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Coastal Unmanned Surface Vehicle (USV) Conceptual Hull Design Study

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Abstract

The Applications of the Unmanned Surface Vehicle (USV) are widely used as can be seen in both commercial and military purposes. As the main design aspect of the hull is to endure the harsh sea condition where is not the human friendly environment, the hull performance in waves is the main area which needs a special investigation. This paper presents the study of the hull performance for three different hull geometries. These hulls are Deep Vee (DV), high-slenderness hull (NPL 5b) and the Royal Thai Naval Dockyard designed patrol boat (T991). Required propulsive power and hull performance in waves are investigated. The results show that the DV model seems to have advantage over other hull geometries.

1. Introduction

In the past few decades, Unmanned Surface Vehicle (USV) has been developed and widely investigated. The applications of USV are recently used in various fields such as oceanography, oceanic archeology, military and commercial. As the USV is normally operated at high sea condition where human abilities are limited due to safety consideration and sea sickness, the performance in the harsh sea conditions is the focus for the early stage design. Those performances for the initial hull design are including resistance and required propulsive powering, and initial seakeeping.

This paper presents the conceptual hull design for the USV which can be used for the Royal Thai Navy to fulfil the missions which are considered as the high risk for the personnel. To demonstrate hull performances for different type of vessels three monohull configurations are evaluated to represent planning hull, high-slenderness hull and displacement hull respectively. The catamaran configuration for the high-slenderness hull is taken into account to compare the differences between those two configurations.

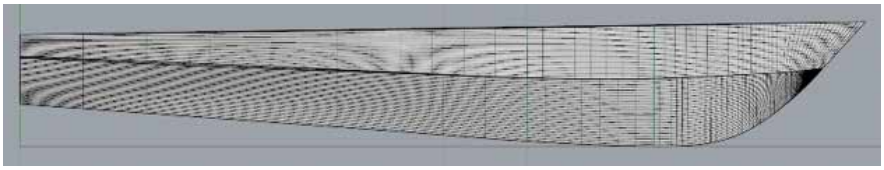
The resistance and required propulsive powering indicate the hull characteristics in term of the power consumption which is the basis for the early stage design. As the USV is normally operated at a high-speed regime, the range of speed evaluated is up to 40 knots. Four different resistance methods are used which are discussed in section 3. The initial seakeeping is another aspect that needs to be assessed. To represent to vessel behaviors in waves the Response Amplitude Operation (RAO) for heave, roll and pitch are investigated.

2. Hull Forms

Three different hull forms are assessed as the beginning point to compare hull characteristics and performance. These three hull forms include Deep-Vee shape hull (DV) and Displacement Hulls. The DV hull was proved that it has a better motion resistance compared with other low deadrise angle planning hull (Kim et. al, 2013). Two high-speed displacement hulls are also investigated here since they are the high-speed design for coastal operation. The first of displacement hulls is The NPL 5b which has been thoroughly investigated since originated and proved that its high slenderness and very streamline configuration is most suit for high-speed craft design. Moreover, this hull is designed for the catamaran application. Another hull focused here is the Royal Thai Naval Dockyard designed patrol boat, T991, the hull is originally designed for the coastal patrol boat project which requires very high performance in term of resistance reducing and motion resistance aspects.

Figures 1, 2 and 3 show the different views for hull forms; figure 1 shows the sheer plan, figure 2 shows top view and figure 3 shows body plan. The hulls are required to have the same length over all (LOL) of 10 m as the goal of this stage to compare characteristics and performance.

From figure 1, for the same length NPL 5b and T991 seem to have similar hull depth while the DV has higher depth. In term of maximum breadth, the DV is higher than both NPL 5b and T991, see figure 2. The smallest beam is found for the NPL 5b which reflects its slenderness. To this point, these models have different characteristics but designed for the same purpose to operate at the high-speed regime. The hull particulars are shown in table 1. The constraints for the design are the hull must be approximately 10 m long, weighs about 4 – 5 tones for monohull and slightly higher for catamaran. The catamaran configuration for the NPL 5b is taken into the consideration as it was originally designed for this application.



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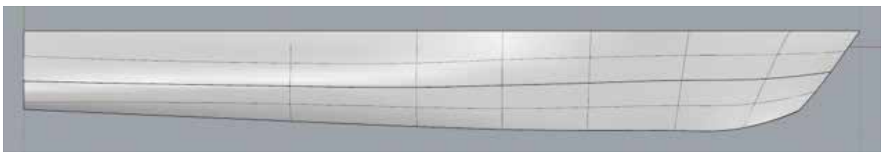

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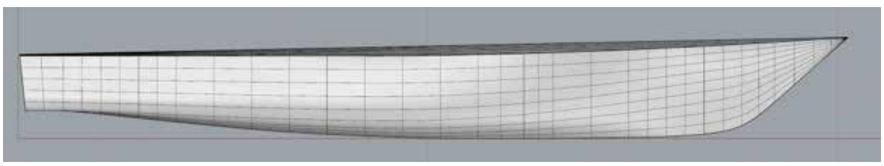
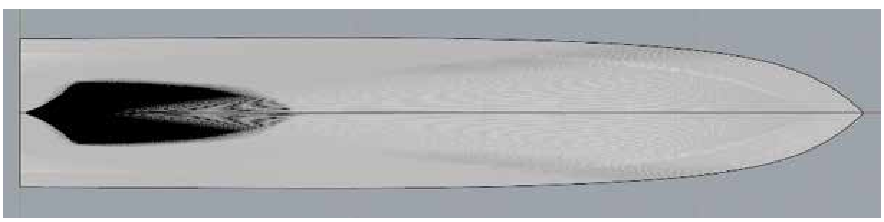


c)

