Sustainability in Ship Design Conference 2022

On-board Ocean Wave Energy Harvesting for Supplemental Powering of Small Autonomous Vessel

Aspa Pacome Kokro
PhD Candidate
Ocean Engineering
Davidson Laboratory

Academic Advisors

- Dr. Muhammad Hajj
- Dr. Raju Datla

Content

- Introduction
- Literature Review
- Theoretical Background
- Methodology
- Preliminary Results
- Further Works
- Conclusion

Introduction

- In the US, many offshore projects for Ocean Energy harvesting are under development and/or implemented to power the blue economy.

- Small autonomous boats monitor blue economy activities in remote offshore areas with limited battery capacity to achieve sufficient autonomy. A wide range and sufficient autonomy require large battery capacity or a battery charger on board (Han, 2022).

- This research aims to improve the overall energy efficiency of small boats operating in remote areas for a long duration by harvesting ocean wave energy. In this study, feasible, practical, and affordable method is developed for supplement power supply.

Literature Review

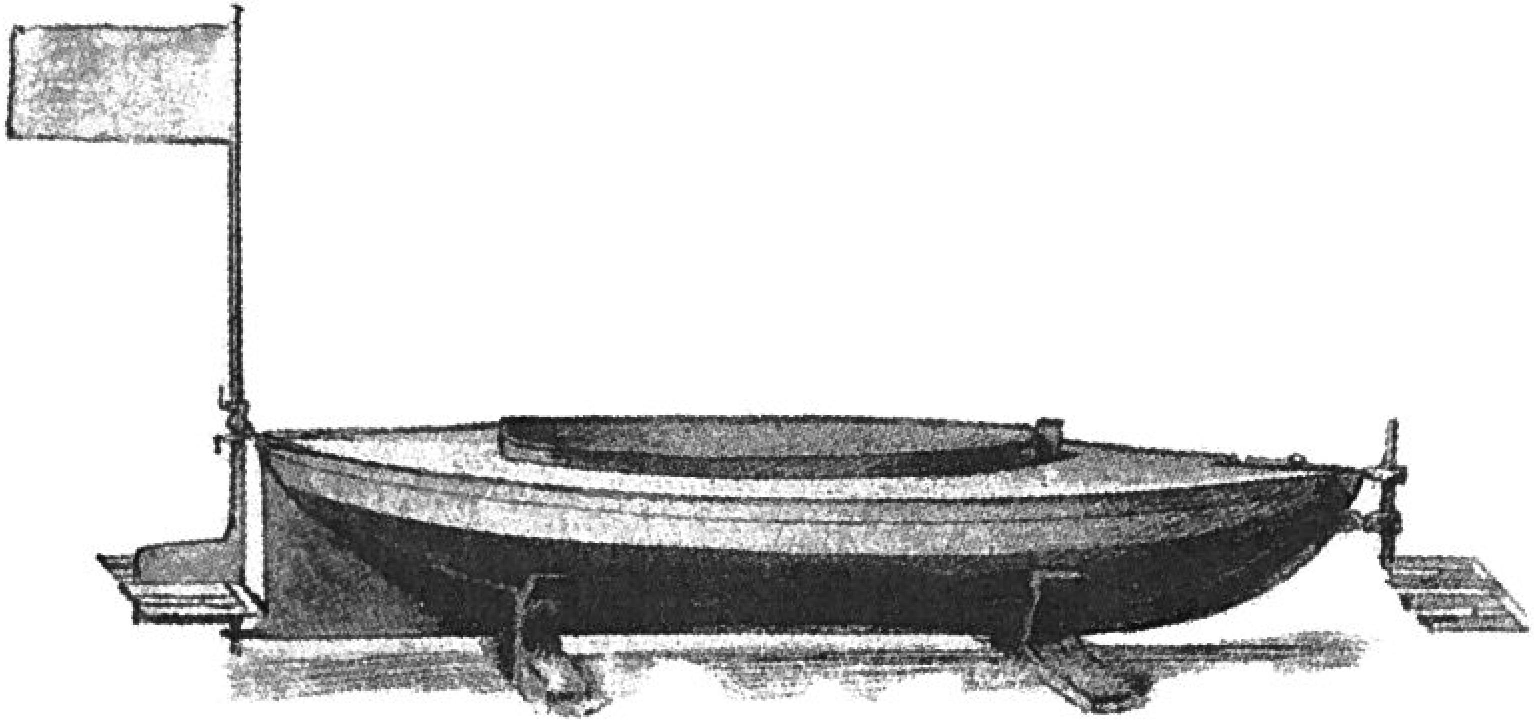


Fig. 1: The “AutoNaut”, Herman Linden, Italy, 1895.

Lehmann (2017)

- Ocean wave energy is more predictable than wind and solar.
- In the U.S the total wave power is about 1594 - 2640 TWh/year.
- Most potential wave energy is located outer the continental shelf.

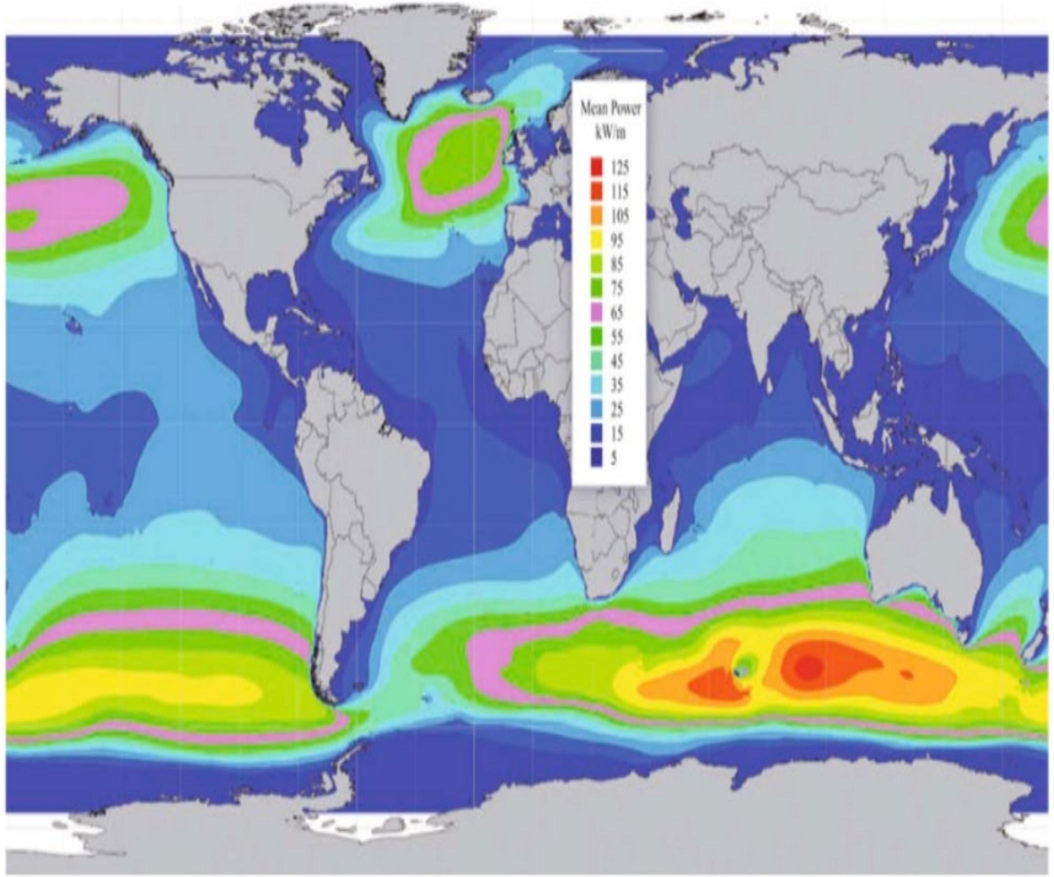


Fig. 2: Ocean Wave energy potential in the world.

Lehmann (2017)

- Many Wave Energy Converter (WEC) projects are in research phase or technological development. DOE targets to produce 12 to 14 cents/KWh from WEC by 2030.

- Offshore floating projects are predominant.

- Main objectives are experimental data collection and dissemination, improvement in monitoring technologies and collaboration (DOE review, 2015).

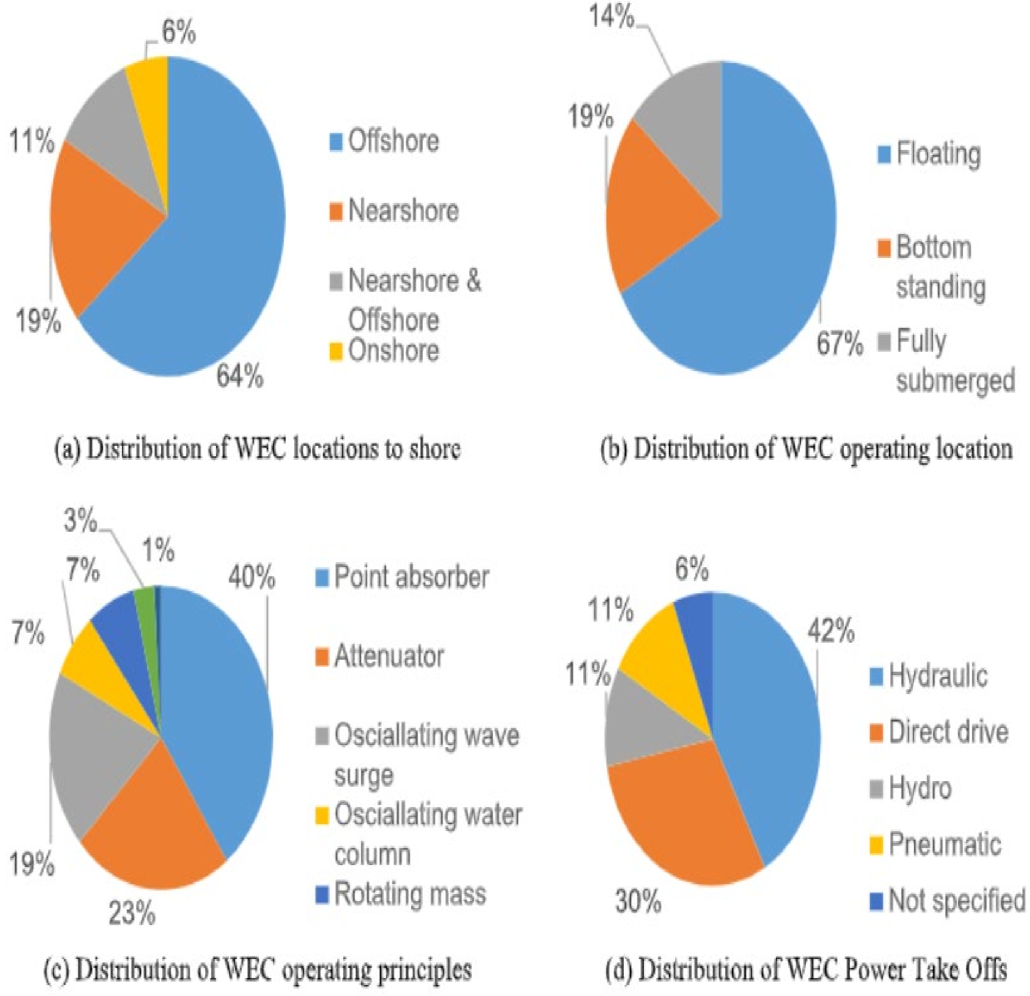


Fig. 3: Global WEC and working principles and locations classification.

