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SEAKEEPING BEHAVIOR OF HEXAGONAL CATAMARAN HULL FORM AS AN ALTERNATIVE GEOMETRY DESIGN OF FLAT-SIDED HULL VESSEL

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The Flat-sided Hull Vessel was introduced to simplify and create an efficient ship production process by eliminating the fairing work, bending, and curved panel line assembly. The built process simplification is expected that the FSHV can be produced by the traditional boat yard. However, the flat hull concept has slightly increased resistance performance. Therefore, implementing a resistance reduction device is endorsed to improve the boat's performance. The focus of the research is to identify the influence of the flat hull concept on seakeeping behavior. The hexagonal catamaran hull form was developed on the deadrise angle, angle of attack, and stern angle variation. Furthermore, the response amplitude operator and the motion spectral density of heave, roll, and pitch motion were calculated. Otherwise, the seakeeping performance of the hexagonal catamaran is compared to the original rounded catamaran. The results show that the hexagonal catamaran hulls have better seakeeping performance in the Beam Sea. However, the conventional catamaran has demonstrated superiority over the hexagonal catamaran in the Bow Quartering and Head Sea conditions.

Keywords: hexagonal catamaran, seakeeping performance, deadrise angle, angle of attack, stern angle

1 INTRODUCTION

Flat-sided Hull Vessel (FSHV) was introduced with novelty to eliminate all curves shaped in the vessel hull form. Removing bending and fairing work can reduce the production cost and delivery time. Flat-sided hull vessels consist of flat plates that are carefully arranged on the lines of the streamlined hull body. The arrangement of the flat plate's interconnection is lined by limiting the angular values between the two connected flat plates. Although the Flat-sided hull design looks unusual and worries many ship owners, the FSHV hull form has shown an acceptable hydrodynamic performance [1].

Gallin [1] presented that the propulsion power of FSHV is nearly similar to the equivalent rounded hull form. The "Basic Pioneer," designed by Blohm and Voss of Hamburg, has shown a propulsion power difference of 5.5% at the service speed. Moreover, the second vessel, "Container Pioneer," performed a propulsion power value close to the rounded hull. These results indicated that the FSHV hull form is not inferior to the rounded hull form. Unfortunately, although 15 ships of FSHV have been built, the shipowners are still reluctant to adopt it due to the unconventional hull form. Otherwise, Germany's wage level was significantly higher than that of the other countries at that time. Therefore, reducing production costs cannot improve the shipyard's competitiveness worldwide.

In recent decades, the efforts to explore the Flat-sided Hull concept as an alternative hull form have pointedly grown in Indonesia. Wibowo and Talahatu [2] began to adopt the FSHV hull concept on the small boat for fishing activities. The boat prototype was built with a length between perpendiculars of 7 meters and 2.6 meters in width. It is stated that the FSHV hull design is reliable enough to support traditional fishing activities. Furthermore, the FSHV boat investment can be funded and supported by banks and an insurance company. These benefits allowed the artisanal fishers to have better opportunities to support their professional activities. Therefore, the Indonesian government has enthusiastically supported the development of the Flat-sided Hull boat, especially for fishing activities.

Putra et al. [3] presented the intact stability characteristics of a semi-trimaran flat hull ship. The inclining test was conducted and compared to the numerical estimation. The result showed that the semi-trimaran Flat-sided Hull ship complies with IMO criteria. The maximum righting lever of the vessel was 1.377 m at 57.3 degrees of heeling angle. The numerical simulation also presented a good agreement with the experiment result. This study concludes that the semi-trimaran FSHV has good intact stability characteristics.

Syahril and Nabawi [4] investigate the effect of bow shapes on the resistance performance of the FSHV vessel. Four kinds of bow shapes, including Raked Bow, Maier Form Bow, Raked Bow II, and Plumb Bow, have been adopted as the fore part of the FSHV vessel. The results showed that the Raked Bow type has the lowest resistance. The Maier Bow type has similar resistance behavior to the Raked Bow II. Furthermore, the highest resistance was performed by the Raked Bow II. The study has indicated that bow-shape design influences the resistance behavior of FSHV.

The other study focused on the FSHV vessel's investment feasibility for public marine transportation. Guswondo [5] presented the net present value of the general cargo FSHV vessel. The break-even point of the investment of the ship is 393 trips, equivalent to 6 investment years. Astiti [6] presented that acquiring FSHV is feasible and reliable for the public shipping fleet. The application of FSHV is adopted as a surrogate for the traditional wooden boat fleet.

Furthermore, the investment feasibility of the FSHV catamaran yacht shows that the vessel is feasible for tourism and leisure activities with a carrying capacity of 20 passengers [7].

Fig. 1 The "Cucut Nusantara" Flat-sided Hull boat developed by the University Indonesia and Juragan Kapal Indonesia Corp [8]

In 2019, the remarkable event was that the Minister of Research, Technology, and Higher Education opened the launching ceremony of the 28 gross tonnages (GT) FSHV fishing boat, "Cucut Nusantara," developed by the University of Indonesia and Juragan Kapal Indonesia Corporation [8]. The principal dimension of the 28 GT fishing boat is 15.5 meters in length and 4 meters in width, Fig 1. Furthermore, the vessel is claimed to be more efficient than glass fiber reinforced polymer (GFRP) and wooden boats.

Regarding the "Cucut Nusantara" success story of reducing production costs, the FSHV research has been focused on improving resistance performance. Some literature might be found on the effort to reduce hull resistance behavior. Initially, modifying the hull geometry through an optimization hull form design to achieve an optimum resistance [9]–[11]. Otherwise, the adoption of resistance reduction devices such as hydrofoil [12], hull vane [13]–[15], stern foil [16]–[18], and stern flap [19]–[23] to generate an improved thrust power.

In the scope of FSHV hull design, Nabawi et al. [24] investigate the influence of the hull vane and the stern foil on the resistance reduction of the Semi-Trimaran FSHV vessel. The original FHSV semi-trimaran's resistance behavior was compared to the hull installed with the hull vane and the stern foil. According to the computational result, it can be found that a significant reduction was performed in the Froude number of 1.1. Furthermore, the hull vane and the stern foil can reduce the hull resistance by 12.44% and 5.25%, respectively.

Although the flat hull concept offers a simplified ship production process by eliminating the plate fairing, bending, and curved panel assembly, it might increase the resistance behavior compared to the rounded hull. Since the flat hull geometry has influenced the resistance performance, the hull design might affect the seakeeping behavior. Therefore, it is essential to investigate the effect of the flat hull concept on the seakeeping behavior. Heave, roll, and pitch motion characteristics will be compared to the original rounded boat. It will be shown that the response amplitude operators (RAO) of ship motions are suggestively different due to the flat hull modification.

In the following, the hexagonal catamaran conceptual design was developed with the configuration of the deadrise angle, angle of attack, and stern angle. The influence of the design parameters on the seakeeping performance is investigated. The seakeeping performance analyses were conducted with the defined service speed of 15 knots. Moreover, the seaway environment has been determined using the JONSWAP wave spectrum. The results and discussion presented the seakeeping characteristics of each design configuration. Afterward, the developed hexagonal catamarans' seakeeping performance was compared to the original hull design. Finally, the conclusion and recommendation for adopting the flat-hull concept as the catamaran hull design is provided.