Figure 1*: Sheer plan of a) Deep Vee (DV), b) NPL 5b and c) T991*



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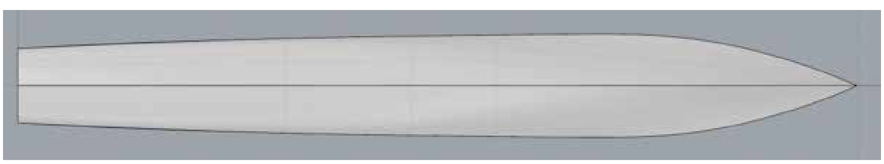

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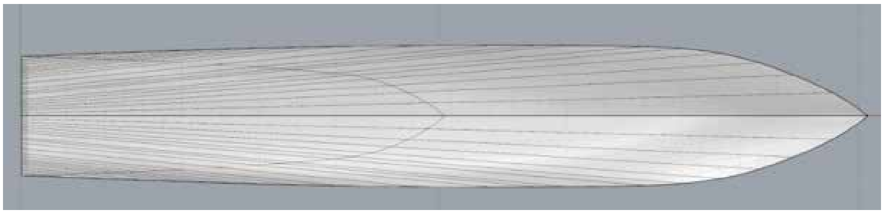
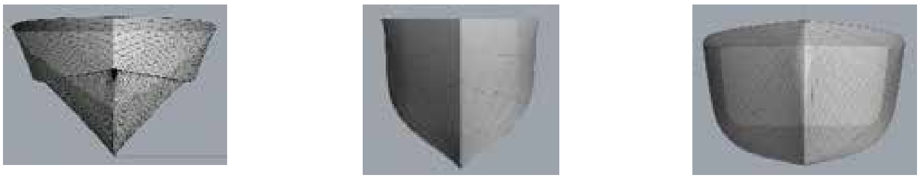


c)

***Figure 2**: Top view of a) DV, b) NPL 5b and c) T991*



a) b) c)

***Figure 3**: Body plan of a) DV, b) NPL 5b and c) T991*

***Table 1**: Comparison of hull particulars for different hull forms*

	DV	NPL 5b	T991	NPL 5b Cat
LOL, m	10.000	10.000	10.000	10.000
Displacement, te	4.491	4.354	4.421	5.220
DWL, m	0.850	0.800	0.550	0.600
WL Length, m	9.392	9.720	9.140	9.720
Beam max., m	1.800	1.250	1.800	5.500
Beam max extents on WL, m	1.550	1.150	1.571	5.300
Wetted Area, m2	18.422	17.531	15.894	35.062
Waterplane Area, m2	14.391	8.902	11.382	17.883
Prismatic coefficient (Cp)	0.644	0.717	0.685	0.717
Block coefficient (Cb)	0.307	0.475	0.546	0.475
Max Sect. area coefficient (Cm)	0.521	0.731	0.802	0.731
Waterplane area coefficient (Cwp)	0.827	0.796	0.792	0.798

3. Resistance and Powering

To assess the resistance and required propulsive power for different hull forms, the design tool, Maxsurf, is used. Four different approaches are used and compared the results. The hull and propulsion efficiency are set as 45% (45 – 50% normal in practical use for propeller propulsor) margin while the fouling due to severe weather is not considered at this stage. The statistical method for determining a required propulsive power at the initial design stage using the regression analysis of random model experiment and full-scale data call Holtrop approach (Holtrop and Mennen, 1984). Slender body approach is also used as the hull models investigated have high slenderness. Another two approaches that are used call Savitsky pre-planning and planning (Savitsky (1964) and Savitsky and Brown (1976)). These two are used as the DV model is considered as the planning hull. The pre-planning model used to determine the required power when the DV model is running at a low speed regime where the hull acts like the displacement hull. The later model, Savitsky planning model is then used to determine required power at the high-speed range where the hull rises and shows the planning characteristics.

Figure 4 shows the results for the DV model using the four different mathematical models mentioned above. The Holtrop model provides the highest required power so at early design stage this model will be used as it gives the highest required propulsive power.