Peter (2016)

In the design of a Wave Energy Converter (WEC), three main parts are considered:

- **The hydrodynamic system**
- **The Power Take-Off system**
- **The Control System**

Babarit (2015)

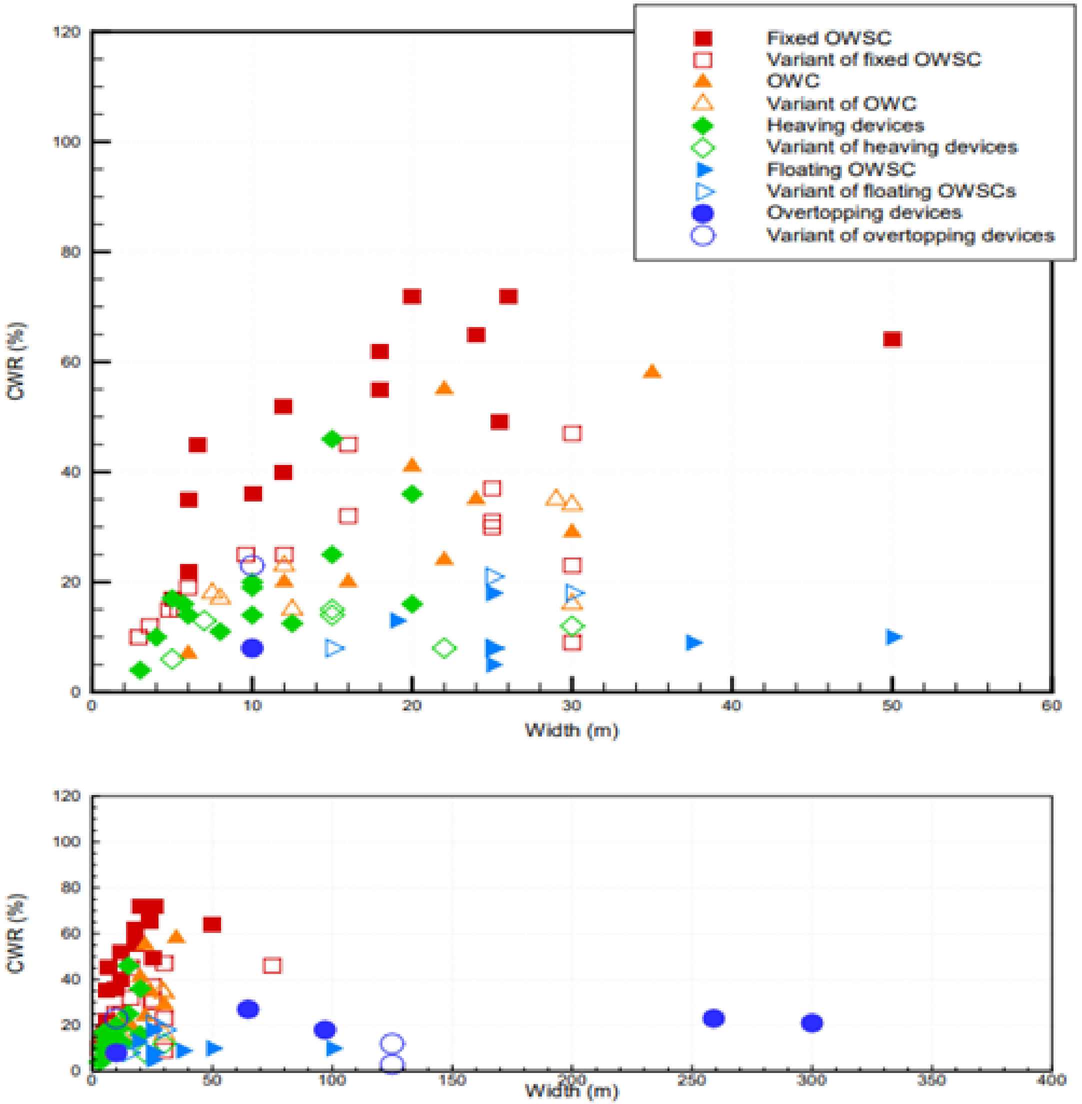


Fig. 4: CWR as a function of the WEC characteristic dimension and the WEC category.

The overall efficiency of the WEC (Wave to Wire) is given by the energy Capture Width Ratio (CWR) :

$$CWR = P / (BJ),$$

P = Absorbed Power [kW]

J = Wave Energy Flux, E.Cg [kW/m]

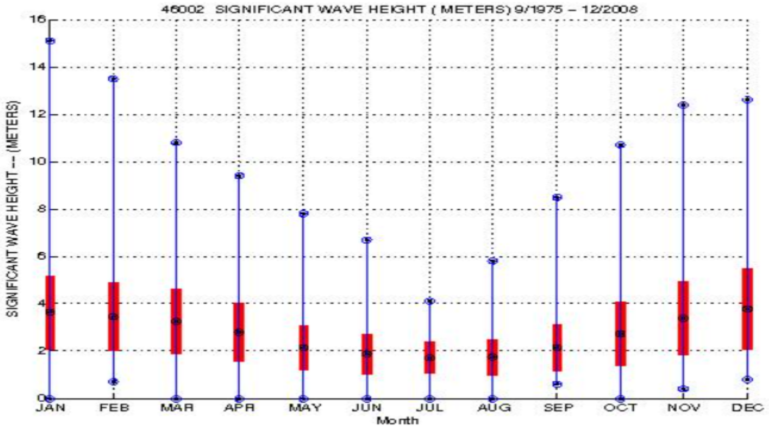
B = Characteristic dimension [m]

Han (2017)

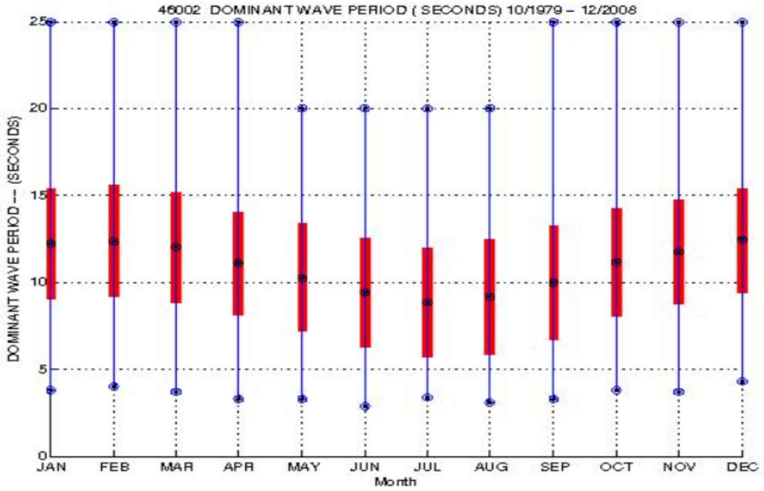
- Large wave heights have greater energy potential.
- Annual wave parameters for North Pacific Ocean:

  Hs = 1.5 m – 5 m; Tp= 6 s – 15 s.

- Wave energy devices need to be stable.



Station 46002 - Climatic Summary Plots for significant wave heigh



Station 46002 - Climatic Summary Plots for dominant wave period

Fig. 5: Annual significant Wave height and dominant period, (source: https://www.ndbc.noaa.gov/).

Xie (2015)

- High cost of batteries, limited range due to auxiliary consumption (air conditioner, electronics), long charging time.

- Vehicle suspension system against road roughness.

- Energy harvesting from suspension vehicle: a piezoelectric bar harvester to absorb energy from vibrations and motions of the suspension system.

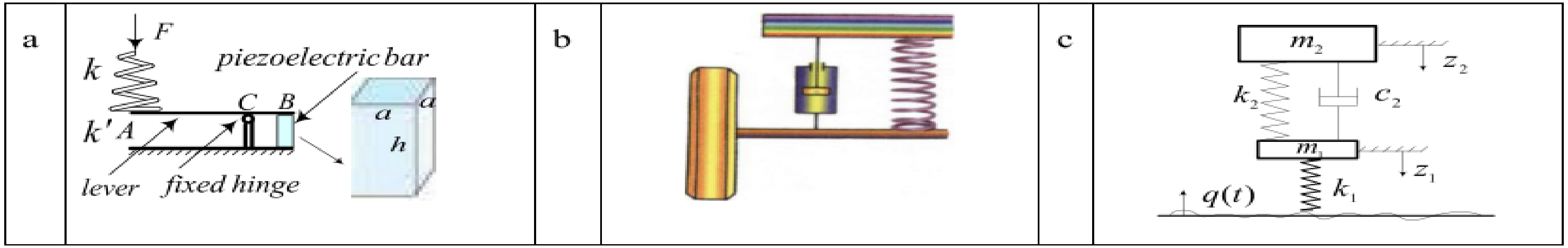


Fig. 6: Typical quarter car model suspension with a wheel, spring and damper(b) and (c).
(a) The bar transducer serves as damper.

- Suspension technology in ship application can be done with :
  - Cushions
  - Hydraulic cylinder
  - Suspension springs.

Takahashi (1986)

- Hydraulic suspension: results showed that measured pitching motion of the cabin was less than 1/8 of that of the main hull. The roll motion was also decreased.
- Energy was dissipated in heat.

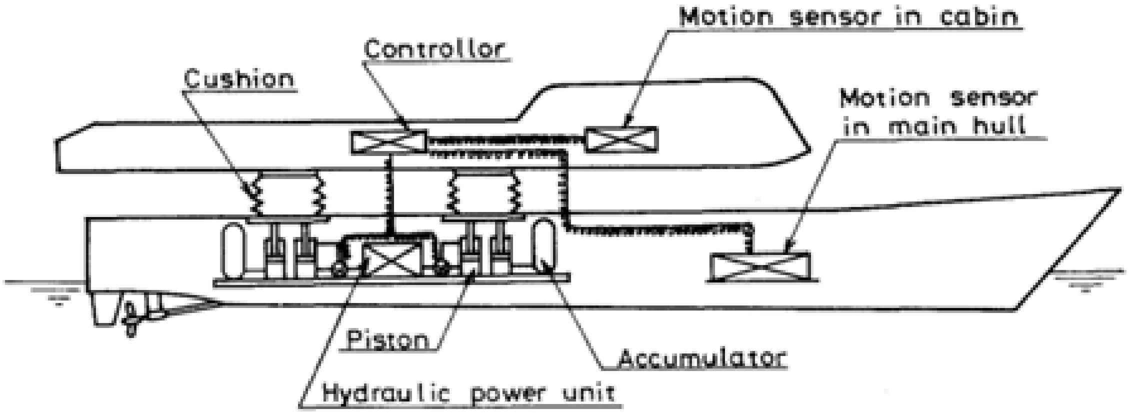


Fig. 7: Principle of “Hi-Stable Cabin”.

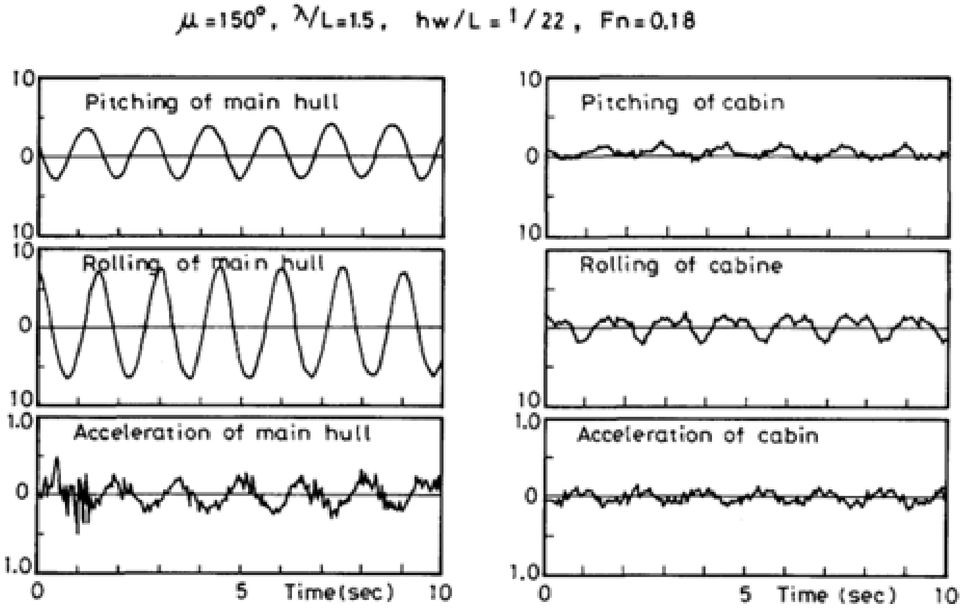


Fig. 8: Measured time history of motion in oblique waves

Han (2019)

- Motions reduction and wave energy harvesting were achieved simultaneously with set of suspensions and semi control at certain wave conditions.