2 MATERIALS AND METHODS

2.1 Descriptions of the Hexagonal Catamaran Hull Form

In the previous study [25], the rounded catamaran was developed with the variation of demi hull spacing (s/L 0.17 – 0.4). The rounded catamaran principal dimension has been defined with the comparison method on 15 existing catamaran data as the parent model to formulate the regression equation, Table 1. Furthermore, the original hull design was modified using a flat hull concept to become the hexagonal catamaran hull. The developed hexagonal catamaran hull is configured with the variation of the deadrise angle, angle of attack, and stern angle. It is defined that the configuration of the waterline angle of attack (α) was 17.38°, 21.01°, and 26.43°. Initially, this angle is determined based on the angle formed by the tangent of the conventional catamaran hull. Further modifications are made by increasing the angle through the addition of a tangent point distance of 2m and 4m. As for the deadrise angle, modifications were made by increasing the height of the hull side base point by 1m and 2m, resulting in deadrise angle values of 0°, 16.48°, and 30.61°. Furthermore, the last configuration is the stern angles (γ) that have been defined at narrow-angle (γ = 10.75°), the same magnitude as the angle of attack (γ = α), and flat stern (γ = 90°). The smallest stern angle is an angle which is generated from the defined stern length as 20% waterline length. The 3D illustration of the hexagonal catamaran hull form design can be seen in Fig. 2. Regarding the design parameters, 27 hull form designs should be investigated for their seakeeping behavior. The detailed design configurations are inTable 2, B (Bow/Angle of attack), F (Floor/deadrise angle), S (Stern angle).

Table 1. The principal dimension of the developed catamaran hull form

Principal Dimension	Units
Length Between Perpendicular	85.90 m
B Demihull	6.77 m
Demihull Spacing	14.2 m
Depth	9.71 m
Draft	5.74 m
Speed	17 knots

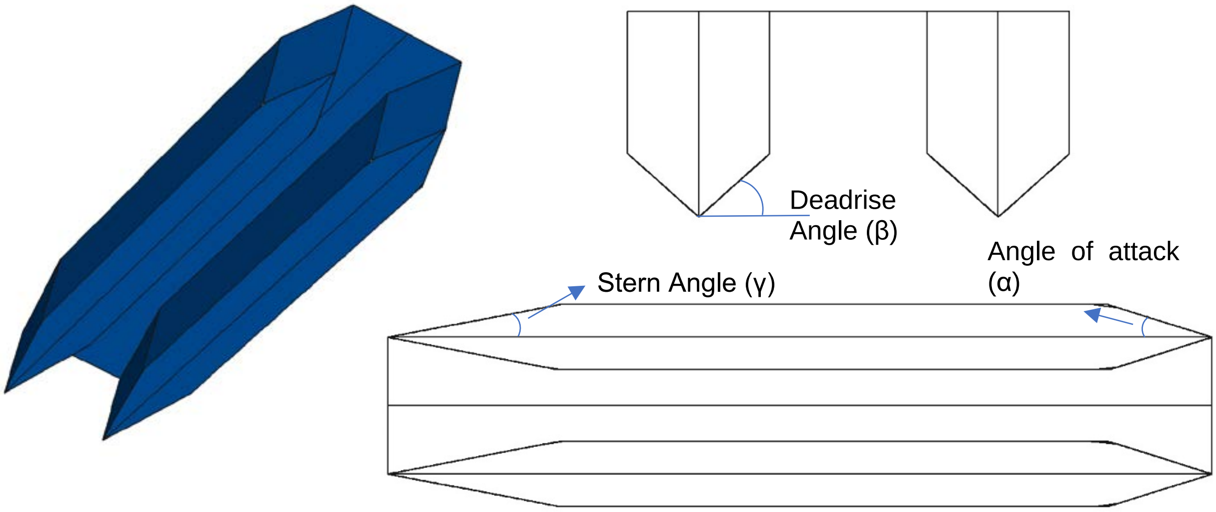


Fig. 2 The hexagonal catamaran hull form 3D illustration and the modified design geometry parameter: attack angle (α), deadrise angle (β), stern angle (γ)

2.2 Seakeeping Analysis of the Hexagonal Catamaran

Seakeeping analysis can estimate a ship's motion behavior, such as a heave, roll, and pitch, and the effect on the passenger and crew comfortability in the seaway's environment. Furthermore, an adequate seaway environment formulation is needed for the numerical seakeeping estimation. Several wave spectrum formulations have been found to represent the irregular sea environment. The available wave spectrum models for the seakeeping calculation are JONSWAP, Bretschneider (ITTC), Pierson-Moskowitz, and the Ochi-Hubble. Therefore, a suitable wave spectrum should represent the fishing boat's operational environment. Otherwise, the ship's motion characteristics are also influenced by the hull form and weight distribution.

Several studies have investigated the appropriate wave spectrum type for seakeeping analysis concerning the operational environment in the Indonesian territorial sea. The JONSWAP spectrum is suitable for representing the wave characteristics in the South Java Island region and the West Sumatera Island region [26]. In the other study, Zakki et al. [25] selected the JONSWAP for the seakeeping characteristics assessment of the catamaran fish processing vessel. Iqbal and Rindo [27] have adopted the ITTC spectrum for the inter-island seaways characteristics in Indonesia. Furthermore, Adrianto et al. [28,29] have shown that the Ochi-Hubble spectrum is presented as suitable for Indonesia sea territory because the wave characteristics measurement has delivered a result with double peak spectrum characteristics.

This research has selected the JONSWAP spectrum because the hexagonal catamaran seakeeping behavior would be compared with the previously rounded catamaran estimated using the wave spectrum. The significant wave height was 3 meters with a modal period of 9.984 seconds. The zero-crossing period was 7.868 seconds, and the peak enhancement factor was 3.30. A detailed description of the JONSWAP formulation can be found in [30].

Table 2. The design configuration of the hexagonal catamaran

No	Design code	(α) angle of attack	(β) deadrise angle	(γ) stern angle
1	B1F1S1	17.38°	0°	10.75°
2	B1F1S2			17.38°
3	B1F1S3			90°

No	Design code	(α) angle of attack	(β) deadrise angle	(γ) stern angle
4	B1F2S1		16.48°	10.75°
5	B1F2S2			17.38°
6	B1F2S3			90°
7	B1F3S1		30.61°	10.75°
8	B1F3S2			17.38°
9	B1F3S3			90°
10	B2F1S1	21.01°	0°	10.75°
11	B2F1S2			21.01°
12	B2F1S3			90°
13	B2F2S1		16.48°	10.75°
14	B2F2S2			21.01°
15	B2F2S3			90°
16	B2F3S1		30.61°	10.75°
17	B2F3S2			21.01°
18	B2F3S3			90°
19	B3F1S1	26.43°	0°	10.75°
20	B3F1S2			26.43°
21	B3F1S3			90°
22	B3F2S1		16.48°	10.75°
23	B3F2S2			26.43°
24	B3F2S3			90°
25	B3F3S1		30.61°	10.75°
26	B3F3S2			26.43°
27	B3F3S3			90°

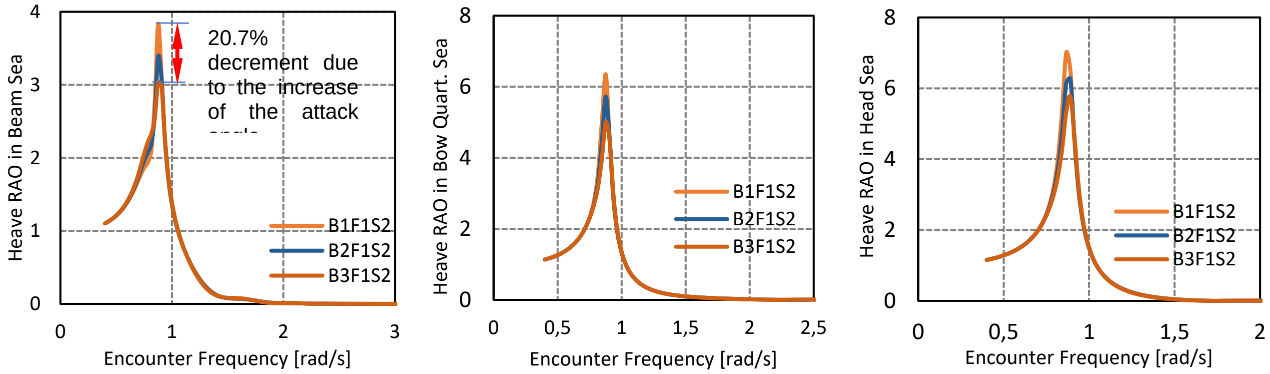
3 RESULTS AND DISCUSSIONS

The motion behavior has been estimated using the strip theory method. This method adopted the Neuman-Kelvin formulation for the slender body. The hull form is divided into several stations that are considered hydrodynamically as some entities of an infinite floating body. The strip theory can be applied to the floating body with a length-to-breadth ratio of more than three (L/B > 3). Otherwise, this requirement complies with the hexagonal catamaran hull forms with a length-to-breadth ratio 5.2.

