Seakeeping Behavior of Axe Bow Patrol Boat with the Variation of Waterline Spline Type and Submerged Bow Depth

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Seakeeping Behavior of Axe Bow Patrol Boat with the Variation of Waterline Spline Type and Submerged Bow Depth

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Abstract – *As a sovereign maritime country, Indonesia has been supported with patrol boats to maintain, protect, and manage the fishery and marine resources. Therefore, enhancing the patrol boat's operability is essentially needed for improving the resources maintenance and protection system. The implementation of an advanced hull forms might be conducted for the improvement of boat performance. The axe-bow hull form is one of the advanced hull forms that might improve the patrol boat operability, especially in high-speed conditions (Fr<0.60). However, in order to determine a reliable axe bow hull form, the body lines and the submerge bow depth should be defined appropriately. Based on the condition, this study focuses on the investigation of seakeeping performance of the developed axe-bow hull forms with variations of waterline spline type and submerged bow depth (the depth of foot). The waterline spline type configurations, which consist of the concave spline, convex spline, and straight spline, have been developed. At the same time, the submerged bow depths configuration have been proposed as 30%, 40%, and 50% of the boat draught. Both parameters should be recognized for the improvement of the axe bow hull seakeeping performance. The strip theory method has been adopted for the calculation of the seakeeping behavior. The results show that the waterline spline type has influenced the heave motion behavior. Otherwise, the larger depth of root might improve the pitch motion performance. It is indicated that suitable combination of spline type and depth of root might generate a reliable seakeeping performance of the axe-bow patrol boat.*

***Keywords**: Seakeeping Behavior, Axe-Bow Hull, Spline Type, Submerged Bow Depth*

I. Introduction

In 1995, the monohull fast boat hull forms were developed by Delft University, incorporating with Damen Shipyards [1]. The extending hull length has shown an improvement in the resistance and seakeeping performance. The Enlarged Ship Concept (ESC) has been introduced as the fast boat hull form with a significantly increased length of 25 %, while the other parameters such as hull breadth, service speed, and payload capacity remain the same. The lengthening hull of ESC might reduce the total resistance by 30 % and improve maneuvering performance [2]. Consequently, the developed ESC concepts have increased the production cost by about 3%-5%. The operability improvement has been made because the main worker region could be shifted to the optimum location due to the length increment. Otherwise, the bow design should be modified to prevent the large slamming load in severe weather conditions. An alternative bow design has adopted very small flares, deep forefoot, high deadrise, and sheer. The axe-bow hull is introduced by applying the design parameters criteria in order to reduce the nonlinear Froude-Krylov and hydrodynamic lift forces.

The axe-bow hull concept has been expected to reduce the peak vertical acceleration. The axe-bow front section has no flare shape but only a vertical line with a sharp front. The vertical upright side bow is connected to the upper deck sideline with significant additional sheer line-height. Afterward, a relatively long stem bottom line is drawn towards the fore bow. Finally, the additional bow depth has been defined for reducing the wave excitation force. Therefore, the bottom line has extended as a downward curve similar to the upward curve of the sheer line. Keuning et al. [3] have conducted an experimental study on the axe-bow seakeeping behavior. The study shows that the vertical acceleration of the bow and the wheelhouse is significantly decreased compared to the ESC hull. The axe-bow concept has been successfully created a soft spring system on the ship motion behavior.

The hull body lines of the proposed axe-bow hull can be seen in Fig. 1. Keuning and Van Walree [4] have conducted a study by comparing three fast patrol boats hydrodynamic behavior. The Enlarged Ship Concept (ESC boat), the axe-bow, and the wave-piercing hull seakeeping performance have been investigated. The axe-bow has superiority over the ESC and wave-piercing hull on the head sea conditions. However, the ESC and the axe-bow type have similar motion behavior in the stern quartering sea. The deck wetness and the green water load have harshly occurred on the wave-piercing type during the head sea.

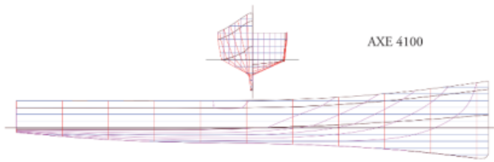


Fig. 1. The axe-bow hull body lines "AXE 4100" [3]

Otherwise, the axe-bow type has 100% operability in the entire period. The axe-bow has the capability to sail on the maximum speeds of 35-50 knots in the North Sea. On the other study, Keuning [5], [6] has investigated the nonlinear behavior of fast monohull in head waves.

The nonlinearity of fast ships' heave and pitch motion in irregular head waves also had been investigated. The computational models have been developed with a concern on the sinkage, trim, hydrodynamic lift force, the significant relative motion, vertical added mas, and wave exciting force. Remarkably, the estimation of vertical acceleration is improved, and the effects of forwarding speed, the deadrise, and the varying hull geometry have been estimated accurately. The investigation of the bow shape effects on the seakeeping behavior of the fast boat can be found in [7]-[9]. Geling [10] has investigated the motion and resistance behavior of a yacht that has adopted the axe-bow hull form. The results have shown that the yacht has excellent seakeeping behavior.

Furthermore, the slamming phenomenon has not appeared due to the axe-bow design. On the high Froude number, the yacht resistance was indicated decreasing.

The wave-making resistance reduction has been identified because of the long slender, streamlined body and the straight-line bow with no flare. The yacht resistance behavior has been also compared to the planing hull and the conventional monohull semi-displacement hull type. The axe-bow yacht has presented better resistance behavior than both hull forms.

Furthermore, the axe-bow hull has positively influenced the intact stability and structural fatigue life. In a recent publication, several research works have been found related to applying the axe-bow hull on the development of fast boat hull and the application of computational fluid for the seakeeping analysis of the nonlinear behavior of fast boat motions. Romadhoni et al [11] have investigated the improvement of fast crew boats due to modifying the bow design to the axe-bow.

The Computational Fluid Dynamic (CFD) analysis has been adopted for the seakeeping characteristics estimation of the modified crew boat [32]. The results show that the modified crew boat seakeeping behavior is better than the original hull, on the higher service speed (Fr>0.6). Kusuma et al. [12] have studied redesigning the conventional bow fast missile boat converted to the axe-bow hull design. The resistance characteristics estimation has been made with the Holtrop method by using the Maxsurf Resistance V8i and the MARIN DESPPC software. The numerical results have shown that the total resistance has decreased 2.75 % on the boat service speed of 28 knots. On the other calculation approach, the total resistance has been decreased by 1.56 %. Niklas and Karczewski [13] have assessed the accuracy of the strip theory method for estimation of the case study of the selected vessel hull. The alternative developed bow forms consist of the axe-bow variant and the X-bow variant. At the same time, the original hull is a research vessel – Nawigator XXI. The experimental study is also conducted in the towing tank. The results have showed that inaccuracy of the strip method is potentially occurred because of the simplification of the hull shaped during the numerical calculation. Otherwise, the simplified hull shape is not capable of estimating the changes of seakeeping behavior due to a slight shape modification.

