188 sec
Natural frequency = 0.842 Hz

ωd = 5.289 Hz

logarithmic decrement = ln(0.755/0.636) = 0.1715
Damping ratio = 0.02728
ωn = 5.291 Hz
M = 6.437 kg
Waterplane area = 201.06 cm2
restoring stiffness coefficient (K) = 197.24 kg/s^2
heave added mass (A) = 0.6086 Kg
Damping coefficient = 74.557 kg/s

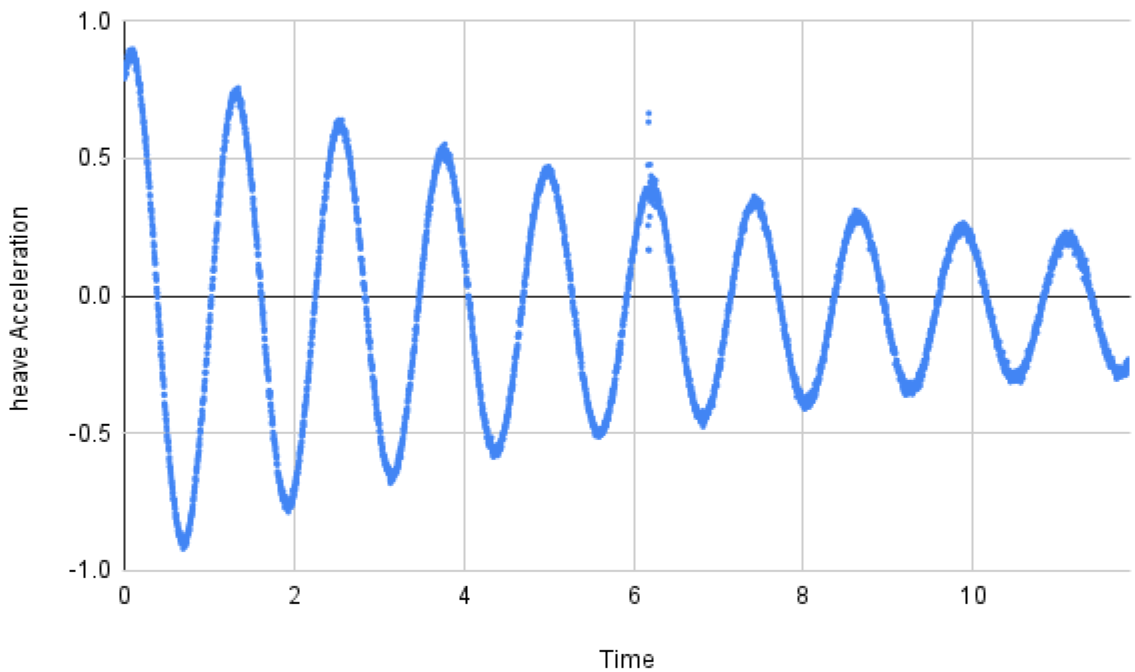


Fig. 4.1: Heave Acceleration v/s Time graph for Unmoored heave decay test

Moored decay test

Time period = 2-0.992 = 1.008 sec
Natural frequency = 0.992 Hz

wd = 6.233 Hz
logarithmic decrement = ln(1.2596/0.9649) = 0.2665
Damping ratio = 0.04238
Wn = 6.2389
M = 6.437 kg
Waterplane area = 201.06 cm2
restoring stiffness coefficient (K) = 197.24 kg/s^2
heave added mass (A) = -1.37 Kg

Damping coefficient = 63.22 Kg/s

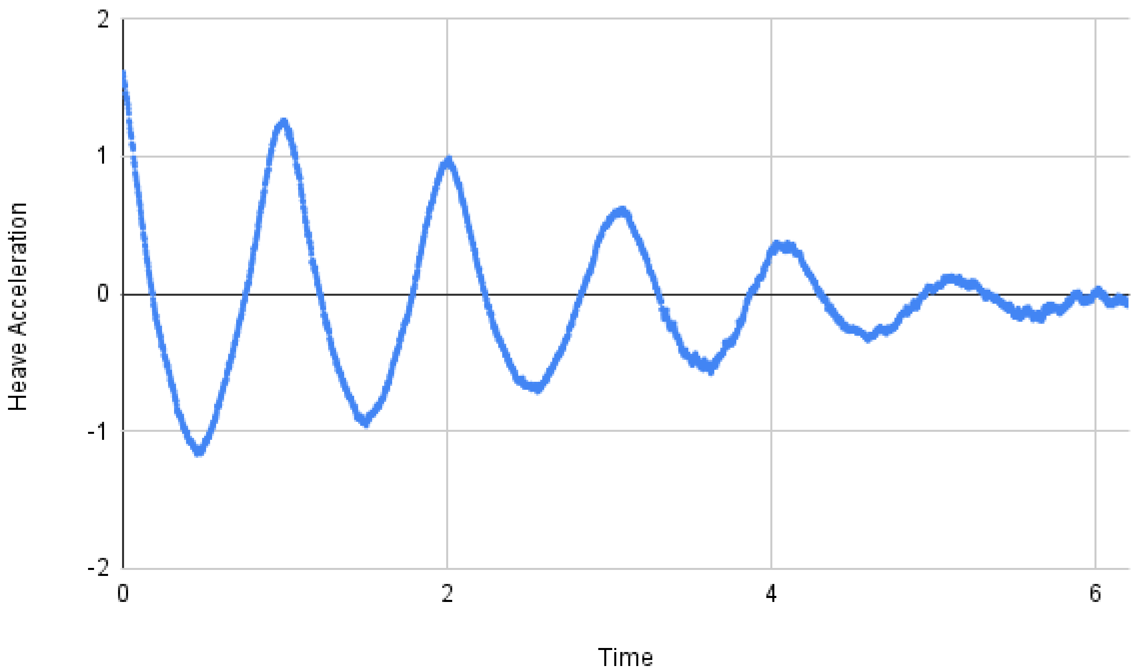


Fig. 4.2: Heave Acceleration v/s Time graph for Moored heave decay test

Hydrodynamic Analysis

- Hydrodynamic analysis means analysing the model response under conditions of external wave forcing by generating waves in the flume and testing the model in those conditions.
- We conducted a moored heave decay experiment of our model by tethering the model to a steel frame which was then also placed in the flume. Wires were used to act as moorings.