Regarding the influence of design parameters on the motion characteristics of the hexagonal catamaran, the response amplitude operator (RAO) was calculated on each ship's motion, namely heave, pitch, and roll. The response amplitude operator is a transfer function that transforms the selected wave spectrum into the motion response spectrum. Therefore, the response amplitude operators (RAO) might describe the floating body response sensitivity to an external environment excitation. Otherwise, the motion response spectra represent the ship's motion characteristics. Moreover, the seakeeping calculation was conducted with three wave heading types: 90°, 135°, and 180°. The defined wave heading represents the Beam Sea, Bow Quartering Sea, and Head Sea environment.

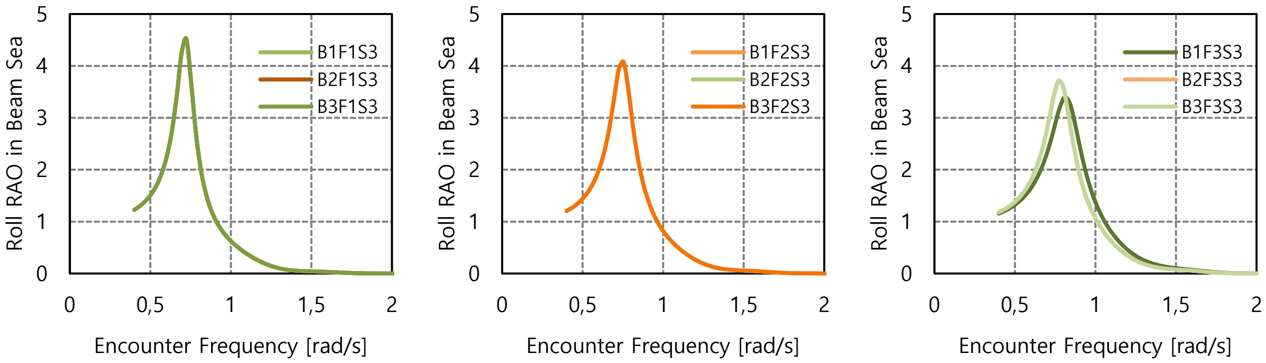
3.1 The influence of the angle of attack on the seakeeping behavior

There are 216 computational RAO data results to represent the seakeeping behavior of the 27-design configuration of the hexagonal catamaran in the wave heading angle and the motion type variation. In the case of the heave motion, the heave RAO has shown that the angle of attack influences the heave motion behavior. Furthermore, it can be identified that the larger angle of attack might reduce the peak point of the RAO. The most significant decrement of the peak point is 20.7%. It is shown on the flat deadrise angle hull (β =0°) with the stern angle equal to the attack angle (γ = α), Fig. 3a. Therefore, it can be identified that the larger angle of attack might reduce the wave effect on the heave motion. Furthermore, the decrement trend due to the increase of the attack angle is also identified on the other wave heading angle (Bow Quartering and Head Sea), Fig. 3b-3c.



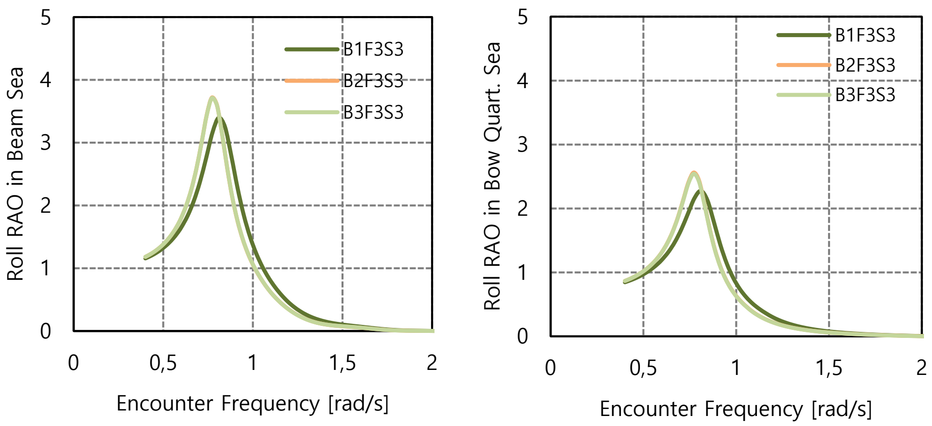
[a] [b] [c]

Fig. 3. The influence of the attack angle on the heave RAO of the Hexagonal Catamaran (β=0°, γ=α) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea; [c] Head Sea



[a] [b] [c]

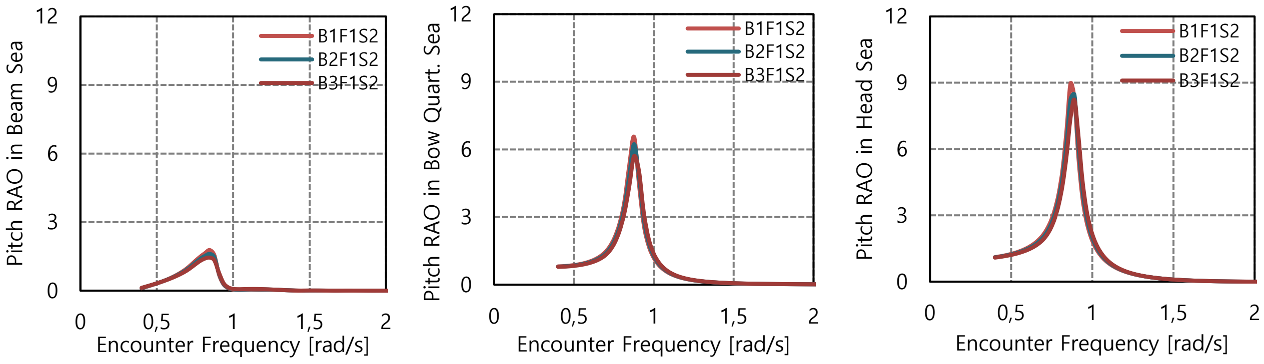
Fig. 4. The influence of the attack angle on the roll RAO in Beam Sea: [a] β=0°, γ=90°; [b] β=16.48°, γ=90°; [c] β=30.61°, γ=90°



[a] [b]

Fig. 5. The influence of the attack angle on the roll RAO of the Hexagonal Catamaran (β=30.61°, γ=90°) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea

The angle of attack does not significantly influence the RAO peak point on the roll motion, Fig. 4. Due to the modified attack angle, almost all design configurations have shown no deviations on the RAO curve line. However, the shifted RAO curve line remains on the flat stern angle hull with the most significant deadrise angle (β = 30.61°), Fig.4c. Furthermore, the larger attack angle has contributed to an increase in the roll RAO peak point. Therefore, it is indicated that the smaller attack angle would have reduced the roll RAO peak point while the deadrise angle was relatively large (β ≥ 30.61°) and the stern tip was flat (γ =90°). Otherwise, the attack angle also shifted the encounter frequency of the peak point, Fig. 4c. Instead of the Head Sea condition, a similar tendency was also presented on the different wave heading angles, Fig. 5.