Furthermore, the strip theory cannot accurately estimate the nonlinear phenomena such as slamming and head wave breaking. Therefore, the application of the strip theory method should be accompanied by the experimental measurement or the complex CFD analysis.

Sutiyo and Utama [14] have investigated the resistance of trimaran hull form using CFD analysis. The trimaran hull has been developed by using The NPL systematic and the modified trimaran with the axe-bow hull. Furthermore, the trimaran hulls have been configured with the variation of demi-hull spacing consisting of s/L=0.3 and 0.4. The CFD analysis has been conducted on the Froude numbers of 0.15, 0.2, 0.25, 0.3, 0.4, and 0.5. The results have showed that the axe-bow design has been reduced the trimaran resistance by 26.6 % compared to the NPL systematic hull design.

Utama, Sutiyo, and Suastika [15] have conducted an experimental and numerical investigation of the influence of axe bow on trimaran's resistance. The trimaran bow-shaped has been modified to the axe-bow form with the main-hull configurations of s/L=0.3 and s/L=0.4. The experimental and numerical estimation has been made on the Froude numbers of 0.15, 0.20, 0.25, 0.3, 0.4, and 0.5.

The results have showed that the axe bow trimaran had reduced the drag force by 8.4 %. The numerical estimation has a good agreement with the experimental measurement. The discrepancy of the numerical estimation is 2.7 % for the modified trimaran hull.

McGibbon et al. [16] have investigated the behavior of an axe bow trimaran hull under nearshore wave reflections. A scaled model has been tested in coastal wave basin. The results show that an axe bow trimaran hull experiences unusual motions when the encounters wave has been influenced by the nearshore reflection.

Setiawan et al. [17] have compared the resistance and fuel consumption characteristics of Axe Bow and Moor Deep Ram Bow hull form using CFD analysis. The results show that the axe bow hull form has a lower resistance than Moor Deep Ram Bow. Rijken and Mikelic [18] have studied the hydrodynamic comparison between conventional and axe bow hull for frigate vessel.

The experimental results show the axe bow presents lower calm water resistance about 9%. Furthermore, the axe bow hull has smaller heave, pitch motions, and might reduce the deck wetness in the large waves. The CFD analysis shows a good agreement with the experimental results. Luhulima et al. [19] have investigated the resistance and Energy Efficiency Design Index (EEDI) of trimaran vessel using axe bow hull. The use of axe bow hull might reduce the total drag and CO_2 emission. The total resistance has been decreased about 2.4%. Amiadji et al. [20] have conducted CFD analysis to estimate the resistance and pitch motion characteristics of novel flat plate panel hull. Although the flat panel hull has adopted the axe bow shape for the stem part. However, the flat panel hull has still presented a larger resistance than the conventional hull. Chen et al. [21] have compared the seakeeping and added resistance performance between X-Bow and Wave piercing monohull in regular waves.

The results show that the wave piercing bow have shown a larger added resistance than X-Bow in the small wave height (*H*=0.04 m). However, the effect of the bow shape is not sensitive in the large Froude number (*Fr*=5). In the large wave height (*H*=0.12 m), the wave piercing bow have presented smaller added resistance than X-Bow.

The wave piercing pitch responses are smaller than X-Bow (*Fr*=0.5). The fast boat with the special hull, such as axe-bow, planing hull, and catamaran, should be supported with optimum appendages to achieve the optimum resistance performance. Zakki et al. [22], [23] have investigated the hydrodynamic characteristics fin and hydrofoil shapes of the sacrificial anodes to reduce the hull appendages effect on the fast boat. Although the research about the axe-bow hull form can be found in several publications, a few studies are related to the effect of the waterline splined type and the depth of the submerged bow on the monohull axe-bow patrol boat. In the previous study, the monohull axe-bow has been developed to investigate the effect of the water spline typed and the depth of the submerged bow (depth of foot) variations on the resistance and stability performance, [24]. The results show that the depth of the submerged bow and the waterline spline type does not significantly influence the resistance performance. However, the slightest resistance can be found on the convex spline type with the submerged foot depth of 30 % vessel draught (T). Furthermore, the effect of both variables does not significantly perform on the intact stability performances. Nevertheless, the concave type with the bow submerged depth of 50 %T. This research is focused on the seakeeping characteristics investigation of the developed axe-bow hull for the patrol boat. In continuing the previous research, [24], the exact configuration of the prior developed axe-bow hull form has been investigated to estimate the seakeeping behavior. The assessment of the seakeeping performance of the developed hull has been significantly needed as the recommendation of the design reliability to fulfil the patrol boat technical requirements. This paper outlined has presented the conceptual axe-bow hull design with the variation of the spline type and depth of foot. The seakeeping calculation procedures have been explained with the provided service speed of 15 knots, 20 knots, and 25 knots.

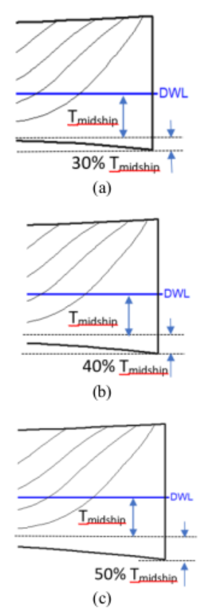
Furthermore, the wave spectrum is determined as a representation of the operational environment. The results and the discussion have presented the seakeeping behavior of the variations axe-bow hull and the influence of the water spline type and bow depth. Finally, this paper has presented the conclusion and recommendation for applying the developed axe-bow hull regarding the analysis and numerical calculation results.

II. Material and Methods

II.1. Geometry Descriptions of the Axe-Bow Patrol Boat Hull Form

In the previous study, [24], the monohull axe-bow has been been developed with the variation of waterline spline type and the depth of submerged bow. The principal dimension on the main hull has been determined with the linear regression equations formulated by using 15 parent boat data as hull dimension references. Furthermore, the depth of the submerged bow has been configured with an additional depth of the bow draught that consisted of 30 %Tmidship, 40 %Tmidship, and 50 %Tmidship, where Tmidship is the vessel draught on the midship part. The variation of the submerged bow depth can be seen in Figs. 2. The second parameter is the waterline spline type. The three kinds of waterline spline types have been adopted for the design of the fore-spline line.

This parameter has been selected since the selected spline type affects the angle of entrance size. Furthermore, the fluid flow and the separation around the vessel hull have been influenced by the magnitude of the entrance angle.



Figs. 2. The variation of the additional bow depth of the axe-bow hull: (a) 30 %Tmidship; (b) 40 %Tmidship; (c) 50 %Tmidship, [17]

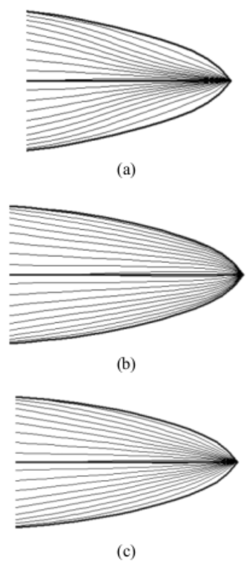
Regarding the theoretical background, the selected spline has been configured as concave, convex, and straight spline type, Figs. 3. Therefore, nine axe-bow hull forms have been made to investigate the seakeeping performance to obtain the optimum patrol boat hull form.