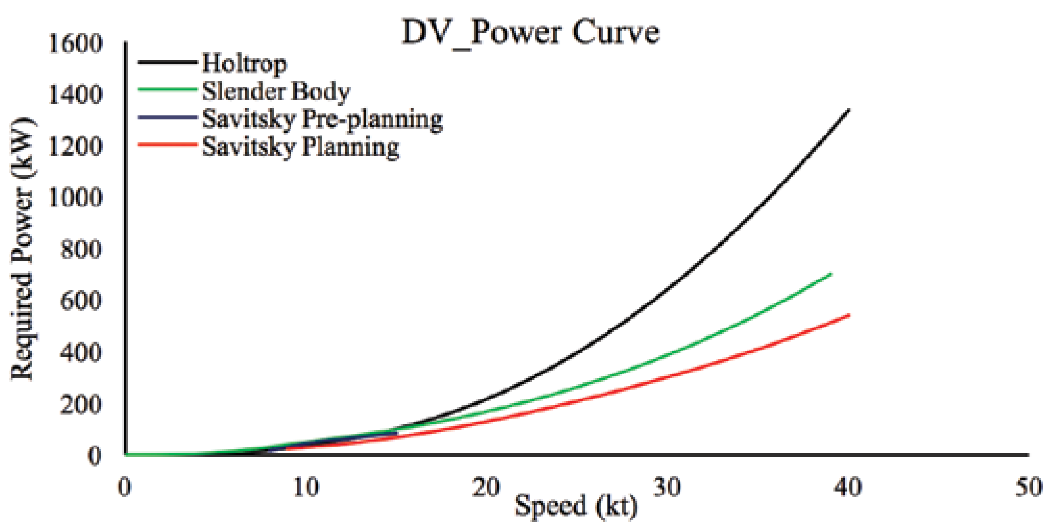


Figure 4: The comparison of required of DV model determined using different models

The results for all models are shown in figure 5. Total required power for the T991 model is highest and slightly higher than the DV model while the NPL – 5b model requires smallest propulsive power. For the low speed regime (< 10kts) the required power is almost similar for all models. At the intermediate speed (10 < U < 20 kts) the DV and NPL 5b seem to require nearly the same amount of power while the T991 requires significantly higher power.

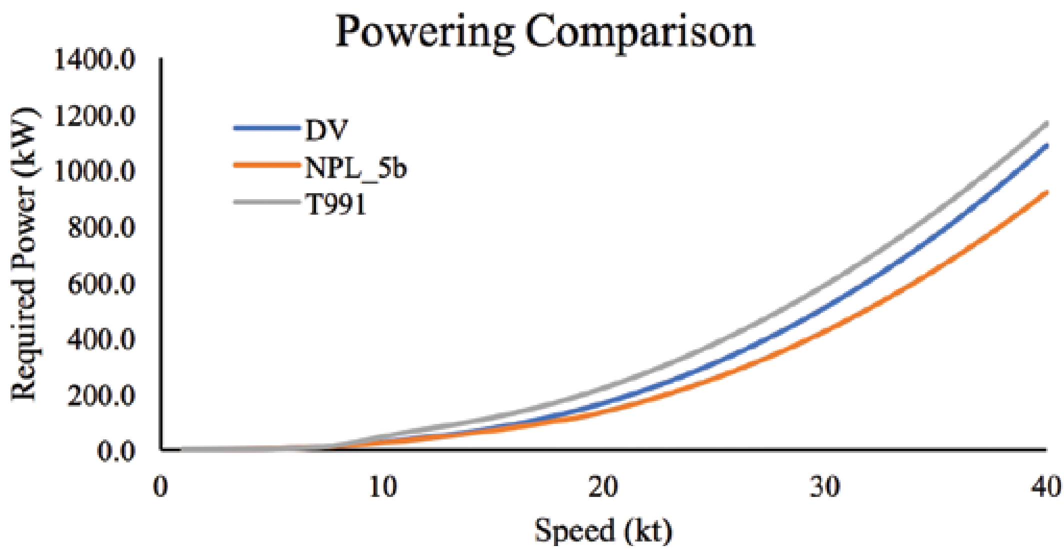


***Figure 5**: The required propulsive power for different models*

4. Initial Seakeeping

Hull performance in rough sea is another aspect which requires the careful investigation. Due to the operation area of the USV close to the shore line hence it is inevitable to face the a very rough sea or high sea state and effects of the sea floor. Three motions including heave, roll and pitch are most concerned. Heave motion might be able to harm the human and equipment onboard the vessel as it can increase or decrease the acceleration rapidly. Pitch motion can cause even more severe damage to the vessel as the slamming can directly damage the hull structure hence reduce hull strength. Apart from that it can cause the engine to stop or damage due to the exceeded angle of operation. Roll motion also cause problem in term of cause keeping and sea sickness. This motion is concerned as the USV is designed to operate remotely as it is comparatively small; hence the small roll motion can cause a large degree of error in course keeping and results in increasing fuel consumption.

The wave encounter angle (β) orientation is shown in figure 6. The first angle of encounter starts from the head wave at 180° (head wave) and decreasing through the side of the ship until reaching 0° (following wave). At his stage the investigation is to demonstrate the effects of (β) at different angles of 180° to 0° with the interval of 45°. The RAO depends on the relationships between wave and ship motions to the fixed frame of reference hence the RAO depends mostly on hull form and angle of encounter (β) not on speed or wave.