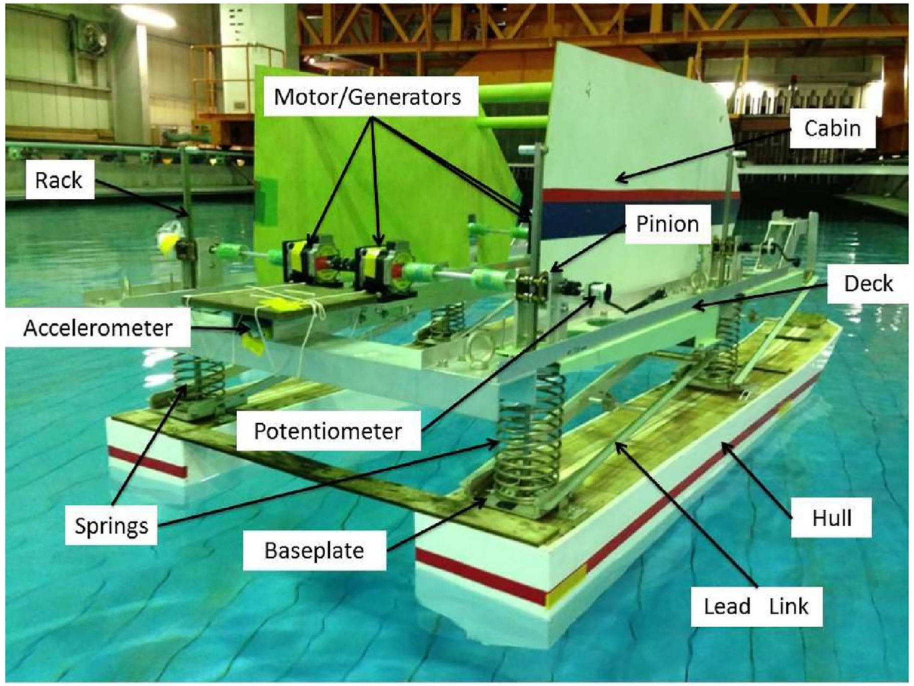


Fig. 9: Planing hull catamaran MSC-4

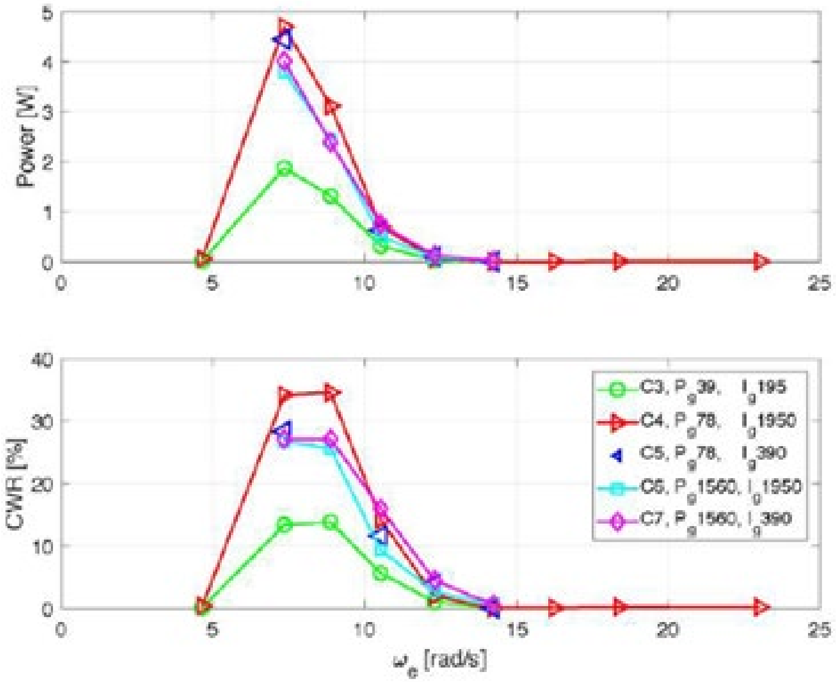
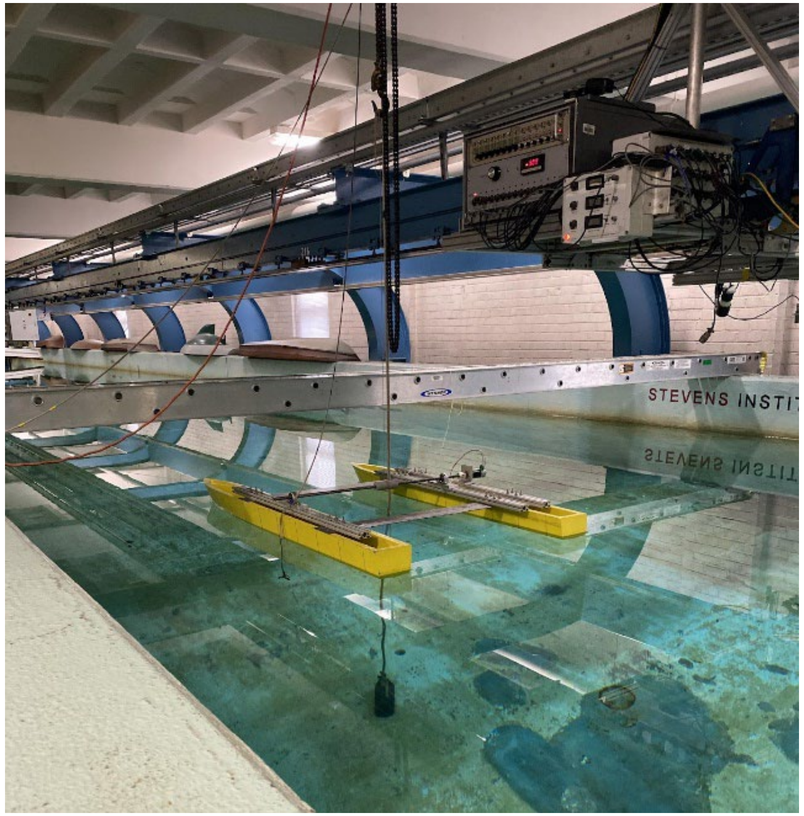


Fig. 10: Wave energy harvesting at Fn = 0.39

Tyler Brunquell (2022)

- Use of Heave Plate Damper



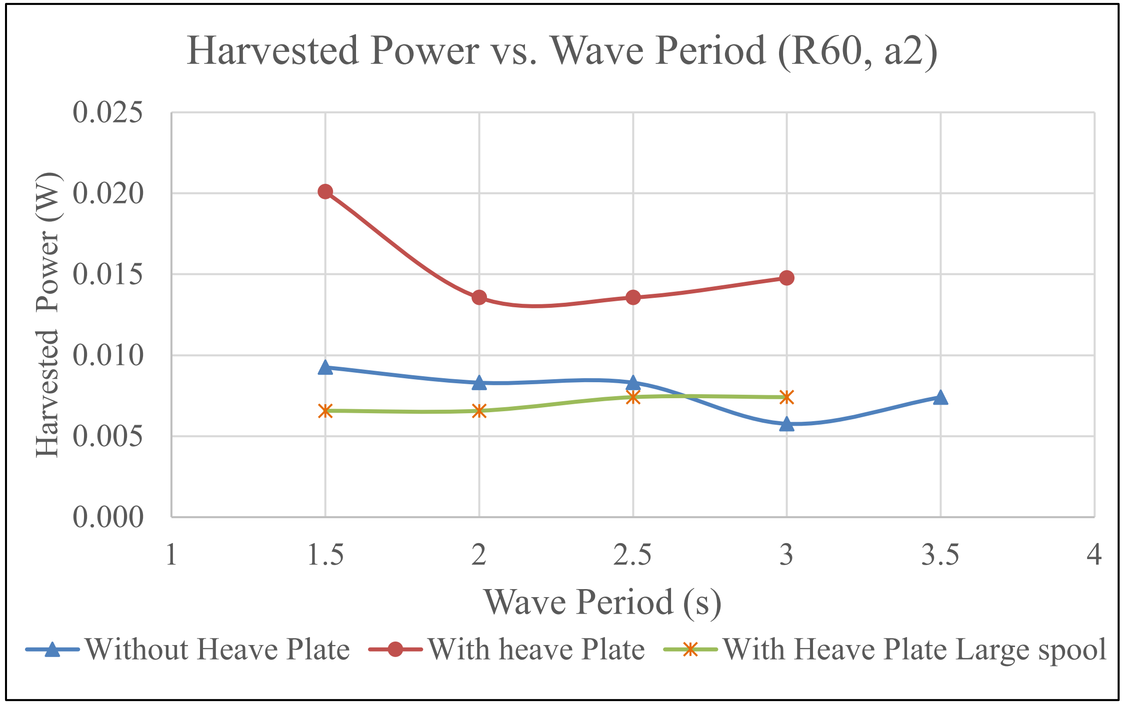


Fig. 11: Senior Design 2022, "Ocean Wave Power Autonomous Robot".

Kokro and Raju (2020)

- Performances of High-Speed Round Bilge (HSRB) Hull from NPL series (Bailey, 1976) are convenient for operations in semi displacement regime.

Series	NPL - HSRB
L/B	6.25
B/T	2.9
CB	0.397
CP	0.693
CX	0.573
CW	0.753
½ IE	11.0 degrees
Deadrise at transom	12 degrees
LCB (%) aft Midship	6.4
AT/AX	0.52
BT/BX	0.815

Table 1: Main characteristics of the hull.

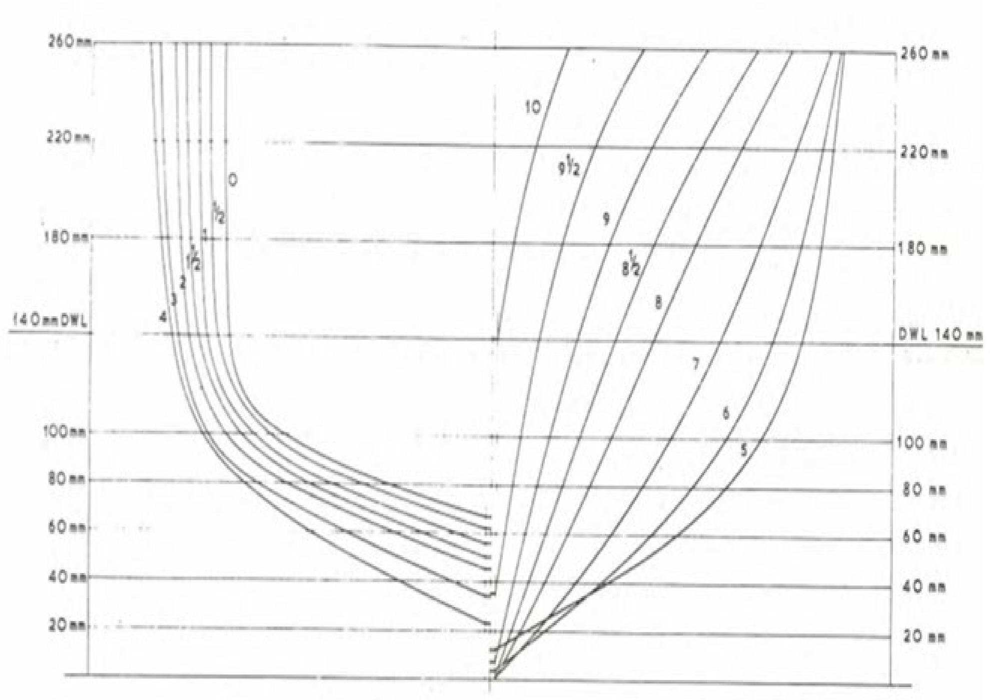


Fig. 12: NPL – HSRB parent hull Body Plan.

Masuda (1985)

“ Necessity is the mother of invention”

- Ocean Wave energy is a valuable source of energy.
- Successful innovation = technical feasibility + sustainability or economically viable + usefulness for the community.

Research Objective

- Design of “DavLab” Suspension Ship, a semi-displacement catamaran with suspension springs to form a top referenced heaving absorber.

- Optimization of hull-form for resistance and power take-off.

- Design of energy storage system and battery management system for 24/7 monitoring of blue economy activities.