The body line of the developed axe-bow hull can be seen in Figs. 4.

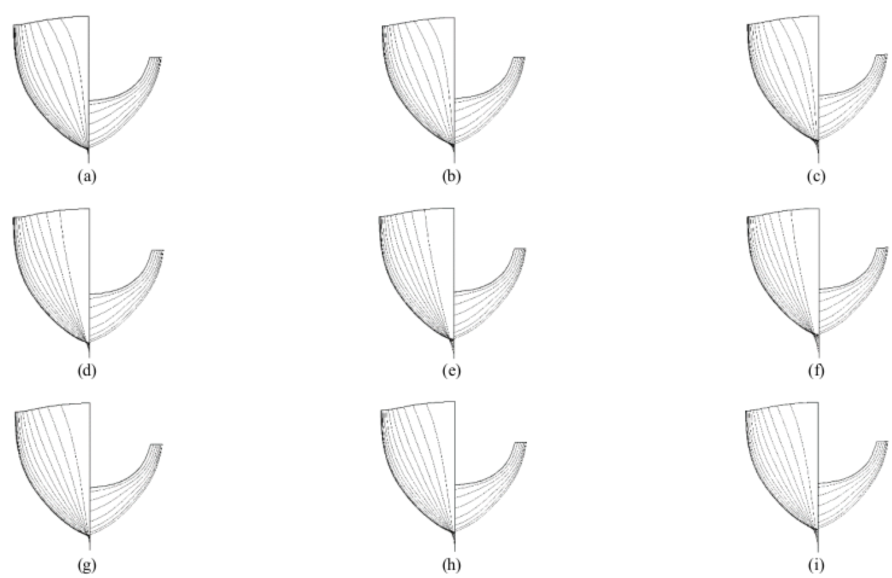
II.2. Estimation of Seakeeping Behavior of The Developed Axe-bow Hull

The operational environment governs a vessel's seakeeping characteristics as the essential external aspect for effectively performing the patrol boat surveillance activities. Consequently, the seakeeping analysis should be supported with an adequate waterway environment formulation. On representing the waterways environment, the appropriate wave spectrum should be selected. Furthermore, the vessel response motion behavior depends on the hull geometry, weights distribution, and the defined wave spectrums.

Several wave spectrum models have been formulated to represent the environment with an irregular sea characteristic for the seakeeping analysis. The available wave spectrum models have been distinctively developed depending on the sea environment that has been modeled. The existing wave spectrum models commonly used on the seakeeping analysis are Pierson-Moskowitz, Bretschneider (ITTC), JONSWAP, and the Ochi-Hubble spectrum. Some research can be found on investigating the territorial sea environment characteristics and the adoption of wave spectrum type for representing wave characteristics in Indonesia. Kurniawan and Khotimah, [25] have shown that the highest wave reaches more than 3 meters in the South China Sea and the Pacific Ocean during the Asian monsoon. The highest wave has occurred in the Indian Ocean and the Arafura Sea with over 2.5 meters wave height among the Australian monsoon. However, the inter-island sea environment has not been inclined to high tides. In the internal sea environment, the significant wave height rarely occurs over 1.7 meters.



Figs. 3. The three kinds of water spline type of the axe-bow hull: (a) concave type; (b) convex type; (c) straight type, [17]



Figs. 4. The nine kinds of axe-bow hull body lines, [17]: (a) Concave-DoB 30%; (b) Concave-DoB 40%; (c) Concave-DoB 50%; (d) Convex-DoB 30%; (e) Convex-DoB 40%; (f) Convex-DoB 50%; (g) Straight-DoB 30%; (h) Straight -DoB 40%; (i) Straight -DoB 50%

Otherwise, the slightly over 2 meters wave height might be found on the south region of Java Island.

Setiyawan et al. [26] have concluded that the JONSWAP spectrum is suitable for representing the wave characteristics in the Pacitan and Meulaboh coast, located on the south region of Java Island and the West region Sumatera Island, respectively. Iqbal and Rindo, [27] have selected the ITTC spectrum for inter-islands sea wave characteristics in Indonesia. The Ochi-Hubble spectrum can also be found suitable because the double peak's spectrum was obtained on the wave characteristics measurement in Indonesia territorial sea, [28], [29].

Recently, Zakki et al. [30] have determined to select the JONSWAP spectrum for assessing the catamaran hull motion behavior. The study has explained that the JONSWAP spectrum appropriately formulates the wave characteristics because the archipelagic sea can be identified as an enclosed water wave condition.

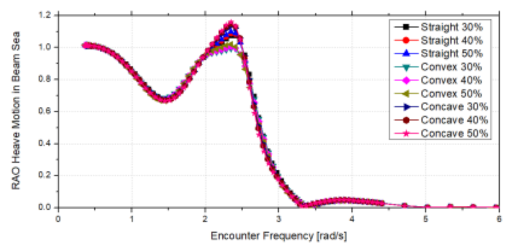
Regarding the previous research, this research has determined to adopt the JONSWAP spectrum for the axe-bow motion performance estimation. The significant wave height has been as large as 2 meters, a modal period of 9.984 seconds, and a zero-crossing period of 7.868 seconds. The peak enhancement factor has been determined with a constant of 3.30. Otherwise, the detailed equation of the JONSWAP spectrum can be found in [31].

III. Results and Discussions

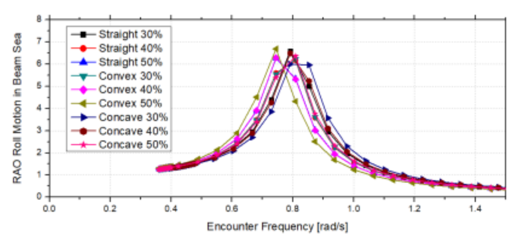
III.1. Response Amplitude Operator of the Axe-Bow Hull Form

The motion performance has been estimated with a seakeeping analysis with the strip theory method for the numerical calculation. Strip theory is a well-known calculation procedure that has adopted the three-dimensional Neumann-Kelvin formulation for the slender body vessel. In the strip theory, the vessel body has been divided transversely on a finite number of stations. Each station has been considered hydro-dynamically as a segment of an infinite floating object. The strip theory has generated an acceptable approximation for a floating object with a length-breadth ratio over three (L/B>3).