4.1 Heading (β) = 180°

Only heave and pitch RAO can be measured for the head wave because waves come and hit purely at the bow of the vessel hence roll motion can be neglected. Figures 7 and 8 show the heave and pitch RAO. The DV model shows a slightly high heave RAO at low frequency of encounter (ω) and decreasing when frequency

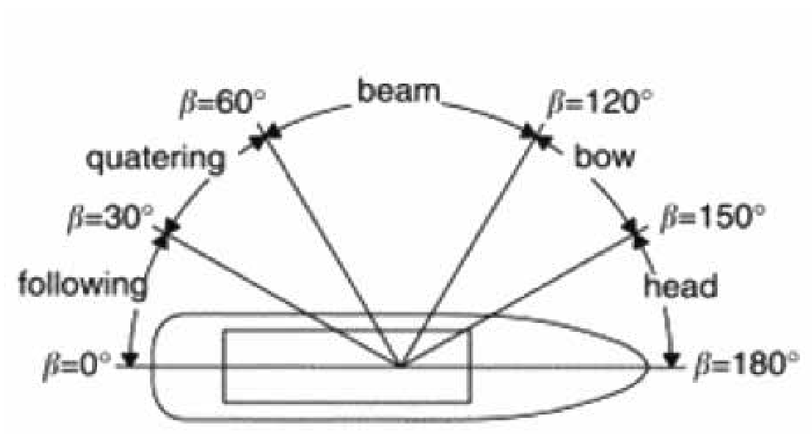


Figure 6*: Angle of encounter (**β**) of wave*

The response amplitude operator (RAO) are measured to demonstrate the performance in waves for all hull forms. These RAOs include heave, roll and pitch. The RAO reflects the relationships between

of encounter decreases and shows the lowest RAO compared with other models. Other models seem to show the same trend of decreasing RAO but slightly higher than DV model.

The DV model shows a lowest pitch RAO compared with other models while the NPL 5b shows the highest RAO and the T991 and NPL 5b catamaran show the similar characteristics which fall in between. This shows that model with the deeper bow part seems to have better pitch motion resistance.

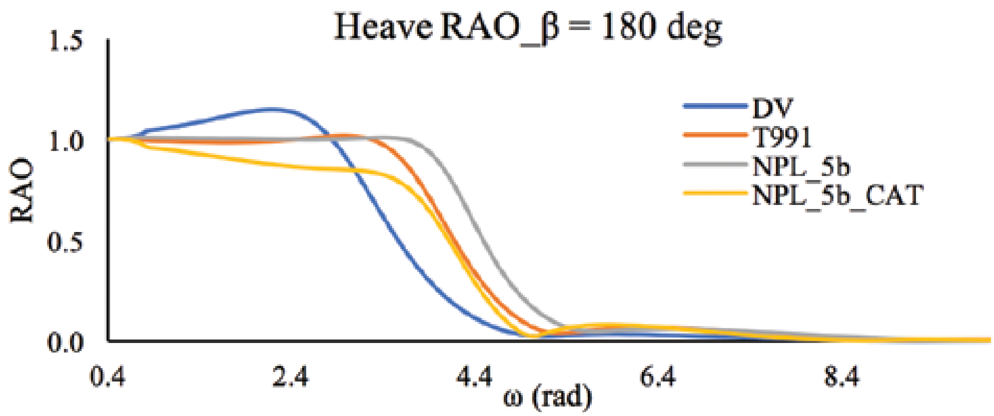


Figure 7: Heave RAO at $\boldsymbol{\beta}$ *= 180°*

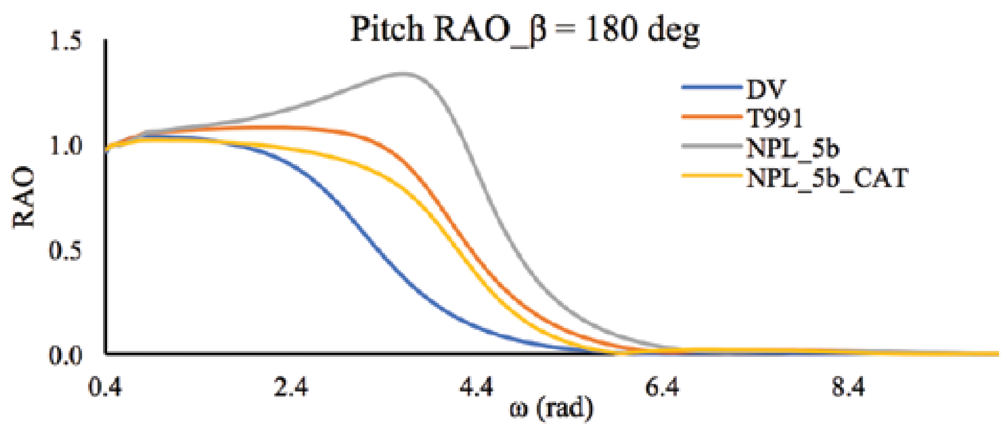


Figure 8: Pitch RAO at $\boldsymbol{\beta}$ *= 180°*

4.2 Heading (β) = 135°

Figures 9, 10 and 11 show the results for β = 135°. At this angle of encounter, the catamaran configuration (NPL 5b catamaran) show the best performance compared with other models, the DV and T991 show similar results while the NPL 5b shows the worst results. However, focusing merely on the highest RAO values for all motion, the results are not much different except for the roll motion which the NPL catamaran shows the best performance.