Theoretical Background

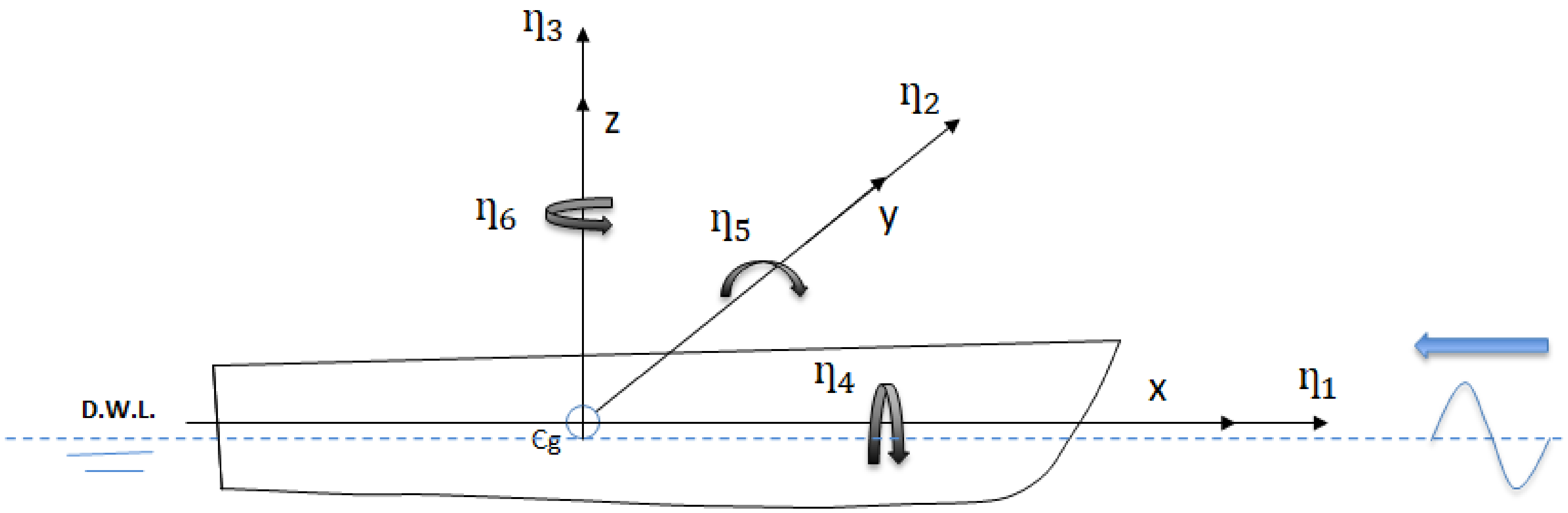


Fig. 13: Schematic of individual hull six-degree motion.

Potential Flow – Wave Forcing on the body

$$\varnothing = \varnothing_I + \varnothing_D + \varnothing_R$$

Wave potential = Incident + Diffracted + Radiated

- L << λ, the incident wave field is not affected by the ship (Froude-Krylov approximation).
- Characteristic length is significant enough, the wave field near the body is affected even when the ship is stationary.

Equations of motion

- Rigid body axes are moving along with the ship, represented by gxyz for the hulls and GXYZ for the cabin, with origin at their respective center of gravity, cg and CG.

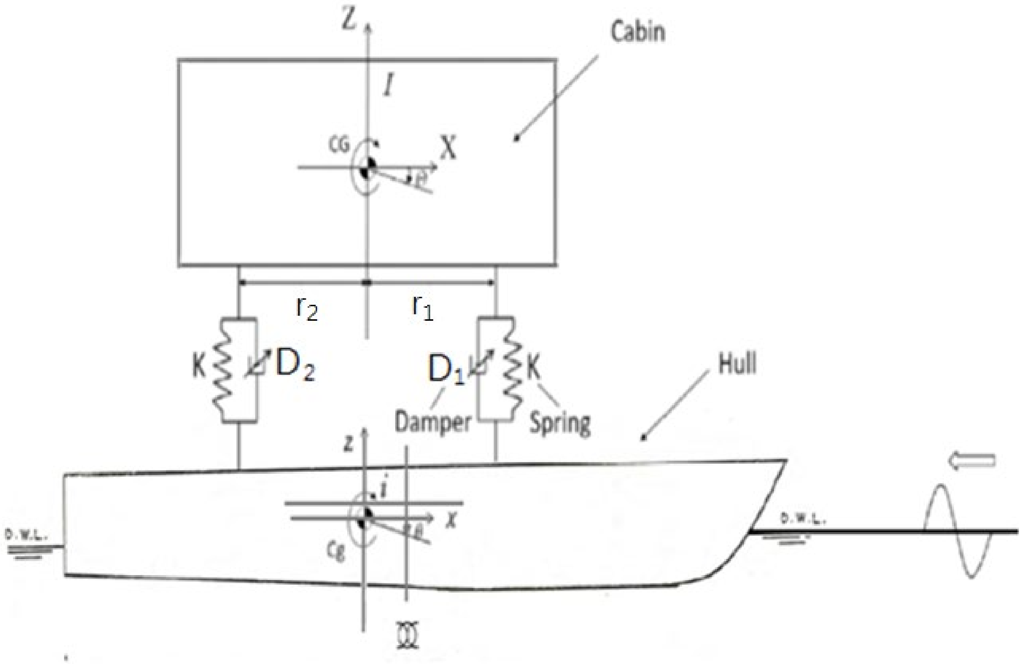


Fig. 14: Dynamic representation of DavLab catamaran.

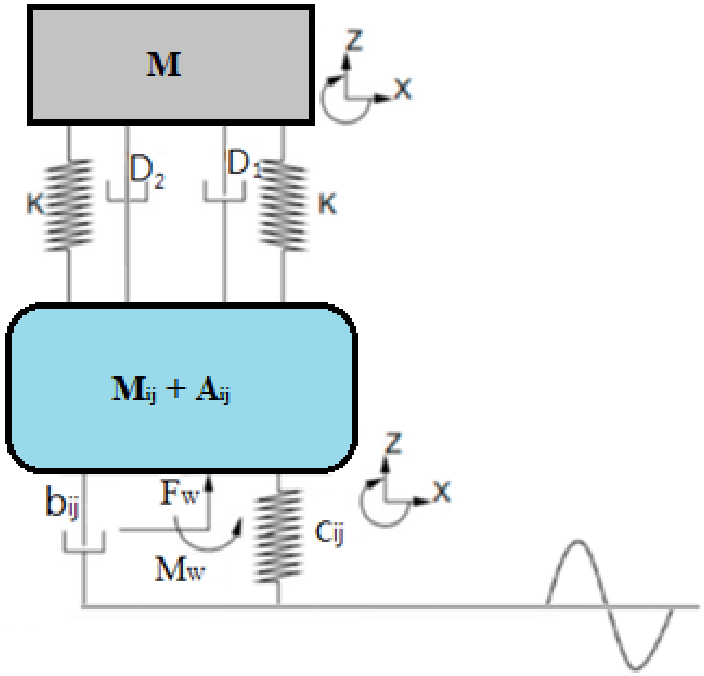


Fig. 15: Body diagram of suspended catamaran system.

- Equations for the six coupled linear steady state sinusoidal motions are given by (Faltinsen 2005):

$$\sum_{i,k=1}^{6}[(M_{ik} + A_{ik})\,\frac{d^2\eta_k}{dt^2} + B_{ik}\,\frac{d\eta_k}{dt} + C_{ik}\eta_k] = F_i e^{jw_e t}.$$

- If surge, sway, roll, and yaw for the hulls and the cabin are constraint, only 4 DOF will remain for the two systems (heave and pitch).

- Hydrodynamic coefficients are calculated for different frequencies then nondimensional added mass (A_{ij}) and damping (B_{ij}) are given as follows:

- $a_{33} = A_{33}/(\Delta)$; $a_{35} = A_{35}/(\Delta L)$; $a_{53} = A_{53}/(\Delta L)$; $a_{55} = A_{55}/(\Delta L^2)$

- $b_{33} = B_{33}/(\Delta/\sqrt{L/g})$; $b_{55} = B_{55}/(\Delta L^2/\sqrt{L/g})$; $b_{35} = B_{35}/(\Delta L/\sqrt{L/g})$; $b_{53} = B_{53}/(\Delta L/\sqrt{L/g})$

- Damping coefficients are also nondimensionalized to find the damping ratio (ζ):

- $\zeta_i = B_{ii}/B_{cr}$

- $B_{cr} = 2\sqrt{C_{ik}\Delta}$

Motion in still water

- ***Undamped motion***

The heaving motion is described by the equation:

$$\frac{d^2\eta_3}{dt^2} + \frac{C_{33}}{\Delta}\,\eta_3 = 0$$

From which the natural period is given $T_z = 2\pi\sqrt{\frac{(\Delta + A_{33})}{C_{33}}}$.

For the individual hull, the pitch motion is governed by the equation:

$$\frac{d^2\eta_5}{dt^2} + \left(\frac{g\overline{GM_L}}{C_{55}^2}\right)\eta_5 = 0$$

The period is $T_\theta = 2\pi\frac{C_{55}}{\sqrt{gGM_L}}$, for very small pitching angles.

- ***Damped motion***

The standard equation for a damped system is:

$$\frac{d^2\eta_k}{dt^2} + 2\zeta_k w_{nk}\frac{d\eta_k}{dt} + w_{nk}^2\eta_k = 0,$$

where w_{nk} and ζ_k are natural undamped frequency and damping ratio in k -direction.

- The natural period in heave becomes: $T_z = \dfrac{2\pi}{w_{n3}\sqrt{1-\zeta_3^2}}$
- Pitch natural period is written $T_\theta = \dfrac{2\pi}{w_{n5}\sqrt{1-\zeta_5^2}}$
- An empirical approximation of natural period in heave and pitch is $T_z = T_\theta = 1.5\sqrt{T}$, where T is the draft in feet.

Ocean Wave Energy

- Wave Power encounter:

  - Regular waves:

$$\overline{P_{wv}^*} = \frac{g^2\rho}{32\pi} \cdot H^2 T - \frac{1}{16}\rho g H^2 v \cdot \cos\beta$$

  - Irregular waves:

$$\overline{P_{wv}^*} = \frac{g^2\rho}{64\pi} \cdot H^2 T - \frac{1}{16}\rho g H^2 v \cdot \cos\beta$$

- Harvested Energy:

$$E_{hrv} = \sum_{i=1}^{4} \frac{1}{n} \int_{t_0}^{t_0+nT} V_i(t) \cdot I_i(t) - R_{cr} \cdot I_i^2(t) dt$$

- Efficiency:

$$\text{CWR} = \frac{\overline{P_{hrv}}}{2b \cdot \overline{P_{wv}^*}} \cdot 100\%$$

• Wave Energy Harvesting Mode

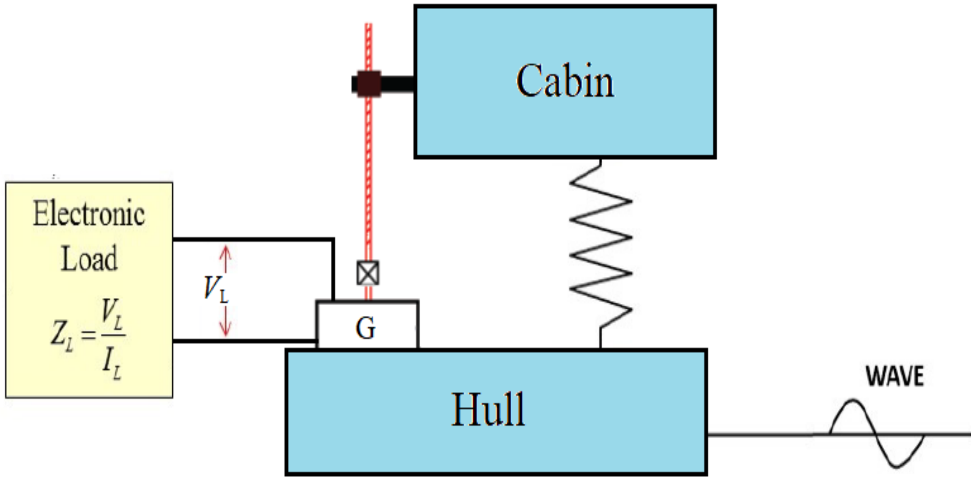


Fig. 16: Diagram of PTO principle.