Therefore, the strip theory can be adopted for the axe-bow hull motion behavior, which has a length-breadth ratio of 5.2, over the defined requirement. One of the seakeeping analysis results is the response amplitude operator (RAO) of each axe-bow hull motion consisting of heave, roll, and pitch motion. The response amplitude operator has determined the influence of wave environment on the vessel motion. Theoretically, RAO is recognized as a transfer function that effectively generates the motion behavior from the selected wave spectrum. Therefore, the second result of the seakeeping analysis is the motion response spectrum of the axe-bow hull. During the calculation, several wave heading angles have been defined on 90°, 135°, and 180° as representing Beam Sea, Bow Quartering Sea, and Head Sea, respectively. Figs. 5 depict the response amplitude operator results of heave, roll, and pitch in Beam Sea condition. The heave RAO has shown the influence of water splined type on the heave motion behavior, Fig 5(a). The convex spline type has generated a minor peak point of the heave RAOs. It is indicated that the convex spline might reduce the effect of the Beam Sea wave on the heave motion response. This phenomenon might be explained that the convex spline type has a more significant damping motion than the other type. The larger waterplane area of the convex plane has generated a larger heave motion damping. Otherwise, the bow depth has also presented an influence on the heave motion response. A greater depth has presented a slight increase in the heave RAO peak point. It can be explained because the depth and sharp bow-shaped might reduce the heave motion damping. On the roll motion, the spline type and the bow depth do not significantly influence the peak point of the RAO. However, both factors have shifted the RAO curve, Fig. 6(b), and Fig. 7(b). The roll RAO curve of the convex spline type is located on the most left side, while the concave spline type is located on the most right-side. Otherwise, the straight spline is located between both curves. A similar tendency has been presented on the effect of bow depth on the roll RAO curve.



(a)



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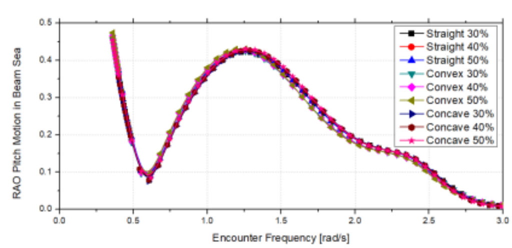
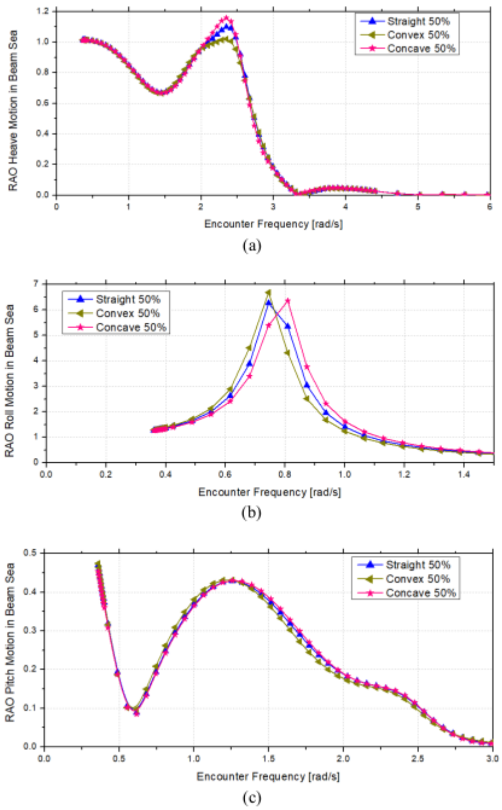
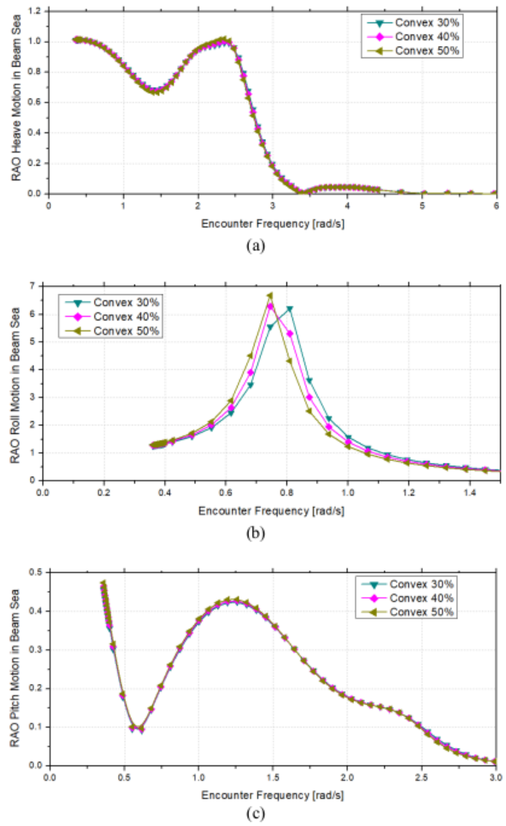


(c)

Figs. 5. Response Amplitude Operators of the Axe-bow Hull in Beam Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion



Figs. 6. The Effect of Spline Type on the RAO in the Beam Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch motion



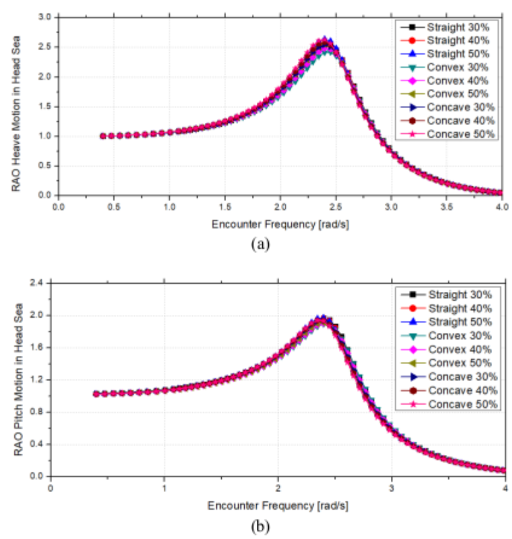
Figs. 7. The Effect of Bow Depth on the RAO in the Beam Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion

The 50% bow depth RAO curve is located on the most left side, while the 30% bow depth is the most right-side.

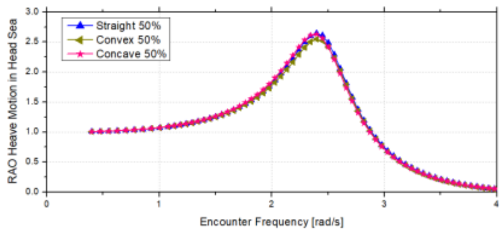
The 40% bow depth RAO has been also obtained between both curves. It is indicated that the changes of spline type and bow depth have shifted the encounter frequency of the roll motion RAO. The convex spline with a larger displacement has shifted the roll RAO in the left direction, while the concave spline has shifted the curve in the right direction. Otherwise, it can be predicted that both factors do not significantly influence the pitch motion RAO curve in the Beam Sea.

Furthermore, the pitch motion has occurred because of the shifted buoyancy center point due to the fluctuation submerged depth. Since the wave excitation force has not directly generated the pitch motion, the changes of the pitch RAO have not been significantly identified.

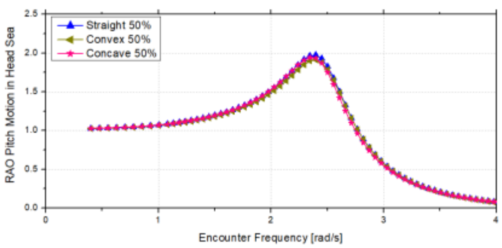
However, it can be seen that the pitch RAO tends to shift the curve than decrease the peak point due to the hull configuration, Fig. 6(c), and Fig. 7(c). In the Head Sea, the wave excitation has been unable to generate roll motion. Therefore, the RAO has presented only on the heave and pitch motion, Figs. 8. On the heave motion, the spline type might reduce the peak point of the RAO curve, Fig. 9(a).