[a] [b] [c]

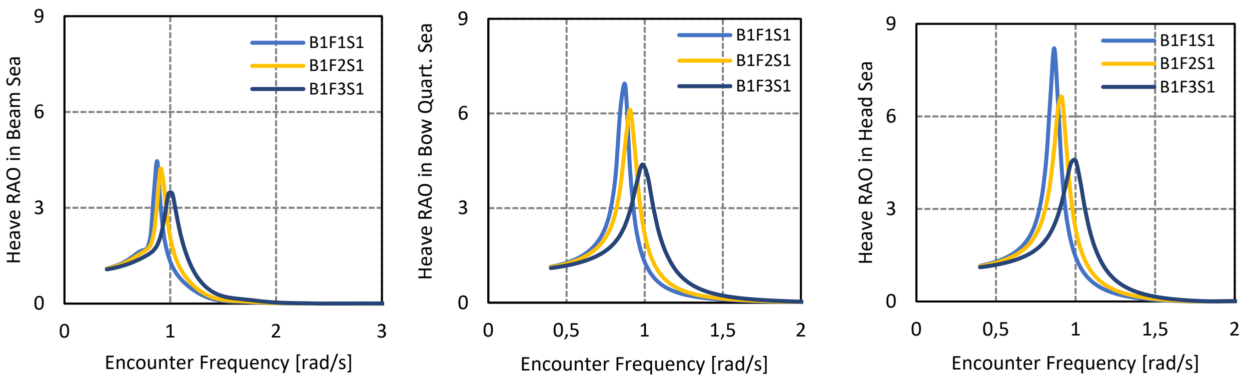
Fig. 6. The influence of the attack angle on the pitch RAO of the Hexagonal Catamaran (β=0°, γ=α) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea; [c] Head Sea

On the pitch motion, the attack angle variation influences the pitch RAO's peak point. The larger attack angle has reduced the peak point of the RAO. In all wave heading angles, the most significant RAO decrement was shown on the flat deadrise angle hull (β=0°) with the stern angle equal to the attack angle (γ=α) due to the increase of the attack angle. The percentage of the pitch RAO decrement is 18.63% in the Beam Sea, 12.96% in the Bow Quartering Sea, and 8.36% in the Head Sea. Therefore, it is indicated that the larger attack angle might decrease the influence of the wave effect on the pitch motion. Furthermore, the effect of the attack angle on the pitch RAO is more minor, while the wave heading angle is more extensive, Fig. 6.

3.2 The influence of the deadrise angle on the seakeeping behavior

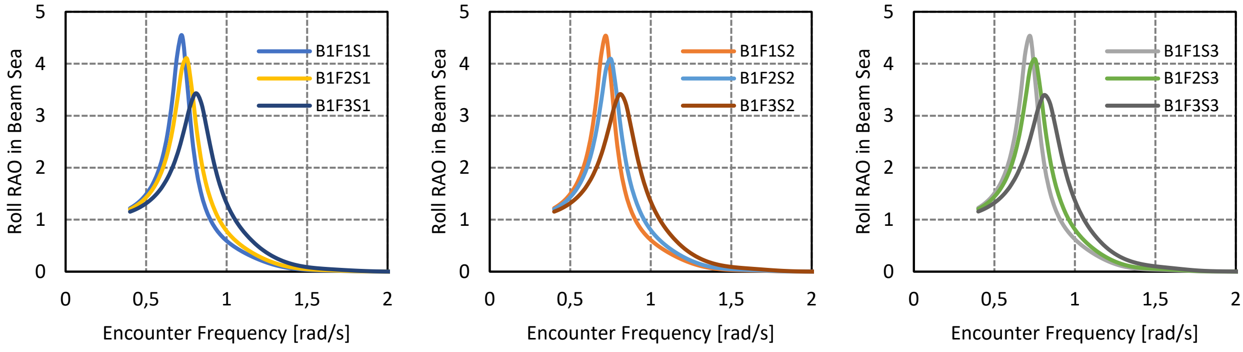
In the heave motion, the effect of the deadrise angle variation is significantly recognized. The most intensive transformation is identified on the hull with α=17.38°, γ=10.75°, Fig. 7. Otherwise, it is recognized that the Head Sea condition might generate a more significant heave RAO than the two others. In each wave condition, the maximum decrements of heave RAO are 22.42%, 36.43%, and 45.31% for the Beam Sea, Bow Quartering Sea, and Head Sea wave heading conditions, respectively. Otherwise, it is indicated that the larger deadrise angle might reduce the effect of wave conditions on the heave motion.

The effect of the deadrise variation on the roll RAO is significantly recognized in all hull design configurations. According to the numerical results, it can be seen that the most significant decrement of the roll RAO is the hull with α=17.38°. Fig. 8 depicts that the roll RAO of the hull with α=17.38° is not significantly influenced by the stern angle variation (γ). Therefore, the maximum decrement was recognized in the three kinds of the developed hexagonal catamaran hull. The percentage of the RAO decrement due to the variation of the deadrise angle for the Beam Sea and the Bow Quartering Sea is 24.45% and 29.77%, respectively, Fig. 9. Furthermore, it can be identified that the larger deadrise angle might reduce the wave effect on the roll motion behavior.



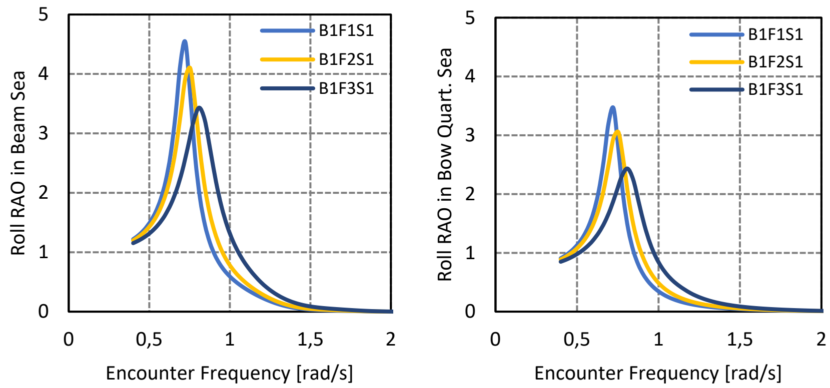
[a] [b] [c]

Fig. 7. The influence of the deadrise angle on the heave RAO of the Hexagonal Catamaran (α=17.38°, γ=10.75°) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea; [c] Head Sea



[a] [b] [c]

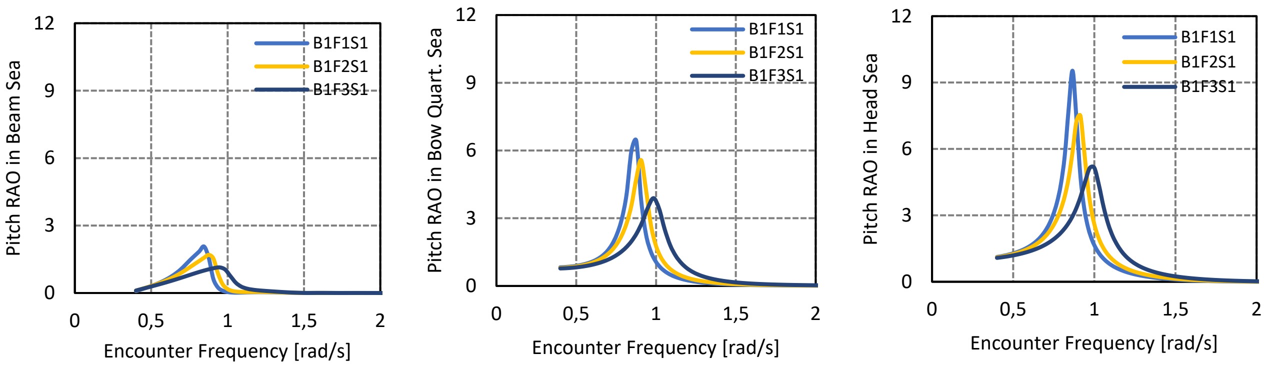
Fig. 8. The influence of the deadrise angle on the roll RAO of the Hexagonal Catamaran (α=17.38°) in Beam Sea: [a] γ=10.75°; [b] γ =17.38°; [c] γ=90°



[a] [b]

Fig. 9. The influence of the deadrise angle on the roll RAO of the Hexagonal Catamaran (α=17.38°, γ=10.75°) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea.

