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1 **Preliminary development of a novel catamaran floating offshore wind turbine platform and**
2 **assessment of dynamic behaviours for intermediate water depth application**

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6 **Abstract:**

7 This paper presents the preliminary development of a novel catamaran Floating Offshore Wind
8 Turbine (FOWT) concept and a numerical assessment of its dynamic characteristics subject to
9 operational conditions when operating in 150 m water depth. A numerical tool, F2A, which couples
10 FAST and ANSYS AQWA numerical tools via a Dynamic Link Library (DLL) is used to conduct
11 efficient aero-hydro-servo-elastic simulations. The tool enables fully coupled time-domain simulations
12 to predict the hydrodynamic loads, mooring tensions (using AQWA) and aero-elastic loads (using
13 FAST) which is required for the complete evaluation of a FOWT's dynamic behaviour and
14 performance. A verification study is conducted by comparing the catamaran FOWT's inherent
15 characteristics against the ITI Energy barge FOWT. Furthermore, validation of the numerical results is
16 achieved through comparisons with published results of similar models. More specifically, performance
17 indicators of wind turbine platforms including dynamic responses, stability, and power production
18 under operational conditions. It has been observed that the catamaran concept has significantly reduced
19 responses (22 % and 7 % reduction in F-A tower-base bending moment and rotor thrust, respectively)
20 and improved stability (50 % reduction in pitch response (RAO)) compared to the barge. The catamaran
21 concept offers steady production in a full range of operation conditions. This research confirms that a
22 catamaran floating support platform offers a viable alternative to existing support FOWT concepts for
23 application in intermediate water and provides greater insight into the behavior of barge-type FOWT
24 concepts.

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25 1. Introduction

26 The offshore wind industry is rapidly growing, stimulated by the urgent need to produce electricity
27 from clean and sustainable energy sources. The demand for renewable energy has been one of the
28 motivations for the recent upsurge in research on Floating Offshore Wind Turbines (FOWTs). The
29 offshore environment offers attractive advantages over the onshore environment for wind power
30 generation which include resource availability and stability, optimum wind speeds, relatively low wind
31 shear and turbulence intensity, and increased probability of higher energy density (Liu et al., 2021).

32 Offshore wind now comprises of two industries which are based on whether the foundation, used
33 to support the wind turbine, is fixed to the seabed or floating. Most existing offshore wind farms are in
34 shallow waters and employ fixed-bottom foundation technology e.g., monopile, to support the wind
35 turbine. However, as viable nearshore sites become exhausted future wind farms will inevitably have
36 to move further from shore into deeper waters (Loughney et al., 2021). Economically, fixed-bottom
37 structures do not represent practical solutions for wind turbine applications in water depths greater than
38 60 m (Goupee et al., 2014). Consequently, floating platforms have become the favoured option for
39 supporting wind turbines in deep waters, hence the major research focus on FOWTs in recent years.
40 (Yang et al., 2021).

41 There are four distinct FOWT groups which are classified based on their rotational (pitch and roll)
42 hydrostatic stability characteristics, see **Figure 1** (Jonkman and Matha, 2011) (Thiagarajan and Dagher,
43 2014).

44 Spars are simple cylindrical structures with excellent hydrodynamic stability owing to its deep
45 draught and low center of gravity (Meng et al., 2020). On the other hand, the draught of the spar is a
46 constraint whereby the minimum water depth for application is restricted (Zheng et al., 2020). Hywind
47 Scotland, developed by Statoil (now Equinor) (Equinor, 2020) was the world's first fully operational
48 floating offshore wind farm. The farm consists of five 6 MW wind turbines using spar platforms.

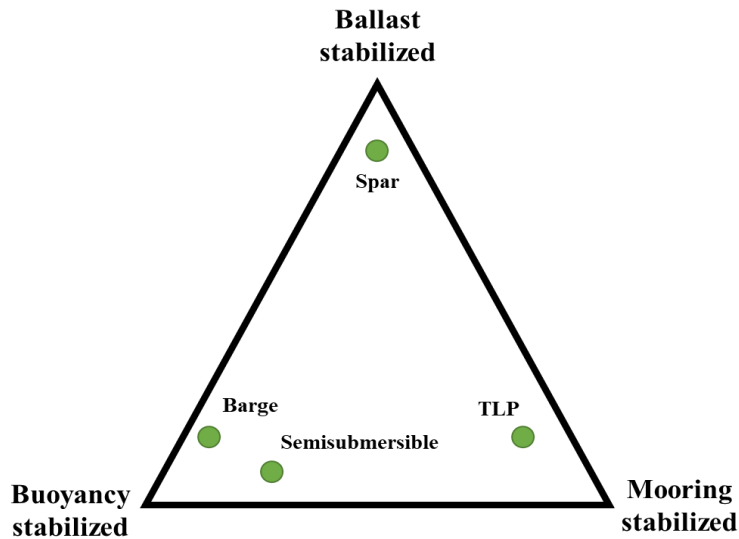


Figure 1. Stability triangle with annotation of common floating offshore wind types (Thiagarajan and Dagher, 2014).

49 A Tension-Leg Platform (TLP) uses a mooring system of taut vertical tendons to keep the platform
 50 upright and in position. The platform has excessive positive buoyancy which keeps the tendons
 51 constantly taut. TLPs are typically smaller structures geometrically compared to the other types
 52 (Taboada, 2016) and has good potentials for application due to its limited motions derived from the
 53 mooring system. (Murfet and Abdussamie, 2019). Despite these positives, the costs, and risks of
 54 application of a TLP remain relatively unknown unless full-scale sea testing is conducted.

55 Semisubmersibles and barge platforms are stabilized through buoyancy by taking advantage of
 56 their large waterplane areas. Semisubmersibles are usually composed of several columns connected to
 57 each other through braces or pontoons. The hydrodynamic behavior of semisubmersibles subject to
 58 wind load excitations is considered particularly good. Application of this platform type is deemed to be
 59 more achievable due to ease and tendency to have lower costs in their installation (Shi et al., 2019).
 60 However, the construction is more difficult despite the ability to be fabricated at dockside. Furthermore,
 61 the design of semisubmersibles is far more challenging due to complexity in their dynamic responses,
 62 caused by the combined effects of wind-wave coupled loads. More specifically, it is the heave response
 63 of this platform type which is a cause of concern because of its influence on general platform stability
 64 (Liu et al., 2016). Three 8.4 MW semisubmersible FOWTs developed by Principle Power (Principle
 65 Power, 2020) are in full operation off the coast of Portugal as part of the WindFloat Atlantic project.

66 These platforms are currently the largest FOWTs in the world with power generated capacity that can
67 supply up to 60,000 users each year.

68 Barge platforms possess good advantages in their fabrication, assembly, deployment and anchoring
69 when compared to other platform types. They have simple geometry, and a wind turbine can be easily
70 mounted onto a barge dockside and the entire assembly can be towed by tugboats to site. This operation
71 can eliminate any need for specialist vessels. Such operations mean barges have lower overall costs of
72 fabrication and installation compared to the others. However, the uptake of barge platforms for
73 intermediate water application is limited by problems that include its sensitivity to pitch stability in
74 waves, high tower-base bending moments (Jonkman and Matha, 2011) and complex requirements for
75 its operational control (Olondriz et al., 2018). Although the ITI Energy barge concept has been around
76 for a while, the only high capacity barge FOWTs in operation are the Ideol demonstrators of its
77 Damping Pool concept, Floatgen (Ideol, 2020a) and Hibiki (Ideol, 2020b), off the coasts of France and
78 Japan, respectively. Each platform type has its own advantages and disadvantages and as the floating
79 wind industry is still in an early stage there is a lack of consensus on which FOWT type performs best.
80 This often means the simplest method to improve on platform dynamics is a redesign of the floater.
81 Therefore, this paper proposes a novel catamaran-type FOWT concept.

82 Catamarans are widely used in the maritime transportation and leisure industries (Fang et al., 1997)
83 and have been adopted to build the largest construction vessel in the world (Allseas, 2021) and green
84 power boats such as ECO SLIM (Drassanes Dalmau, 2021). Catamarans are renowned for their good
85 stability and large usable deck areas, both of which are beneficial for offshore renewable energy
86 platforms. The deck area can be used to enhance safety when carrying out operation and maintenance
87 work and utilized to support infrastructure for other functions such as ocean energy generation, solar
88 panels, and hydrogen generation. Within the context of marine vehicles, vessel stability is governed by
89 transverse stability (roll). A catamaran primarily depends on its beam (width) and demi-hull buoyancy
90 for heeling stability. This means that the wider the beam and longer the dimensions, the greater the
91 stability. These features help catamarans resist rolling to one side because the other hull's buoyancy
92 overcomes the force of the rising or falling sea. For a FOWT, its longitudinal stability (pitch) can be

93 considered an important criterion in design as it directly affects the generated power quantity (Johlas et
94 al., 2021). Typically, the longitudinal stability of a marine vessel is greater than its transverse, hence
95 the reason for emphasis on transverse stability on the safety aspects of vessels in ship research (Dzan et
96 al., 2013). Based on this, there is good possibility that modifying a catamaran into a FOWT support
97 platform has worth because of their renown transverse stability. Moreover, there have been some studies
98 on converting a conventional catamaran into a tidal energy platform (Qasim et al., 2018), (Junianto et
99 al., 2020), (Brown et al., 2021). There is a lack of literature that attempt to modify a catamaran into a
100 suitable support platform for wind turbine operations which presents the opportunity for research and
101 incentive for this investigation.

102 To conduct feasibility studies, advanced numerical tools are required which enable the analysis,
103 optimization, and preliminary design of FOWTs for a variety of configurations so that the technical and
104 economic feasibility can be determined. Jonkman (2009) presented FAST, now known as OpenFAST
105 due to its open-source nature, which is a framework that couples numerical codes capable of modelling
106 aerodynamics, hydrodynamics for offshore structures, control and servo dynamics and structural
107 dynamics to enable fully coupled time-domain simulation of FOWTs. OpenFAST is one of the most
108 widely adopted numerical tools used to evaluate wind turbines. Barooni et al. (2018) presented the
109 development of an open-source numerical model to enhance understanding of governing equations of
110 a fully coupled nonlinear FOWT. In order to strengthen simulation capabilities of existing numerical
111 tools for the FOWT design, Yang et al. (2020) published research on the development of a coupling
112 framework called FAST2AQWA (F2A). F2A couples two well-known analysis tools via a dynamic
113 link library to create a superior numerical tool for predicting nonlinear dynamics of a FOWT subject to
114 wind, wave, and current loadings.

115 In this preliminary development of a novel catamaran-type FOWT concept the hydrodynamic
116 characteristics and dynamic responses are numerically investigated using F2A for a range of operational
117 load cases in intermediate water depth. An evaluation of the FOWT's dynamic behaviours and
118 performance is carried out following the prediction of dynamic responses. A verification study has been
119 conducted by comparing the catamaran concept developed in this study with a conventional barge

120 platform known as the ITI Energy barge. The results of the comparison are required for validation
 121 purposes and as part of the feasibility of the catamaran design. The results also provide insight into how
 122 the catamaran FOWT performs against another platform of a similar capacity. Thus, this paper is
 123 organized as follows: a description of the models is detailed in Section 2. Section 3 introduces the
 124 numerical tool used to analyze the FOWT systems in this research. Load cases and validation is
 125 discussed in Section 4, and results and discussion are presented in Sections 5 and 6. Conclusions are
 126 drawn in Section 7.

127 2. Model descriptions

128 This study uses the NREL 5 MW reference wind turbine (properties given in **Table 1**) to assess
 129 the capability of the proposed concept to function as a FOWT. The wind turbine is a conventional three-
 130 bladed horizontal-axis, upwind variable-speed wind turbine and comprises of blades, hub, nacelle, and
 131 tower. The main components of the FOWT system are the following: (1) wind turbine, (2) floating
 132 platform, and (3) mooring system.

133 **Table 1.** Properties of NREL 5 MW Reference Wind Turbine.

| 134 | Parameter (Units) | Value |
|-----|--|-------------|
| 135 | Rated Power (MW) | 5 |
| 136 | Rotor & hub diameter (m) | 126 & 3 |
| 137 | Cut-in, rated, cut-out wind speed ($\text{m}\cdot\text{s}^{-1}$) | 3, 11.4, 25 |
| 138 | Hub height (from the bottom of the tower) (m) | 90 |
| | CM (Centre of Mass) location (from bottom of the tower) (m) | 64 |
| | Rotor mass (kg) | 110,000 |
| | Nacelle mass (kg) | 240,000 |
| | Tower mass (kg) | 347,460 |
| | Total mass (including tower) (kg) | 697,460 |

139 The proposed concept is inspired by a typical catamaran vessel with a large deck mounted atop
 140 two equally spaced demi-hulls. The wind turbine is situated in the middle of the platform so that the
 141 tower centreline and platform centreline align and pass through the origin (0, 0, 0). As a preliminary
 142 design, the dimensions of the catamaran platform were selected so that the volume and displacement
 143 are similar to a barge platform. Any improvement or deterioration in performance would therefore be
 144 attributable to the platform design.

145 The barge FOWT model used for benchmarking and verification in this study is the ITI Energy
 146 barge, a preliminary barge concept developed by the Universities of Glasgow and Strathclyde, and ITI
 147 Energy. Further details of the platform can be found in (Jonkman, 2007).