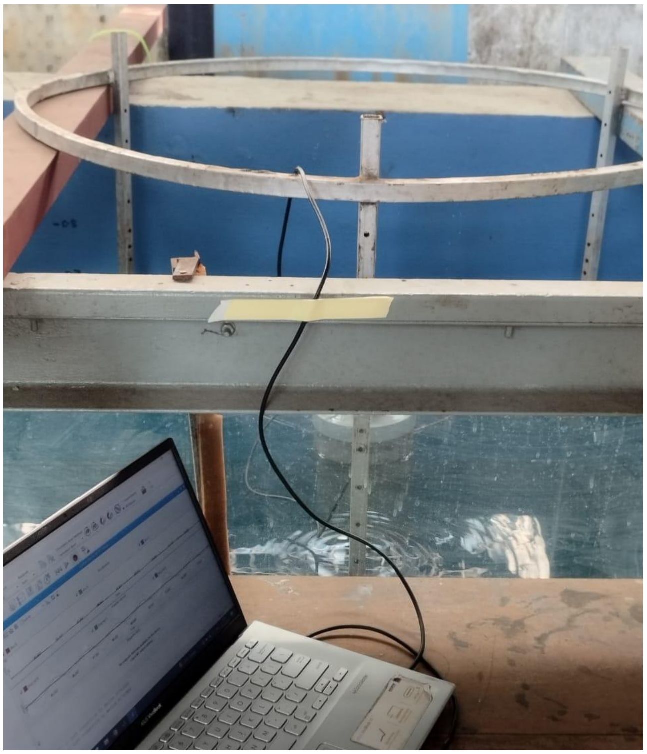


Image 5.1: Mooring frame placed in the flume with model in between, and Xsens sensor attached

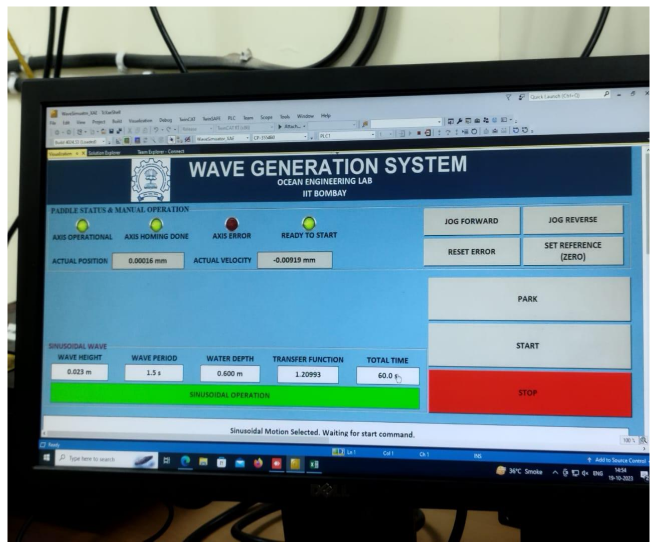


Image 5.2: IIT Bombay Wave Generating System in the Ocean Engineering Lab

- We conducted experiments using different wave height and time step conditions, with three trials under each wave condition. This was followed with one extreme condition analysis
- The following are the conditions we tested on:

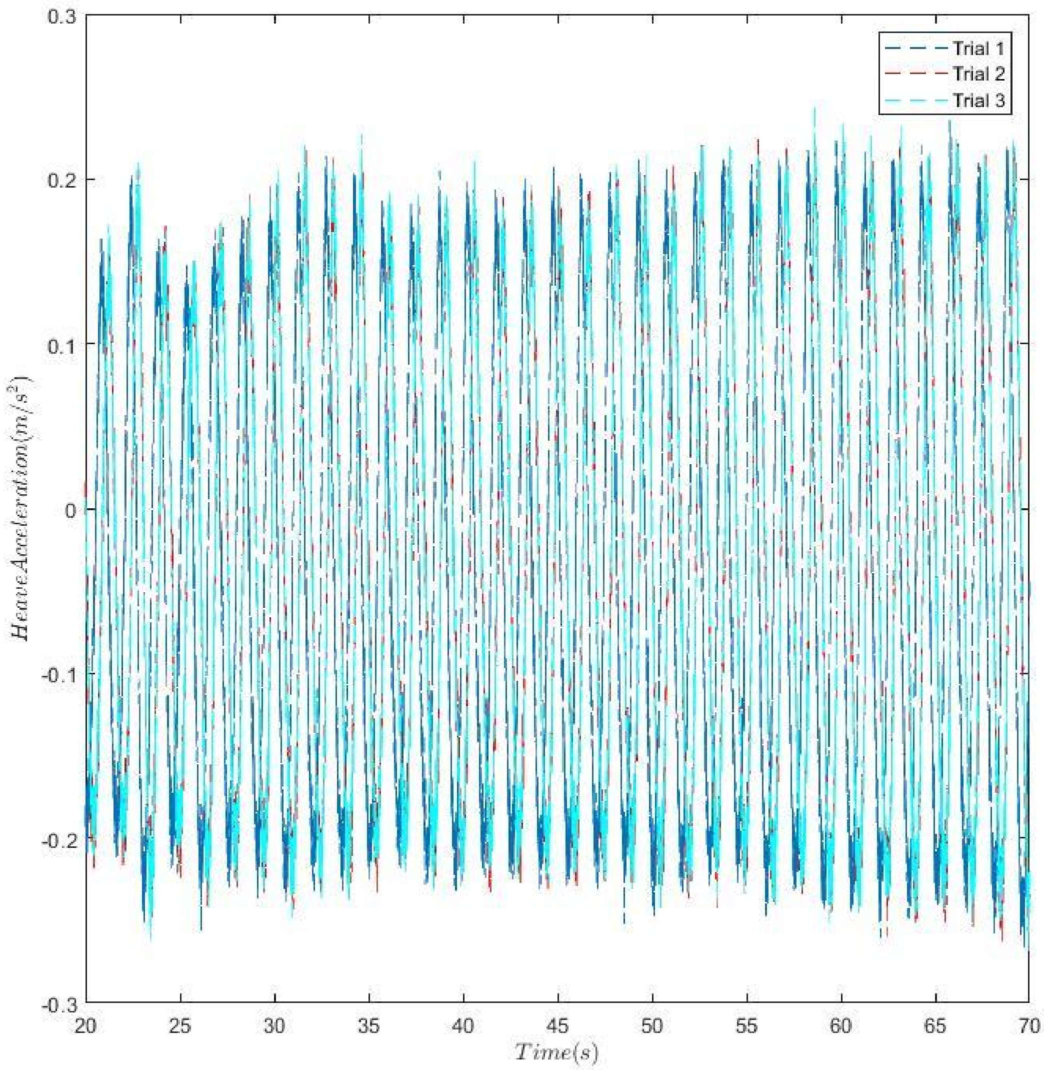
Table 5.1: Summary of Wave Testing Conditions