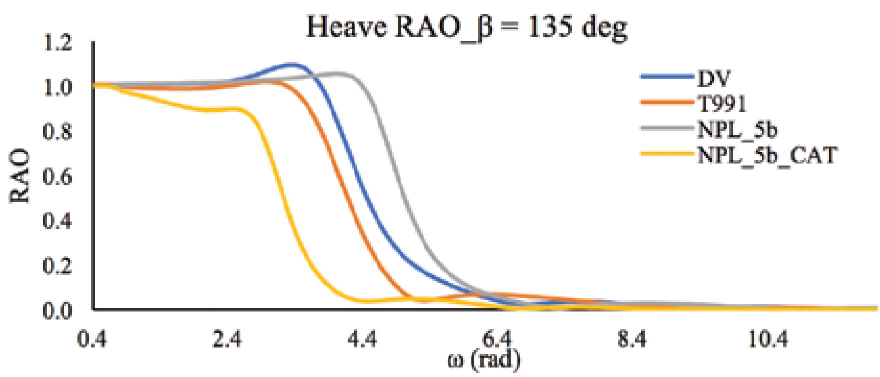


Figure 9: *Heave RAO at* $\boldsymbol{\beta}$ *= 135°*

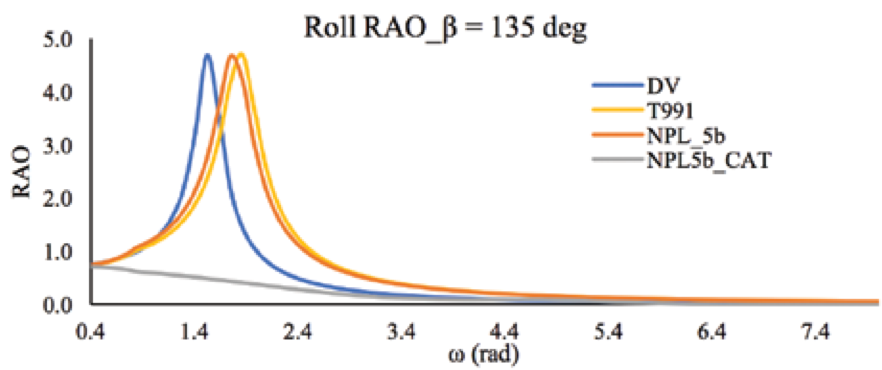


Figure 10: *Roll RAO at* $\boldsymbol{\beta}$ *= 135°*

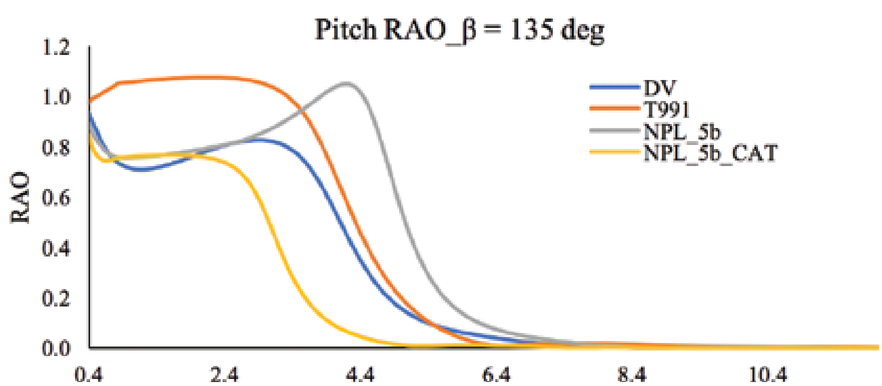


Figure 11: *Pitch RAO at* $\boldsymbol{\beta}$ *= 135°*

4.3 Heading (β) = 90°

The results for the β = 90° show in figures 12, 13 and 14. The DV model shows the best performance for the heave motion resistance while shows the worst for the pitch motion resistance. This might be from the fact that the underwater wedge-shape design of the DV is very thin compared with other models. Again, the catamaran configuration shows the best performance for roll motion resistance.