148 To prevent drifting from installed location, each floating platform is moored by a system of eight
 149 slack, catenary lines. For both platforms, at every bottom corner two mooring lines connect to the
 150 platform separated by a 45° angle. The properties of the floating platforms are listed in **Table 2** and the
 151 mooring system properties are given in **Table 3**. **Figures 2 & 3** present the CAD model of the catamaran
 152 floating platform labelled with appropriate dimensions and the mooring system configurations of both
 153 platforms created in ANSYS AQWA.

154 **Table 2.** Platform Properties.

| | Catamaran | ITI Energy barge |
|---|--------------------------|-------------------------|
| Diameter or width × length (m), (LOA = length overall) (m) | 45 × 60, (LOA = 77.3) | 40 × 40 |
| Space between demi-hulls (m) | 25 | - |
| Draught (m) | 4 | 4 |
| Elevation to platform top (tower base) above SWL (m) | 6 | 6 |
| Total volume (m ³) | 15,684 | 16,000 |
| Water displacement (m ³) | 5,480 | 6,400 |
| Mass (kg) | 4,901,080 | 5,452,000 |
| CM location (m) | (0, 0, 1.51) | (0, 0, -0.2818) |
| Roll inertia about CM (kg m ²) | 4,672,683,194 | 726,900,000 |
| Pitch inertia about CM (kg m ²) | 6,800,310,371 | 726,900,000 |
| Yaw inertia about CM (kg m ²) | 11,190,569,096 | 1,454,000,000 |

155

156 **Table 3.** Mooring System Properties.

| | Catamaran | Barge |
|---|---------------------------|---------------|
| Number of mooring lines | 8 | 8 |
| Depth to fairleads & anchors (m) | 4 & 150 | 4 & 150 |
| Radius to fairleads & anchors (m) | 42.436, 429.095 & 439.566 | 28.28 & 423.4 |
| Section length (m) | 474.1 | 473.4 |
| Mooring line diameter (m) | 0.0809 | 0.0809 |
| Line mass density (kg m ⁻¹) | 130.4 | 130.4 |
| Line extensional stiffness, EA (N) | 589,000,000 | 589,000,000 |

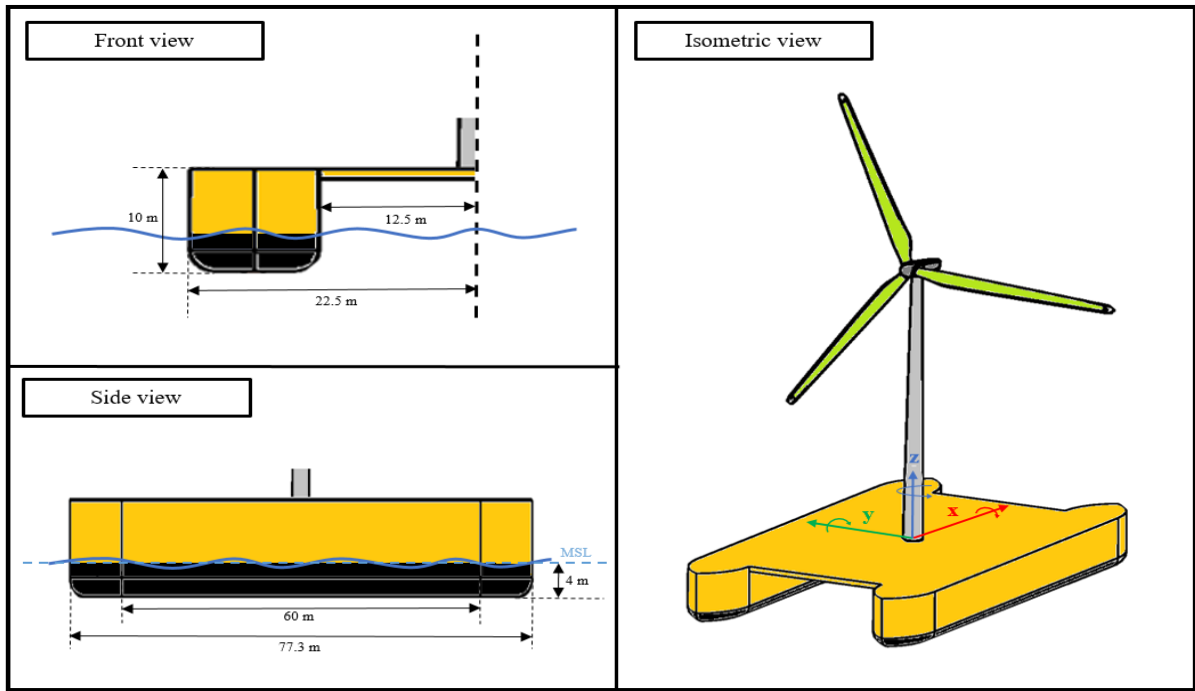


Figure 2. Preliminary catamaran FOWT concept schematics.

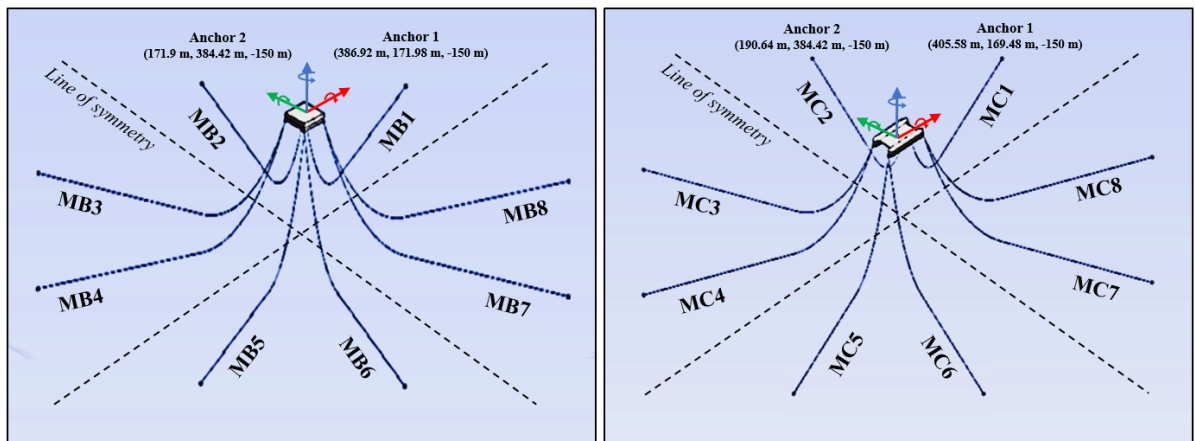


Figure 3. Mooring system configurations in ANSYS AQWA: barge (left), catamaran(right).

157

158 3. Theoretical background and numerical modelling framework

159 3.1 Linear potential flow theory

160 External flows around bodies can be represented by linear potential flow theory. For a bluff body
 161 in waves, its radiation and diffraction problems must be solved to obtain the hydrodynamic coefficients
 162 required for subsequent analysis of its dynamic behaviours. Application of potential flow theory is done
 163 based on the assumption that the fluid is irrotational (without vorticity), incompressible (constant

164 density), and inviscid (zero viscosity). The fluid field velocity around the floating body is calculated
 165 once the velocity potential, ϕ , as a function of spatial displacement x, y, z and time, t and the relevant
 166 boundary conditions satisfy the conservation of mass and momentum conditions. The velocity potential
 167 equation must also satisfy the Laplace equation (Eq. 1):

$$\nabla^2 \phi = 0 \quad [1]$$

168 The total velocity potential induced by fluid flow around the body is expressed as a combination
 169 of incident wave, diffraction (incoming waves would scatter due to existence of floating body) and
 170 radiation (waves are radiated due to structure motions). This is represented by (Eq. 2):

$$\phi(x, y, z; t) = \phi_I(x, y, z; t) + \phi_D(x, y, z; t) + \phi_R(x, y, z; t) \quad [2]$$

$$\phi_R(x, y, z; t) = \sum_{k=1}^6 \zeta_k \phi_{R_k}(x, y, z; t) \quad [3]$$

171 where $\phi_I(x, y, z; t)$ is the incident wave component of velocity potential in space and time,
 172 $\phi_D(x, y, z; t)$ is the spatial diffraction wave potential as a function of time, $\phi_R(x, y, z; t)$ is the radiation
 173 potential also in space and time. $\phi_{R_j}(x, y, z; t)$ is the radiation potential of the floating body induced by
 174 the platform movement in the k -th mode, ζ_j represents the platform's displacement in the k^{th} mode
 175 under the action of a unit wave amplitude, and $k = 1, 2, \dots, 6$ represents the floating body's six degrees
 176 of freedom (surge, sway, heave, roll, pitch, and yaw).

177 Detailed representation of the incident wave potential $\phi_I(x, y, z, t)$ is given in equation (Eq.4) as:

$$\phi_I(x, y, z, t) = \frac{-iga}{\omega_0} e^{k_0 z} e^{i(k_0 x \cos \theta + k_0 y \sin \theta - \omega_0 t)} \quad [4]$$

178 where i is the imaginary unit component of the incident wave, a is the unit incident wave amplitude,
 179 gravitational acceleration is represented by g , while k_0 is the wave number, and θ is the incident wave
 180 angle.

181 When the wave velocity potentials are known, the first-order hydrodynamic pressure distribution
 182 may be calculated using the linearized Bernoulli equation given in (Eq.5).

$$p = -\rho \cdot \frac{\partial \phi(x, y, z, t)}{\partial t} \quad [5]$$

183 Following the prediction of the water pressure distribution, the various fluid forces may be obtained
184 by integrating the pressure over the wetted surface of the body.

185 The first order hydrodynamic force and moment components can be represented in a generalized
186 form:

$$F(x, y, z; t) = \iint_S p \cdot n_j(x, y, z; t) dS = -i\omega\rho \iint_S [\phi(x, y, z; t)] \cdot n_j(x, y, z; t) dS \quad [6]$$

187 where ρ is the seawater density (kg/m³), S is the floating body's wetted body surface area (m²), and n_i
188 is the wetted body surface's normal vector in the j -th mode.

189 From (Eq. 2) and (Eq.3), the total first order hydrodynamic wave force can be written as:

$$F_j = \left[(F_{I_j} + F_{D_j}) + \sum_{k=1}^6 \zeta_k F_{R_{jk}} \right] \text{ where } j = 1, 6 \quad [7]$$

190 where (Eq.8) defines the j^{th} Froude-Krylov force, F_{I_j} , due to incident wave:

$$F_{I_j} = -i\omega\rho \iint_S [\phi_I(x, y, z; t)] \cdot n_j(x, y, z; t) dS \quad [8]$$

191 (Eq.9) defines the diffracting force, F_{D_j} , due to diffraction:

$$F_{D_j} = -i\omega\rho \iint_S [\phi_D(x, y, z; t)] \cdot n_j(x, y, z; t) dS \quad [9]$$

192 (Eq.10) defines the radiation force, $F_{R_{jk}}$, due to the radiation wave induced by the k^{th} unit amplitude
193 body rigid motion:

$$F_{R_{jk}} = -i\omega\rho \iint_S [\phi_{R_k}(x, y, z; t)] \cdot n_j(x, y, z; t) dS \quad [10]$$

194 The hydrodynamic wave force can be further characterized in terms of active and reactive
195 components. The active force, or the exciting force, is the combination of the Froude-Krylov force and

196 diffraction force. The reactive force is the radiation force due to the radiated waves induced by body
 197 motions.

198 If the radiation wave potential is expressed in terms of real and imaginary parts, then the added
 199 mass and radiation damping coefficients can be obtained:

$$\begin{aligned}
 F_{R_{jk}} &= -i\omega\rho \iint_S \{Re[\phi_{R_k}(x, y, z; t)] + Im[\phi_{R_k}(x, y, z; t)]\} \cdot n_j(x, y, z; t) dS \\
 &= \omega\rho \iint_S Im[\phi_{R_k}(x, y, z; t)] \cdot n_j(x, y, z; t) dS \\
 &\quad - i\omega\rho \iint_S Re[\phi_{R_k}(x, y, z; t)] \cdot n_j(x, y, z; t) dS \\
 &= \omega^2 A_{jk} + i\omega B_{jk}
 \end{aligned} \tag{11}$$

$$A_{jk} = \frac{\rho}{\omega} \iint_S Im[\phi_{R_k}(x, y, z; t)] \cdot n_j(x, y, z; t) dS \tag{12}$$

$$B_{jk} = -\rho \iint_S Re[\phi_{R_k}(x, y, z; t)] \cdot n_j(x, y, z; t) dS \tag{13}$$

200 where A_{jk} is the added mass coefficient, and B_{jk} is the damping coefficient (Lin and Yang, 2020).

201 3.2 FAST2AQWA tool

202 A newly developed aero-hydro-servo-elastic coupled tool is adopted in this study to predict the
 203 coupled dynamic responses of the FOWTs induced by operational wave and wind climates. The tool is
 204 based on the integration of an aero-servo-elastic solver, FAST (Jonkman and Buhl Jr, 2005) into a
 205 commercial hydrodynamic analysis software tool, AQWA (ANSYS, 2012). F2A enables fully coupled
 206 nonlinear aero-hydro-servo-elastic simulation to be conducted in the time domain. The new tool
 207 operates by replacing the hydrodynamic module in FAST, known as HydroDyn, with AQWA to
 208 calculate the hydrodynamic loads of a FOWT. The justification for the choice of F2A is that it uses the
 209 superior predictive capabilities of AQWA to calculate the hydrodynamic loads acting on the FOWT.
 210 FAST simulation capabilities are implemented within the coupled tool F2A via a coupling framework
 211 to synchronously calculate the effects of wind induced loads and hydrodynamic forces. The coupling
 212 of F2A is achieved through the user_force64.dll interface, which is a built-in Dynamic Link Library
 213 (DLL) of AQWA for external force calculation. The coupling framework is represented by a flowchart
 214 presented in **Figure 4** (Yang, 2020).