Figs. 8. Response Amplitude Operators of the Axe-bow Hull in Head Sea: (a) Heave Motion; (b) Pitch Motion



(a)



(b)

Figs. 9. The Influence of Spline Type on the RAO in the Head Sea: (a) Heave Motion; (b) Pitch Motion

The convex spline has apparently reduced the RAO peak point more than the straight and the concave spline. Otherwise, the influence of the bow depth also has shown an increased the heave RAO peak point by increasing the bow depth, Fig. 10(a).

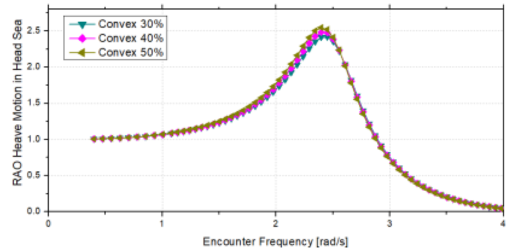
Conversely, in the pitch motion, the changes of the bow depth do not significantly influence the RAO curve, Fig. 10(b). The pitch RAO curve has shown the same curve size and shape due to the bow depth changes.

Nevertheless, the convex spline type has reduced the pitch RAO than two others. In comparison, the straight spline shows a slightly increased peak point compared to the concave spline in the Head Sea. Finally, the seakeeping estimation has been made on the Bow Quartering Sea. Figs. 11 depict the variation of axe-bow hulls RAO consisting of heave, roll, and pitch motion.

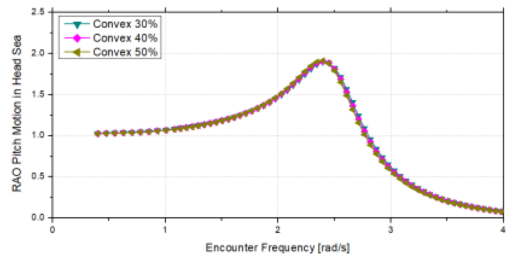
Regarding both parameters, it can be seen that the RAO curves have shown a similar pattern with the Head Sea condition. However, the roll motion RAO magnitude is not zero as in the Head Sea. On the heave RAO, the spline type and the bow depth have decreased the magnitude of the RAO curve peak-point. The convex spline has generated the lowest peak point than the others.

This curve trend is similar to the heave RAO on the Head Sea. However, the magnitude of the RAO is slightly low compared to the Head Sea. It is a reasonable result because the wave excitation magnitude is slightly decreased due to the heading angle changes. Otherwise, the modified bow depth effect has also presented a decreased RAO peak-point due to the shallow bow depth.

Therefore, the lowest peak-point has shown on the convex spline axe-bow hull with the bow depth of 30%Tmidship.



(a)



(b)

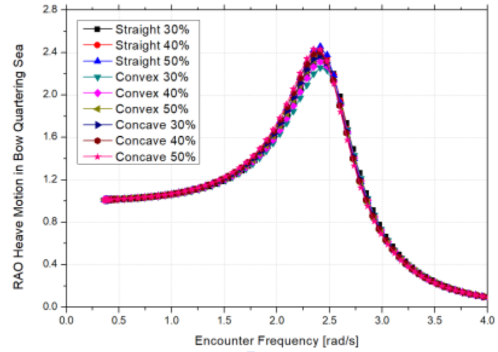
Figs. 10. The Influence of Bow Depth on the RAO in the Head Sea: (a) Heave Motion; (b) Pitch Motion

Fig. 11(b) presents the roll motion RAO in Bow Quartering Sea. It can be seen that the RAO encounter frequency has been shifting due to both parameters' variation. This phenomenon also can be found on the Beam Sea and Head Sea. The convex spline type has influenced the RAO by shifting the curve line on the left side, while the concave spline has shifted the curve on the right side, Figs. 12. Otherwise, the shallow bow depth has shifted the RAO on the right side, Figs. 13.

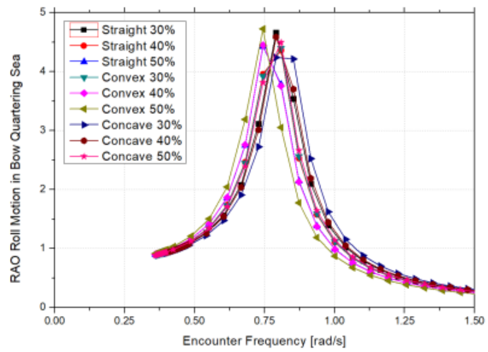
Therefore, the axe-bow with the bow depth of 50%Tmidship generates the RAO curve on the more left-side than the others. Regarding the roll motion behavior on Head Sea, the effect of both parameters does not significantly influence the magnitude of the roll motion RAO. Finally, the numerical results show the pitch motion RAO on the Bow Quartering Sea. Fig. 11(c) shows that the spline-type has decreased the magnitude of pitch RAO. The convex spline has conducted a more significant decrement than the others have. This behavior is similar to the convex spline's effect on the Head Sea condition. However, the maximum value of RAO is slightly decreased due to the different wave heading angles. On the other side, the modified bow depth does not significantly influence the pitch motion RAO. It can be seen that the RAO curves line of the axe-bow hull with bow depth variation has coincided with each other.

III.2. Motion Response Spectral Density of the Axe-Bow Hull Form

The motion response spectra have been generated from the multiplication of the RAO with the wave spectrum. The selected wave spectrum is JONSWAP, with a significant wave height of 2 meters.



(a)



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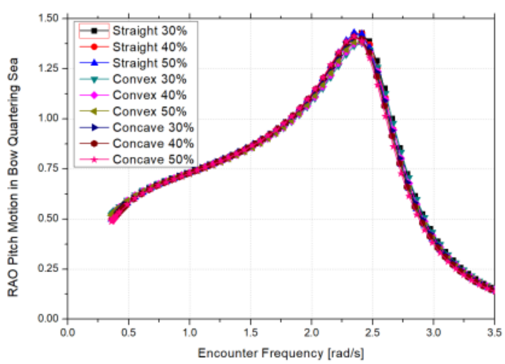
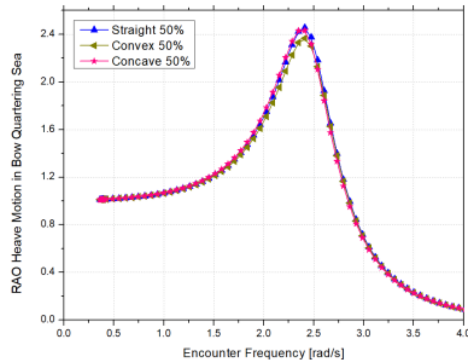
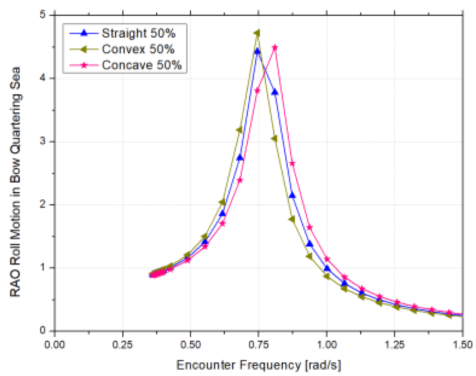