Finally, the effect of the deadrise angle variation on the pitch motion is estimated. The numerical results show that the most significant decrement is shown on the hull with α=17.38°, γ=10.75°. Moreover, the Head Sea condition generated a larger pitch RAO than the others. Fig. 10 depicts that the wave heading angle has influenced the value of the pitch RAO. The decrement percentage of the deadrise angle variation effect on the pitch RAO is 44.93%, 39.5%, and 45.95% for Beam Sea, Bow Quartering Sea, and Head Sea. The numerical results indicate that the deadrise angle escalation might reduce the pitch RAO value.



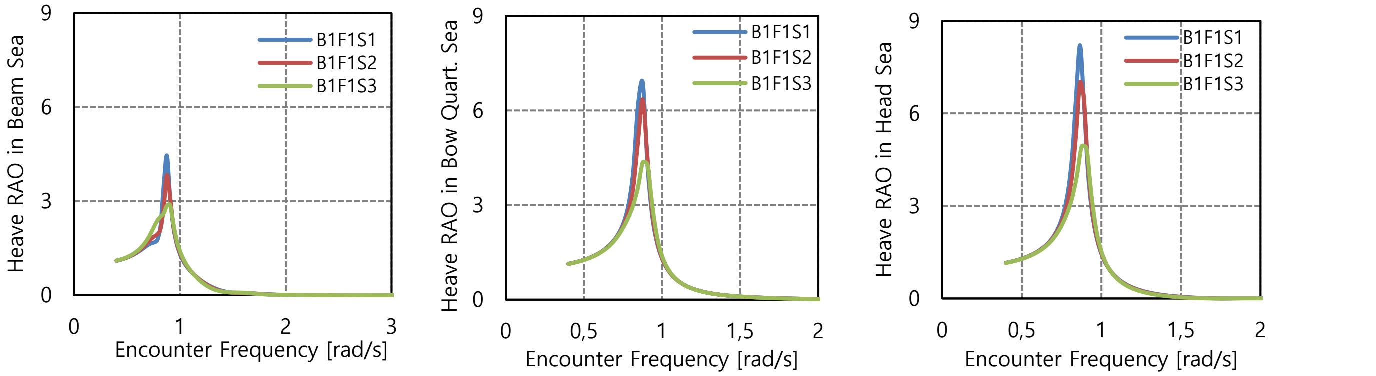
[a] [b] [c]

Fig. 10. The influence of the deadrise angle on the pitch RAO of the Hexagonal Catamaran (α=17.38°, γ=10.75°) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea; [c] Head Sea

3.3 The influence of the stern angle on the seakeeping behavior

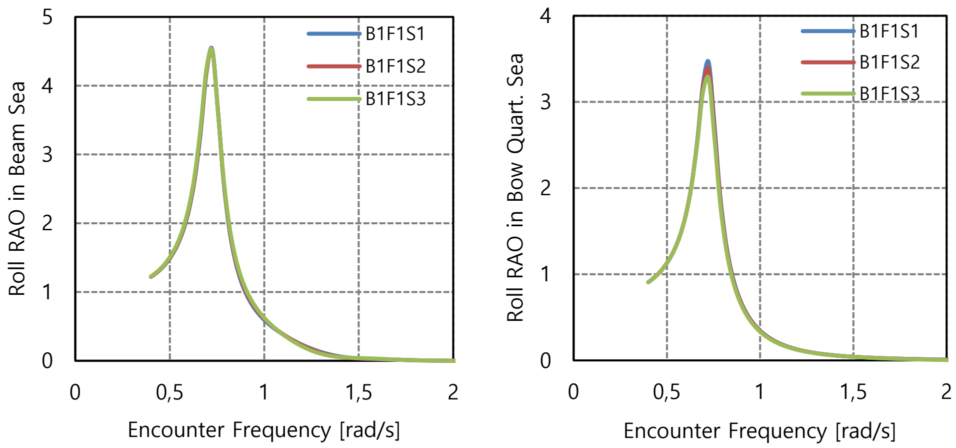
In the heave motion, the effect of the stern angle variation is not significantly recognized. The most intensive transformation is identified on the hull with α=17.38°, β=0°, Fig. 11. Otherwise, it can be specified that the Head Sea condition might generate a larger heave RAO than the two others. In each wave condition, the maximum decrements of heave RAO are 36.1%, 37.88%, and 40.56% for the Beam Sea, Bow Quartering Sea, and Head Sea wave heading conditions, respectively. Otherwise, it is indicated that the larger stern angle might reduce the effect of wave conditions on the heave motion.

In the case of the roll motion, the stern angle does not significantly influence the RAO peak point. Due to the modified stern angle, almost all design configurations have shown no deviations on the RAO curve line, Fig 12. The RAO curve line was presented similarly in each configuration of the stern angle. However, it still can be identified that the larger stern angle reduces the roll RAO peak point. Therefore, it is indicated that the stern angle would have reduced the roll RAO peak point while it was relatively large (γ = 90°).



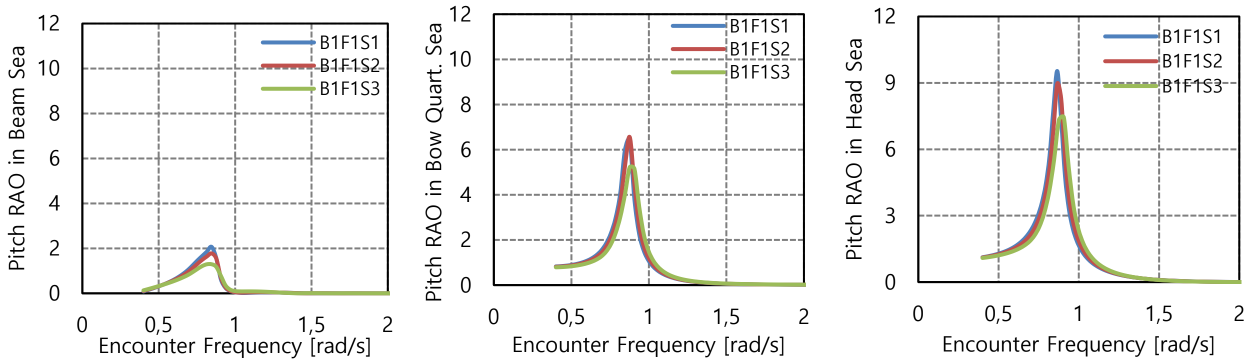
[a] [b] [c]

Fig. 11. The influence of the stern angle on the heave RAO of the Hexagonal Catamaran (α=17.38°, β=0°) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea; [c] Head Sea



[a] [b]

Fig. 12. The influence of the stern on the roll RAO of the Hexagonal Catamaran (α=17.38°, β=0°) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea.



[a] [b] [c]

Fig. 13. The influence of the stern on the pitch RAO of the Hexagonal Catamaran (α=17.38°, β=0°) in the different wave heading angles: [a] Beam Sea; [b] Bow Quartering Sea; [c] Head Sea.