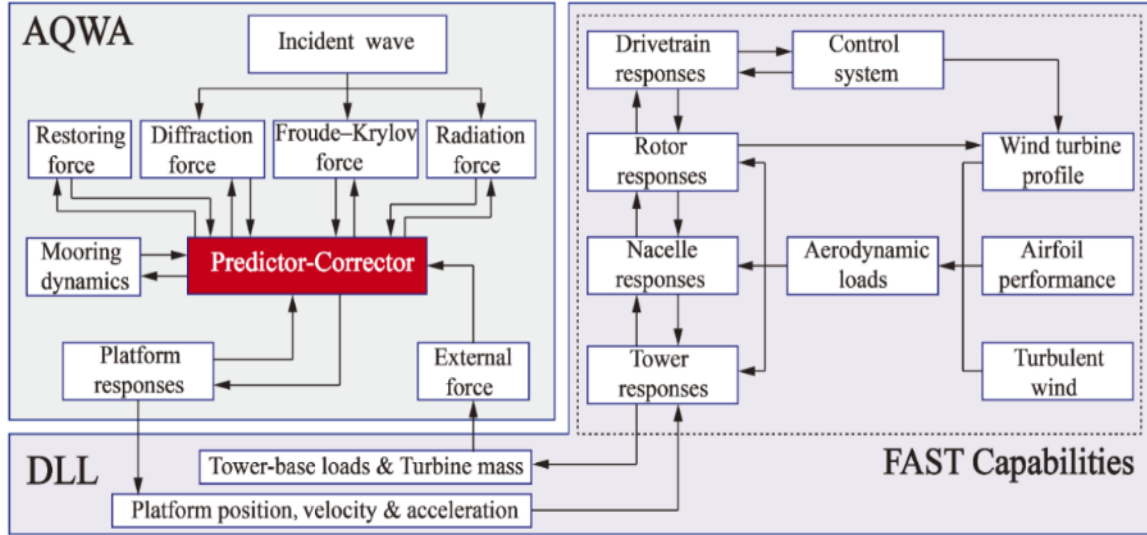


Figure 4. Flowchart of F2A (Yang, 2020).

215 It can be seen in **Figure 4** that the dynamic responses of a FOWT are predicted in different
 216 modules. More explicitly, the upper structures of the wind turbine (tower, rotor, and nacelle) are
 217 modelled in FAST, and the coupled dynamic responses are predicted within the DLL considering the
 218 platform kinematics obtained in AQWA. The terms within both AQWA and FAST are transformed to
 219 coincide with the platform's local coordinate system from their respective inertial coordinate systems
 220 before being fed into the DLL. This transformation becomes necessary to enable FAST to correct the
 221 kinematics of FOWT's upper structures in relation to its platform responses calculated in reference to
 222 its local coordinate system. Therefore, a transformation is needed as the platform responses predicted
 223 by AQWA are referred to its inertial coordinate system. Following successful transformation of the
 224 coordinate system, the platform's tower-base loads are subsequently calculated by FAST subroutines.
 225 The lower structure of the FOWT, which consists of the platform and mooring lines, is modelled in
 226 AQWA. The resulting dynamic responses, mainly hydrodynamic, are calculated in AQWA by solving
 227 the equation of motion of the platform using the calculated tower-base loads as an external force. The
 228 governing equation of motion of the platform is defined in (Eq.14):

$$(\mathbf{M} + \mathbf{A})\ddot{\mathbf{x}} + \mathbf{B}_{ext}\dot{\mathbf{x}} + \mathbf{B}_2\dot{\mathbf{x}}|\dot{\mathbf{x}}| + \int_0^t \mathbf{h}(t - \tau)\dot{\mathbf{x}}(\tau)d\tau + \mathbf{C}\mathbf{x} = \mathbf{F}_{ext} \quad [14]$$

229 where \mathbf{M} is the inertial mass matrix, \mathbf{A} is the added mass matrix, and x, \dot{x}, \ddot{x} are the unknown FOWT
 230 platform's displacement, velocity, and acceleration vectors, respectively, for each degree of freedom.
 231 \mathbf{B}_{ext} and \mathbf{B}_2 are the linear and quadratic viscous damping coefficients respectively, typically obtained
 232 from model tests, $\mathbf{h}(t)$ is the radiation impulse function defined by

$$\mathbf{h}(t) = \frac{2}{\pi} \int_0^{\infty} \mathbf{B}_{Pot}(\omega) \cos(\omega t) d\omega \quad [15]$$

233 where $\mathbf{B}_{Pot}(\omega)$ is the potential damping matrix corresponding to the wave frequency of ω , and \mathbf{C} is the
 234 stiffness matrix with contributions from hydrostatic and the mooring line restoring forces. Matrix \mathbf{A} and
 235 \mathbf{B}_{Pot} can be computed numerically using the potential theory-based solver. in AQWA. This, in turn,
 236 can provide the total external force vector denoted by \mathbf{F}_{ext} . For more information on the F2A coupling
 237 framework and coordinate system transformations refer to (Yang et al., 2020).

238 4. Simulation

239 4.1 Load cases and environment

240 **Table 4** details the several types of analysis carried out and Load Case (LCs) conditions simulated.
 241 The first set of analyses focuses on system identification, including frequency-domain analysis to obtain
 242 hydrodynamic coefficients, free-decay simulations to find natural frequencies, hydro-elastic response
 243 with regular waves in absence of wind, and RAOs for a complete assessment of hydrodynamic
 244 characteristics. The next set of simulations are fully coupled aero-hydro-servo-elastic time-domain
 245 simulations used to investigate the performance of the catamaran floating wind turbine system under
 246 combined wind and wave excitation. For these simulations, the met-ocean data used is from a site
 247 located off the north coast of Scotland. LC 1 – 7 are defined in accordance with IEC 61400-3 where U_w
 248 is the locations' turbulent wind speed, measured at FOWT's hub-height (m/s), H_s is the significant wave
 249 height (m) and T_p is the spectral peak period (s). The wind characteristics of the selected site are
 250 modelled as three-dimensional turbulent wind fields based on the Kaimal turbulence model for IEC
 251 Class C and using TurbSim, a sub-program in FAST (Jonkman and Buhl Jr, 2006). The site wave
 252 conditions are modelled as irregular waves using the Pierson-Moskowitz wave spectrum in AQWA.

253 Furthermore, the length of each simulation is 4,600 s, with the first 1,000 s discarded to remove transient
 254 effects potentially interfering with final results.

255 **Table 4.** Load Cases.

| LC | Description | U_w [m/s] | H_s [m] | T_p [s] |
|-----|---|-------------|-----------|-----------|
| HDC | Frequency-domain analysis to obtain hydrodynamic coefficients | - | - | - |
| FD | Free decay analysis | - | - | - |
| RW | Regular wave | - | 2.1155 | 5.2555 |
| RAO | Response amplitude operators (white-noise wave) | - | 2 | 10 |
| 1 | Cut-in | 4 | 1.6146 | 3.4985 |
| 2 | Below-rated | 8 | 1.8037 | 4.2657 |
| 3 | Rated | 11.4 | 2.1155 | 5.2555 |
| 4 | Above-rated | 18 | 2.9585 | 7.1203 |
| 5 | Cut-out | 25 | 4.0257 | 8.8897 |
| 6 | Rated (Wave Dir 30°) | 11.4 | 2.1155 | 5.2555 |
| 7 | Rated (Wave Dir 90°) | 11.4 | 2.1155 | 5.2555 |

256

257 **4.2 Validation**

258 The novelty of the catamaran FOWT concept means that no experimental or numerical data, or
 259 benchmark model is available in public domain, yet the numerical model requires verification and
 260 validation for results to attain credibility. Consequently, the methodology used to verify the catamaran
 261 is based on a comparison of results of the ITI Energy barge model with published research. Good
 262 agreement between the results of the barge numerical model and published research reassures the
 263 credibility of this new concept by verifying the procedure to obtain the results. Following verification,
 264 the behavior of the catamaran model is validated through comparisons with published results of similar
 265 models.

266 **5. Assessment of hydrodynamic characteristics**

267 **5.1 Hydrodynamic coefficients**

268 The hydrodynamic coefficients of the catamaran and barge are calculated using ANSYS AQWA
 269 and presented in **Figures 5 & 6**. The coefficients are obtained in six degrees-of-freedom for a wave

270 frequency range of 0.05 – 4.0 rad/s at intervals of 0.05 rad/s and incident angles varying between 0 –
 271 90° at intervals of 30°. The calculated hydrodynamic coefficients of the barge platform were validated
 272 against the results published by (Olondriz et al., 2018). Overall, there is good agreement between the
 273 results which ensures the 3D analysis method used to obtain the hydrodynamic coefficients for both
 274 platforms is accurate and reliable. However, there is some discrepancy for heave and yaw radiation
 275 damping coefficients. Concerning heave damping coefficient, the plots follows a similar trend, however
 276 the peak amplitude of the present numerical model occurs at a higher frequency to the published results
 277 and concerning yaw, the plots follow an identical trend however the curve does not fall as sharply as
 278 frequency increases. Next, the trend of the hydrodynamic coefficient plots of the catamaran follows a
 279 similar pattern to the hydrodynamic coefficients plots of three catamarans modelled by (Fang, 1996)
 280 and one catamaran modelled by (Wellicome et al., 1995). The successive occurrence of peaks at discrete
 281 frequencies is inherently a characteristic of catamaran vessels. The similarity in results provides
 282 additional reassurance that the model is behaving as expected.

283 Catamarans experience a phenomenon known as dynamic amplification which is caused by
 284 entrapped wave action between its demi-hulls. This phenomenon can lead to enhanced motion
 285 behaviours. A series of characteristic frequencies, ω_r , exist where demi-hull oscillation strongly excites
 286 the motion of the entrapped fluid; these frequencies can be identified by the following formula:

- Symmetric interaction: $\omega_r = \sqrt{2n\pi g/d_r}$ for n = 1, 2, 3 ... [16]

- Antisymmetric interaction: $\omega_r = \sqrt{(2n - 1)\pi g/d_r}$ for n = 1, 2, 3 ... [17]

287

288 where d_r is the demi-hull separation (m).

289 The characteristic frequencies can be either separated into symmetric or anti-symmetric
 290 interaction. Symmetric interaction affects the vertical plane motions (surge, heave, pitch) and
 291 antisymmetric interaction affects the horizontal plane motions (sway, roll, yaw). These frequencies are
 292 analogous to the resonant modes of a standing wave between two vertical walls.(Fang, 1996). Moreover,
 293 the fact that catamarans have negative added mass in a stationary condition suggests that the effect of
 294 hydrodynamic interaction between the demi-hulls is strong. The frequency of the standing wave

295 depends on the distance between the demi-hulls. The wider the distance is between the demi-hulls, the
296 lower the frequency at which the phenomenon occurs (Dabssi et al., 2008).

297 In **Figures 5 & 6**, the characteristic frequencies are distinct. Using (Eq.16) and (Eq.17) to calculate
298 the characteristic frequencies, for heave and pitch plots of added mass and radiation damping
299 coefficients, small peaks occur at 1.57 rad/s due to symmetric interaction. For the added mass
300 coefficients, a smaller peak can be seen at a frequency of 2.22 rad/s. Peaks also exist for surge mode,
301 however due to the scaling of the axis, they are not visible.

302 For horizontal plane motions, peak responses occur at 1.11, 1.92, 2.48, 2.93, 3.33 and 3.68 rad/s
303 due to asymmetric interaction between the demi-hulls. Only the first two frequencies are dominant for
304 the added mass and radiation damping coefficients of sway, roll, and yaw motions. Similar to pitch, a
305 small peak occurs before the first characteristic frequency for roll. This peak corresponds to the roll
306 resonant frequency.

307 Comparison of hydrodynamic coefficients show that the catamaran exhibits lower surge and heave,
308 and higher sway, roll, pitch, and yaw added mass and damping coefficients. This observation suggests
309 that the platform has lower hydrodynamic restoring stiffness and potential damping for surge and heave
310 modes. At the same time, hydrodynamic restoring stiffness and damping for sway, roll, pitch, and yaw
311 modes are higher. Moreover, it is expected that the barge platform will be more sensitive to aerodynamic
312 loading due to smaller pitch coefficients, whilst the catamaran will be more sensitive to wave loading
313 as a result of smaller surge coefficients.