Condition Number	Wave Height (cm)	Time Period of Wave (s)
1	2.3	1.5
2	2.3	1
3	4.6	1.5
4 (extreme condition)	15	3

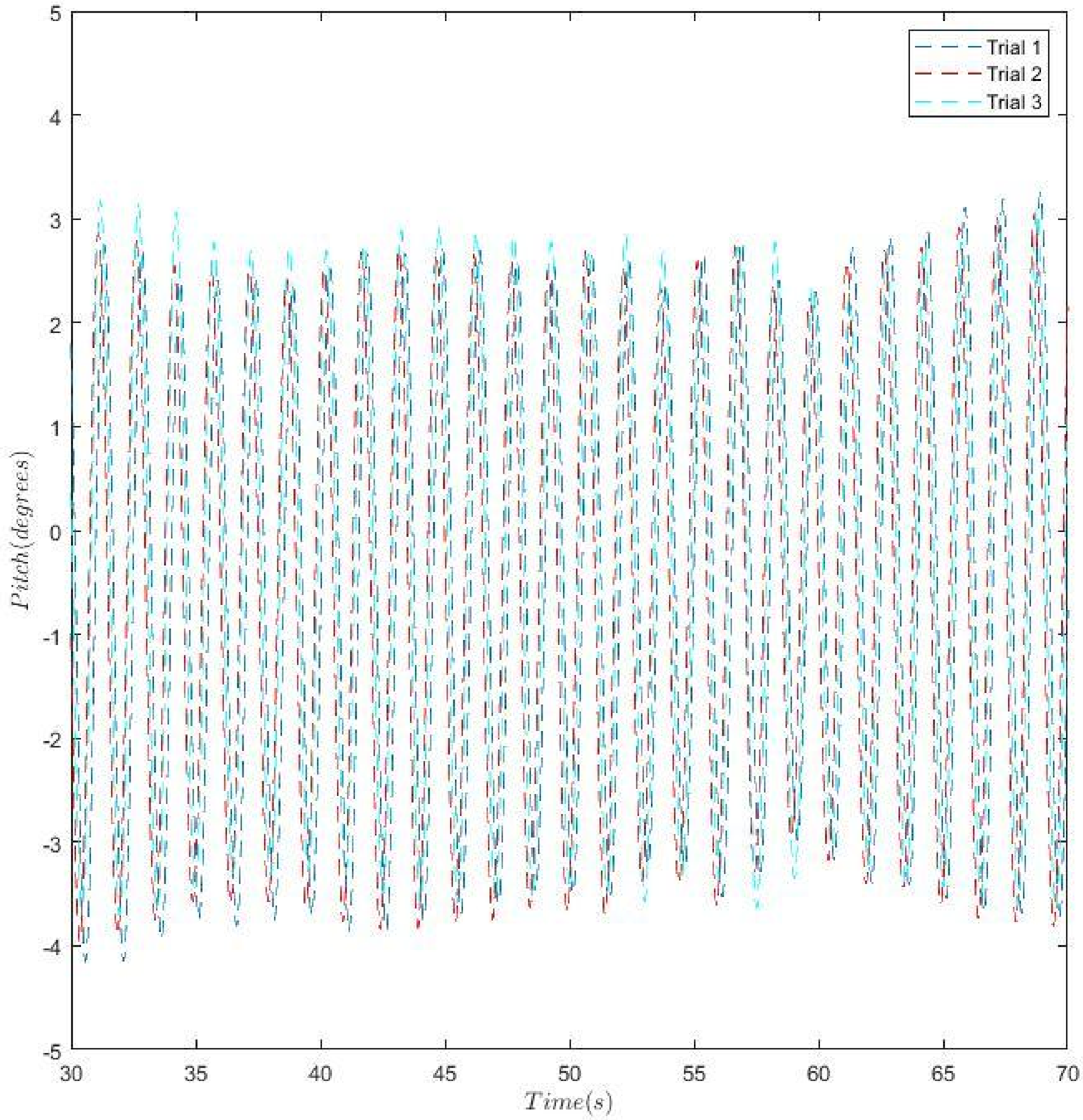
- The Xsens 6 DOF sensor measured the acceleration in all 3 directions (heave, sway, surge) as well as the pitch, roll and yaw of the model in degrees. Of these, the heave and pitch are of interest
- The acceleration due to gravity was subtracted from the obtained acceleration in the Z direction (heave direction)

The following plots were obtained for the different conditions:

1) <u>Condition 1: Wave height = 2.3cm, Time period = 1.5s</u>



(a)

