Comparative Study on the Operability and Safety of 450T Monohull and SWATH Fast Patrol Search and Rescue Vessels

Eko B Djatmiko[1,a,*], **Setyo Nugroho**[2], **Heri Supomo**[3] **and Murdjito**[1]

[1] *Department of Ocean Engineering, Institute Teknologi Sepuluh Nopember, Surabaya, Indonesia*
[2] *Department of Marine Transportation Engineering, Institute Teknologi Sepuluh Nopember, Surabaya, Indonesia*
[3] *Department of Naval Architecture, Institute Teknologi Sepuluh Nopember, Surabaya, Indonesia*
a. ebdjatmiko@oe.its.ac.id
**corresponding author*

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Abstract: A comparative study is performed to explore the operability and safety of 450-tonne displacement Fast Patrol Search and Rescue (FPSR) vessels designed with monohull and SWATH configurations. The first part addresses the peculiar designs of Monohull and SWATH FPSRs. The second part explain about the motion characteristics of the FPSRs in regular waves, followed by the evaluation of their motions in random waves by way of spectral analysis. Results of this analysis are weighted against the seakeeping criteria to examine the operability and safety of FPSRs' operations. In this respect the Monohull-FPSR is capable of conducting general operation above Hs of 3.0 m at V of 0.0 knots and 15.0 knots, but should be limited to 2.49 m when V is 30.0 knots. Helicopter operation should not be conducted when Hs is above 2.0 m, especially at 30.0 knots. General operation on SWATH-FPSR may be performed at Hs above 4.0 m at low and medium speeds, and Hs of 3.21 m at maximum speed of 30.0 knots. Whereas helicopter operation at 0.0. knots and 15.0 knots could be made at Hs slightly lower than 3.0 m, but below 2.0 m when V is 30.0 knots. The aforementioned figures indicate the SWATH-FPSR has a better safety of operation in severe waves than the Monohull-FPSR.

1. Introduction

The current Indonesian government has established the world maritime axis as one of the major national programs. In this respect four pillars of developments have been defined, namely: a) strengthening maritime sovereignty, b) improving management natural resources and maritime services, c) enhancing maritime infrastructure, and d) strengthening human resource, scientech and maritime culture. In response to this a study on advanced marine vechicle designated as small water-plane area twin hull (SWATH) ship is performed, as put forward in this paper. The vessel is sized

450-tonne (450T) in displacement. This will be compared with its monohull counterpart in performing the mission as a fast patrol search and rescue vessel (FPSR).

The development of SWATH ship has been pioneered by the US Navy in the early 1970s [1]. The adoption of SWATH ship configuration chiefly is attracted by its predominance seakeeping characteristic attainable from the low motions when advancing in waves [2,3]. The conceptual approach of achieving low motions is by constructing an aerofoil slender body, designated as the strut, at the sea-air surface intersection and torpedo like-lower hull, to provide the majority of the buoyant volume, located well below the wave action. Two identical strut-hull combinations are positioned at a certain distance and connected by a cross-deck structure sitting on haunches, the upward extension of the strut. The cross deck structure is positioned well above the sea surface, so that slamming and the shipping of green seas may be minimized.

In general SWATH arrangement is similar to catamaran except in its hull configuration. Due to its unique composition a SWATH ship has much lower natural frequencies in heave, pitch and roll compared to monohull ships. Therefore resonance with most sea waves can be significantly avoided. The positioning of main buoyancy well below the water surface yields pertinently lower wave excitation, as it is decreases exponentially in parallel with the water depth, hence lower motions are readily achievable.

Further, many investigators indicate some other advantages of SWATH ships, such as: a) more comfort to passenger and crew on board brought about by low motions, whilst for military operation it is suitable for weaponry deployment, b) lower speed degradation when operated in high waves, c) more spacious deck area gives amenable deck arrangement and match up with the need of helicopter or aircraft operation, d) abundant stability and survivability, even when both side of the hull is damaged, e) the position of the lower hull well below the water surface is appropriate to house underwater surveillance devices such as sonar, f) the location of cross deck structure well above the water surface essentially prevents the deck wetness to take place, hence the damaging effects of seawater to the weapon and machinery on the deck are avoidable, g) SWATH hull has less 3-D curvature works hence more producibility is achievable even when constructed with the currently available shipyard technology [4,5].