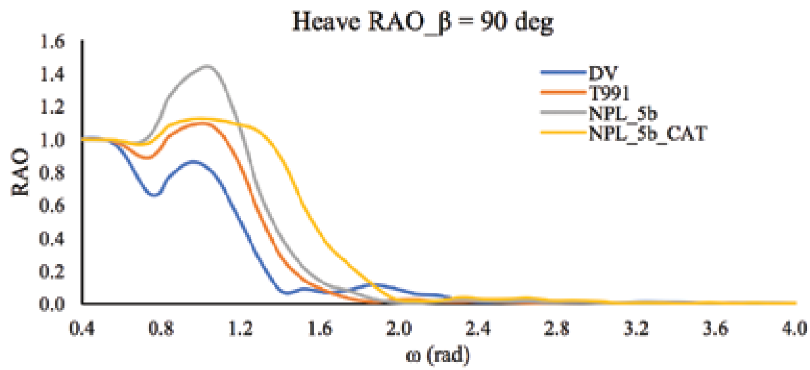


***Figure 12**: Heave RAO at* $\boldsymbol{\beta}$ *= 180°*

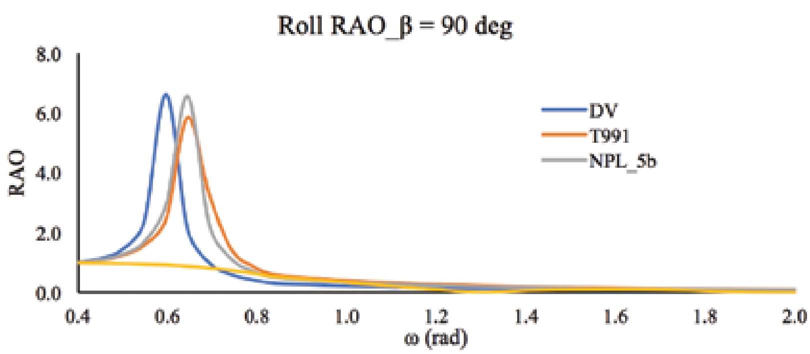


***Figure 13**: Roll RAO at* $\boldsymbol{\beta}$ *= 90°*

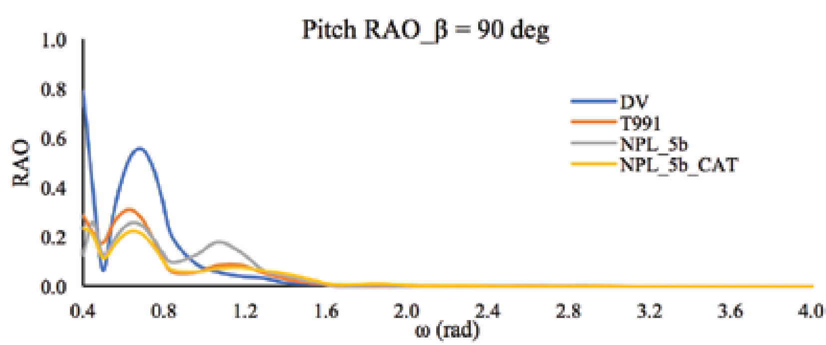


***Figure 14**: Pitch RAO at* $\boldsymbol{\beta}$ *= 90°*

4.4 Heading (β) = 45°

The results for β = 45° are shown in figures 15, 16 and 17. The results are quite difficult to justify however the DV model seems to show better heave motion resistance while show quite worse roll motion resistance which is like the T991 model. The NPL 5b model shows the worst performance for pitch motion. The NPL 5b catamaran model shows the superior performance compared with other models.