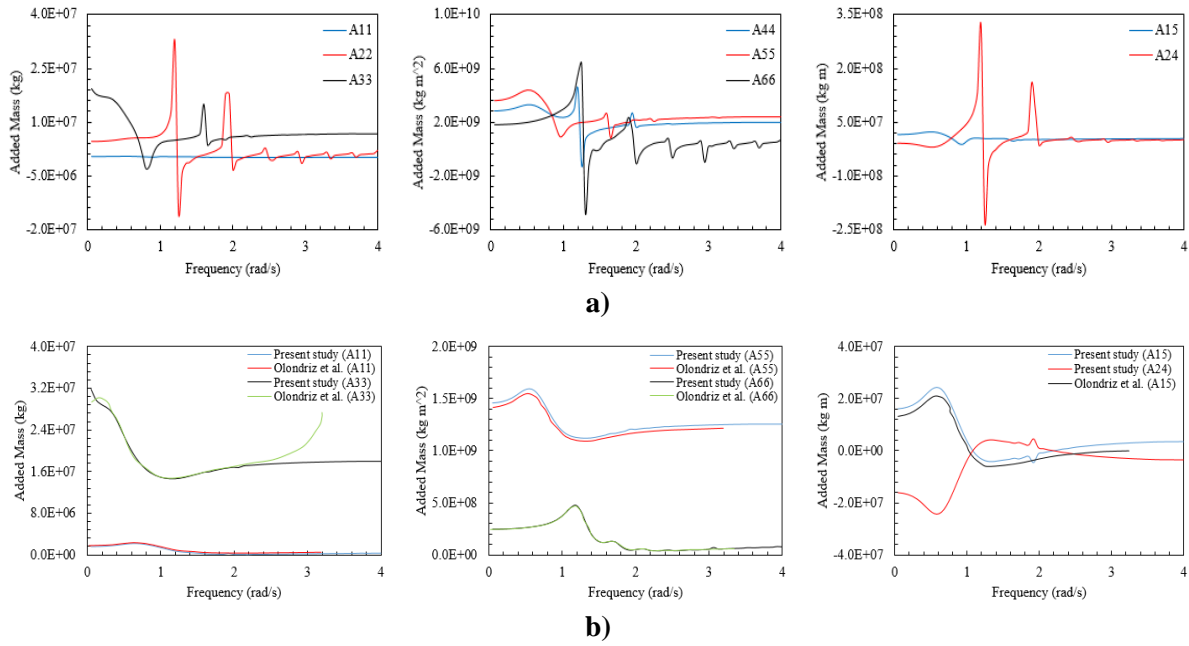


Figure 6. Hydrodynamic added mass coefficients a) catamaran b) barge.

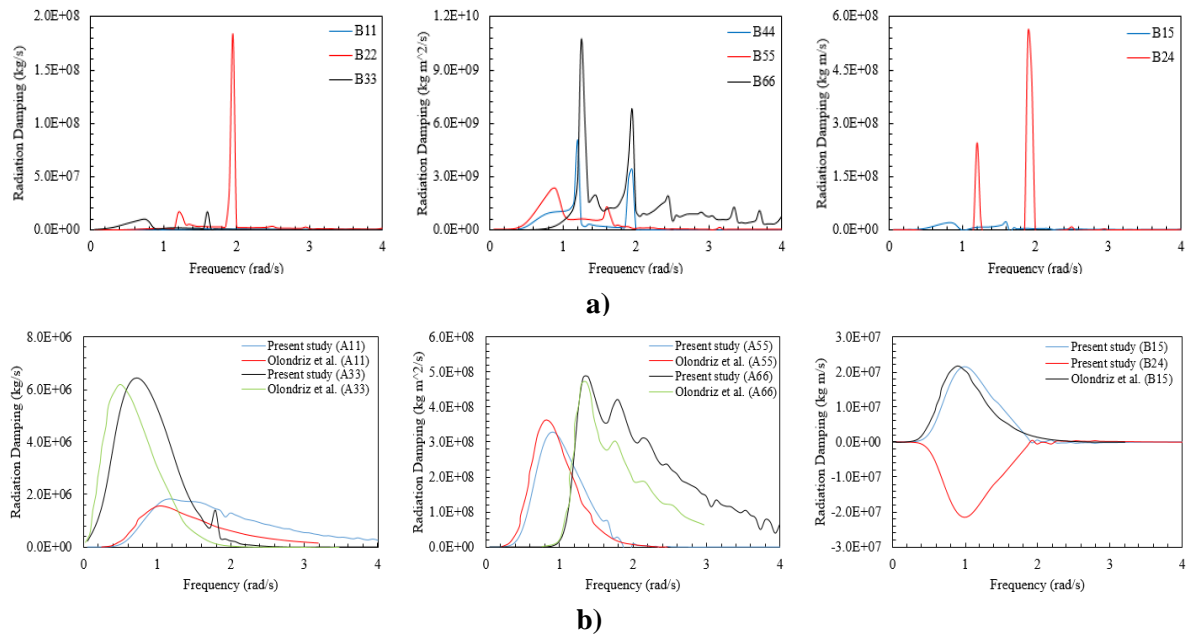


Figure 5. Hydrodynamic radiation damping coefficients a) catamaran b) barge.

314 **5.2 Free decay**

315 A free decay analysis was conducted for both platforms in six degrees of freedom. The natural
 316 periods of the platforms are presented in **Table 5** and plotted graphically in **Figure 7**.

317 **Table 5.** Natural periods (s) of the FOWT systems.

| | Surge | Sway | Heave | Roll | Pitch | Yaw |
|--|-------|------|-------|------|-------|-----|
|--|-------|------|-------|------|-------|-----|

| | | | | | | |
|------------------|-------|-------|-----|------|------|-------|
| Catamaran | 121.6 | 157.1 | 5.4 | 10.6 | 9.8 | 109.5 |
| Barge | 137.7 | 137.7 | 7.1 | 11.8 | 11.8 | 52.5 |

318

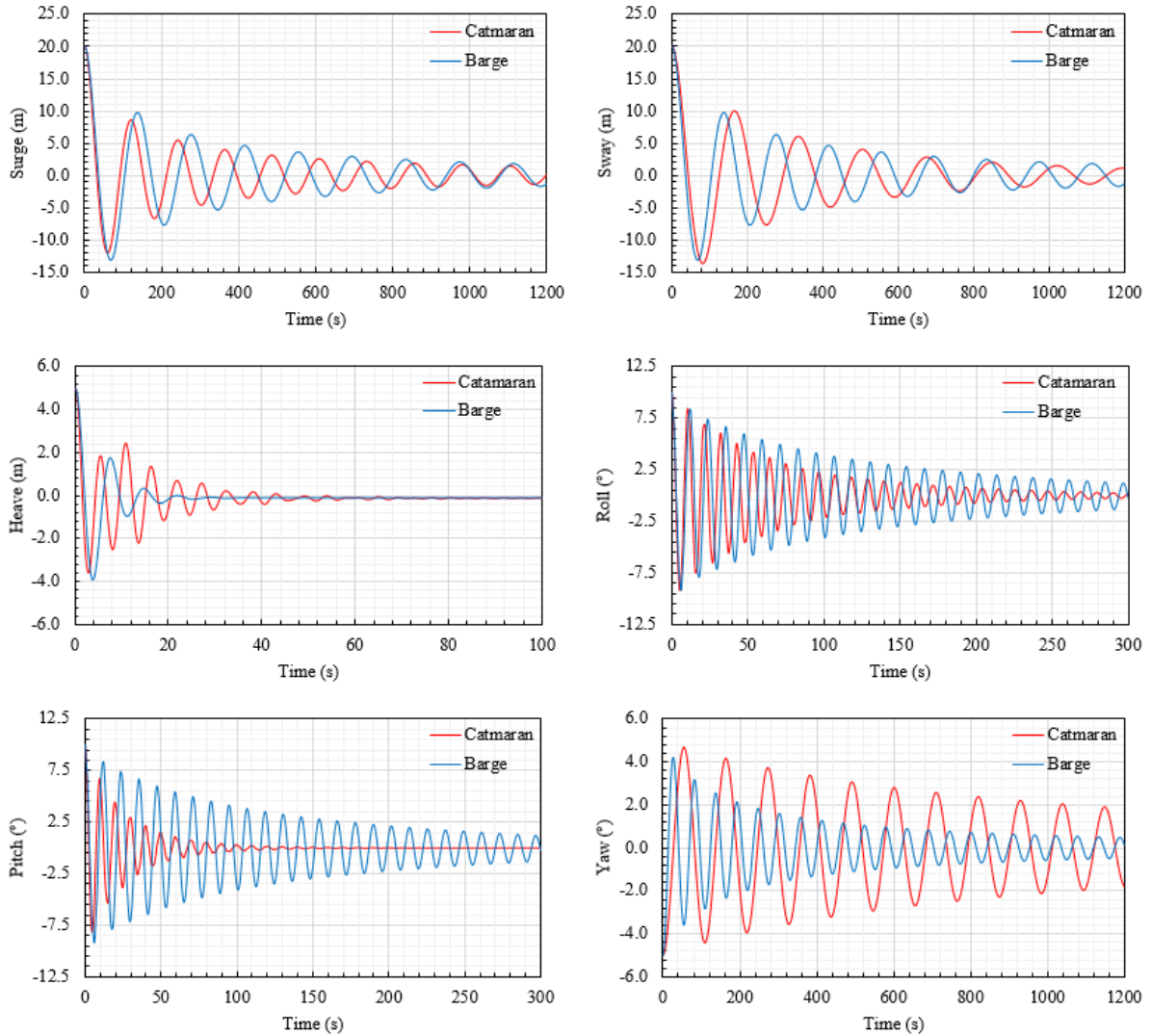


Figure 7. Free decay results.

319 **5.3 Hydro-elastic response under regular waves**

320 **Figure 8** shows the time histories of platform surge, heave and pitch displacements, tower-top
321 fore-aft displacement, tower-base force in the x-direction, and fairlead tensions (MB4/MC4) of both
322 platforms subject to a regular wave with properties $H = 2.1155$ m and $T = 5.2555$ s. The results show
323 the barge exhibits greater surge and pitch displacement, tower-top fore-aft displacement, tower-base
324 force, and mooring line tension, whilst the catamaran has greater heave displacement.

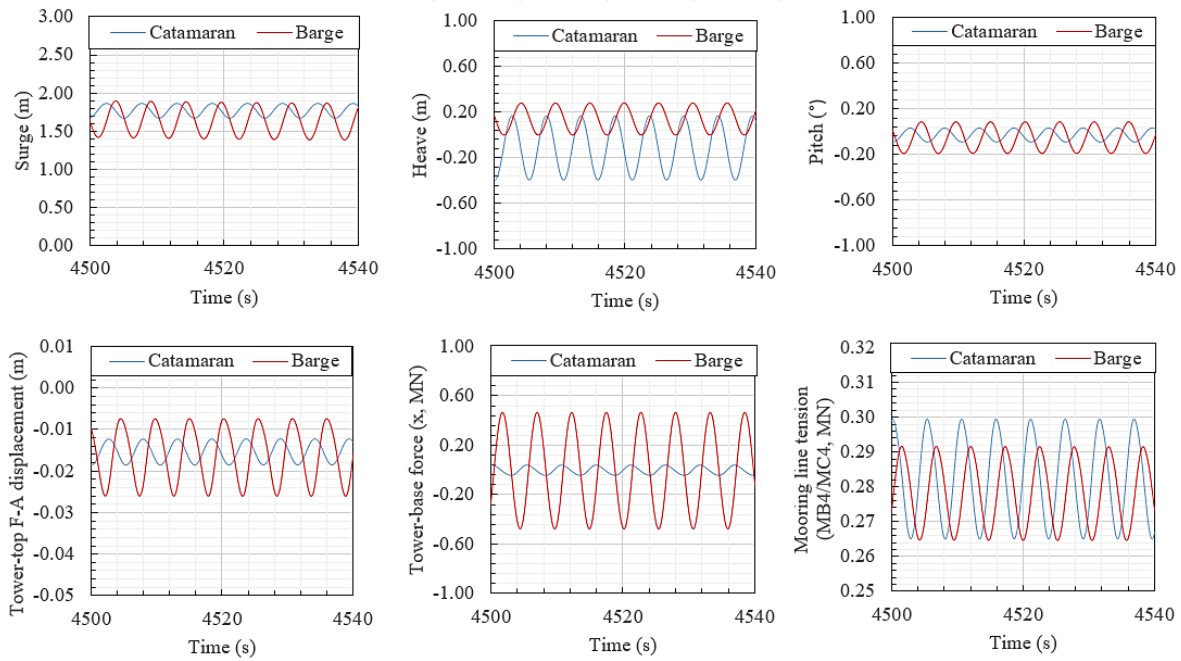


Figure 8. Hydro-elastic response with regular wave in absence of wind
($H = 2.1155$ m, $T = 5.2555$ s).

325 **5.4 Response Amplitude Operators (RAOs)**

326 Response Amplitude Operators (RAOs) are used in hydrodynamic analysis to initially assess the
 327 frequency-domain linear wave response of floating platforms (Robertson et al., 2014). In FOWT design,
 328 the hydrodynamic loads coupled with wind induced aerodynamics, structural dynamics, and servo-
 329 controller dynamics must be accounted in order to quantify their contribution and effects on platform
 330 responses (Aboutalebi et al., 2021). Simulations to predict the RAOs were performed in OpenFAST
 331 (National Renewable Energy Laboratory (NREL), 2021) with the process described in (Ramachandran
 332 et al., 2013) and (Aboutalebi et al., 2021). The RAOs for both catamaran and barge platforms are plotted
 333 in **Figure 9**. Similar to the methodology adopted in validating hydrodynamic coefficients, published
 334 numerical results for the RAOs of the barge exist; these have been used for validation. The RAO outputs
 335 in this study for the barge FOWT agree with the results published by (Aboutalebi et al., 2021).

336 RAOs are plotted for a frequency range of 0.1 – 1.25 rad/s and they show considerable excitation
 337 in surge, heave, and pitch modes. Since only wave response in a zero-degree heading was simulated,
 338 the responses for sway, roll and yaw are considerably less in magnitude due to the wave heading and
 339 absence of wind forcing.

340 Considering the surge mode, there is a shift in peaks from 0.52 rad/s to 0.62 rad/s. These peaks are
 341 attributable to the pitch resonant frequency of the corresponding platform. Furthermore, the catamaran
 342 RAO is slightly lower which suggests it is less responsive than the barge. The actual surge resonant
 343 frequency of both platforms occurs at a much lower frequency, hence why as frequency decreases the
 344 RAOs increase.