(c)

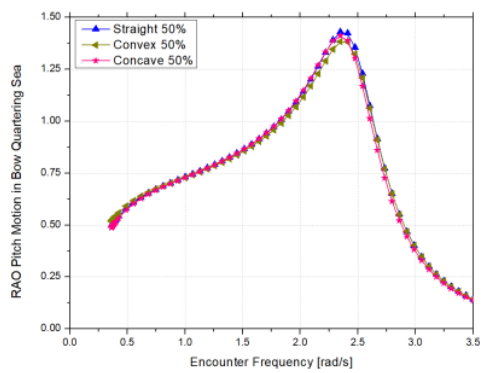
Figs. 11. Response Amplitude Operators of the Axe-bow Hull in Bow Quartering Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion



(a)



(b)



(c)

Figs. 12. The Influence of Spline Type on the RAO in the Bow Quartering Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion

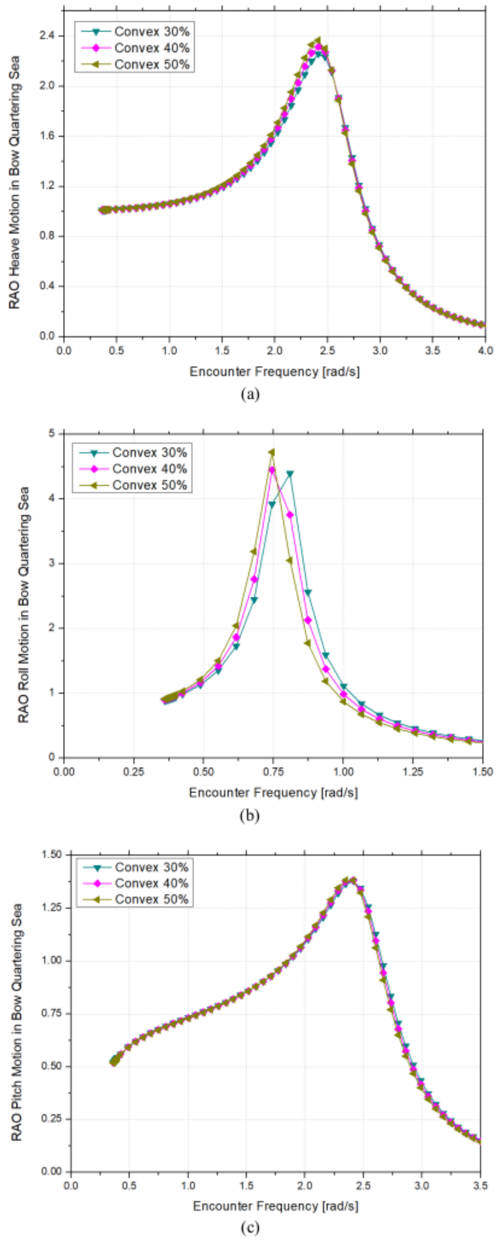
Furthermore, the maximum service speed of 25 knots has been defined for the numerical calculation. The motion spectra density of each motion in Beam Sea, Head Sea, and Bow Quartering Sea can be seen in Figs. 14 to Figs. 20.

In Beam Sea, Figs. 14, the motion spectral density has a similar curve line shape and trend with the RAO.

However, the heave spectra density has presented the same magnitude and shaped for all axe-bow hull variations.

It can be explained that the maximum heave motion RAO does not locate on the peak value of the wave spectrum.

Thus, the effect of the spline type and bow depth on the motion response has not significantly occurred, Fig. 15(a) and Fig. 16(a). Furthermore, the effect spline type and the bow depth can apparently be recognized on the roll motion, Fig. 15(b), and Fig. 16(b).

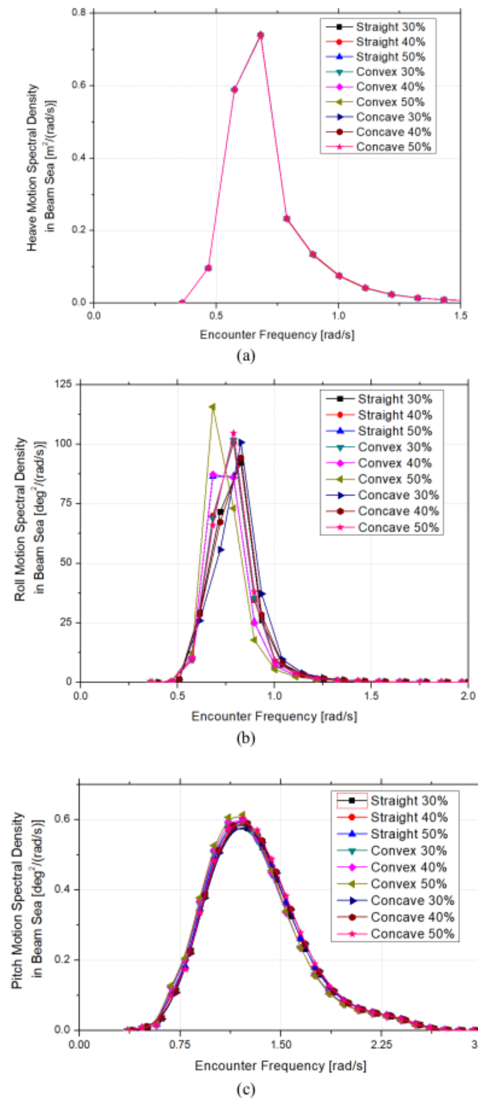


Figs. 13. The Influence of Bow Depth on the RAO in the Bow Quartering Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion

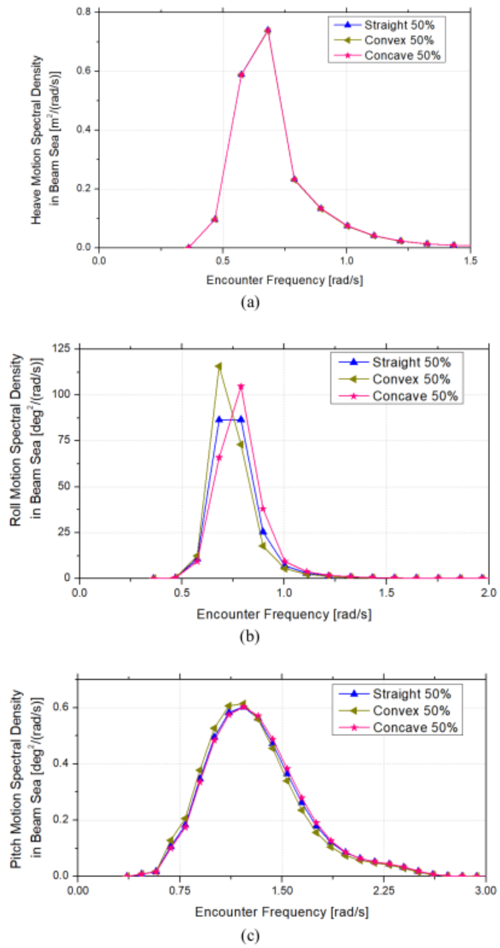
It is indicated that the RAO has magnified the magnitude of the wave spectrum value because the RAO value is larger than 1 (RAO value >1). Therefore, the effect of spline type on the peak-point of the motion spectral density also can be identified. The convex spline type has presented the higher motion spectral motion compared to the others. Otherwise, the bow depth effect also can be obtained on the curve peak value. The convex spline with 50%T bow depth has the highest peak-point than the others.