Despites some advantages SWATH configuration also renown certain drawbacks, such as: a) more sensitive to any weight change during operation due to low water-plane area leads to lower TPC and MTC, b) lower ratios of payload to displacement and deadweight to displacement compared to monohull, hence consideration of lightweight structure material is an important aspect in SWATH design and construction, d) larger resistance when advancing in calm water due to the increase in frictional resistance since twin-hull configuration inherently has a larger wetted surface, e) restriction of operation in shallow water and harbor due to deeper vessel draught, f) larger depth often brings difficulties in the transferring operation of passenger or goods to ports or other vessels [6,7].

The primary objective of this study covers: a) the development of the basic design of 450T FPSR configured with SWATH and monohull, b) evaluation of the vessels motion characteristics, and c) comparison of operability and safety of the two vessel configurations. Further aims of this study is to contribute in the acceleration of the four pillars national program towards the world maritime axis

2. The Design of 450T FPSR Vessels

The design of 450T FPSR vessels with both configurations, SWATH and monohull, have been developed by referring to the well-known Indonesian military vessel FPB57 series, built since 1985s. FPB57 design averagely has the displacement of 425 tons, which is then enlarged into 450 tons for the current design. The new vessels to be operated at maximum speed of 30 knots and economical service speed 15 knos, supported by some 50 crews.

Table 1. Main dimensions of 450T Monohull and SWATH-FPSR

PARTICULAR	MONO	SWATH
Length over all, *LOA* (m)	60.00	35.00
Length of waterline, *LWL* (m)	56.50	24.80
Length of submerged hull, *Lh* (m)	-	32.00
Length of strut, *Ls* (m)	-	24.80
Hull diameter, *Dh* (m)	-	3.10
Strut thickness, *ts* (m)	-	1.90
Breadth over all, *BOA* (m)	7.80	13.00
Draught, *T* (m)	2.80	4.40
Main deck height, *H* (m)	4.90	7.70
Displacement, Δ (tonnes)	450.00	450.00
Maximum engine power (HP)	2 x 3125	2 x 3945
Maximum speed, *Vmax* (knots)	30.00	30.00
Service Speed, *Vs* (knots)	15.00	15.00
Endurance, (nautical miles)	2200	1850
Number of crew	50	50

2.1. 450T Monohull-FPSR Design

Hull design of the 450T Monohull-FPSR is established on the basis of geometric similarity to FPB57 hull form. Further design process has been accomplished by adopting general procedure as outlined in [8]. Helipad is arranged at the aft area of the main deck, sized sufficiently to support the operation of Gazelle SA-342M military class. Principal dimensions of this vessel can be seen in Table 1. Powering prediction using Holtrop-Mennen method [9,10] yields the engine power of 2 x 3125 HP for endurance of approximately 2,200 nm.

2.2. 450T SWATH-FPSR Design

The 450T SWATH-FPSR design is established by adopting the procedure, existing data and empirical formulae made available by MacGregor [11]. Beside this the recent SWATH designs and projects as reported by Grannemann [12] have also been especially considered. Following this the first parameter to be determined is the length over all *LOA* as a function of displacement cubed root, $\Delta^{1/3}$, and speed squared, V^2. Based on *LOA* so obtained, other main parameters are determined, namely breadth over all *BOA*, lower hull length *Lh*, and strut length *Ls*. Main deck height *H*, draught *T*, hull diameter *Dh*, and strut thickness *ts*, are then derived as functions of $\Delta^{1/3}$, combined with certain coefficients.

Utilizing the afore mentioned correlation $\Delta^{1/3}$ and V^2, the *LOA* of 35.00 m is obtained. The *BOA* of 13.00 m is determined with consideration of sufficiency in the deck area. This value gives the *LOA*/*BOA* ratio of 2.69, which is eventually within the common range of SWATH design, i.e. between 1.4 to 4.0. The deck height *H* of 7.70 m is determined to provide sufficient under deck clearance. Whereas the draught *T* of 4.40 m is calculated to assure the lower hull is placed well below the wave action. The hull length *Lh* is further derived as the function of *LOA*, and found to be 32.00 m.