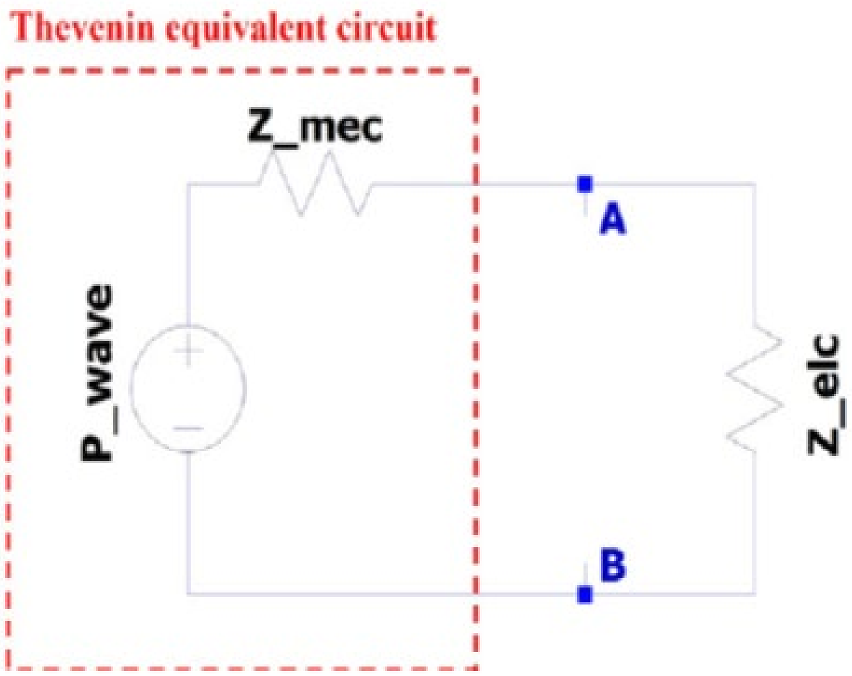


Fig. 17: Thevenin equivalent circuit of the PTO.

Block Diagram of ocean wave powered electric ship

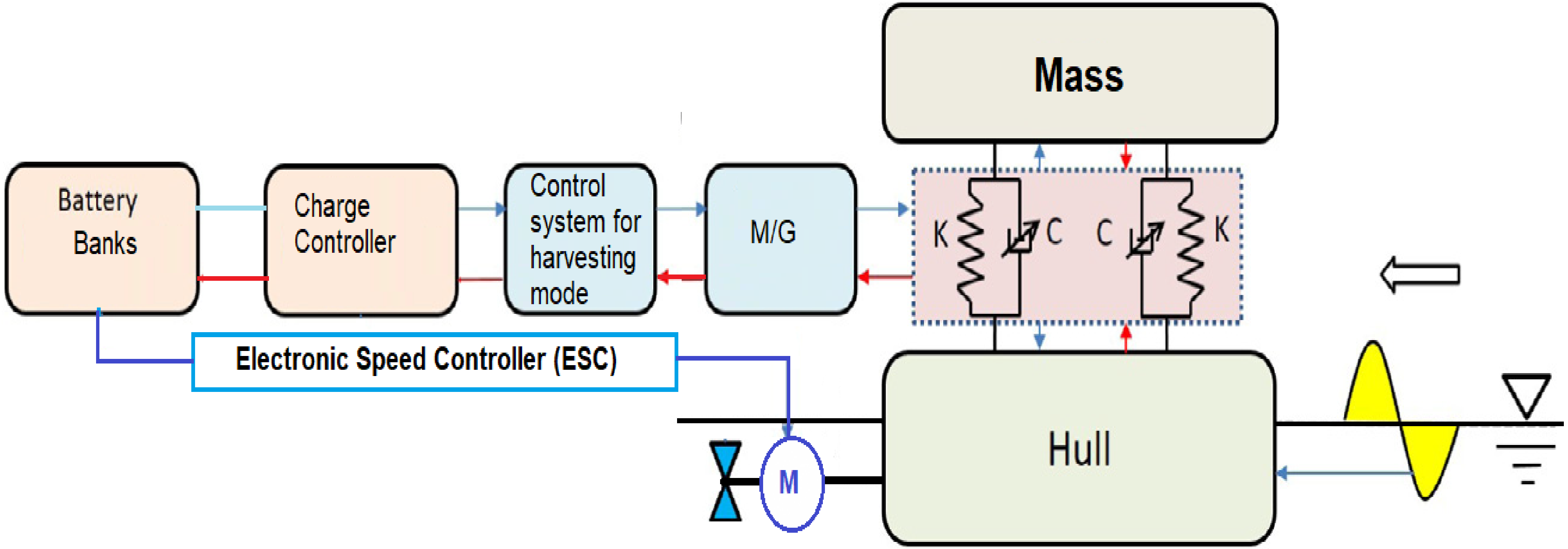


Fig. 18: Working Principle of “DavLab” Catamaran.

Methodology

Conceptual Design (CAD)

- The DavLab suspension Catamaran consists of twin hulls High-Speed Displacement Round Bilge from NPL separated by a distance equivalent to the third of the length of the design waterline; four (04) compression springs, two on each hull symmetrically front and aft of the cg. The PTO is composed of a ball screw system connected/coupled to a generator via gearbox and bearing.

- The suspensions help control and reduce the motions.

- For maximum wave energy absorption, the optimal condition is selected so that the natural undamped oscillation of the system would match the frequency of dominant waves (resonance rule), (Falcao, 2010).

Resistance Prediction (Michlet 9.33).

- Michlet is a research code developed by Tuck et al (2008) to perform a triple numerical integration of the ship's resulting inviscid drag force. The program computes Michell's integral for wave resistance (Michell, 1898) and combines with the standard ITTC-1957 line for viscous frictional resistance to find the ship total drag of ship in steady motion.

- During preliminary design, Michlet helps the Naval Architect to investigate some aspects of the ship hydrodynamics such as resistance, wave elevation patterns and bottom pressure signature for monohulls or multihulls.

- The program works best for slender bodies (L/B >5).

Hull Motion Prediction: Seakeeping Prediction Program (SPP)

- SPP is a probabilistic analysis program based on 2D-strip theory. This program computes the motion responses in heave, pitch, and roll and calculates natural frequencies and periods of the hull in specified sea spectrum, ship speed, and ship heading relative to the waves.

- SPP program was used to calculate the motion responses in heave and pitch of individual hull at model speed in head seas.

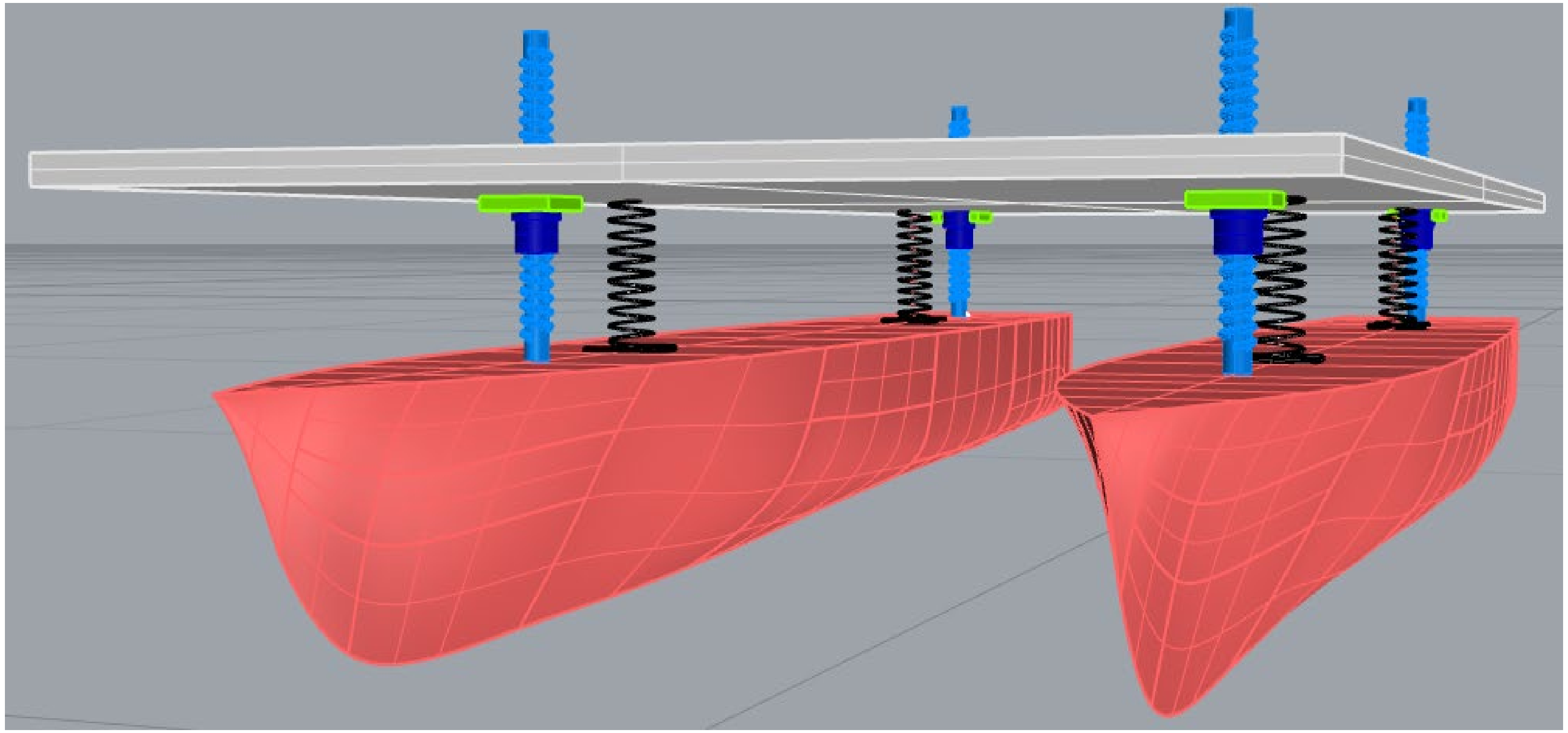
- During calculations, interaction between hulls was not considered.

Hydrodynamic Characteristics: CFD Method

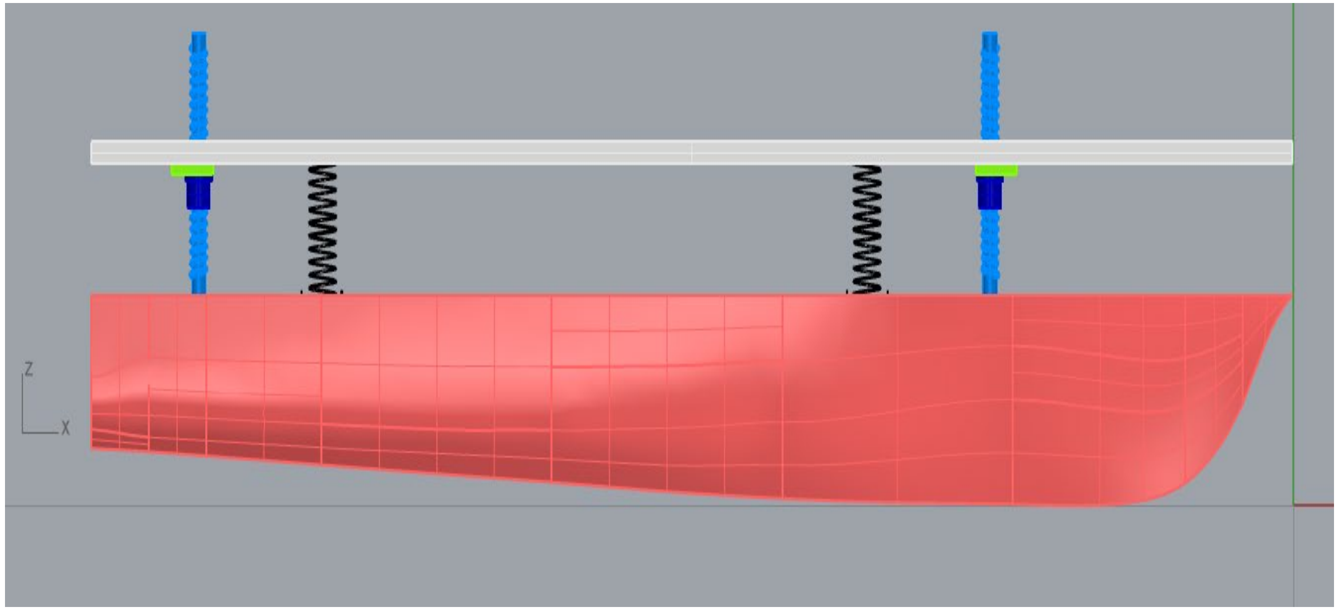
- The hydrodynamic coefficients A_{ik} and B_{ik} were calculated with extensive computation using a source distribution method in CFD. Forward speed correction was considered.