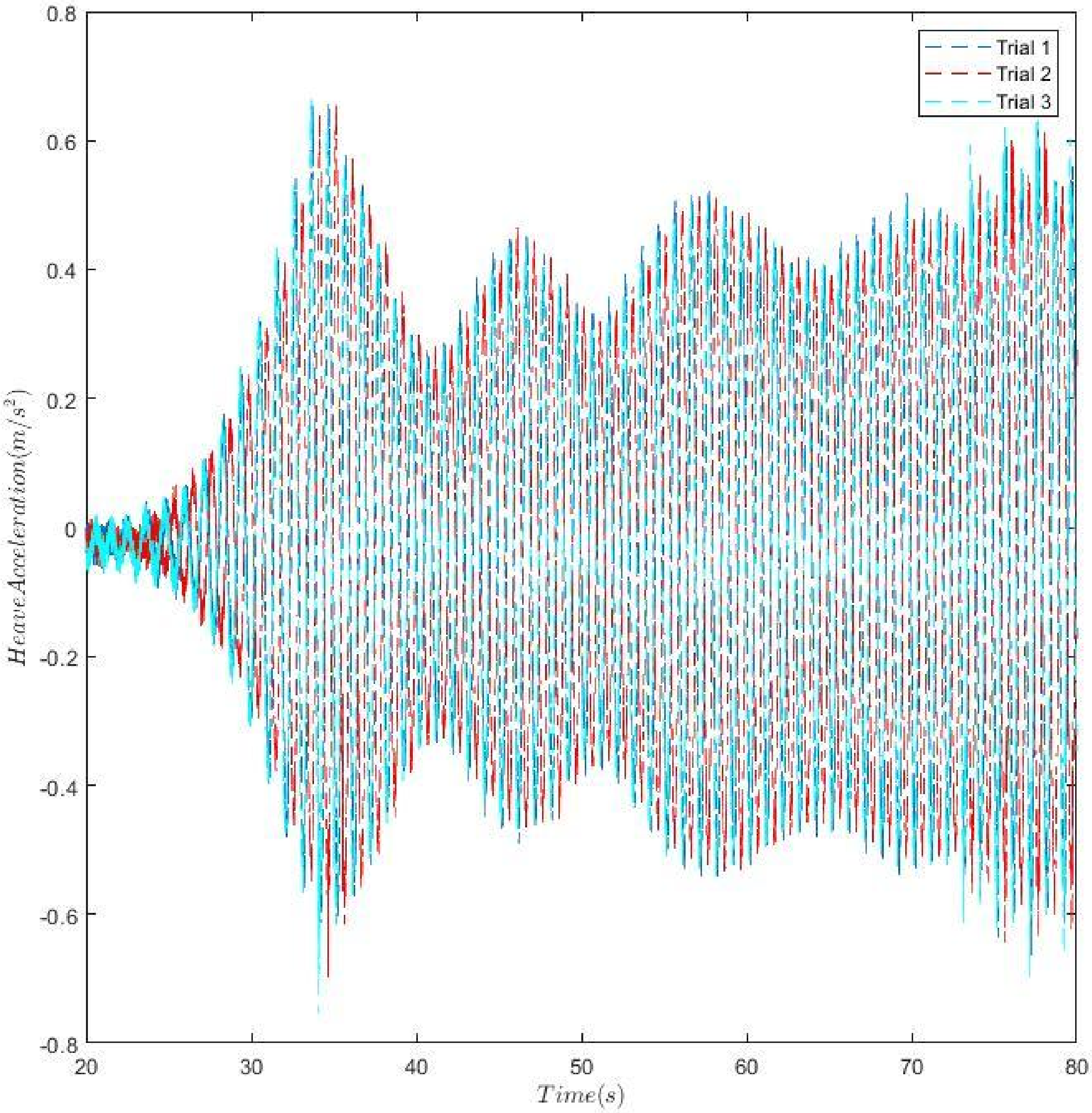


(b)

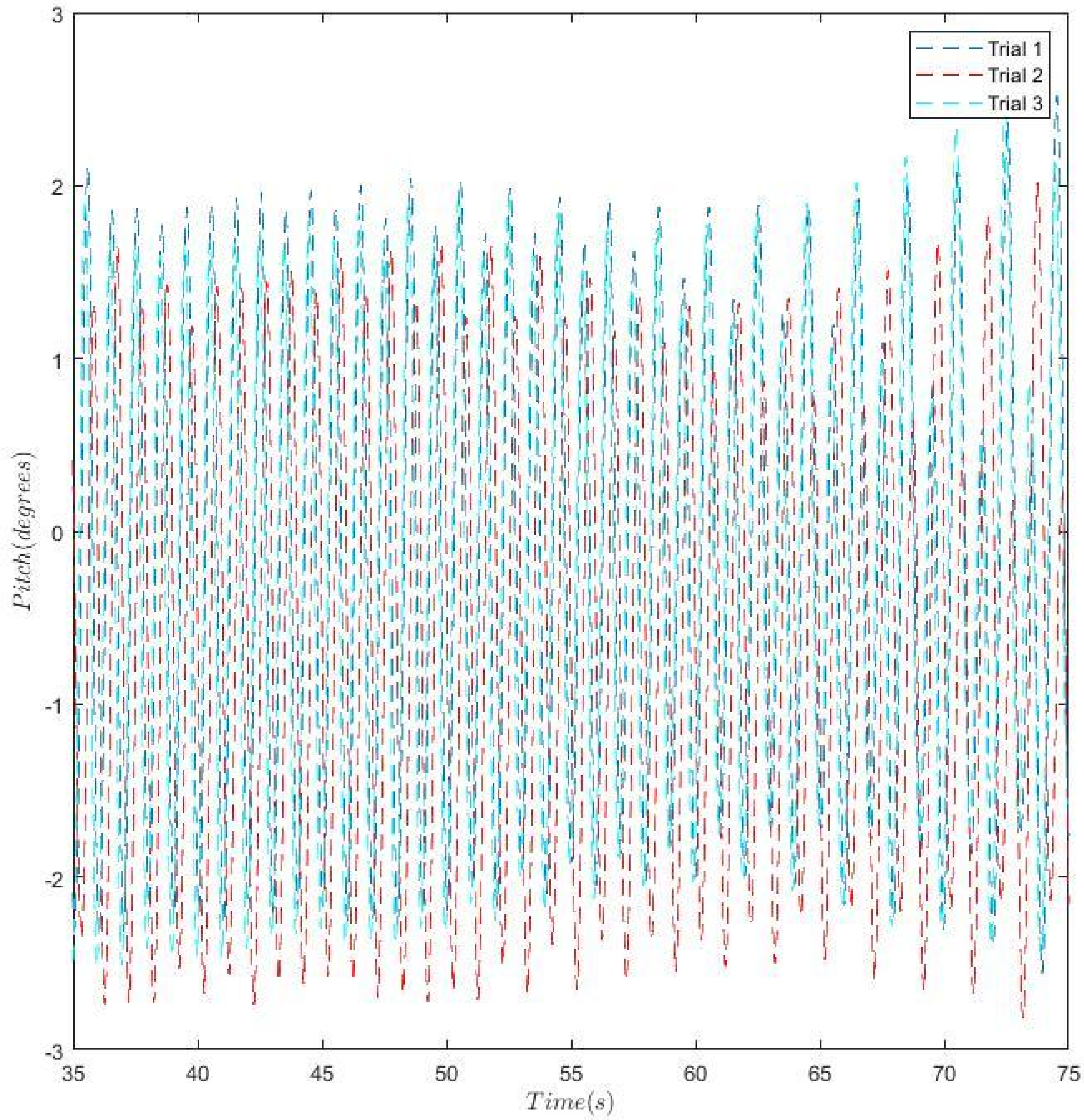
Fig 5.1 Heave decay analysis of Heave Acceleration and Pitch vs Time under wave conditions of wave height = 2.3cm, time period = 1.5s