According to Kennel [1], there are eventually three types of SWATH hull forms may be selected, that is conventional torpedo like hull, coke-bottle contoured hull and dog bone contoured hull. The latter is claimed to be appropriate for design with higher speed. For this reason, the current 450T SWATH-FPSR is arranged to have the dog-bone contoured lower hulls, as shown by the black line offset graph in Figure 1. Further, the vessel is equipped with short strut, as shown by the red line offset graph in Figure 1. The strut length *Ls* of 24.30 m is determined from equation accounting for *LOA*, and considering also the hull length *Lh*.

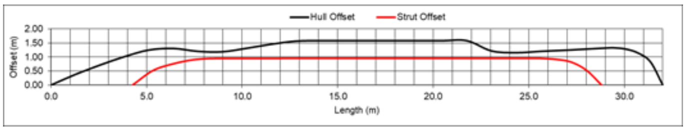

Figure 1. 450T SWATH FPSR hull and strut offsets

General SWATH design suggests the hull length to diameter ratio *Lh*/*Dh* commonly within the range of 11.0 to 14.0 [1,7]. None the less, due to the consideration of possibility positioning the main engine inside the main hull the ratio has been slightly lowered to 10.32, and gives the hull diameter *Dh* of 3.10 m. The strut thickness of 1.90 m is derived from the equation taking into account the $\Delta^{1/3}$ as well as consideration of ease access to the lower hull, but slender enough so as not to generate magnified wave making resistance.

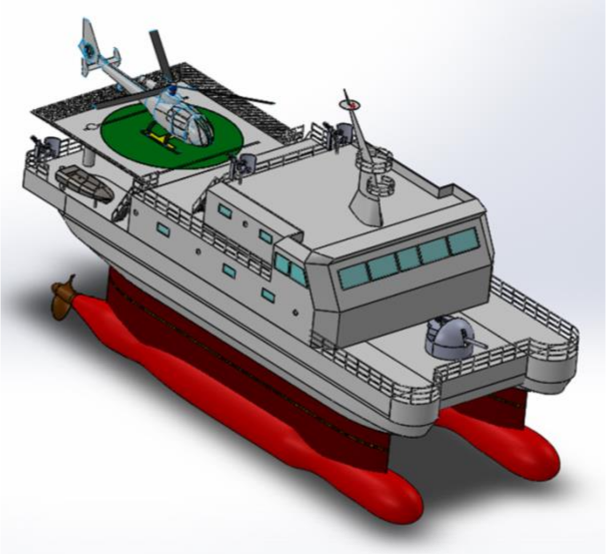

Figure 2. 450T SWATH-FPSR design – upper part view

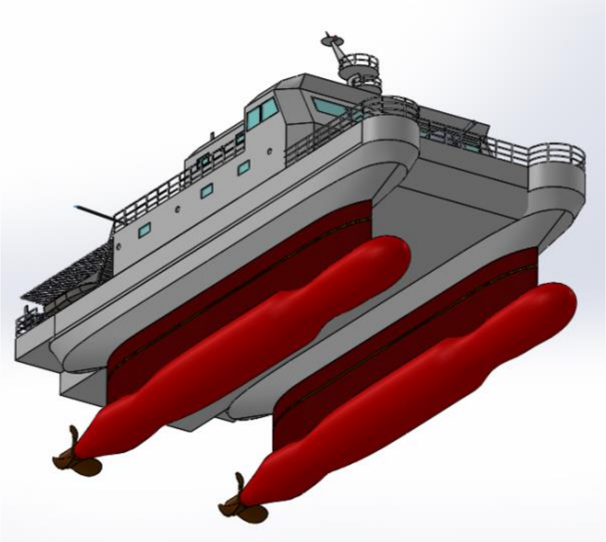

Figure 3. 450T SWATH-FPSR design – lower part view

Considering the main dimensions of the current SWATH-FPSR design so derived above and listed in Table 1, the computation of ship resistance and powering is conducted. The general equation of total ship resistance R_T is applied covering the frictional resistance R_F, the appendage resistance R_{APP}, the air resistance R_A, and the wave making resistance R_W. Detail formulation of each resistance component and computation has been described in ref. [13]. In this respect the frictional resistance has been solved by accounting for the hull and strut contribution as well as their interference effect. For the appendage resistance, computation has been developed especially due to the presence of control fins [14]. As generally applied, the air resistance is derived as the function of vessel's projected area above the water. Whereas the wave making resistance is conducted by adopting the approach as described by Chun [15], by adopting a plane source distribution on the centreplane of the submerged hulls, with the depth effect being considered. Other approaches such as described in ref. [16,17] could also be applied.