345 The heave RAO plots of both platforms are identical in the lower frequency range and follow the
 346 incident wave until approximately 0.4 rad/s. The RAO of the catamaran in the higher frequency range
 347 falls more sharply than the barge. However, at approximately 1.0 rad/s the barge RAO begins to level

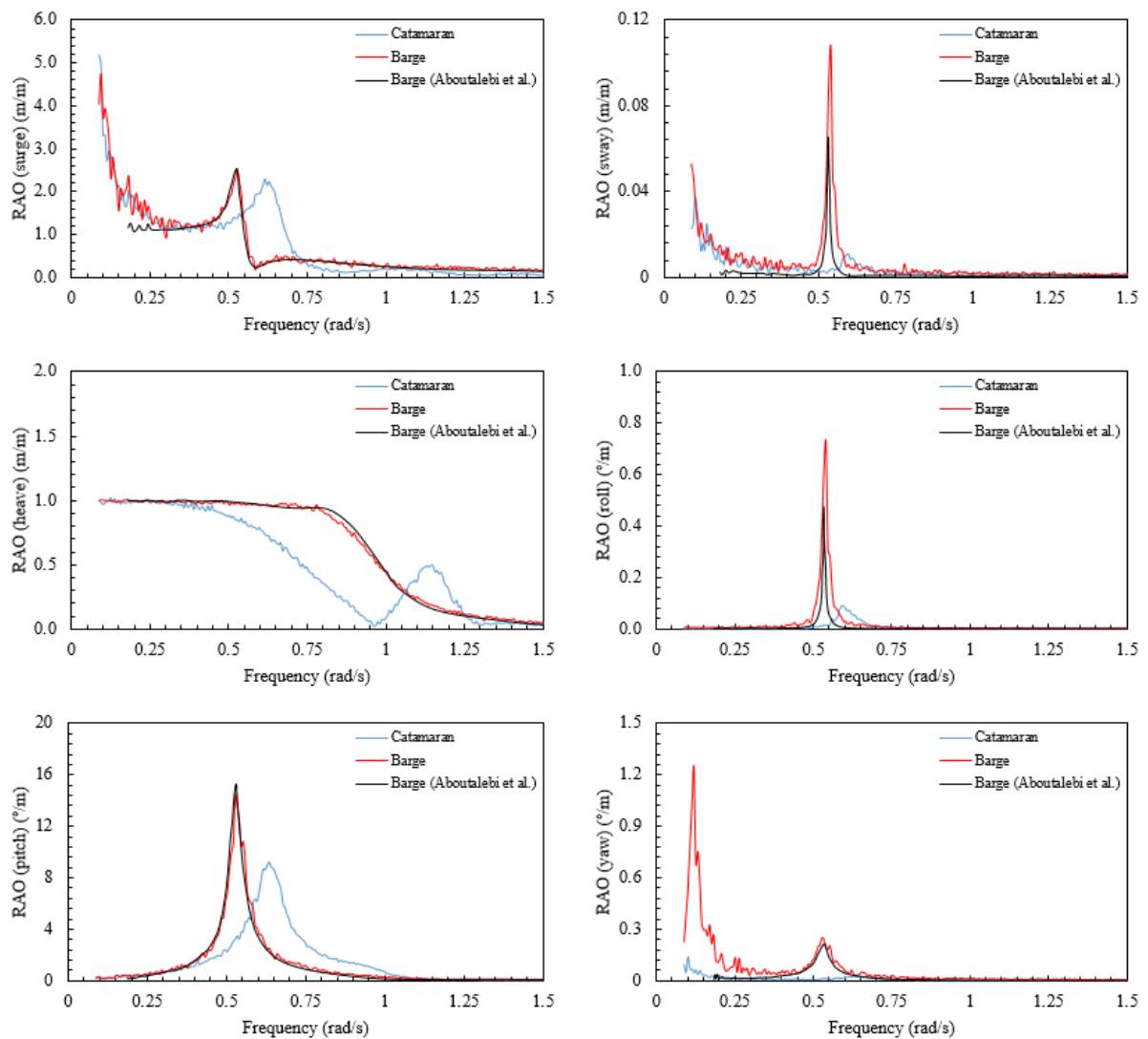


Figure 9. RAOs for 6 degrees of freedom of catamaran and barge platforms.

348 out whereas the catamaran experiences another peak. This peak corresponds to the frequency of the
349 standing wave created by the catamaran's demi-hulls.

350 For pitch mode, it is observed that the catamaran exhibits close to a 50 % reduction in response
351 compared to the barge. As mentioned above, the pitch resonance frequency of the catamaran is higher
352 than the barge. Also, the peak response of the catamaran has a wider band compared to the barge, which
353 means the catamaran is more responsive to a greater frequency range, whereas for the barge the peak
354 rises and falls more sharply.

355 **5.4.1 Varying angle of incidence wave**

356 The RAOs of the catamaran platform for varying angles of incident wave are plotted in **Figure 10**.
357 These results aim to provide a better understanding into the behaviour of the platform subject to wave
358 misalignment.

359 The response of the platform in surge and sway are similar in magnitude of peaks and shape. The
360 largest response occurs in wave heading angles parallel to the direction of motion i.e., 0° for surge and
361 90° for sway, and the smallest response occurs in wave heading angles perpendicular to the direction of
362 motion i.e., 90° for surge and 0° for sway. For sway mode, a small peak occurs at approximately 1.3
363 rad/s for a wave heading angle of 90°, this response is due to standing wave phenomenon between the
364 demi-hulls.

365 Considering the heave mode, in the frequency range 0.85 – 1.25 rad/s hydrodynamic interference
366 caused by the entrapment of wave between the two demi-hulls is prevalent. For a wave heading angle
367 of 90°, this phenomenon is most significant and has a maximum response of 1.8 m/m. At approximately
368 1.6 rad/s, another peak occurs which corresponds to the characteristic frequency for vertical plane
369 motions due to symmetric interaction.

370 Similarly, to surge and sway, roll and pitch follow the trend that the largest response occurs in wave
371 heading angles parallel to the direction of motion i.e. 0° for pitch and 90° for roll, and the smallest
372 response occurs in wave heading angles perpendicular to the direction of motion i.e. 90° for pitch and

373 0° for roll. One major difference is that the roll maximum amplitude is three times that of pitch; this is
374 because the catamaran is vessel-shaped and when exposed to oblique waves significant rolling can be
375 induced.

376 Considering yaw mode, for wave heading angles 0° and 90° there is insignificant response, and for
377 30° and 60° one peak and two peaks occur, respectively, explained by the characteristic frequencies for
378 horizontal plane motion due to antisymmetric interaction.

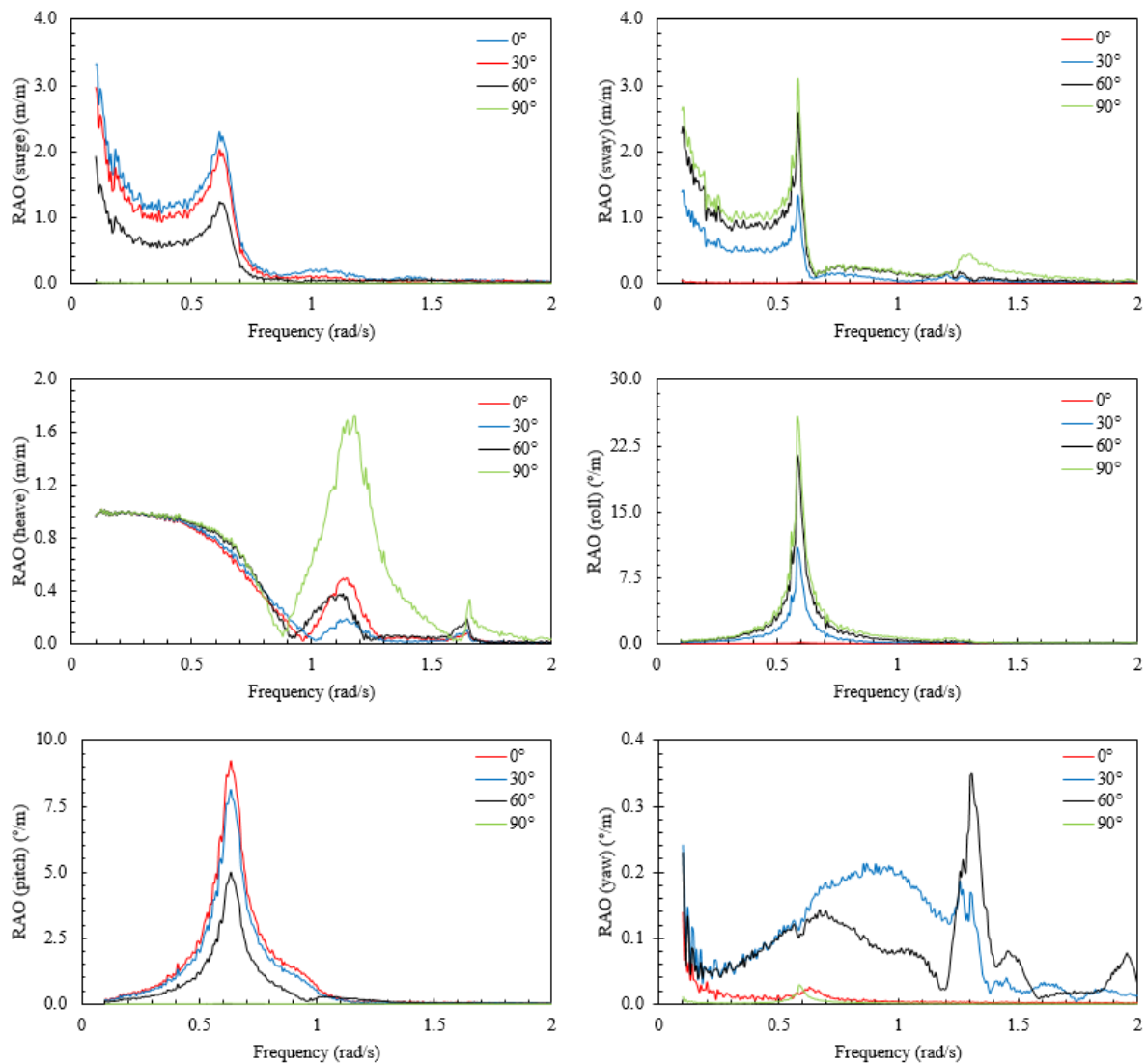


Figure 10. RAOs of catamaran for varying angle of incidence.

379 6. Dynamic Responses

380 6.1 Platform motions

381 The statistical motions of the two platforms are presented in **Table 6**. For LCs 1 and 2, the surge
 382 statistics are almost identical. Under LC 3, some differences are observed, it is predicted the catamaran
 383 has a smaller mean surge with greater fluctuation and a greater maximum surge. The highest mean surge
 384 for both platforms was predicted under LC 3, corresponding to the rated wind speed condition. A wind
 385 turbine operating at rated wind speed produces maximum rotor thrust (approx. 800kN for 5 MW wind
 386 turbine), which significantly influences the surge of FOWTs. Under LCs 4 - 5, the catamaran has a
 387 greater mean and maximum surge and increased fluctuation compared to the barge. Both platforms
 388 experience their greatest maximum surge under LC 5 because of the largest wave loads. For all five
 389 LCs, the heave statistics of the two platforms are indistinguishable apart from the maximum responses
 390 for the last 3 LCs. This was expected due to the comparable dimensions of the water plane areas.
 391 Considering pitch, for all LCs the catamaran platform has the smallest mean. The elongated geometry
 392 of the catamaran compared to the barge provides a greater restoring moment about the y-axis. The
 393 highest mean pitch response for both FOWTs is observed under LC 3. The fluctuation of the catamaran
 394 under LC 4 is noticeably greater compared to the barge. This is most likely due to combined wind and
 395 wave loading exciting the catamaran at its natural pitch period, nonetheless performance of the
 396 catamaran is good with a predicted mean pitch of 0.2° and maximum pitch of 8.52°.

397 **Table 6.** Statistical results of platform motion responses (1000 – 4600 s).

| LC | Type | Surge (m) | | Heave (m) | | Pitch (°) | |
|----|---------|-----------|--------------|---------------|--------------|--------------|--------------|
| | | Catamaran | Barge | Catamaran | Barge | Catamaran | Barge |
| 1 | Max | 16.96 | 16.35 | 0.066 | 0.300 | 0.314 | 1.025 |
| | Mean | 8.343 | 8.490 | -0.125 | 0.123 | 0.067 | 0.328 |
| | Std.dev | 2.734 | 3.198 | 0.059 | 0.059 | 0.080 | 0.179 |
| 2 | Max | 34.68 | 33.35 | 0.456 | 0.645 | 1.581 | 2.153 |
| | Mean | 22.25 | 22.32 | -0.115 | 0.115 | 0.295 | 1.094 |
| | Std.dev | 3.809 | 3.674 | 0.114 | 0.156 | 0.312 | 0.226 |
| 3 | Max | 48.14 | 45.52 | 0.410 | 1.149 | 2.936 | 3.826 |
| | Mean | 27.18 | 29.29 | -0.143 | 0.108 | 0.370 | 1.726 |
| | Std.dev | 11.31 | 7.050 | 0.151 | 0.308 | 0.712 | 0.545 |
| 4 | Max | 44.41 | 30.08 | 1.720 | 2.148 | 8.519 | 4.243 |
| | Mean | 21.92 | 19.30 | -0.134 | 0.118 | 0.200 | 0.997 |

| | | | | | | | |
|---|---------|--------------|--------------|---------------|-------|--------------|---------------|
| | Std.dev | 8.046 | 4.298 | 0.398 | 0.593 | 2.492 | 1.026 |
| | Max | 50.03 | 37.19 | 2.727 | 3.352 | 12.770 | 12.190 |
| 5 | Mean | 20.60 | 8.583 | -0.104 | 0.122 | 0.179 | 0.862 |
| | Std.dev | 10.78 | 11.53 | 0.733 | 0.895 | 4.046 | 3.775 |

(**BOLD** = minimum)

398

399 6.2 Time- & Frequency-domain results

400 The time- and frequency-domain platform responses of both models under LC 3 are presented in
 401 **Figures 11 & 12**. Considering time-domain platform responses, it is obvious the catamaran has
 402 increased fluctuation from mean surge compared to barge. The mooring system is mainly responsible
 403 for surge stability, therefore in future research the mooring system is one aspect that will be further
 404 investigated. Considering heave, the stability of the catamaran is excellent, whilst the barge experiences
 405 greater fluctuation. The mean pitch of the catamaran is smaller compared to the barge; however greater
 406 variation is observed. Even with increased fluctuation, the maximum pitch of the catamaran does not
 407 exceed $\pm 3^\circ$.