The variation of the stern angle influences the peak point of RAO on the pitch motion. The larger stern angle has reduced the peak point of the RAO. In all wave heading angles, the most significant RAO decrement was shown on the hull with α=17.38°, β=0° is 37.68% in Beam Sea, 21.49% in Bow Quartering Sea, and 23.08% in Head Sea. Therefore, it is indicated that the larger stern angle might decrease the influence of the wave effect on the pitch motion. Furthermore, the effect of the stern angle modification on the pitch RAO is more significant when the wave heading angle is 90°, Fig. 13.

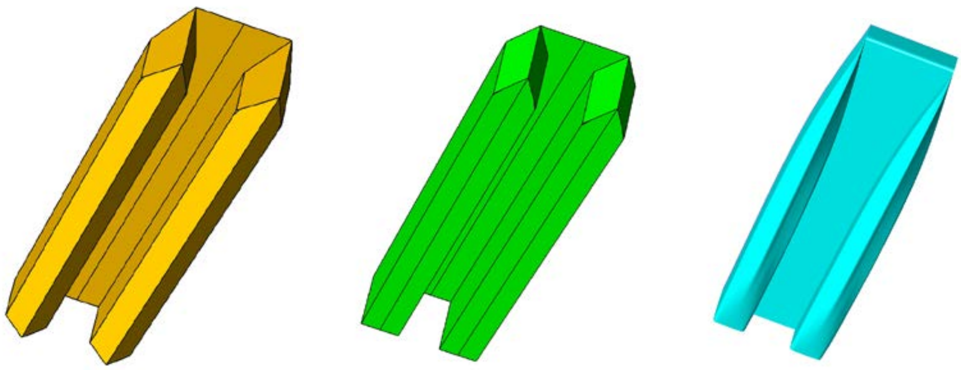
3.4 The seakeeping performance comparison between the hexagonal and the conventional catamaran.

The root mean square of all hull form design configurations was calculated for each motion and wave heading angle. Among all the developed designs, the hexagonal hull with the minimum root mean square in each motion and wave heading angle type was selected. The selected hexagonal hulls are of B1F3S3 type and B3F1S3 type. In order to benchmark the seakeeping performance, the hexagonal catamarans were compared to the conventional catamaran hull. The conventional catamaran has similar principal dimensions to the hexagonal hull form, but it adopts a curved hull body line and a flat stern (γ=90°). Figure 14 presents a 3D model illustration of the selected hull form and the conventional catamaran.

Subsequently, the motion response spectral density of the nominated hexagonal hull was calculated to recognize its motion response behavior in the specified wave spectrum. The motion response spectra were obtained by multiplying the RAO with the wave spectrum. The designated wave spectrum used was JONSWAP, with a significant wave height of 3 meters. Additionally, the vessel's service speed was defined as 20 knots. Furthermore, the motion response spectra were calculated using the same wave heading configuration.

Table 3. The developed hull form with the minimum RMS motions and wave heading angles

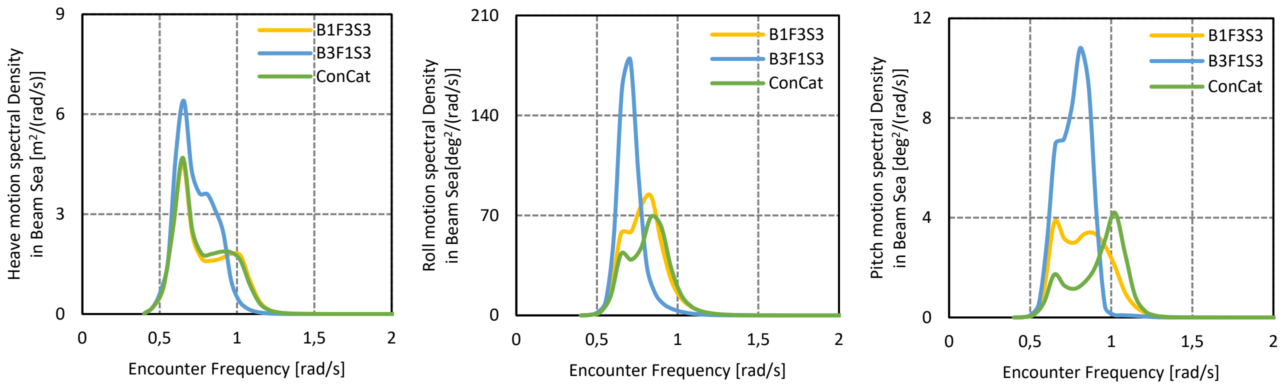
Wave heading angle	Motion Type	Hull with Min. RMS	RMS motion
Beam Sea	Heave	**B1F3S3**	1.134 m
	Roll	**B1F3S3**	4.960 deg
	Pitch	**B1F3S3**	1.240 deg
Bow Quartering Sea	Heave	**B1F3S3**	1.531 m
	Roll	B3F1S3	1.220 deg
	Pitch	**B1F3S3**	3.110 deg
Head Sea	Heave	B3F1S3	1.211 m
	Pitch	B3F1S3	3.280 deg



[a] [b] [c]

Fig. 14 The selected hexagonal and the conventional catamaran hull: [a] B1F3S3 type; [b] B3F1S3 type; [c] the conventional catamaran (ConCat)

Figure 15 depicts the spectral density of the motion of the selected hexagonal hull in the Beam Sea. It is apparent that the hexagonal B3F1S3 type exhibits the most prominent peak within the entire motion spectrum. The B1F3S3 type demonstrates the lowest peak value in heave and pitch motion. The numerical findings indicate that the hexagonal catamarans B1F3S3 display a similar motion response to the conventional catamaran in the Beam Sea condition. However, the conventional catamaran outperforms the hexagonal catamaran in terms of roll motion response. These results suggest that a slight attack angle (α=17.38°), a large deadrise angle (β=30.61°), and a flat stern (γ=90°) may alleviate the impact of waves on the motion performance of hexagonal catamarans in the Beam Sea condition.

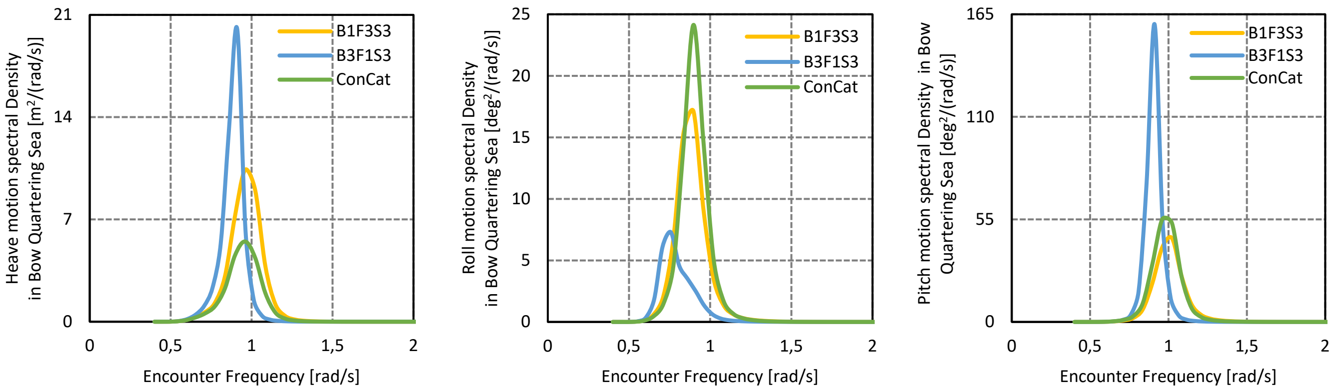


[a] [b] [c]

Fig. 15. Comparison between the motion spectra density of the hexagonal catamaran and the conventional catamaran in Beam Sea condition: [a] Heave motion; [b] Roll motion; [c] Pitch motion