Result of resistance computation is then accounted for in determining the required installed engine power *BHP*. Firstly, effective power is found simply from $EHP = R_T \times V$. This is followed the determination of shaft power from correlation of $SHP = EHP/QPC$, where the *QPC* value of 0.718 is taken. Finally, the *BHP* is obtained from *SHP* plus 3% and a certain additional, some 15%, due to sea margin. For the current design the required *BHP* is some 7,890 HP, provided by two engine with power of 3,945 HP each. This required power to drive the SWATH-FPSR is some 26% larger than required for Monohull-FPSR to generate the same maximum speed.

The 450T SWATH-FPSR design evaluated in this study is as exhibited in Fig. 2 and 3. The vessel is equipped with a helipad at the aft mezzanine deck.

3. Motion Performance of FPSR Vessels

3.1.Motion Prediction for 450T FPSR Vessels

The prediction of FPSR vessel motions is conducted by numerical model based on the 3-D diffraction theory. In this respect computation of the 6-DOF vessel motions is accomplished by the second order differential equation of [18]

$$\sum_{n=1}^{6}\left[\left(\mathbf{M}_{jk}+\mathbf{A}_{jk}\right)\right]\ddot{\zeta}_k+\mathbf{B}_{jk}\dot{\zeta}_k+\mathbf{C}_{jk}\zeta=F_j e^{i\omega t} \quad \text{for } j,k=1,2,3,4,5,6 \tag{1}$$

where $\mathbf{M}_{jk}$ is mass and mass moment inertia matrix, $\mathbf{A}_{jk}$ is added mass and added mass moment inertia matrix, $\mathbf{B}_{jk}$ is hydrodynamic damping matrix, $\mathbf{C}_{jk}$ is restoring force and moment matrix, j,k=1,2,3,4,5 and 6 represent the mode of motions, ie. surge, sway, heave, roll, pitch and yaw, respectively. The first three mode of motions are essentially translational motions, whereas the later three are rotational motions. Further, surge, sway and yaw are classified as the horizontal plane motions, whilst heave, roll and pitch are classified as the vertical plane motions.

The hydrodynamic properties of vessel motions are derived by evaluating the flow pattern in the vicinity, as defined by the suitable velocity potential. This velocity potential comprises of two components, that is the time-independent steady component due to vessel advancing movement and the time-dependent unsteady component due to the incident wave and vessel unsteady motions, expressed as

$$\mathbf{\Phi}(x,y,z,t)=\left[-U_x+\mathbf{\Phi}_s(x,y,z)\right]+\mathbf{\Phi}_T(x,y,z)\,e^{i\omega t} \tag{2}$$

In eq. (2) the first variables on the right hand side represent the contribution steady velocity potential, $\mathbf{\Phi}_S$, and the vessel advancing speed U_x. Whereas the second variable represent the contribution of unsteady velocity potential, namely

$$\mathbf{\Phi}_T = \zeta(\mathbf{\Phi}_I + \mathbf{\Phi}_D) + \sum_{j=1}^{6} \zeta_j \mathbf{\Phi}_j \tag{3}$$

where $\mathbf{\Phi}_I$ and $\mathbf{\Phi}_D$ are, respectively, the incident and diffracted wave velocity potentials, in which their intensities are affected by the wave elevation ζ. While $\mathbf{\Phi}_j$ is the radiation velocity potential resulting from the j^{th} mode of motion or written as $\zeta_{.j}$. Solution of incident and diffraction velocity potentials will give the wave excitation forces and moments. While solution of radiation velocity potential generates the hydrodynamics coefficients, that is added mass and damping factors. In the current numerical model, pulsating-translating velocity potentials are considered and distributed over the 3-D submerged vessel hull panels to solve the motion intensities [19,20].

3.2.Natural Frequencies and Periods of FPSR Vessels

Natural frequencies or reversely natural periods are fundamental factors ought to be determined in examining the behavior of dynamic systems, such as the motions of ocean going vessels. Information on natural frequency will give earliest indication on the tendency and quality of vessel behavior from the motion point of view. Efforts are made to design the hull configuration in such a way so as to obtain the natural frequency which is well away from the dominant frequency(ies) of the incident waves. This will assure the resonance with the dominant external excitation to be reasonable avoided.