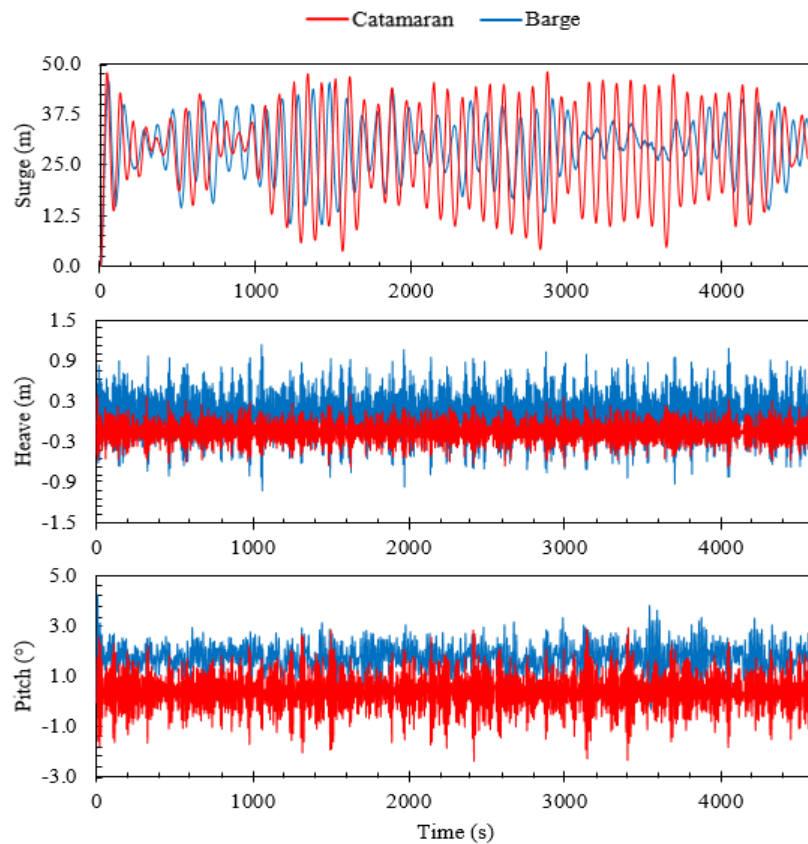


Figure 11. Time-domain responses of FOWT concepts under LC3 (rated wind speed).

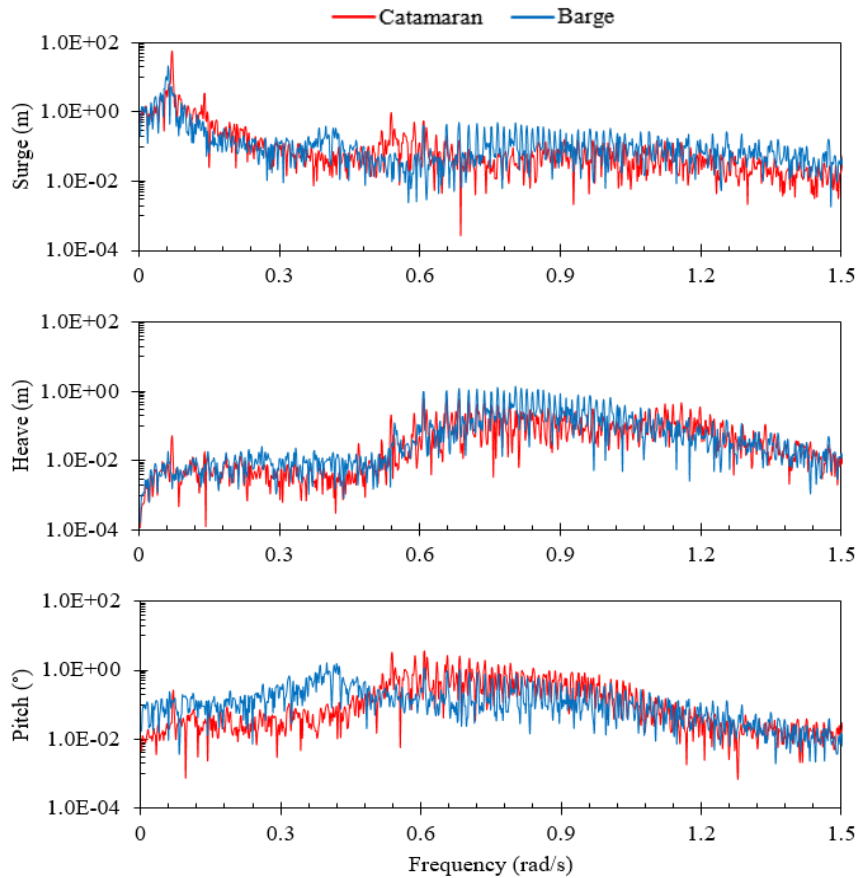
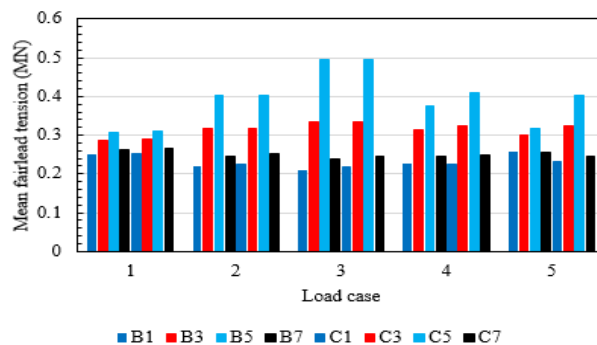


Figure 12. Frequency-domain (spectral) responses of FOWT concepts under LC3 (rated wind speed).

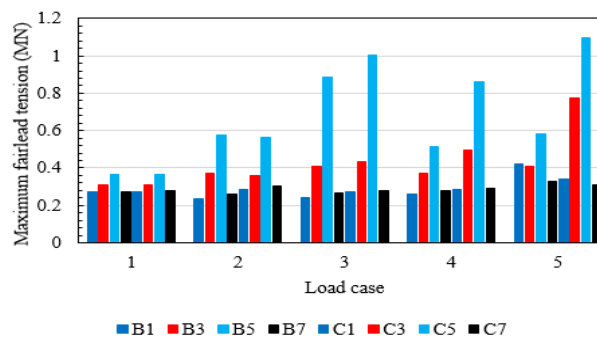
408 Considering frequency-domain platform responses, the amplitude of surge response in frequency-
 409 domain for the catamaran and barge platforms is dominant near 0.06 rad/s, corresponding to the resonant
 410 frequency of this mode for both platforms. Smaller peaks are observed at approximately 0.4 rad/s and
 411 0.54 rad/s for the barge and catamaran, respectively, which equate to the pitch natural frequency of each
 412 platform. The response suggests the coupling between surge-pitch for both platforms is somewhat
 413 small. Concerning heave, there is a limited response in lower frequency region. Peaks occur at 0.80
 414 rad/s and 1.14 rad/s, for the barge and catamaran, respectively, which is due to the heave natural
 415 frequency of the respective platform. Considering pitch, an obvious peak can be seen at approximately
 416 0.4 rad/s, which corresponds pitch resonant frequency of the barge platform. The pitch resonant
 417 frequency of the catamaran platform is approximately 0.54 rad/s and the amplitude of the peak is slightly
 418 higher compared to the peak at resonant frequency of the barge.

419 **6.3 Mooring line responses**

420 **Figures 13a) and 13b)** present the mean and maximum fairlead tensions of the two FOWTs. Both
 421 mooring system configurations use eight catenary lines to keep the platform in position. The symmetric
 422 nature of the mooring systems requires only certain mooring lines to be examined. Therefore, four
 423 mooring lines of the barge (MB1, MB3, MB5, MB7) and catamaran (MC1, MC3, MC5, MC7) mooring
 424 systems are selected. Due to incident waves, prevailing wind and rotor thrust all acting or travelling
 425 downstream, the fairleads upstream of the origin will experience the greatest tension. This is because
 426 such external forces cause the platform to drift downstream. As this happens, the mooring lines
 427 upstream will stretch increasing tension in the lines, in order to prevent drifting, whilst the mooring
 428 lines downstream will slack. Consequently, MB5 and MC5, exhibit the greatest tension. The barge and
 429 catamaran mooring lines have similar mean tensions under all LCs, except for mooring line MC5 in
 430 LCs 4 and 5 where MC5 is fractionally higher than MB5. Under these two LCs, the maximum tension
 431 of mooring line MC5 is approximately 1.5 times the tension of MB5 under LC4 and 2 times the tension



a) Mean fairlead tension.



b) Maximum fairlead tension.

Figure 13. Fairlead tension (MB1 = barge line 1, MC1 = catamaran line 1).

432 under LC 5. This can be explained by the large surge response of the catamaran platform under these
 433 two LCs.

434 6.4 Power production

435 The generator power statistics for LC 1 - 5 are charted in **Figure 14** and the time-domain generator
 436 power under LC3 is presented in **Figure 15**. For LC 1 – 2, the results are incomparable. Under LC 3 -
 437 5, the catamaran has greater maximum generator power but larger standard deviation, whilst the barge
 438 has greater minimum and mean generator power. In **Figure 15**, it can be seen both FOWTs follow
 439 similar trends for the entire simulation, however the barge has better quality power because of less
 440 fluctuation.

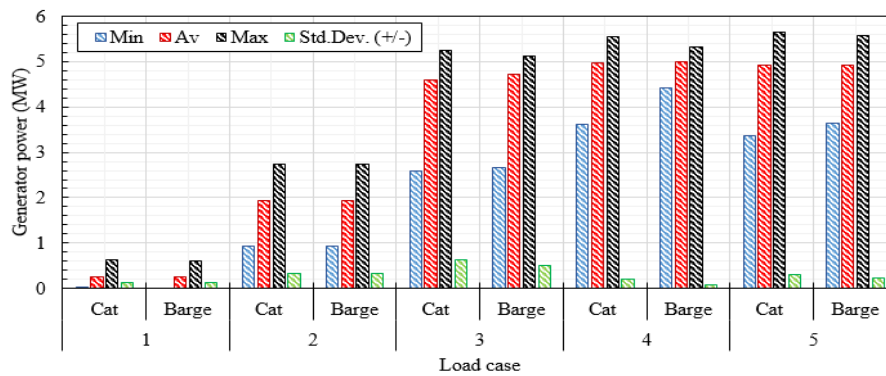


Figure 15. Comparison of generated power between catamaran and barge FOWTs.

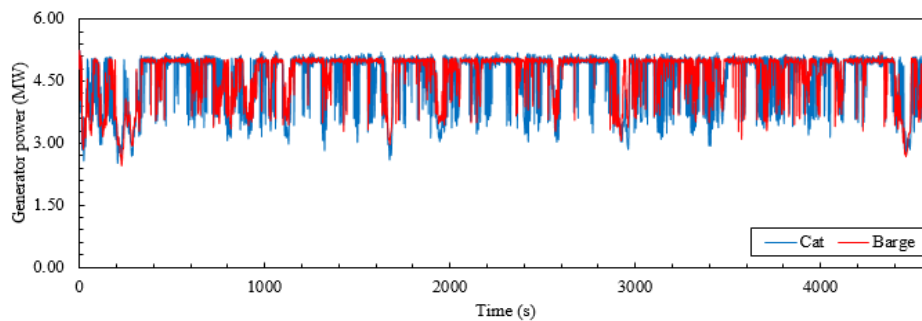


Figure 14. Generator power of the catamaran and barge FOWTs under LC3.