- The strong overlap in the above graphs of the three iterations of the wave shows that an average value of all three may be considered for comparing against the different wave conditions.
- Acceleration values range from -0.2m/s^2 to +0.2m/s^2, and continue as such since there is a regular wave produced periodically to act as forcing on the model
- Pitch values are largely ranging to 3 degrees on either side of the mean

2) Condition 2: Wave height = 2.3cm, Time period = 1s



(a)



(b)

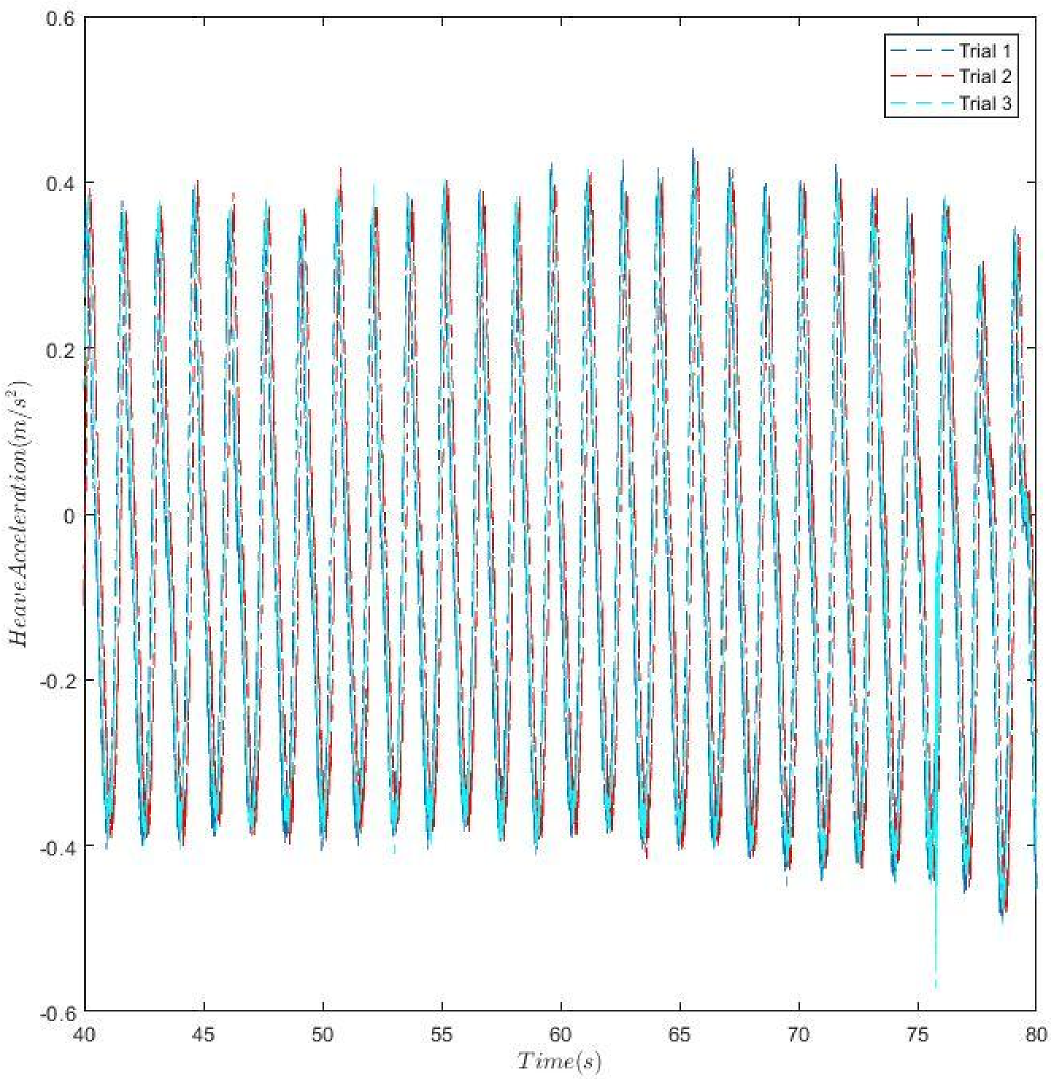
Fig 5.2 Heave decay analysis of Heave Acceleration and Pitch vs Time under wave conditions of wave height = 2.3cm, time period = 1s

- In this wave condition we have kept the wave height the same as original but reduced the time period of the wave to 1s
- **Resonance**: Acceleration values are ranging between roughly -0.6m/s^2 and +0.6m/s^2, higher than those in the previous condition. This shows that bringing the time period of the wave closer to the natural moored frequency of the model (=1 Hz) gives us a condition akin to resonance and, thus higher magnitude of acceleration on either side of the mean.
  Similarly, the destructive interference also causes antinodes to form, and the resulting waveform of the heave acceleration vs time is similar to a standing wave
- The Z acceleration shows considerable overlap in the three iterations, but there is an unexpected drop in the magnitude, and subsequently, the magnitude drops by smaller