It is indicated that the larger hull displacement represented as the convex type and the bow depth of 50%Tmidship might generate the largest motion spectral motion compared to the other configuration.

Figures 17 depict the motion spectral of the various axe-bow hull forms in the Head Sea. Regarding the RAOs results, it can be seen that there are only two kinds of motion: heave and pitch motion. The roll motion response is zero due to the wave exciting on the Head Sea.



Figs. 14. Motion Spectral Density of the Axe-bow Hull in Beam Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion

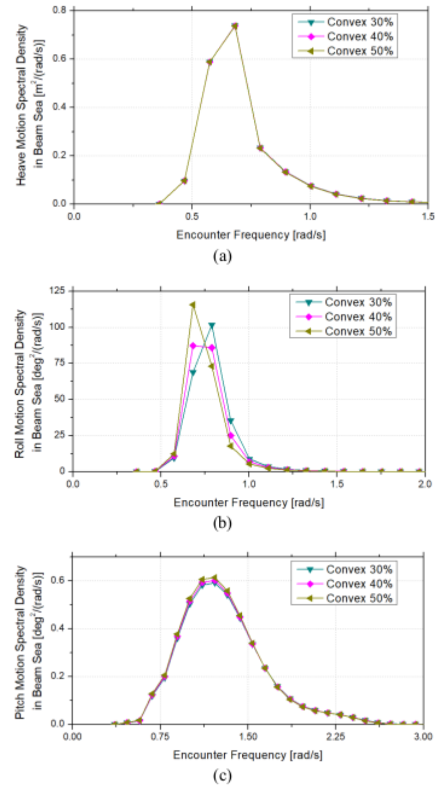


Figs. 15. The Influence of Spline Type on the Motion Spectral Density in Beam Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion

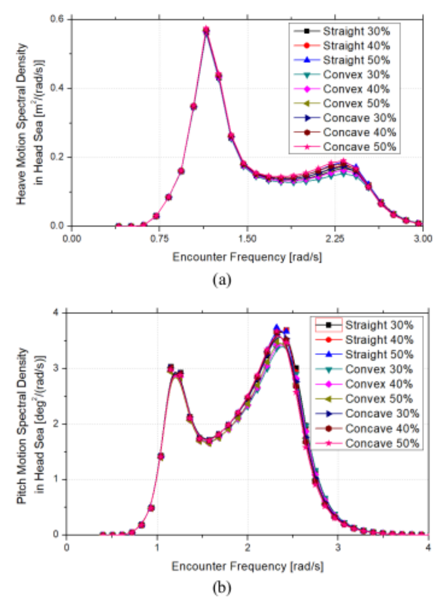
The heave motion spectral has shown that the various axe-bow hulls have the same characteristics on the encounter frequency between 0.56 rad/s to 1.4 rad/s.

However, among the encounter frequency of 1.4 rad/s to 2.58 rad/s, the spline type, and the bow depth have influenced the heave motion spectra, Fig. 18(a) and Fig. 19(a). The convex spline has reduced the motion spectral density, while the bow depth of 30%Tmidship has shown a smaller heave motion spectral density than the others.

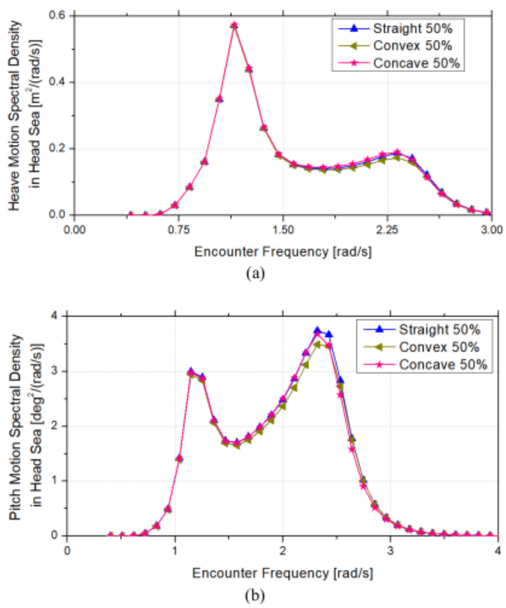
The spline type and the bow depth effect can be recognized due to the large value heave motion RAO occurred on the encounter frequency of 1.4 rad/s to 2.58 rad/s. However, the peak point has occurred on the encounter frequency of the enormous magnitude of the JONSWAP wave spectral density. A similar behavior can also be seen on the pitch motion spectral density. The maximum peak point of the pitch motion spectral density curve has located on the encounter frequency of 2.25 to 2.5 rad/s.



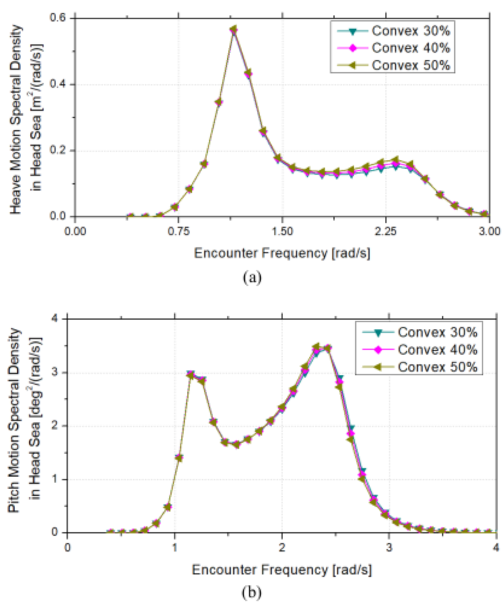
Figs. 16. The Influence of Bow Depth on the Motion Spectral Density in Beam Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion



Figs. 17. Motion Spectral Density of the Axe-bow Hull in Head Sea: (a) Heave Motion; (b) Pitch Motion