In the current study the natural frequencies and periods of FPSR vessels have been computed for the vertical motions, namely heave, roll, and pitch. These are recognized as the primary modes for free floating and advancing vessel in waves. In this case the SWATH-FPSR design is varied, firstly without fins and secondly with fins. Fins are installed on SWATH-FPSR to enhance its motion performances, and further to counteract the tendency in static trim due to the presence of Munk moment [3] and reducing sinkage occurrence, so as to minimize the resistance.

Table 2: Natural Frequencies and Periods of 450T FPSR Vertical Motions

Mode of Motion	**Monohull**		**SWATH w/o Fins**		**SWATH w Fins**	
	ω_n (rad/s)	T_n (sec)	ω_n (rad/s)	T_n (sec)	ω_n (rad/s)	T_n (sec)
Heave	0.846	7.423	0.587	10.698	0.541	11.608
Roll	0.726	8.650	0.495	12.687	0.474	13.249
Pitch	0.654	9.602	0.457	13.742	0.421	14.917

Table 2 lists the natural frequencies and periods of the observed FPSR vessels. The Monohull-FPSR in general has higher natural frequencies and reversely lower natural periods. This indicates the probability of resonance with the waves commonly develop in Indonesian waters is rather high. For the SWATH-FPSR with no fin the natural periods are higher than 10 secs, and even higher in the case of SWATH-FPSR with fins. These facts point out the vulnerability towards resonance is considerably prevented.

3.3.Motion Characteristics of FPSR Vessels

Hydrodynamics modeling to predict the motion characteristics of the 450T FPSR vessels in regular waves has been performed for three advancing speed variations, that is 0.0 knots, 15.0 knots and 30.0 knots. Results of the modeling are presented in the response amplitude operator (RAO) graphs, as exemplified in Figure 4-6 for the vessels at V = 15.0 knots. Maximum heave and pitch responses happens to be when the vessels are excited by head seas. Whereas maximum roll responses are instigated by the beam sea waves. All the RAO curves turn up to have the general tendency of dynamic system response, where they start with gradual increase at the sub-critical region and approaching maximum at the natural frequencies, and then followed by steeper decline in the super-critical frequency region.