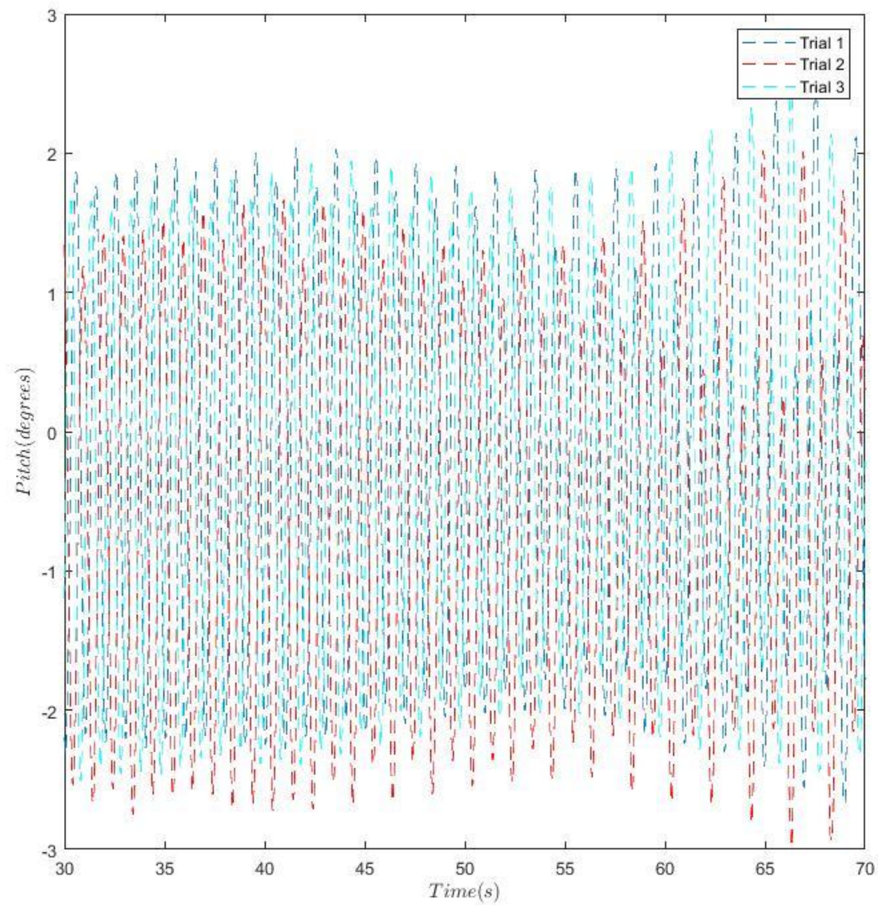
amounts, against expectations. This could be due to the gaps in the data, as well as any errors during the experiment (discussed at the end of this chapter).

- The pitch of the three iterations overlap to a smaller extent and seem to have a different mean or neutral value. This implies that the wave forcing in one direction was particularly strong, due to which the model was tilted towards that side and did not completely return to the neutral position during the forcing. Alternatively, there may have been some initial effects or residual ripples from the previous iterations, causing the mean to be registered not at the zero position but at some deviation.
  This error is seen most in the transition from iteration wave 2 to iteration wave 3.

3) <u>Condition 3: Wave height = 4.6cm, Time period = 1.5s</u>



(a)

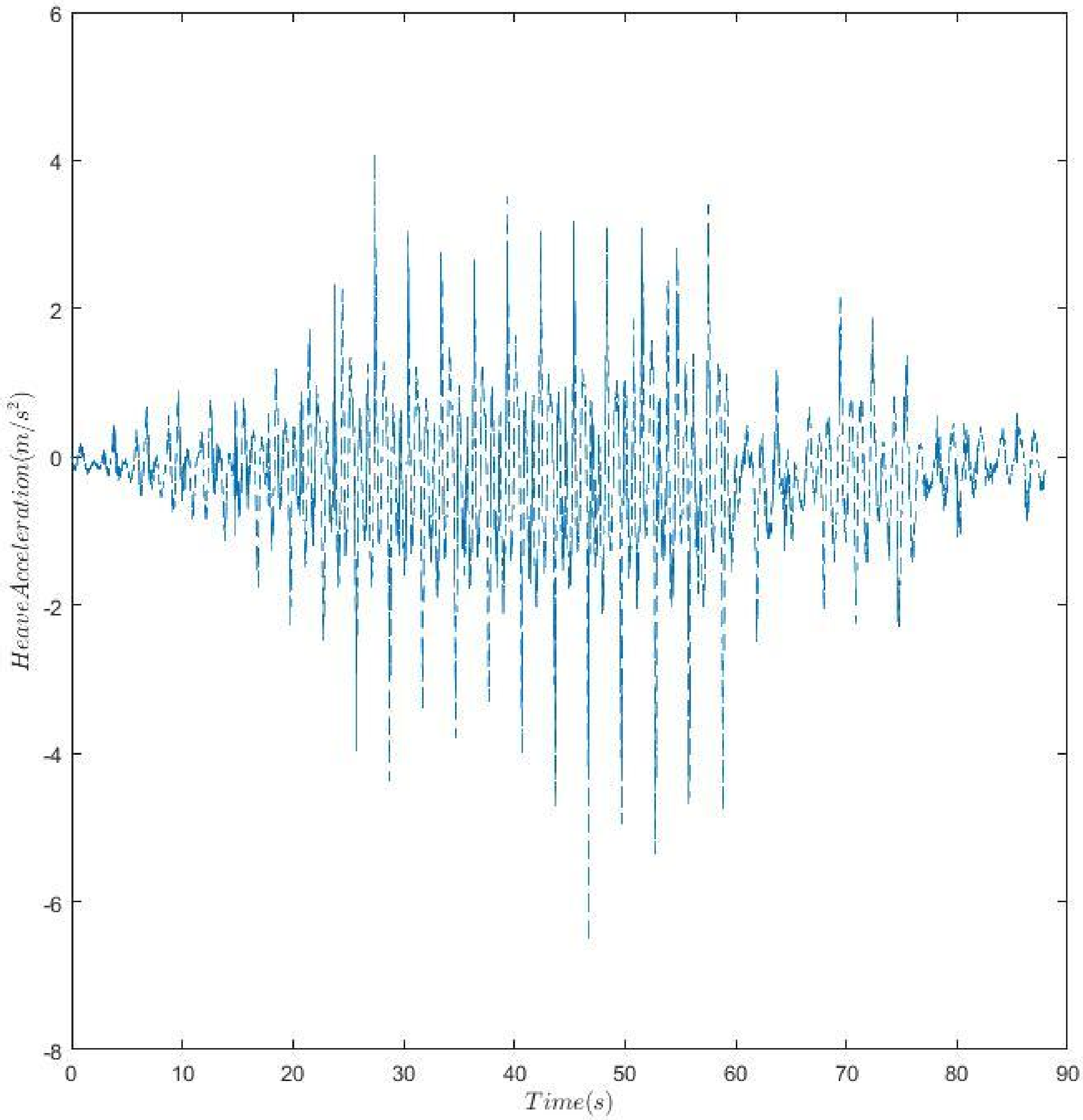


(b)