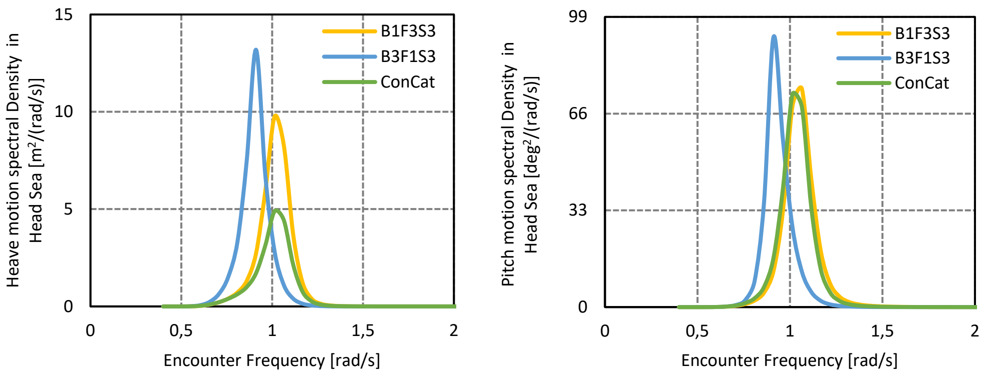
In the Bow Quartering and Head Sea, the hexagonal catamaran presented a significant increment in the motion spectra density, Fig. 16 and Fig. 17. The B3F1S3 type has performed the most significant peak point of motion spectra density on the heave and pitch motion. Otherwise, the conventional catamaran presented the most intensive peak point of roll motion spectra in the Bow Quartering Sea. Regarding the behavior, it can be seen that the heave and pitch motion of the hexagonal with the flat deadrise (β=0°) is relatively sensitive to the front wave (Bow Quartering and Head Sea). These phenomena might have occurred because the flat bottom might generate the larger lift force due to the wave motion. However, the flat bottom has positive influenced to reduce the wave effect in roll motion.

Although the effect of a larger attack angle has shown a slightly decrement in the pitch RAO, the motion spectral density of the conventional catamaran and the hexagonals has shown a different response. It might occur because the deadrise angle have more intensive influence on the motion performance than the attack angle. Therefore, the B1F3S3 (α=17.38°, β=30.61°) was identified to have a smaller motion spectra density than the B3F1S3 type (α=26.43°, β=0°). The flat deadrise angle (B3F1S3) has significantly increased the motion spectra density (heave and pitch).



[a] [b] [c]

Fig. 16. Comparison between the motion spectra density of the hexagonal catamaran and the conventional catamaran in Bow Quartering Sea condition: [a] Heave motion; [b] Roll motion; [c] Pitch motion



[a] [b]

Fig. 17. Comparison between the motion spectra density of the hexagonal catamaran and the conventional catamaran in Head Sea condition: [a] Heave motion; [b] Pitch motion

The NORDFORSK criteria were employed to assess the motion performance of the developed hexagonal catamaran in terms of acceptance criteria. According to the selected criteria, the root mean square (RMS) of motion acceleration should meet the standard limit value. Table 4-6 illustrates that the entire hull form met the NORDFORSK criteria. Although the roll motion amplitude criteria were not met for the entire hull in the Beam Sea, the developed hull can still be considered as an alternative hull form for environments with lower wave heights in the Beam Sea. Additionally, the MSI analysis revealed that the entire hull form exhibited acceleration below the 30-minute exposure criteria in the Beam Sea, as shown in Fig. 18. This MSI value represents the lowest acceleration compared to other wave heading angles, such as Bow quartering and Head Sea.

Table 4. Comparisons of the motion performance between the hexagonal catamaran and the conventional catamaran and in Beam Sea Condition, with NORDFORSK criteria

Description	Beam Sea			NORDFORSK	
	B1F3S3	B3F1S3	ConCat	Criteria	Remarks
RMS of Vertical Acceleration at FP	0.561	0.450	1.222	6.374	Passed
RMS of Vertical Acceleration at Bridge	0.953	0.942	0.834	2.697	Passed
RMS of Lateral Acceleration at Bridge	0.766	0.645	0.867	0.981	Passed
RMS of Roll	0.087	0.095	0.122	0.070	Not Passed

Table 5. Comparisons of the motion performance between the hexagonal catamaran and the conventional catamaran in Bow Quartering Sea Condition, with NORDFORSK criteria

Description	Bow Quartering Sea			NORDFORSK	
	B1F3S3	B3F1S3	ConCat	Criteria	Remarks
RMS of Vertical Acceleration at FP	2.547	2.470	3.733	6.374	Passed
RMS of Vertical Acceleration at Bridge	1.794	1.697	1.201	2.697	Passed
RMS of Lateral Acceleration at Bridge	0.348	0.184	0.450	0.981	Passed
RMS of Roll	0.033	0.021	0.036	0.070	Passed

Table 6. Comparisons of the motion performance between the hexagonal catamaran and the conventional catamaran in Head Sea Condition, with NORDFORSK criteria

Description	Head Sea			NORDFORSK	
	B1F3S3	B3F1S3	ConCat	Criteria	Remarks
RMS of Vertical Acceleration at FP	3.398	2.415	4.473	6.374	Passed
RMS of Vertical Acceleration at Bridge	1.965	1.365	1.135	2.697	Passed
RMS of Lateral Acceleration at Bridge	0	0	0	0.981	Passed
RMS of Roll	0	0	0	0.070	Passed

Figure 18 illustrates that the hexagonal catamaran hulls have demonstrated acceleration similar to that of the conventional catamaran in the Beam Sea. The MSI-120min results show percentages of 18.36%, 21.03%, and 22.70% for the concat, B3F1S3 type, and B1F3S3 type, respectively. In the Bow Quartering, both B1F3S3 and B3F1S3 exhibit a similar peak point and curve, as shown in Fig. 19. However, the peak point is located at different encounter frequencies. When compared to the conventional catamaran, both hexagonal hulls have exhibited larger acceleration. However, the acceleration peak point for the entire hulls has exceeded the 30-minute exposure criteria. In the Head Sea, the highest acceleration was observed in B1F3S3. B3F1S3, as depicted in Fig. 20, exhibits better acceleration than B1F3S3. The conventional catamaran has presented the lowest acceleration compared to the hexagonal hulls. Table 7 presents a comparison of the MSI-120min between the hexagonals (B1F3S3, B3F1S3) and the conventional catamaran.

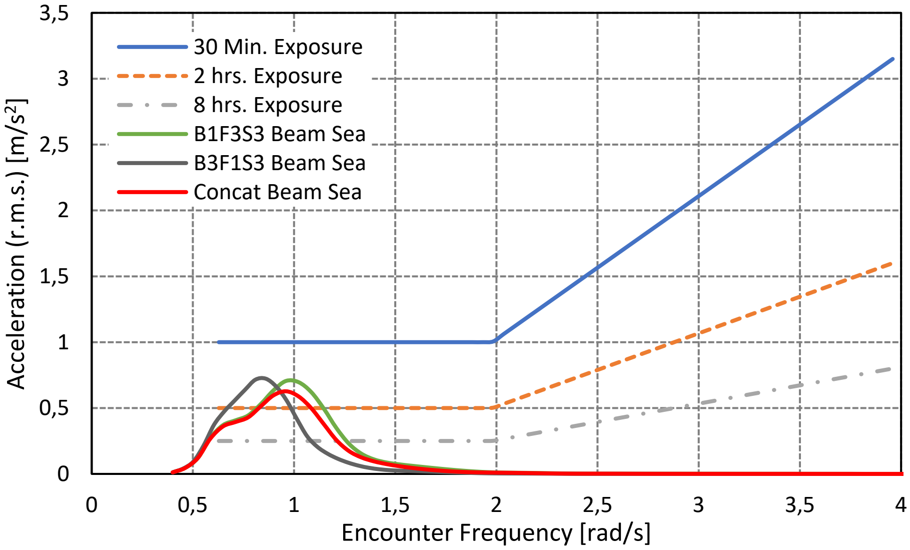


Fig. 18. Comparison between the Motion Sickness Incidence (MSI) the hexagonal catamaran and the conventional catamaran in Beam Sea condition