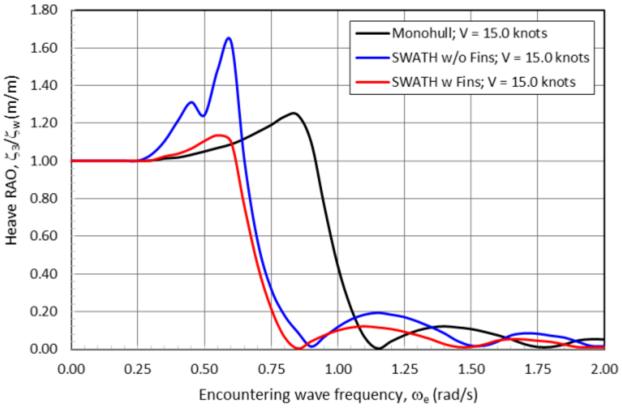

Figure 4. Heave RAO of 450T FPSR vessels in head seas at $V = 15.0$ knots

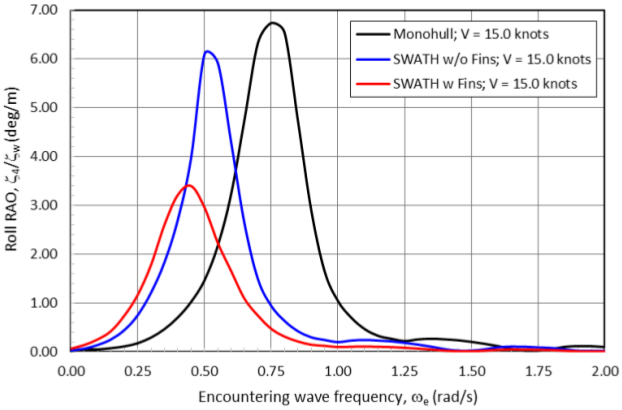

Figure 5. Roll RAO of 450T FPSR vessels in beam seas at $V = 15.0$ knots

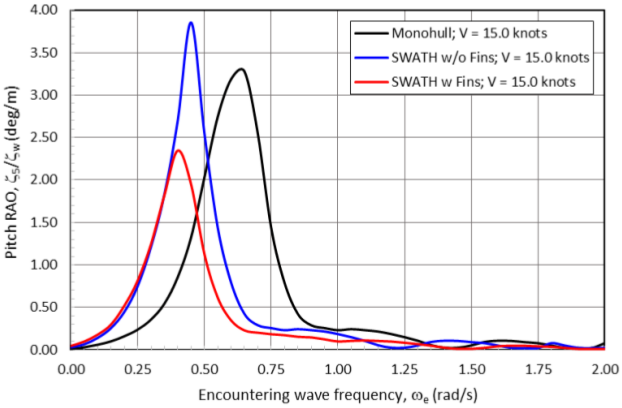

Figure 6. Pitch RAO of 450T FPSR vessels in beam seas at $V = 15.0$ knots

The 450T Monohull-FPSR has a maximum heave RAO of some 1.24 m/m, which is lower than the SWATH-FPSR without fins of 1.63 m/m, but higher than SWATH-FPSR with fins, which is only

1.13 m/m. There are visibly two peaks of RAO heave curve on SWATH-FPSR without fins, in which the first peak at lower frequency is due to the coupling effect with the pitch motion. Even though the maximum heave RAO value of SWATH-FPSR without fins is higher than that of Monohull-FPSR, but the total area under the curve is lower, hence the magnification with the wave energy spectra could be expected to be lower as well.

The largest roll RAO, both in term of maximum value and the area under the curve, is obvious to appear for the case of Monohull-FPSR. The SWATH-FPSR without fins is the second largest, with maximum value of 6.09 deg/m. While the SWATH-FPSR with fins are much lower than the others, with maximum roll RAO of only 3.39 deg/m.

In the case of pitch motion, the general trend is similar to that of heave motion. Maximum RAO is found to be on the SWATH-FPSR without fins, followed with the Monohull-FPSR and SWATH-FPSR with fins, in the order of 3.85 deg/m, 3.27 deg/m, and 2.35 deg/m, respectively. But again, the area under pitvcch RAO of the Monohull-FPSR seems to be the largest.

4. Operability and Safety Evaluation of FPSR Vessels

Evaluation of operability and safety on FPSR vessels is commenced by conducting spectral analysis based upon the RAO values to generate the motion statistical data in conjunction with the sea severity. The method and procedures of spectral analysis is fully described in [18]. As the vessels are to be operated in Indonesian waters, then the spectral formulation from JONSWAP with peakedness value γ = 2.5 is considered appropriate to be applied. Analysis has been performed by inducing the wave severity represented by the significant wave height *Hs* ranging from 0.0 m up to 8.0 m.

Table 3. Selected seakeeping criteria and categories [2,3,4]

GENERAL OPERATING CRITERIA:	
Criteria-1	12^o single amplitude average roll (personal effectiveness)
Criteria-2	3^o single amplitude average pitch (personal and equipment effectiveness)
Criteria-3a	Motion sickness indicator 0.2g when people working onboard
Criteria-3b	Motion sickness indicator 0.4g when people working onboard
HELICOPTER OPERATING CRITERIA:	
Criteria-4	12.8^o double amplitude significant roll
Criteria-5	2.54 m double amplitude significant vertical displacement at the flight deck
Criteria-6	2.13 m/s significant vertical velocity at the flight deck

Results of the spectral analysis are then presented in graphs of incremental motion statistical values against the increasing of significant wave height. The motion statistical values so observed include the average heave acceleration, significant amplitude vertical motion and vertical velocity at the helipad, amplitude of average and significant roll, and average amplitude of pitch. These statistical motion values will be examined against the seakeeping criteria of military vessels as proposed by Olson [21], as shown in Table 3.

The seakeeping criteria from Olson [21] is divided into two part, firstly is the general operating criteria, and secondly the helicopter operating criteria. The first criteria addresses the possibility of motion sickness effects on the crews and consequences of roll and pitch motion intensities on the obstruction of onboard activities. While the second criteria accounting for the roll motion, which basically implying the difficulty of helicopter operation to take off and landing, and vertical motion and displacement, which indicate the probability of impact occurrence between the helicopter footage and the helipad.

In this section the evaluation of operability and safety is made by comparing the performance of 450T Monohull-FPSR and 450T SWATH-FPSR with fins. The SWATH-FPSR without fins is left aside for obvious reason that the performance will be in between the two counterparts.