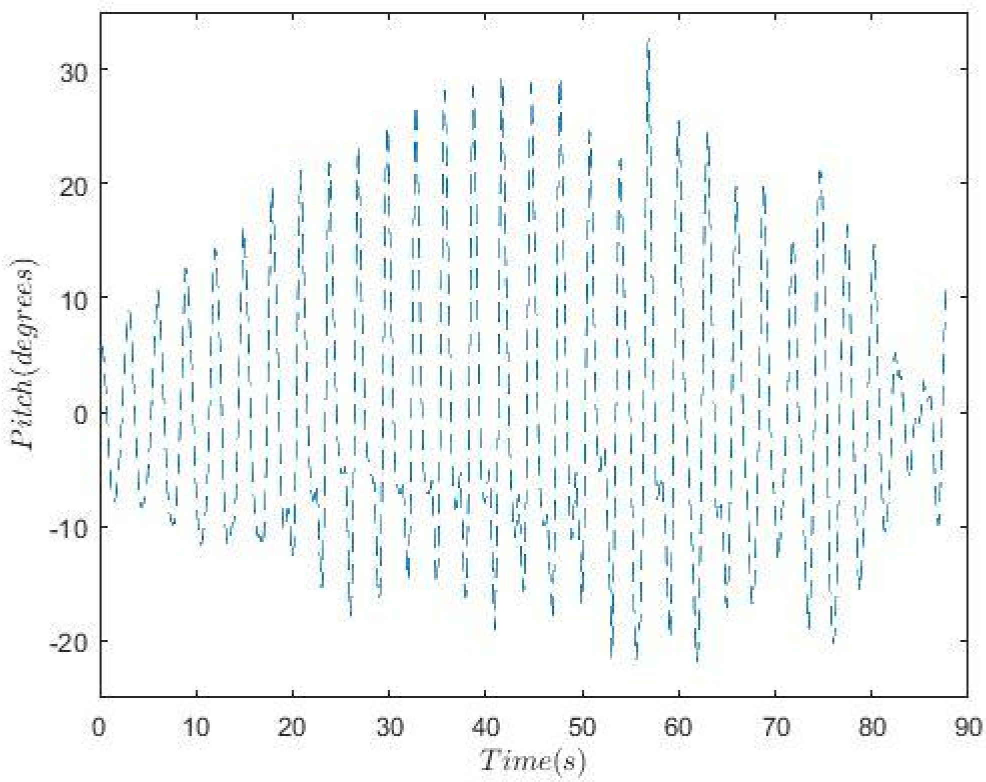
Fig. 5.3: Heave decay analysis of Heave Acceleration and Pitch vs Time under wave conditions of wave height = 4.6cm, time period = 1.5s

- In this wave condition, we have doubled the wave height from the first condition but maintained the same time period
- We find that the Z acceleration is between -0.4m/s^2 and +0.4m/s^2, greater than the first condition. Thus on increasing the wave height with the same period, the Z acceleration has increased, too, due to increased external forcing.
- The z acceleration again showed considerable overlap however, the magnitude of the pitch in each iteration differed, although the trend followed by the value of pitch remained the same in each iteration
- The higher wave height in this iteration gives greater pitch values

4) Condition 4: Wave height = 15cm, Timestep = 3 (extreme condition)



(a)



(b)

Fig. 5.4: Heave decay analysis of Heave Acceleration and Pitch vs Time under extreme wave conditions of wave height = 15cm, time period = 3s

- In this wave condition we used a wave height of 15cm, more than 10 times of the previously used heights of 2.3cm and 4.6cm
- Consequently the heave acceleration is seen to range from about -5m/s^2 and +5m/s^2, also 10 times more than the previous values of roughly -0.4m/s^2 and +0.4m/s^2
- The pitch also saw a 10x increase with values ranging upto 20 degrees on each side, as compared to the previous 2-3 degrees
- The model was tossed around in the wave and the mooring was also tested in these conditions
- The wave height just went over the model, and a scaled prototype of the model would not have been stable in similar ocean conditions

Overall Comparison of the Model Response Under Different Wave Conditions

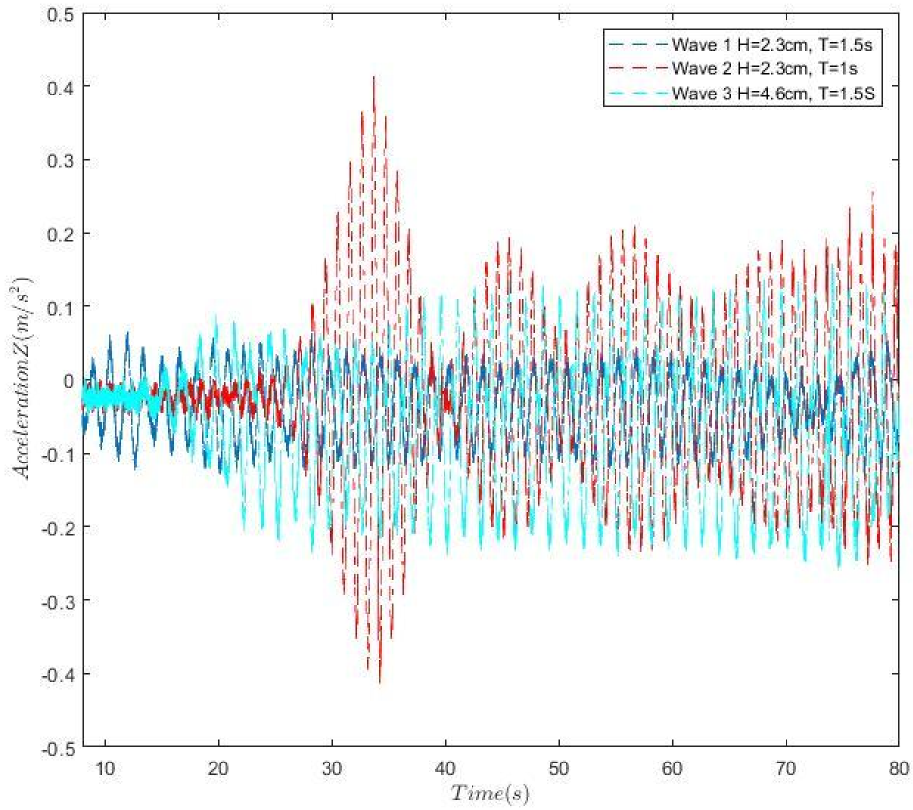


Fig 5.5a. Heave decay plots of the average value Z acceleration of each wave condition against time

- As observed in the graph above, the magnitude of Z acceleration is much higher in the 2nd wave condition, which has a frequency of 1 second. This is because this wave condition is closest to the moored natural frequency of the model (=0.939 Hz). This also explains why the dips are also of greater value in this wave condition.
- When the height was doubled from wave 1 to wave 3, we see that the entire oscillation magnitude increases while still following a similar trend.