- Complex exciting forces and moments can be determined to solve equations of motion.

Preliminary Results



Design of the Catamaran



Figs. 19: Model design of “DavLab” Catamaran in CAD.

Model	DavLab Hull
Scale	3
Displacement	2.07 Kg
Length of Waterline	0.85 m
Beam	0.15 m
Draft	0.05 m
CB	0.397
CP	0.693
CX	0.573
Natural Period	0.59

Table 2: Hull main parameters

Power Prediction

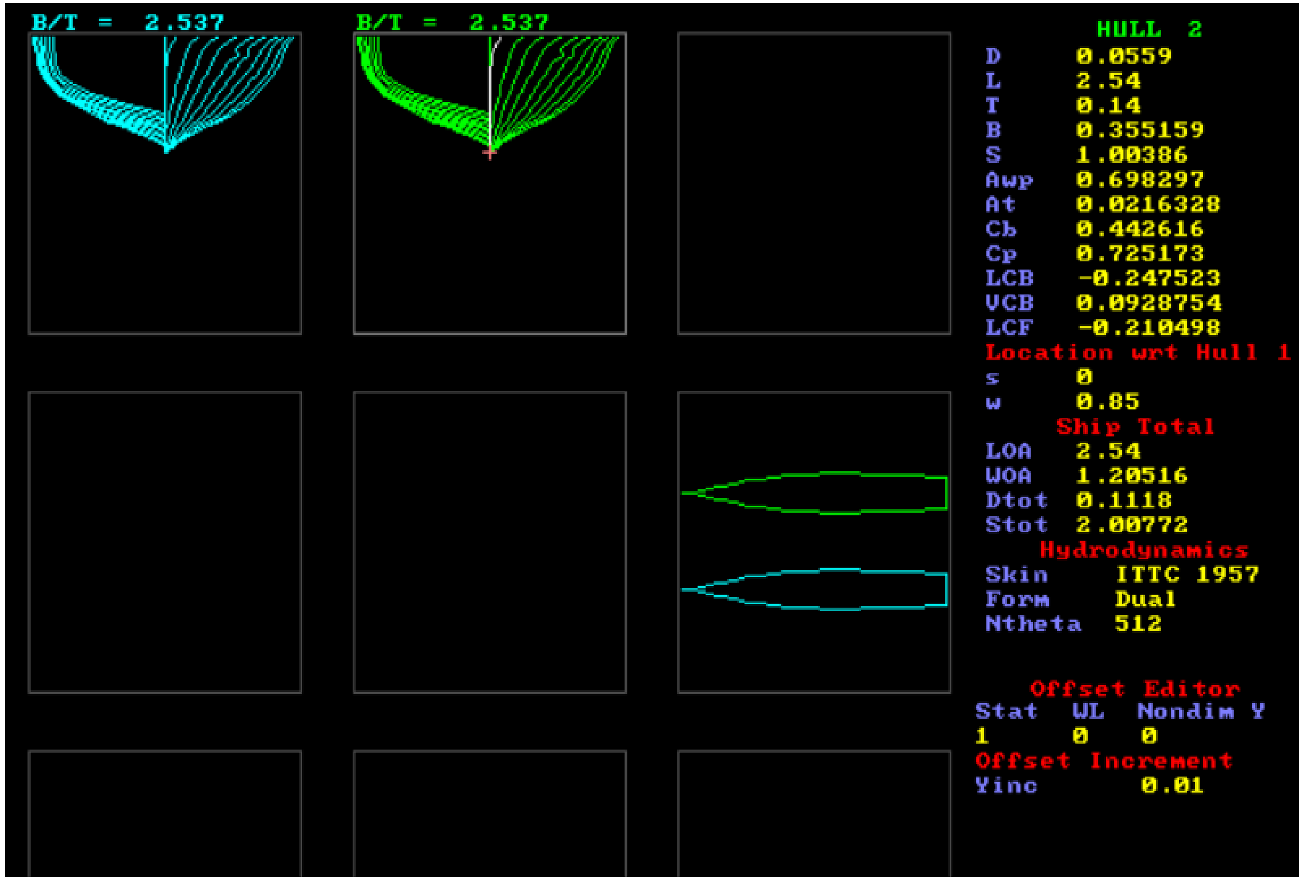


Fig. 20: Michlet program interface.

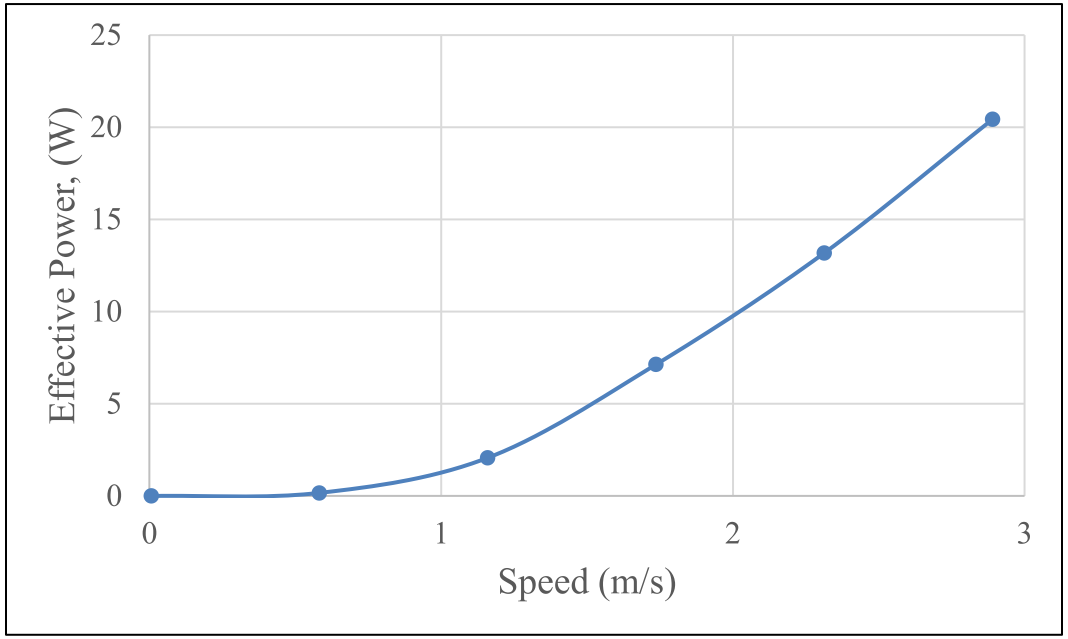
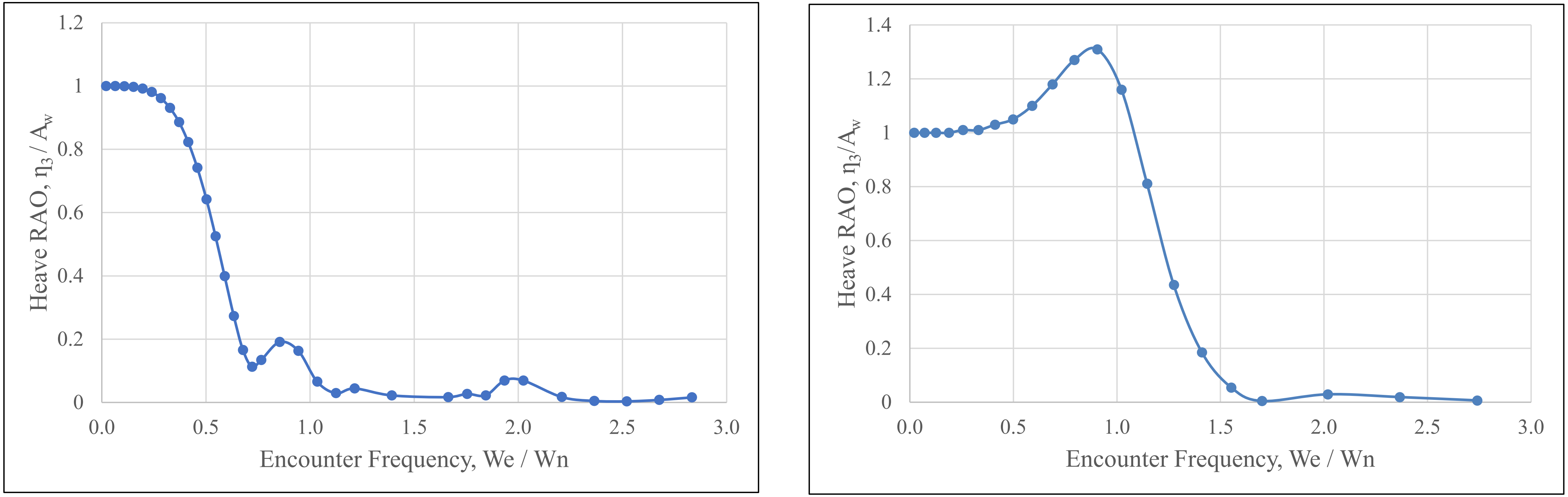


Fig. 21: Power curve at model scale.

The required power at model speed V = 1.15 m/s (F_n = 0.4):

- EP = 2.1 W
- Overall efficiency, QPC = 0.6
- Power required: 3.5 W

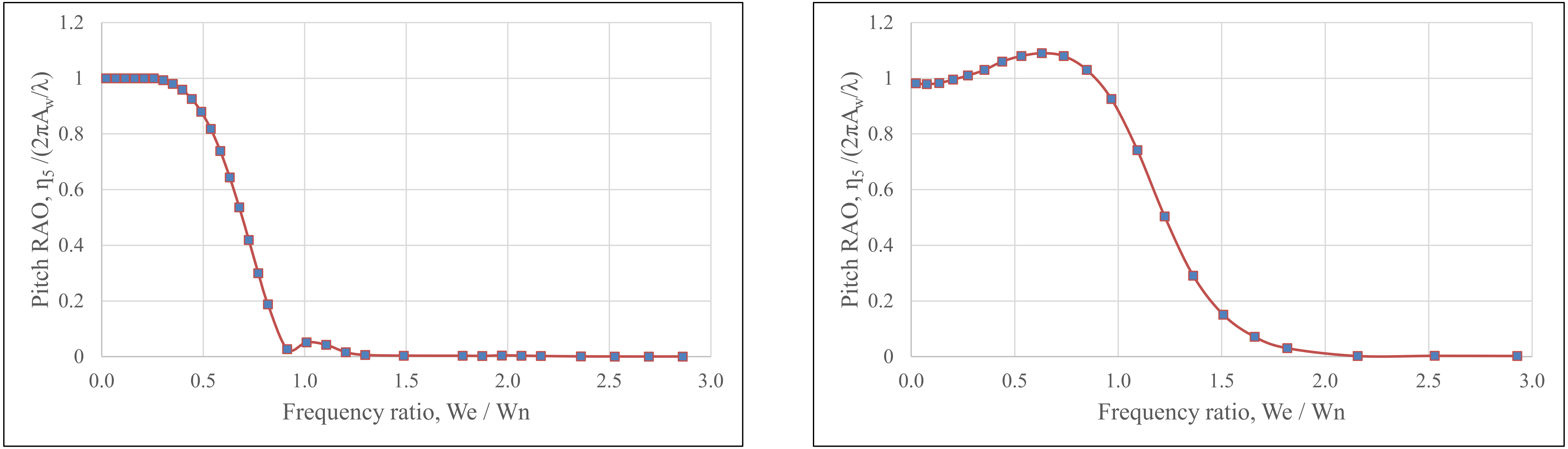
Motion Responses for individual hull (SPP)



a) V = 0 m/s

b) V = 1.15 m/s

Fig. 22: Heave RAO in head seas at zero forward speed (a) and $F_n = 0.4$ (b).



a) V = 0 m/s

b) V = 1.15 m/s

Fig. 23: Pitch response in head seas at zero forward speed and $F_n = 0.4$.