Table 4. Limiting significant wave height H_S for operation of 450T Monohull-FPSR

OPERATIONAL CRITERIA	**Speed *V* (knots)**		
	0.0	**15.0**	**30.0**
General Criteria:			
Criteria – 1	5.47 m	6.68 m	> 8.00 m
Criteria – 2	**3.75 m**	**3.49 m**	**2.49 m**
Criteria – 3a	> 8.00 m	> 8.00 m	> 8.00 m
Criteria – 3b	5.33 m	4.30 m	2.81 m
Helicopter Criteria:			
Criteria – 4	**1.98 m**	**1.59 m**	1.55 m
Criteria – 5	2.56 m	2.26 m	**1.23 m**
Criteria - 6	5.74 m	5.37 m	4.34 m

Table 5. Limiting significant wave height H_S for operation of 450T SWATH-FPSR with fins

OPERATIONAL CRITERIA	**Speed *V* (knots)**		
	0.0	**15.0**	**30.0**
General Criteria:			
Criteria – 1	7.66 m	> 8.00 m	> 8.00 m
Criteria – 2	**4.84 m**	**4.51 m**	**3.21 m**
Criteria – 3a	> 8.00 m	> 8.00 m	> 8.00 m
Criteria – 3b	6.35 m	5.12 m	3.34 m
Helicopter Criteria:			
Criteria – 4	**3.05 m**	**2.78 m**	2.46 m
Criteria – 5	3.16 m	3.05 m	**1.82 m**
Criteria – 6	6.83 m	6.39 m	5.17 m

Based on the graphs obtained from the spectral analysis and considering the seakeeping criteria from Olson [21], tabulation on the limiting significant wave heights for both general and helicopter operations are made, as presented in Table 4 and Table 5. From those tables it can be seen that Criteria-1 and Criteria-3a will not be violated even at high waves when the vessels operated in any speed. Criteria-3b will be violated at somewhat lower *Hs* when compared with the two previous criteria. Therefore, the limitation of general operation is more dominated by the pitch motion intensities. On the Monohull-FPSR onboard general operation will be safe to be performed up to *Hs* of 3.75 m when the vessel is stationary, and slightly lower when V = 15.0 knots that is *Hs* is about 3.49 m, and *Hs* of 2.49 m when the ship at maximum speed of 30.0 knots. For the SWATH-FPSR the onboard general operation with three speed variations may be performed at higher waves that is, respectively, 4.84 m, 4.51 m and 3.21 m.

In the case of helicopter operation criteria, the take-off and landing will be limited by Criteria-4 at speeds of 0.0 knots and 15.0 knots, and by Criteria-5 at maximum speed of 30.0 knots. Helicopter operation on Monohull-FPSR should not be conducted when the significant wave height *Hs* is higher than 2.0 m, even should be much lower when the speed is 30.0 knots. For SWATH-FPSR at stationary the helicopter operation can be performed up to Hs = 3.05 m, and reduced to 2.78 m at V = 15.0 knots and further down to 1.82 m at maximum speed of 30.0 knots.

By observing the limiting wave height for general and helicopter operations it implies that 450T SWATH-FPSR with fins has a better safety for operation in higher waves in comparison to the 450T Monohull-FPSR.

5. Conclusions

A comparative study has been performed on 450-tonne Monohull- and SWATH-FPSR vessels capable of supporting helicopter operation, with the findings as follows:

- SWATH-FPSR should be installed with engine power capacity some 23% larger than the Monohull-FPSR to generate maximum speed of 30.0 knots;
- Monohull-FPSR is capable of conducting general operation above Hs of 3.0 m at V of 0.0 knots and 15.0 knots, but should be limited to 2.49 m when V is 30.0 knots. Helicopter operation should not be conducted when Hs is above 2.0 m, and especially at 30.0 knots should not be carried out above Hs of 1.23 m.
- SWATH-FPSR is capable of conducting general operation above Hs of 4.0 m V of 0.0 knots and 15.0 knots, and Hs of 3.21 m at maximum speed of 30.0 knots. Helicopter operation at 0.0. knots and 15.0 knots could be made at Hs slightly lower than 3.0 m, but below 2.0 m when V is 30.0 knots.
- The aforementioned figures indicate the SWATH-FPSR has a better safety of operation in severe waves than the Monohull-FPSR.

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