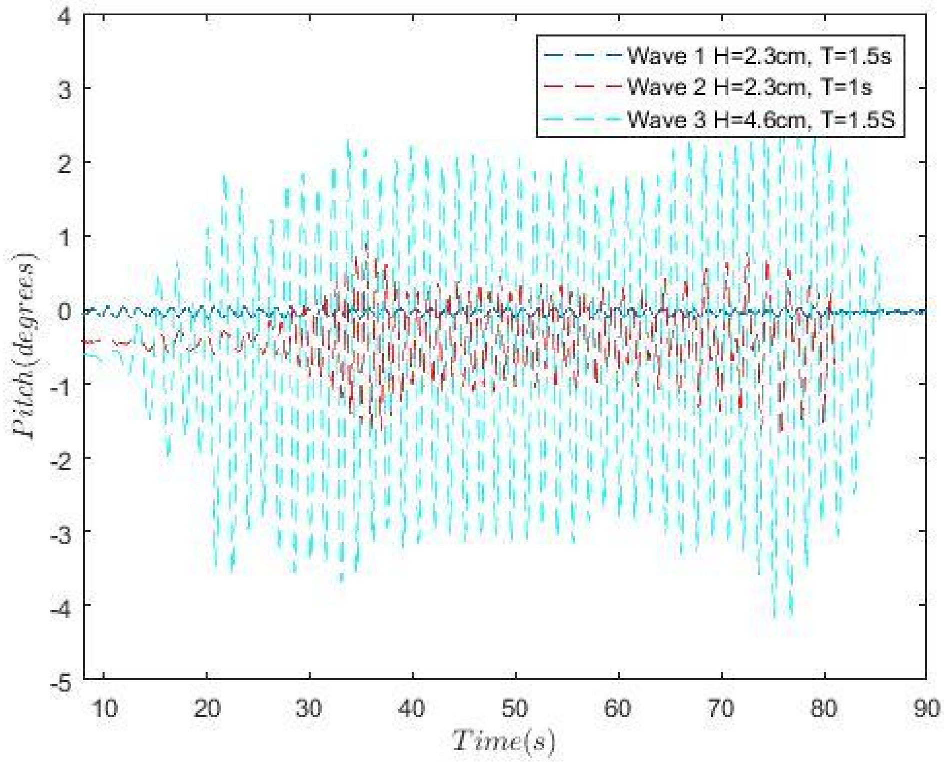


Fig 5.5b. Heave decay plots of the pitch of each wave condition against time

- The pitch of the model increased significantly on increasing wave height, as can be seen when comparing wave 1 and wave 3
- When the time period of the wave was made similar to the natural frequency of the model in wave 2, again the pitch increased but not as much as in the case of wave 3 which had twice the wave height

Sources of Error in the Hydrodynamic Analysis:

1) Approximations: Some approximations made in the model fabrication itself, such as for calculating the centre of gravity, or negating the polystyrene, would alter results
2) Inconsistent data: The biggest challenge for this analysis was the inconsistent data since at some timestamps the sensor read null values and the number of these null values was not the same for each iteration, hence giving us differently sized datasets for each iteration and some at possibly different time values. These errors, however minor in isolation, would not be perceivable by the final graph or chart alone and hence creep into the analysis.
3) The flume generates shallow water waves; however, the model is to be made for a deep sea spar platform. This is another approximation that may affect the final readings.
4) Rigid or unequal mooring will also affect the final values obtained, as displacement or rotation may be differentially restricted in the various degrees of freedom
5) Data Processing Errors:
    a) Interpolation of Missing Data: Given the inconsistent data with null values, there might be a need to interpolate or guess the values. This can introduce errors.

   b) Temporal Resolution: If the sensor readings are not taken at consistent time intervals, or if the intervals are too large, certain rapid changes in hydrodynamic behavior might be missed.

6) Environmental Factors:
   Temperature Variation: Changes in water temperature during the experiment can affect the density and viscosity of the water, leading to inconsistent readings
7) Instrument Calibration:
   Sensor Calibration: Sensors might not have been calibrated correctly or might require frequent recalibrations. Using uncalibrated sensors can introduce significant errors
8) Physical Constraints:
   a) Boundary Effects: If the flume is not large enough, the waves can reflect off the walls and interfere with the readings.
   b) Vibration: External vibrations (from nearby machinery or even natural sources) can disturb the water in the flume and influence the readings.
9) Data Processing Errors:
   a) Interpolation of Missing Data: Given the inconsistent data with null values, there might be a need to interpolate or guess the values. This can introduce errors.
   b) Temporal Resolution: If the sensor readings are not taken at consistent time intervals, or if the intervals are too large, certain rapid changes in hydrodynamic behavior might be missed.
10) External Forces and Interactions:
   a) Currents and Turbulence: Even if the flume aims to generate consistent waves, there might be unintended currents or turbulence affecting the model.
   b) Biofouling: Over time, microorganisms or small aquatic creatures might attach to the model, affecting its hydrodynamic behavior.

Results

In our pursuit to understand the response of the Spar platform model to wave-induced loads, our project has made significant strides. Acknowledging the challenge in obtaining optimal ballast, we innovatively integrated a steel plate as a solution. This adaptation ensured the attainment of the desired ballast configuration for our model, proving effective during subsequent testing. Conducting hydrostatic and hydrodynamic analyses, we delved deeper into the behavior of the model. Within the hydrostatic analysis, calculations of the damped natural frequency for both moored and unmoored conditions yielded insightful results. For the unmoored configuration, the damped natural frequency was measured at 0.842Hz with a damping coefficient of 74.557 kg/s. Conversely, the moored condition exhibited an undamped natural frequency of 0.992Hz, accompanied by a damping coefficient of 63.22kg/s. These findings hold paramount importance in comprehending the Spar platform's response under different environmental conditions. The natural frequencies and damping coefficients serve as pivotal indicators, shedding light on the model's behavior when exposed to wave-induced forces. Our innovative use of the steel plate for ballast has proven effective, enhancing the model's accuracy during testing.

The hydrodynamic analysis of the model response showed the variation in response of model to different wave conditions, particularly wave height and time period. We found that the pitch increases with wave height, while the heave acceleration was dependent on the wave period and model natural frequency. Additionally, we also tested in extreme conditions and found the pitch and heave acceleration of the model to increase proportionately with a large increase in the wave height.

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