441 **6.5 Blade, rotor, and tower responses**

442 **Figures 16 & 17**, plot the rotor thrust, Out-of-Plane (O-o-P) blade-tip deflection and tower-base
443 bending moments of both platforms. Rotor thrust, O-o-P blade-tip deflection and Fore-Aft (F-A) tower-
444 base moment all follow a similar trend because of the direct and indirect influence of the incoming
445 wind. The rotor thrust, being the axial force, is applied by the wind kinematics on the wind turbine rotor
446 and it is the dominant load acting on each FOWT. The O-o-P blade-tip deflection is the result of wind-
447 induced force on the wind turbine blades. The F-A tower-base bending moment is mainly caused by the
448 rotor thrust and has the most prominent influence on stress at the tower base. The peak thrust acting on
449 both wind turbine rotors occurs under LC 3. This is also true for peak F-A tower-base bending moment
450 and O-o-P blade-tip deflection. Comparing the two FOWTs, for all LCs, the barge platform has higher
451 rotor thrust. Under LC 3, the barge and catamaran platforms have an approximate mean rotor thrust of
452 750 kN, and 700 kN, respectively, which is a difference of 7 %. The maximum rotor thrust of the barge
453 and catamaran is 1066 kN and 1123 kN, respectively. The mean F-A tower-base bending moment is 64
454 MN·m and 52 MN·m for the barge and catamaran, respectively, representing a difference of 23 %. The

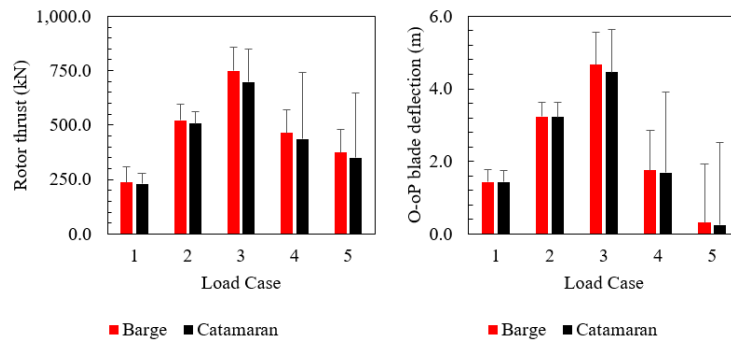


Figure 16. Comparison of mean rotor thrust and blade-tip deflection.

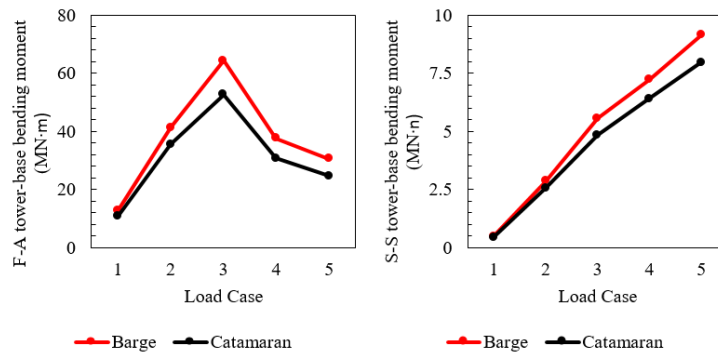


Figure 17. Comparison of barge and catamaran tower-base bending moments.

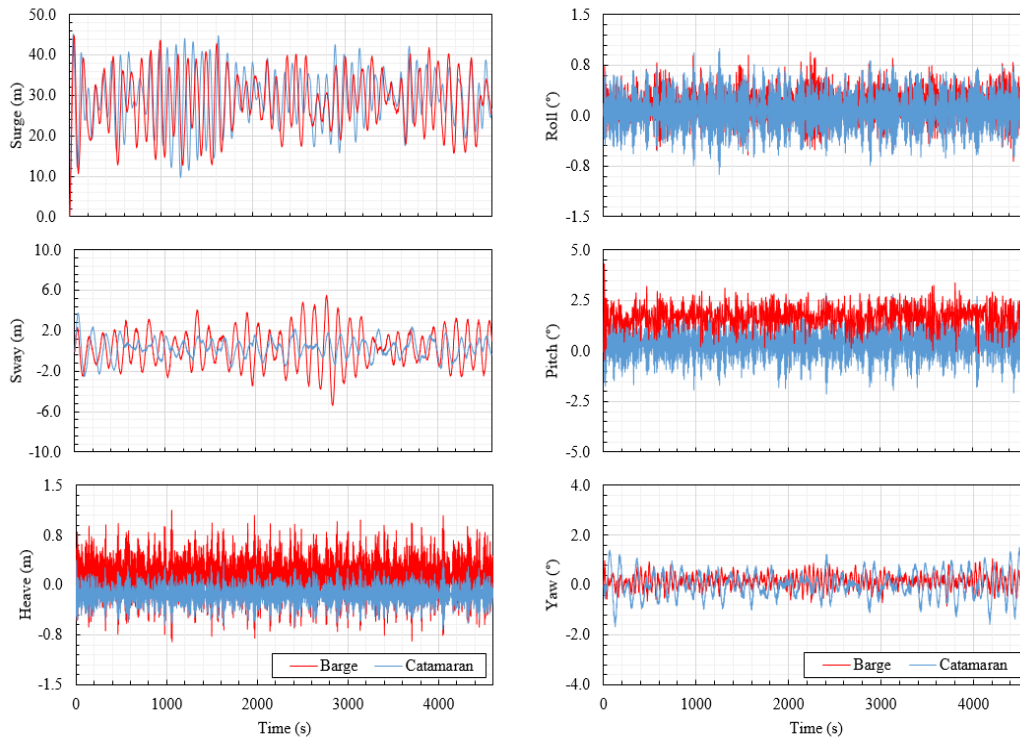


Figure 19. Time-domain platform motions under LC 6.

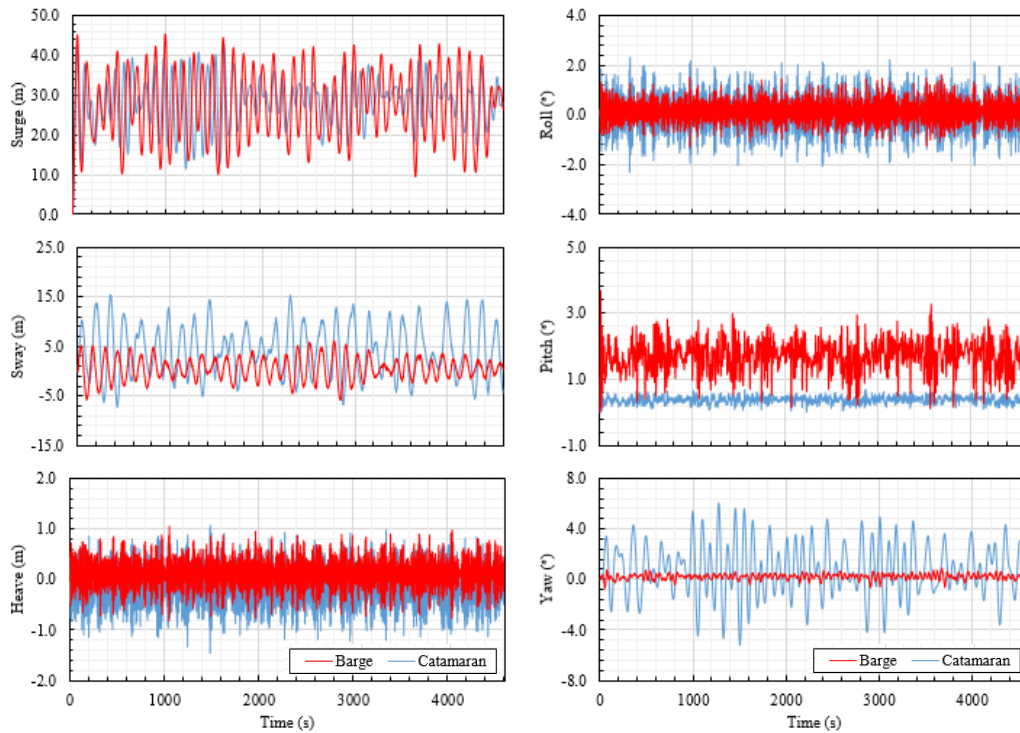
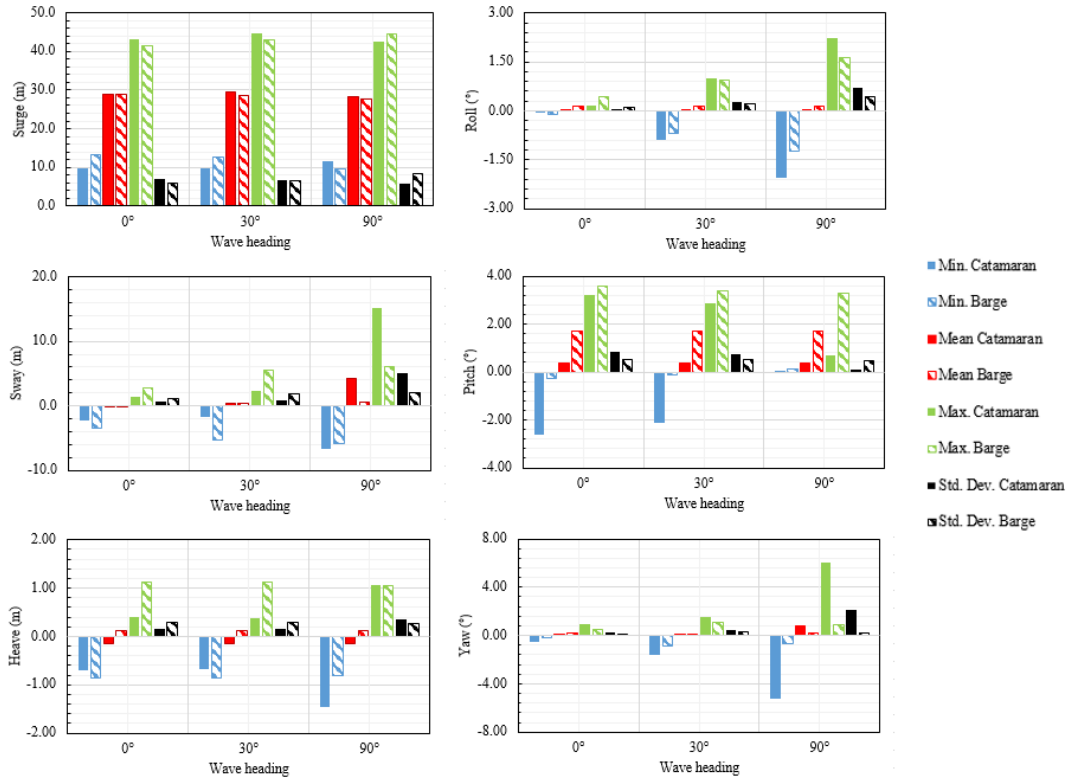


Figure 18. Time-domain platform motions under LC 7.

455 maximum F-A tower-base bending moment is 140 MN·m and 104 MN·m for the barge and catamaran,
 456 respectively. The mean O-o-P blade-tip deflection of both concepts for all LCs is similar. For LC 4 – 5,
 457 the standard deviation is higher for the catamaran compared to the barge. For all LCs, the barge has the



458 greatest side-side (S-S) tower-base bending moment, which stems from the tangential forces, or
 459 aerodynamic drag, that tend to bend the blades and tower in the rotor plane. Comparing the two
 460 platforms, the differences in the first two LCs are insignificant. For LC 3 - 5, there is approximately a
 461 15% difference between the S-S tower-base bending moments of the barge and catamaran platforms.

462 6.6 Incident wave angle at 30° and 90°

463 This next section presents and discusses the results of LC 6 - 7 which were simulated to investigate
 464 the dynamic responses, in terms of platform motions, mooring line tensions, produced power and tower-
 465 base bending moments, of the two FOWTs when the alignment between the incoming wind and waves
 466 change.

467 6.6.1 Platform motions

468 **Figures 18 & 19** compare the platform motion time histories of the two platforms under LC 6 – 7,
 469 and **Figure 20** charts the platform motion statistics. Considering surge, the mean of both platforms is
 470 similar for all wave headings which is approximately a 25-30 m offset. As the wave heading angle goes
 471 around the compass, the variation in surge of the catamaran reduces whereas for the barge it increases.
 472 For sway mode, this is mirrored with the catamaran fluctuating more compared to the barge. However,

473 the amplitude of catamaran sway when the waves are incoming at 90° is reasonable with a maximum
474 amplitude of 15 m. The heave response of the barge is similar for all wave headings, meanwhile the
475 variation in heave response of the catamaran noticeably increases when the waves are incoming
476 perpendicular to wind inflow. This is due to entrapped water between the demi-hulls amplifying the
477 heave response as discussed in the previous sections. A maximum heave of 1.5 m is observed which
478 means the effect of this dynamic amplification is insignificant. For roll and pitch motion of the
479 catamaran similar but opposite trends occur. The roll response increases whilst pitch response decreases
480 as the wave heading angle increases towards 90°. The roll behaviour of the barge is similar to the
481 catamaran; however, the pitch behaviour is slightly different in that the response is nearly identical for
482 varying wave headings. This suggests the pitch response of the barge is dominated by wind loading
483 whilst the catamarans pitch response is dependent on wave loading. The yaw response of the catamaran
484 when the wave heading is 90° is much larger compared to the barge. This is because the catamaran is
485 much longer which means it will tend to yaw with incident waves perpendicular to the x-axis. **Figure**
486 **20** and **21**, shows the effect of yawing on power generation for the catamaran. When the platform is
487 positioned directly facing the incoming wind, the power produced is 4.9 MW. This is the maximum
488 power the turbine can produce given its efficiency. When the platform is yawed 5°, 10°, and 15°, the
489 produced power is 4.85 MW, 4.71 MW, and 4.50 MW, equating to a reduction of 1%, 3.82%, and 8%
490 in generated power, respectively. Therefore, it can be said that if the platform does not yaw more than
491 15°, then reduction in power cannot exceed 8%, and for 10°, 3.82% and for 5°, 1%. Under LC 7, the

492 catamaran only experiences a maximum yaw of 6° during the one-hour simulation for a brief period of
493 time which means that the produced power is not significantly affected.