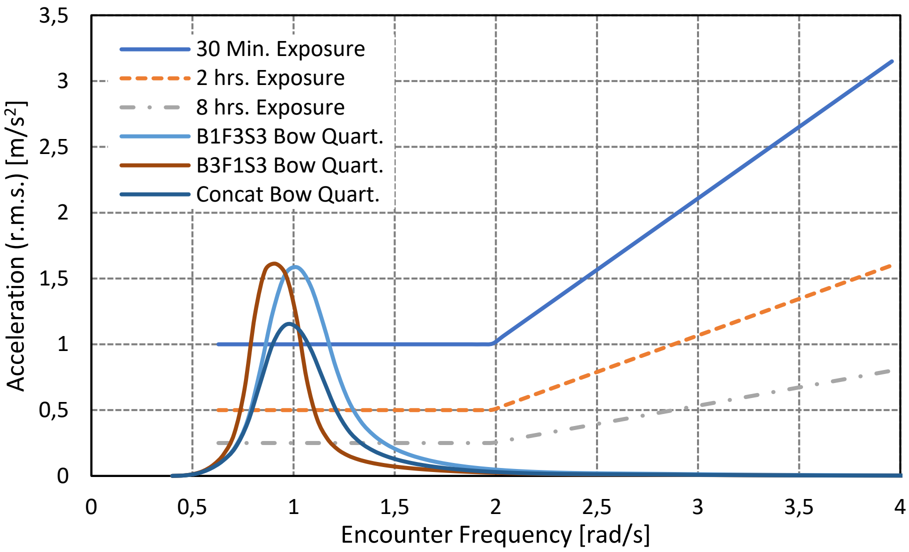


Fig. 19. Comparison between the Motion Sickness Incidence (MSI) the hexagonal catamaran and the conventional catamaran in Bow Quartering Sea condition

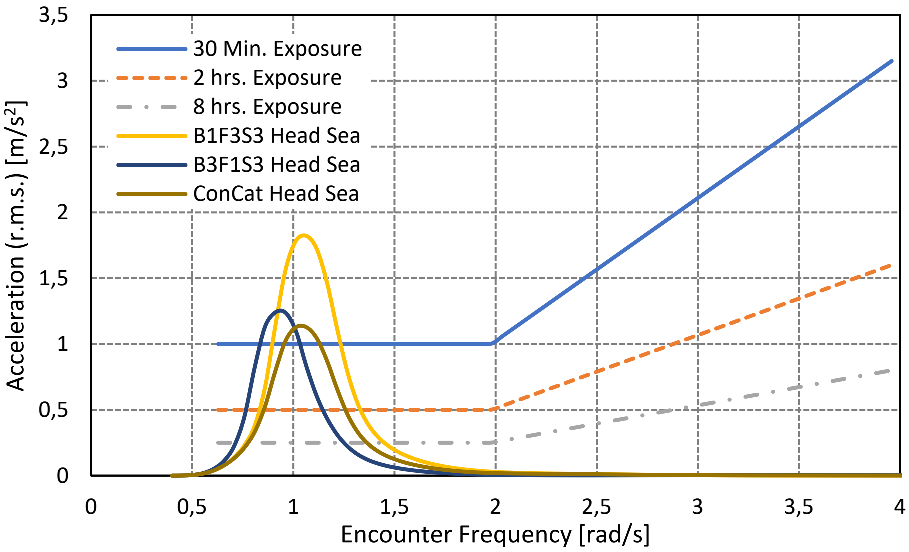


Fig. 20. Comparison between the Motion Sickness Incidence (MSI) the hexagonal catamaran and the conventional catamaran in Head Sea condition

Table 7. Comparisons of the motion sickness incidence (MSI-120min) between the hexagonal catamaran and the conventional catamaran.

Hull Type	Wave Heading Angle	MSI-120min
B1F3S3	Beam sea	22.70%
B3F1S3		21.03%
Concat		**18.36%**
B1F3S3	Bow Quart.	48.35%
B3F1S3		45.43%
Concat		**31.64%**
B1F3S3	Head Sea	52.20%
B3F1S3		36.49%
Concat		**29.46%**

Based on the seakeeping analysis, it is evident that the hexagonal catamaran can serve as a viable alternative hull form for catamarans. Both the B1F3S3 and B3F1S3 variants meet the motion acceleration criteria set by NORDFORSK. While the B1F3S3 type exhibits a superior peak point in the motion spectral density of heave, roll, and pitch motion compared to other hexagonal types, the B3F1S3 type demonstrates better motion acceleration in both vertical and lateral directions than the B1F3S3 type. This suggests that the maximum peak point in the motion spectral density does not always indicate better acceleration performance. In terms of MSI and NORDFORSK criteria, the B3F1S3 variant outperforms other hexagonal designs in terms of motion performance. However, conventional catamarans still exhibit better MSI values than hexagonal catamarans. This discrepancy may be attributed to the steep angle of attack in conventional catamarans, which potentially reduces wave excitation, particularly in heave and pitch motion.

4 CONCLUSIONS

The present study investigates the seakeeping capabilities of a configuration consisting of hexagonal catamaran hulls. A total of 27 design configurations were considered, with variations in the angle of attack, deadrise angle, and stern angle type. In order to assess the seakeeping characteristics of the developed hexagonal catamaran, a total of 216 computational RAO data and motion spectra-density data results were generated.

The analysis of the motion response amplitude operators (RAO) reveals that a larger angle of attack may result in a reduction of the peak point in the heave motion RAO curve for all wave heading angles. The most significant reduction, amounting to 20.7%, is observed in the hexagonal hull with a flat deadrise angle and a stern angle equal to the angle of attack. However, the angle of attack does not have a significant influence on the roll motion behavior. With regard to pitch motion, a larger angle of attack leads to a decrease in the peak point of the RAO curve. The percentage reduction in the pitch RAO is smaller as the wave heading angle increases. Consequently, the reduction in the peak point in the Head Sea is smaller compared to the Beam Sea.

The influence of the deadrise angle on seakeeping behavior has been identified as more significant than that of the attack angle. Additionally, the hull with α=17.38° and γ=10.75° exhibits the most pronounced transformation in the heave RAO curve. The reduction in the heave RAO peak point becomes more significant with an increase in the wave heading angle. It can be observed that the maximum reduction in the peak point is more pronounced in the Head Sea. Furthermore, the deadrise angle has a significant impact on the roll and pitch motion behavior, exhibiting similar transformation trends to the heave motion.

The variations in the stern angle have a more significant influence than the effect of the attack angle. The heave RAO peak points decrease by 36.1% - 40.56% due to variations in the wave heading angles. A larger stern angle results in a reduction of the wave effect on the heave motion. However, the stern angle does not influence the roll motion behavior. In terms of pitch motion, the variation in the stern angle has a slight influence on the peak point of the pitch RAO.

The comparison of the seakeeping performance between the hexagonal and conventional catamarans revealed that the conventional catamarans exhibit a lower incidence of motion sickness compared to the hexagonals. However, the hexagonal catamarans demonstrate superior acceleration performance, particularly in terms of lateral acceleration at the forepeak under various wave heading angles. Additionally, the hexagonals meet the NORDFORSK criteria. Consequently, the hexagonal catamaran can be considered as a viable alternative hull design.

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