Prediction of Hydrodynamic Coefficients in Head Seas

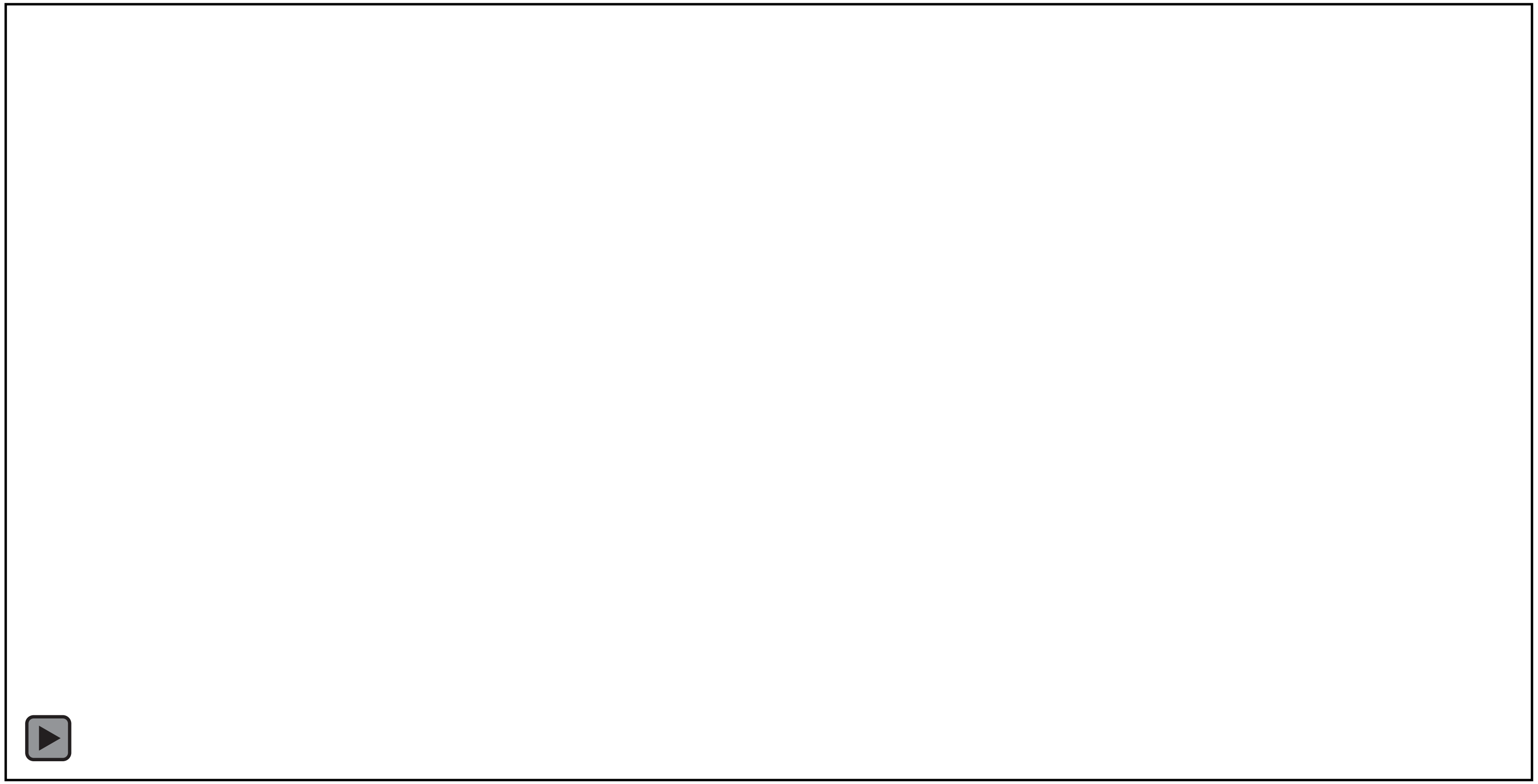


Fig. 24: Simulation of individual Hull in CFD

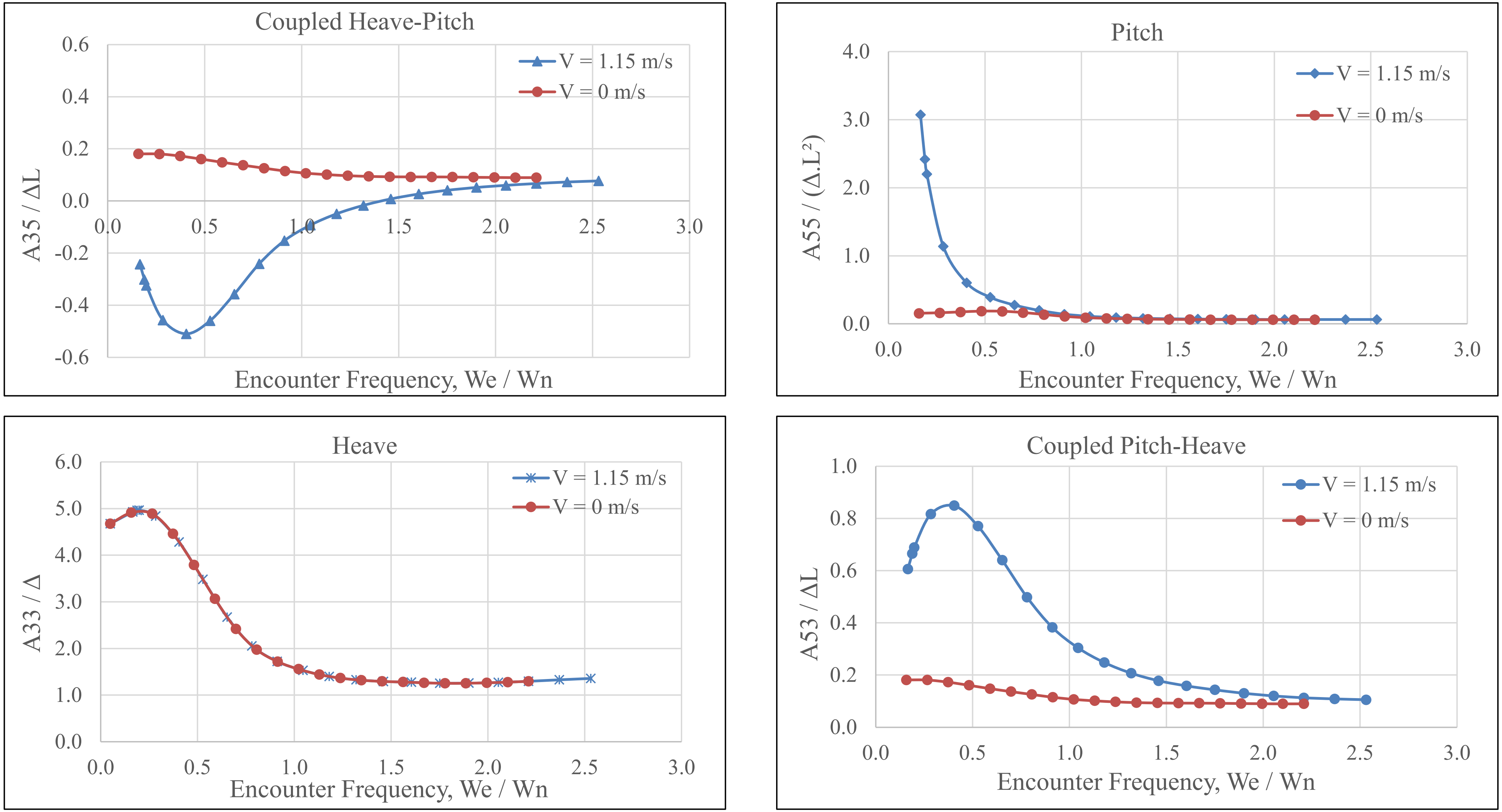
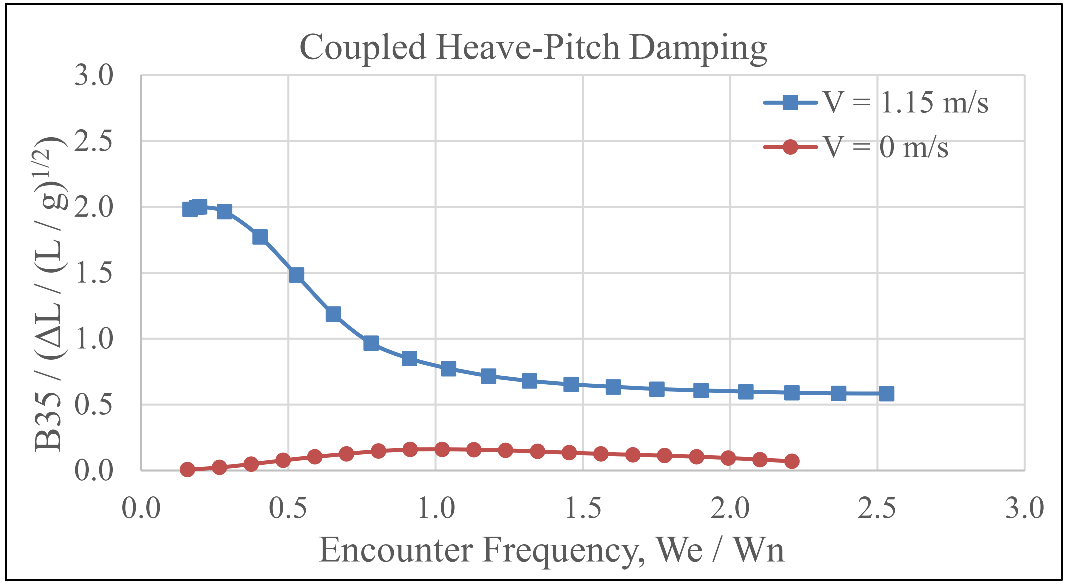
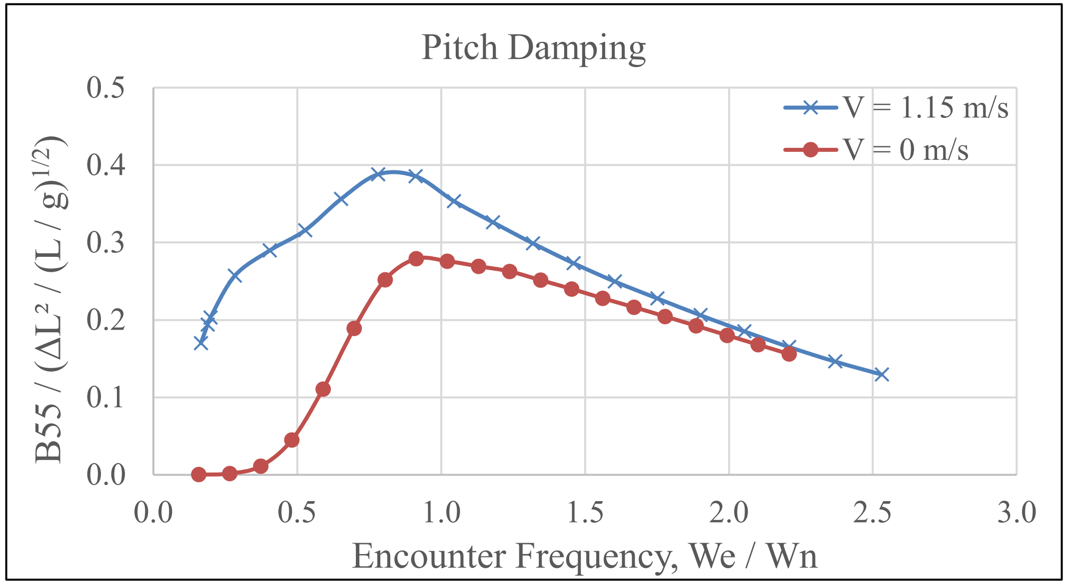
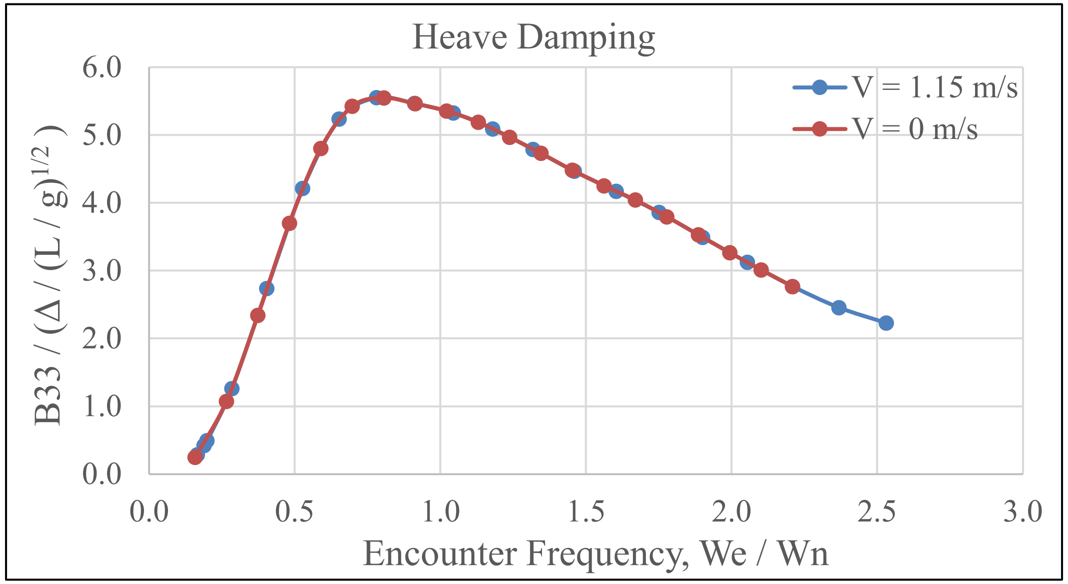
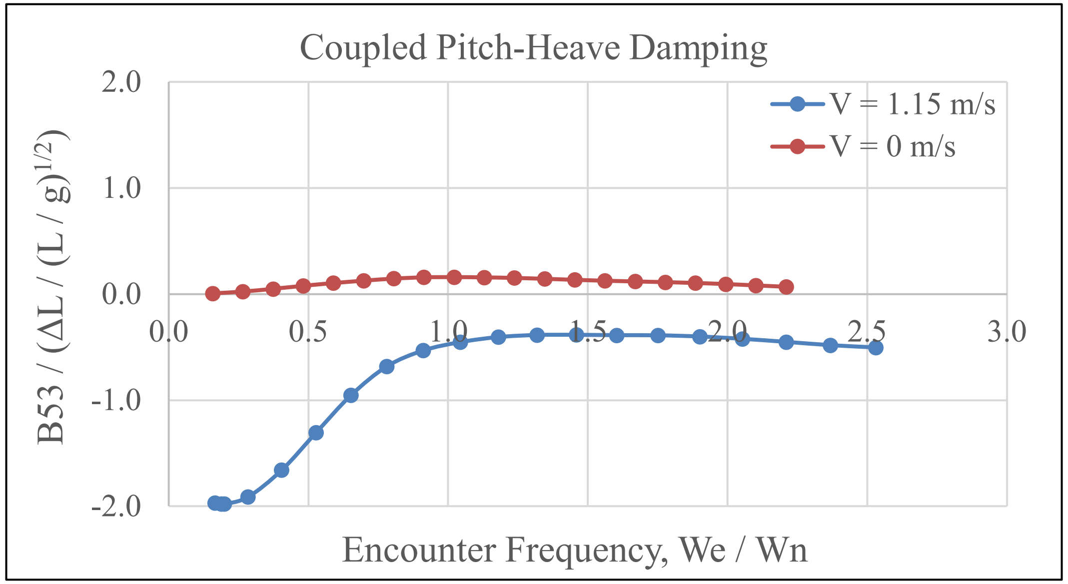