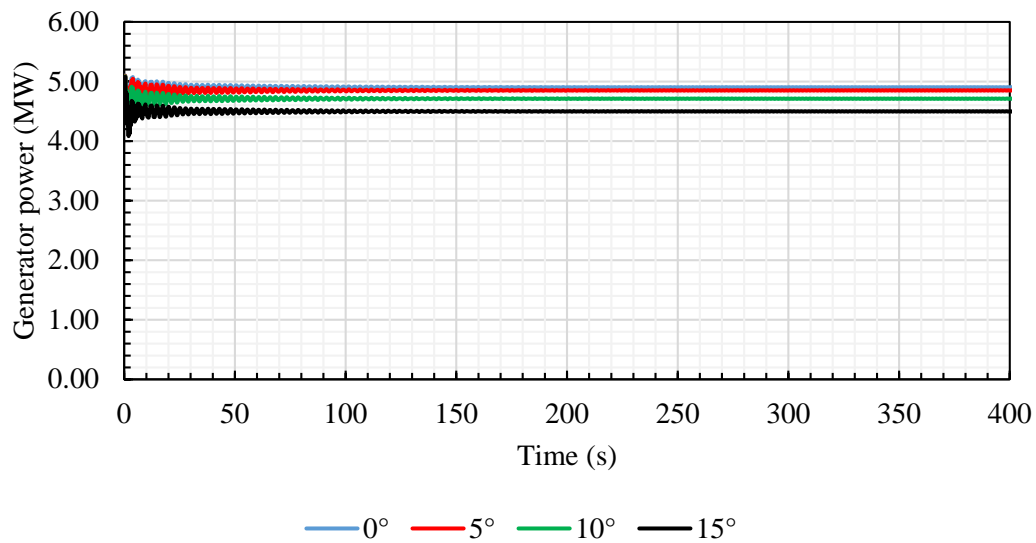


Figure 20. Effect of yawing on power generation.

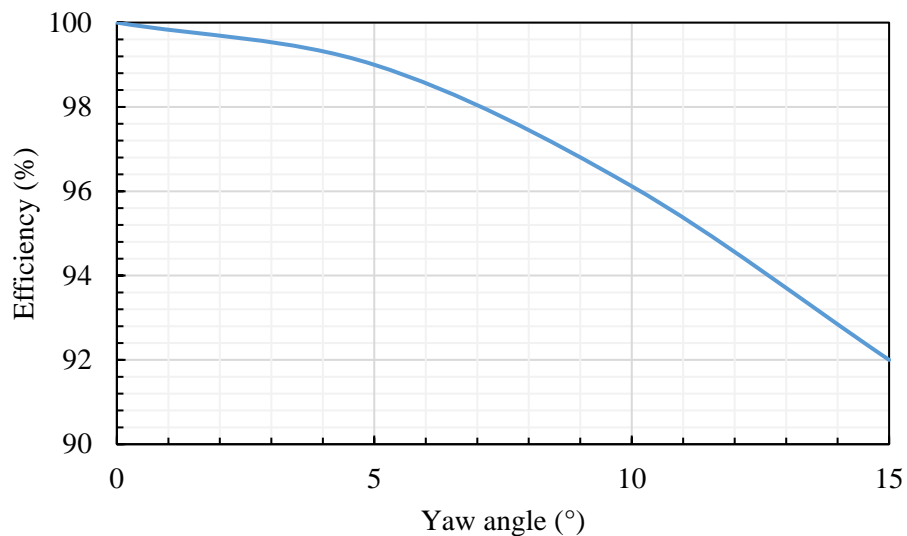


Figure 21. Wind turbine efficiency vs platform yawing.

494

495 6.6.2 Mooring tensions

496 **Figure 22** compares the time-domain fairlead tensions of both platforms under LC 6 – 7.
497 Considering LC 6, there is negligible differences in the fairlead tension of all mooring lines between
498 both platforms. The maximum fairlead tension is approximately 0.84 MN. Under LC 7, the waves are

499 incoming perpendicular to the direction of wind flow. The surge response for the catamaran under this
 500 load case reduces. As a result, the predicted maximum fairlead tension is lower. Conversely, the surge
 501 response of the barge is similar for both load cases and the mooring line tension follows a similar trend
 502 in both simulations.

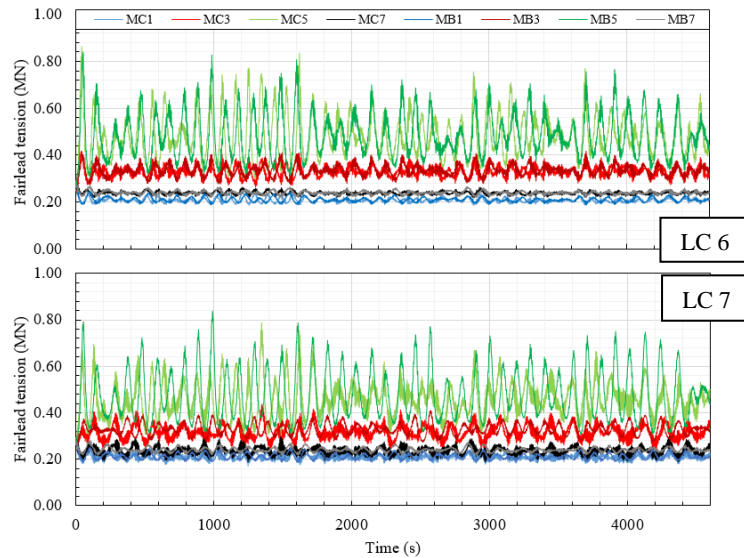


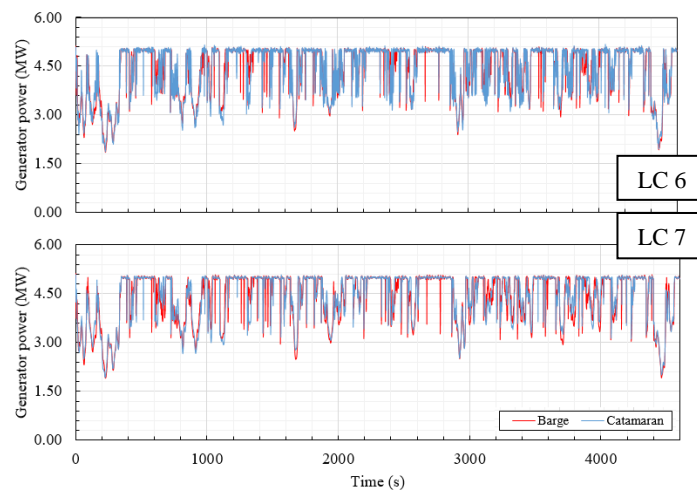
Figure 22. Time-domain fairlead tensions under LC 6 - 7.

503 6.6.3 Power production

504 **Table 7** tabulates the power production statistics under LC 6 – 7, whilst **Figure 23** graphs the
 505 generator power time histories of both platforms. From **Table 7**, it can be said that the quality of power
 506 produced by the catamaran improves as the misalignment between the incoming wind and waves
 507 increases up to 90°. This is because the minimum and mean power produced increases whilst the
 508 standard deviation decreases. The maximum produced power also decrease however, this is by a small
 509 amount. On the other hand, the quality of power produced by the wind turbine supported by the barge
 510 is constant for all wave heading angles. Subject to LC 6 **Figure 21** shows the produced power by the
 511 wind turbines supported by operate similarly. Under LC 7, the power generated by the wind turbines
 512 follow a similar trend, however the power produced by the wind turbine supported by the catamaran
 513 platform is of better-quality power due to less fluctuation.

Table 7. Power production of both platforms under varying wave headings.

| | 0° | | 30° | | 90° | |
|-----------|-----------|----------|-----------|----------|-----------|----------|
| | Catamaran | Barge | Catamaran | Barge | Catamaran | Barge |
| Min. | 1.961 | 1.967 | 1.955 | 1.933 | 2.007 | 1.917 |
| Mean | 4.507389 | 4.52403 | 4.520281 | 4.523217 | 4.542581 | 4.518437 |
| Max. | 5.184 | 5.125 | 5.18 | 5.111 | 5.085 | 5.09 |
| Std. Dev. | 0.711707 | 0.673443 | 0.694152 | 0.672026 | 0.648891 | 0.674523 |

**Figure 23.** Time-domain generator power of both platforms under LC 6 - 7.

515 **6.6.4 Tower-base bending moments**

516 **Figure 24** presents the tower-base bending moments about the x- and y-axis of both platforms for
517 30° and 90° wave headings. The results show that the bending moments at the tower-base of the wind
518 turbine supported by the catamaran are smaller and experience less fluctuation compared to the barge
519 for both wave headings. In addition, as the misalignment between the incoming wind and waves
520 increase, the bending moments about the y-axis decreases whilst the bending moment about the x-axis
521 increases for both platforms. This as expected as the wave hydrodynamic loading is the dominant
522 loading.

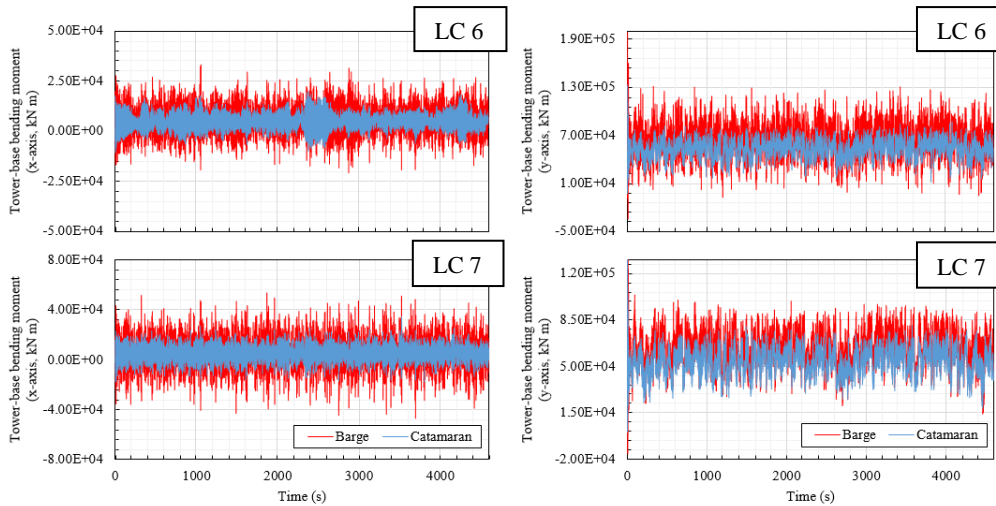


Figure 24. Time-domain tower-base bending moments of both platforms under LC 6 - 7.

523 7. Conclusions

524 The hydrodynamic characteristics and dynamic responses of a novel catamaran FOWT operating
 525 in intermediate water depth are assessed, and the results are compared with a well-known barge FOWT,
 526 the ITI Energy barge. The FOWTs are modelled using OpenFAST and ANSYS AQWA numerical tools
 527 coupled via a DLL, namely F2A, to conduct efficient fully coupled aero-hydro-elastic-servo
 528 simulations. The current research has revealed advantages which a catamaran-type floater has over a
 529 conventional barge-type floater. Firstly, the catamaran has a large deck area; this can be used for other
 530 functions such as marine power generation, solar panels, or hydrogen conversion. If utilised properly
 531 the additional functionality would ultimately lead to cost reductions. Secondly, evaluation of
 532 hydrodynamic characteristics has shown that the catamaran has better hydrodynamic performance over
 533 the barge. The catamaran platform has higher sway, roll, pitch, and yaw hydrodynamic coefficients
 534 compared to the barge. This mean the catamaran floater has increased hydrodynamic restoring stiffness
 535 and damping for these modes of motion. The hydrodynamic coefficients also revealed that a catamaran
 536 responds distinctively at certain frequencies for vertical and horizontal plane motions due to symmetric
 537 or anti-symmetric interaction, respectively. These frequencies are analogous to the resonant modes of
 538 a standing wave between two vertical walls. Moreover, the frequencies are characteristic to the
 539 individual platform and depend on demi-hull separation. Findings from the free decay results showed
 540 that the catamaran floater increased natural damping in the system for roll and pitch, and especially for
 541 pitch damping was increased considerably. This was confirmed in the RAO analysis; the amplitude

542 observed at the pitch natural frequency of the catamaran floater was reduced by 50% compared to
543 amplitude observed at the pitch natural frequency of the barge. The time-domain simulations showed
544 the response of both platforms were similar for simulated conditions, and that the expected
545 improvement in pitch stability was not necessarily reflected. The reason for this was that the simulated
546 wave periods coincided with the natural pitch period of the catamaran which amplified the platform's
547 dynamic response. Nevertheless, the pitch response of the catamaran was similar to that of the barge.
548 The fact that the catamaran behaves similarly to the barge whilst being excited at its natural frequency
549 highlights the platform's good hydrodynamic performance. One future avenue for research could be
550 how the geometric characteristics of the catamaran floater affect its pitch natural period. The results of
551 this study also showed that the catamaran floater had reduced tower-base bending moments (both F-A
552 and S-S) for all simulated conditions. For rated wind speed (LC 3) and corresponding wave condition,
553 the F-A tower-base bending moment was reduced by 22%. Considering this research was a preliminary
554 investigation into catamaran-type floaters and the design was a first iteration, there is clear evidence
555 that a catamaran floater has advantages over a conventional barge. With optimization and further
556 concept development, it would be anticipated that the performance can be further enhanced which
557 makes this a promising concept to support a wind turbine in intermediate water depths.

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