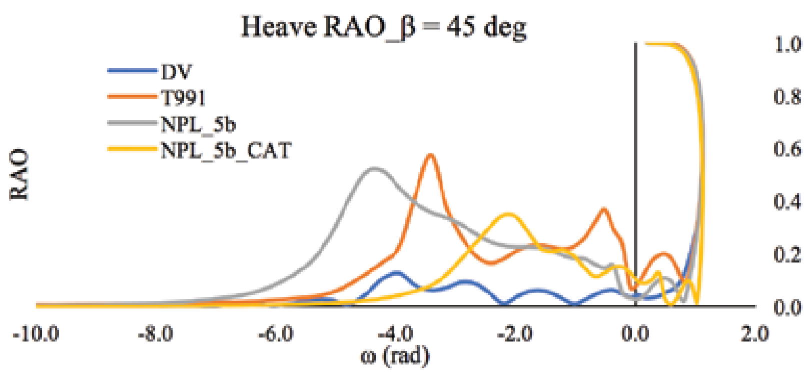


Figure 15: Heave RAO at ***β*** *= 45°*

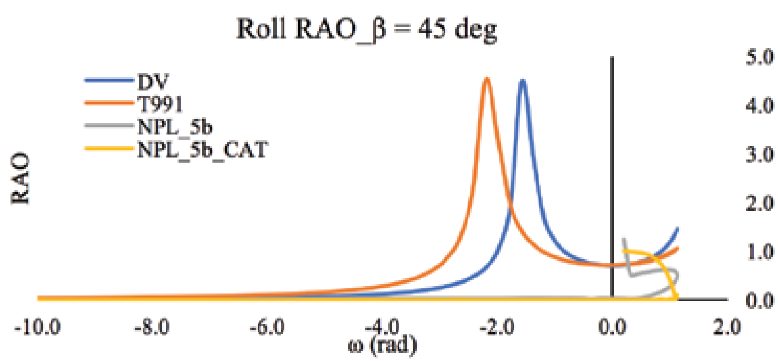


Figure 16: Roll RAO at ***β*** *= 45°*

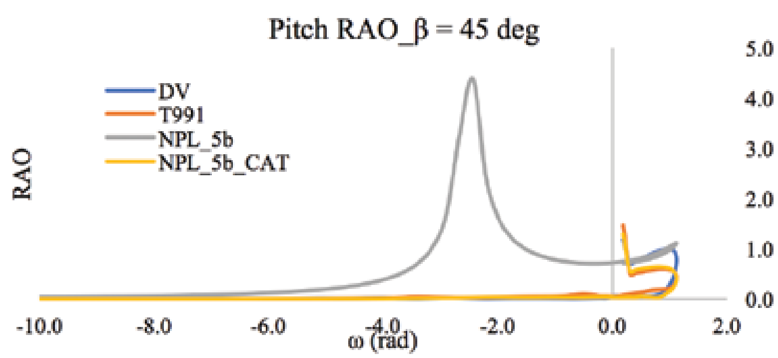


Figure 17: Pitch RAO at ***β*** *= 45°*

4.5 Heading (β) = 0°

The following wave encounter performance are shown in figures 18, 19 and 20. The DV and T991 show a high amplitude for the heave motion at the same frequency of encounter compared with the NPL 5b and the NPL 5b catamaran models. The results for the pitch motion are quite similar for all models.

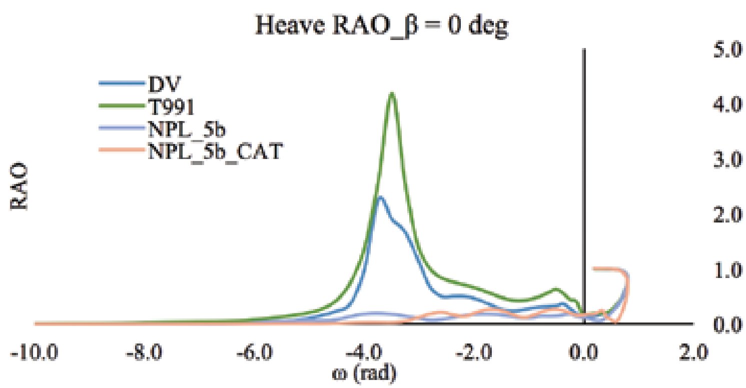


Figure 18: Heave RAO at β *= 0°*

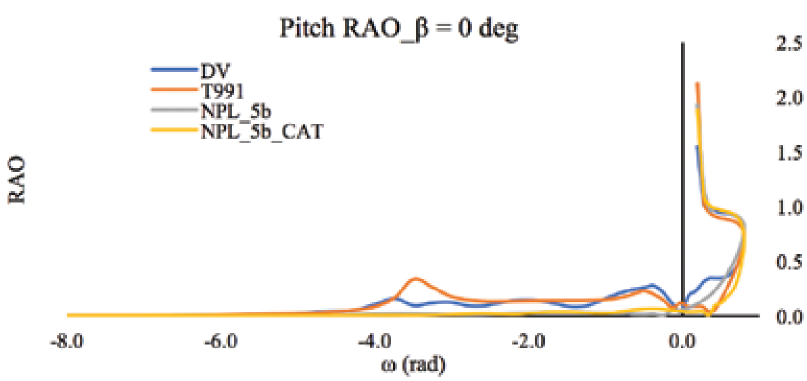


Figure 19: Pitch RAO at β *= 0°*

4.6 First Spectral Moment of Motion (M_0)

The first response spectra show the probability of the peak motion or the motion to happen for the different angle of encounter (β). Figures 20, 21 and 22 show the results for all RAOs discussed previously. It can be seen that all hulls show quite similar trend except for the roll motion which the catamaran configuration shows the best result. The DV shows quite high value for pitch motion for the following wave. This might be from the fact that the aft part of the DV is quite wide and shallow which is prone to emerge when hit by the following waves.