Fig. 25: Nondimensional Added Mass at Zero Forward Speed and $F_n = 0.4$.









Figs. 27: Nondimensional damping coefficients at zero forward speed and $F_n = 0.4$.

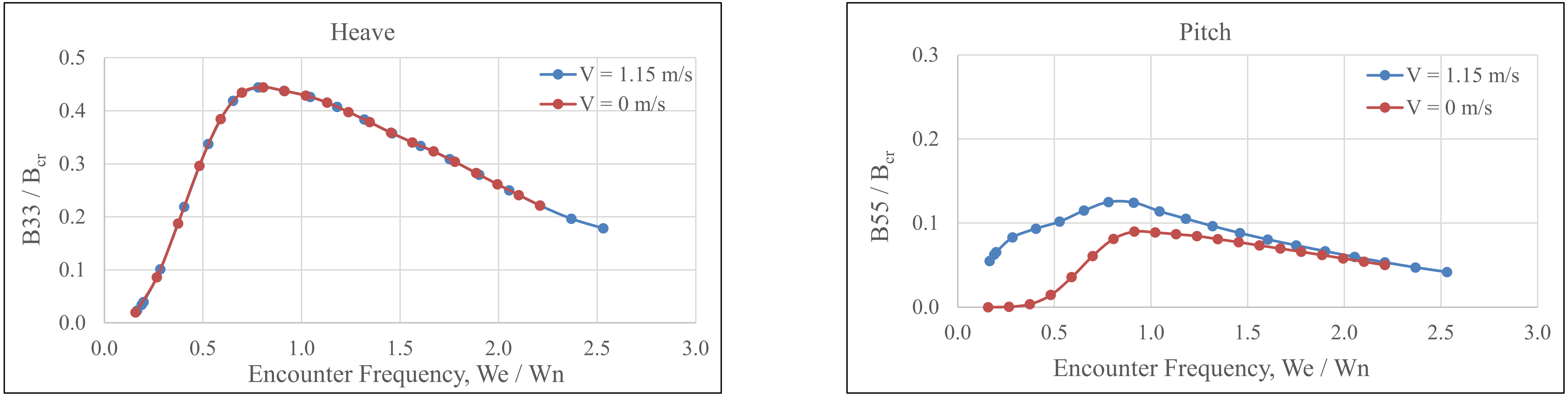


Fig. 29: Damping ratio (ζ) in heave and pitch at zero forward speed and F_n= 0.4.

- Close to the natural frequency heave RAO presents an amplification factor greater than 1 but less than 1.5.

- Forward speed influences the hydrodynamic coefficients.

- An alteration of the shape of the hull (L, B, D, or A33) would modify the vessel's dynamic amplification factor and increase the heave response around the natural frequency for an optimization of the relative displacement between the hull and the superstructure.

Wave Run Prediction

- Model Heading: β = 180 degrees
- Model speed: V1 = 1.15 m/s; V2 = 0 m/s
- Energy Capture Ratio: CWR = 0.4
- Required Power: P = 3.5 W

Wave Period T (s)	Wave Height H (m)	Harvested Power V = 0m/s, (W)	Harvested Power V =1.15 m/s (W)
1.5	0.2	1.92	**3.80**
1.5	0.25	2.99	**5.95**
1.5	0.3	**4.31**	**8.56**
2	0.2	2.55	**4.44**
2	0.3	**5.75**	**10**
2	0.4	**10.22**	**17.77**
2.5	0.2	3.19	**5.08**
2.5	0.3	**7.18**	**11.43**
2.5	0.4	**12.77**	**20.33**
3	0.2	3.83	**5.72**
3	0.3	**8.62**	**12.87**

Table 3: Estimation of harvested power during model testing in head seas.

Further Works

- Prediction of motions for a range of L/B ratio will be tested for optimum power take off.

- Assessment of different hull forms design to optimize resistance and energy harvesting.

- Towing Tank testing

- Other alternatives including:

  - Optimization of locations

  - Optimization of control system: transit configuration and wave energy harvesting mode (two-body system, inflatable boat design,…).

Conclusion

- “DavLab” catamaran is a small autonomous boat designed to monitor the blue economy activities 24/7. Ocean wave energy is harvested from relative displacement between hulls and cabin to supplement the power.

- In this study, prediction of motion responses of individual hull showed that the encounter frequency and hydrodynamic coefficients would influence the response amplitudes and energy harvesting could result from the combined motions in pitch and heave.

- Upon completion of preliminary studies, a model of DavLab will be tested in Davidson Laboratory towing tank#3 to extract a power of 2.5 W.

References

1. Bahrami, Hassan, and Hassan Ghassemi. 2022. "Dynamic Motions of the Cabin Mounted on the Mono-Hull Planing Boat Using Suspension System in Waves." *Polish Maritime Research* 29 (1): 13–25. https://doi.org/10.2478/pomr-2022-0002.
2. Han Jialin, Maeda Teruo, Kinoshita Takeshi, and Kitazawa Daisuke. 2015. "Towing Test and Motion Analysis of a Small Motion-Controlled Ship - Based on an Application of Skyhook Theory." *Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles*, no. June: 879–88.
3. Han, Jialin, Daisuke Kitazawa, Takeshi Kinoshita, Teruo Maeda, and Hiroshi Itakura. 2019. "Experimental Investigation on a Cabin-Suspended Catamaran in Terms of Motion Reduction and Wave Energy Harvesting by Means of a Semi-Active Motion Control System." *Applied Ocean Research* 83 (February): 88–102. https://doi.org/10.1016/j.apor.2018.12.003.
4. Han, Jialin, Teruo Maeda, Hiroshi Itakura, and Daisuke Kitazawa. 2022. "Experimental Study on the Wave Energy Harvesting Performance of a Small Suspension Catamaran Exploiting the Maximum Power Point Tracking Approach." *Ocean Engineering* 243 (November 2021): 110176. https://doi.org/10.1016/j.oceaneng.2021.110176.
5. Price, W. G. and Bishop, R. E. D., *Probabilistic Theory of Ship Dynamics*, Halsted Press, 1974.
6. Raff, A. I., "Program SCORES - Ship Structural Response in Waves," Ship Structures Committee Report SSC-230, 1972.
7. Troesch, A. W., "Naval Architecture NA440 Ship Dynamics II," Course Notes.
8. https://www.bluebird-electric.net/wave_powered_ships_marine_renewable_energy_research.htm

Appendix

Natural Periods	Empirical approximation (s)	Prediction SPP (s)
Heave	**0.59**	**0.46**
Pitch	**0.59**	**0.5**

Table 1: Predictions of natural period in heave and pitch for DavLab hull.

- Equations of motion for the suspended cabin and the twin hulls are written as follows (Han, 2018):
  - Heave of Cabin

$$M\frac{d^2Z(t)}{dt^2} + D_1\frac{dZ_{r1}(t)}{dt} + \mathrm{K}Z_{r1}(\mathrm{t}) + D_2\frac{dZ_{r2}(t)}{dt} + \mathrm{K}Z_{r2}(\mathrm{t}) = 0$$

  - Pitch of Cabin

$$\mathrm{I}\frac{d^2\Theta(t)}{dt^2} + r_1D_1\frac{dZ_{r1}(t)}{dt} + r_1\mathrm{K}Z_{r1}(t) - r_2D_2\frac{dZ_{r2}(t)}{dt} - r_2\mathrm{K}Z_{r2}(\mathrm{t}) = 0$$

  - Heave of the hull

$$(m + A_{33})\frac{d^2z(t)}{dt^2} + B_{33}\frac{dz(t)}{dt} + C_{33}\mathrm{z}(\mathrm{t}) - (D_1\frac{dZ_{r1}(t)}{dt} + \mathrm{K}Z_{r1}(\mathrm{t}) + D_2\frac{dZ_{r2}(t)}{dt} + \mathrm{K}Z_{r2}(\mathrm{t})) + A_{35}\frac{d^2\theta(t)}{dt^2} + B_{35}\frac{d\theta(t)}{dt} + C_{35}\theta(\mathrm{t}) = F_w(\mathrm{t})$$

  - Pitch of the hull

$$(I_{55} + A_{55})\frac{d^2\theta(t)}{dt^2} + B_{55}\frac{d\theta(t)}{dt} + C_{55}\theta(\mathrm{t}) - (r_1D_1\frac{dZ_{r1}(t)}{dt} + r_1\mathrm{K}Z_{r1}(t) - r_2D_2\frac{dZ_{r2}(t)}{dt} - r_2\mathrm{K}Z_{r2}(\mathrm{t})) + A_{53}\frac{d^2z(t)}{dt^2} + B_{53}\frac{dz(t)}{dt} + C_{53}\mathrm{z}(\mathrm{t}) = M_w(\mathrm{t})$$

- where, Z_{r1} (t) = Z - $r_1\Theta$ – z + $r_1\theta$, and Z_{r2} (t) = Z - $r_2\Theta$ – z + $r_2\theta$, are relative displacement of the front and aft suspensions.

- $W_0 = \left(\frac{\rho g A_{wp} + K}{m + A(w)}\right)^{1/2}$ and c = B(w) , where c is PTO damping & B is radiation damping.
- However, ocean waves are stochastic and encounter frequency will change depending on the speed of the boat (V), and the direction (β) and wavelength (λ) of the waves.
- Encounter frequency: $W_e = W_0 - W_0^2 \frac{V\cos(\beta)}{g}$