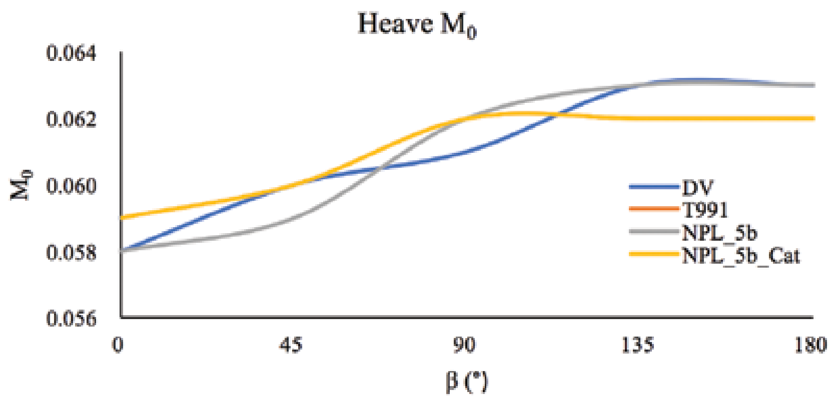


***Figure 20**: comparison of heave M0 for different models at various* $\boldsymbol{\beta}$

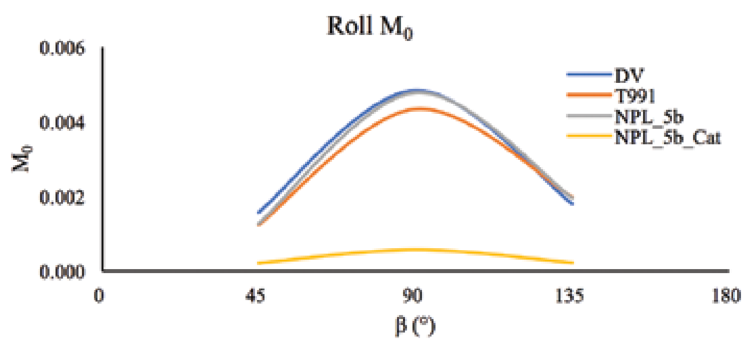


***Figure 21**: comparison of roll M0 for different models at various* $\boldsymbol{\beta}$

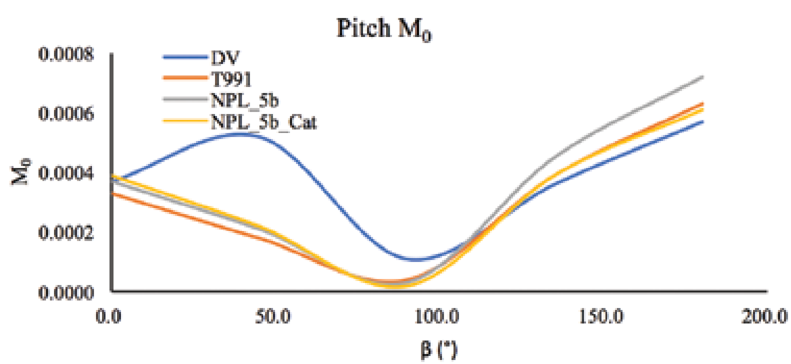


***Figure 22**: comparison of pitch M0 for different models at various* $\boldsymbol{\beta}$

5. Hull evaluation and Conclusion

5.1 Required Propulsive Power and Space

The required propulsive power assessment shows that the high slenderness NPL 5b seems to be beneficial for the USV design compare with other model as it required lowest power to operate through the water. However, in term of space, the DV model seems to have advantage over other monohull configuration models as seen in table 1. The maximum breadth of the DV model is approximately 3.24 m compared with 1.25 m and 1.80 m for the NPL 5b and T991 models respectively. The maximum breadth at the DWL shows that the DV models has the maximum length compared with other monohull models. Hence, the DV model seems to be the better option for the investigation as it provides larger space compared with other monohull models. Moreover, the NPL 5b Catamaran model provides the largest deck area as it has more area between demihulls to carry more equipment and payloads. However, the construction complexity is the challenge as the strength of the connected part between demihulls are more concerned.

5.2 Seakeeping performance

The evaluation of hull performance in waves is presented in table 2. The most capable of handling heave motion is the DV models. The best hull with the capability to resist the roll motion is the NPL 5b catamaran configuration model. The best hull to handle pitch motion is also the NPL 5b catamaran while another two models that show capability in handling pitch motion are DV and T991 models. However, the DV model seems to show slightly advantage over the T991 model because it has ability to handle both head and following waves.

***Table 2**: The evaluation of hull performance in waves*

β	Heave				Roll				Pitch			
	DV	NPL 5b	T991	NPL 5b Cat	DV	NPL 5b	T991	NPL 5b Cat	DV	NP 5b	T991	NPL 5b Cat
180	/								/			
135				/				/				/
90	/							/			/	/
45	/					/		/	/		/	/
0		/								/		/

5.3 Concluding remarks

5.3.1 Conclusions

Three monohull and one catamaran configuration models are investigated including Deep Vee (DV), NPL 5b, T991 and NPL 5b catamaran. Propulsive powering and initial seakeeping are assessed. The required propulsive power study shows that the T991 model requires the largest amount of power at the very high-speed regime which is slightly higher than the DV model. The high slenderness NPL 5b requires least amount of power for the high-speed regime compared with those two models. The powering for catamaran configuration model cannot be calculated using the ship design tool, Maxsurf, hence at this stage it is assumed to be doubling of the monohull for the same draught. However, for the low speed regime (< 10 kts) where the USV is expected to operate, the required propulsive power for all models are quite similar.

The initial seakeeping results show that the DV model has the better heave motion resistance performance while the DC model shows the better performance in handling roll and pitch motions. To this point, the suitable models to be further investigated is the DV and DC models.

5.3.2 Comments

From the conclusions made above, the DV hull is recommended for the USV project. Although it has less ability to handling pitch motion, the further investigation to study hull variants by varying deadrise angle, the parallel horizontal keel design, and length etc. The catamaran configuration seems to have advantages over the monohull, but it might bring the complexity to the project through the construction process. However, the catamaran model is still the possible option for other investigations.

5.4 Future works

5.4.1 Numerical Investigation

The early design stage mostly relies on the statistical model-based software hence the data acquired can be used as the starting point. The further numerical studies are needed for example to determine required propulsive power CFD software will be used. The initial seakeeping is also determined using the same package, so the data again can be used as only for the beginning point. In some cases, for more accurate and reliable results, the experiment will be considered.

5.4.2 Structural Investigation

The structural analysis is needed for the further investigation. As the USV will mostly operate at the high sea condition where the vessel will face the harsh force and pressure form waves, the finite element analysis (FEA) is recommended. Various FEA software can overcome this challenge such as Abaqus and ANSYS Fluent. The choice of material is another option to focus as this directly relate to the ease of build and maintenance, and price.

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