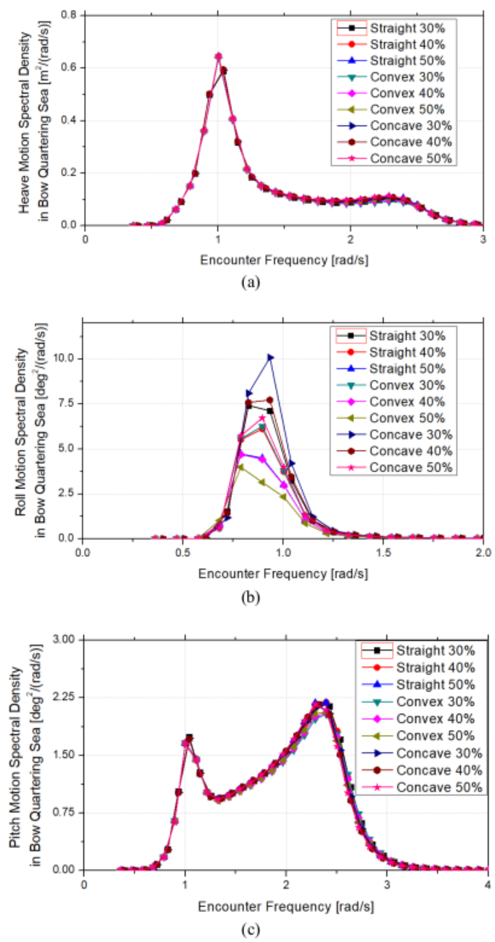


Figs. 18. The Influence of Spline Type on the Motion Spectral Density in Head Sea: (a) Heave Motion; (b) Pitch Motion

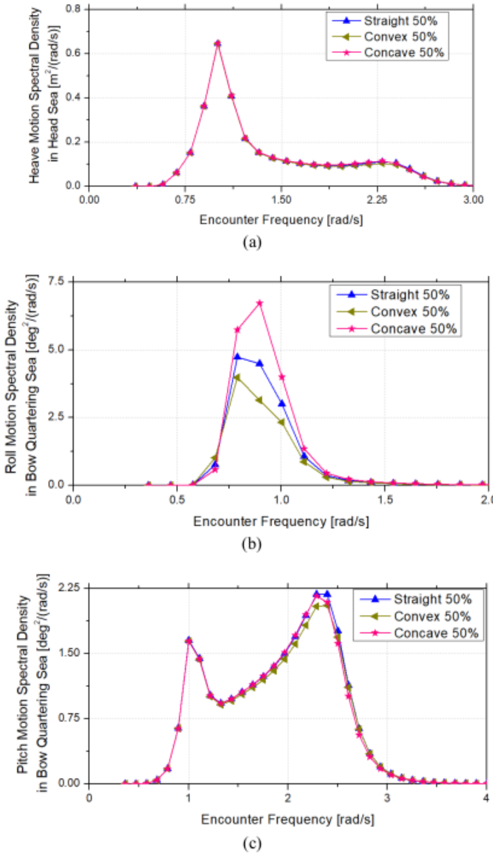


Figs. 19. The Influence of Bow Depth on the Motion Spectral Density in Head Sea: (a) Heave Motion; (b) Pitch Motion

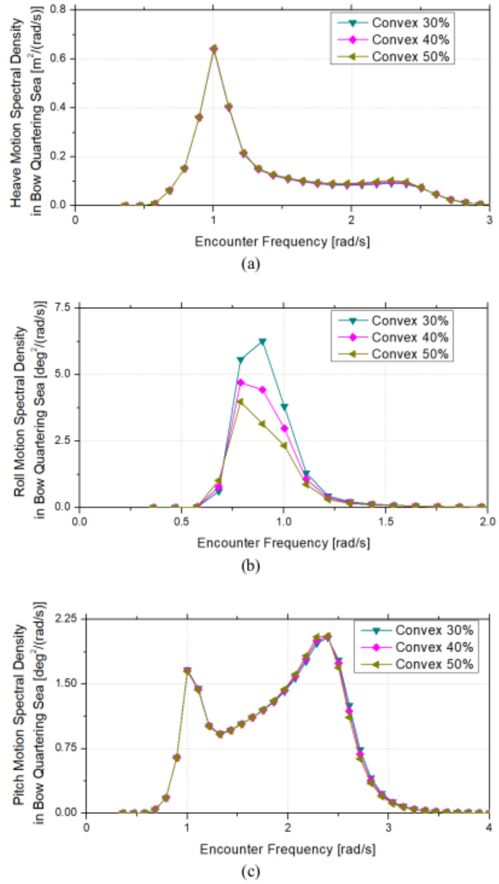
The encounter frequency is also the maximum encounter frequency of the pitch RAO. Therefore, the influence of both parameters on the pitch motion spectral density has shown similar with the pitch RAO curve in Head Sea. Otherwise, the convex spline type has reduced the pitch motion spectral density, while the bow depth of 30%Tmidship was slightly decreased the curve line, Fig. 18(b) and Fig. 19(b). Furthermore, two peak points can be found on the pitch motion spectral density. The first peak point has been generated by the maximum value of the wave spectral density, while the additional peak-point has occurred due to the pitch motion RAO. In Figs. 20, the behavior of response motion spectral density, consisting of heave, roll, and pitch, has been presented due to the wave excitation in the Bow Quartering Sea. It can be seen that the heave and the pitch motion spectral density have a similar curve pattern with the motion spectral density in Head Sea. This behavior can be explained because the wave excitation in the Bow Quartering Sea has similar characteristics to the wave in the Head Sea. Furthermore, the wave heading angle of Bow Quartering Sea has generated a lower heave and pitch motion compared to the wave excitation in Head Sea, Fig. 20(a) and Fig. 20(c).



Figs. 20. Motion Spectral Density of the Axe-bow Hull in Bow Quartering Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch motion



Figs. 21. The Influence of Spline Type on the Motion Spectral Density in Bow Quartering Sea: (a) Heave Motion; (b) Roll Motion; [c] Pitch Motion



Figs. 22. The Influence of Bow Depth on the Motion Spectral Density in Bow Quartering Sea: (a) Heave Motion; (b) Roll Motion; (c) Pitch Motion

The effect of spline type and bow depth has also presented similar behavior with Head Sea, Figs. 21 and Figs. 22. However, the roll motion has shown the effect of spline type and bow depth significantly. The convex spline has reduced the roll motion spectra density compared to the others, while the bow depth of 50%Tmidship has generated the lowest roll motion spectral density. Based on the computational results, it can be concluded that the convex spline type and bow depth of 50%Tmidship have significantly influenced the roll motion characteristics in the Bow Quartering Sea.

As a final stage of the seakeeping analysis, the motion characteristics of the various axe-bow hulls can be obtained on the root mean square of the motion spectrum.

The spectrum means square is the area below the spectra density curve. The area represents the vessel's entire motion response behavior. The root means square of the developed hull form with the configuration of spline type and bow depth in three kinds of wave heading angles has been presented in Tables I-III. It can be seen that the motions amplitudes have the same tendency as the motion spectral density results.

In Beam Sea, the heave and pitch motion amplitudes of the entire modified hull form are similar. It is indicated that the spline type and the bow depth modification have no significant influence on the heave and pitch motion in the Beam Sea. However, the influence of spline type and bow depth has slightly influenced the roll motion. The convex spline hull has showed the smallest roll amplitude with 50%Tmidship bow depth, Table I. In the Head Sea, the convex spline hull with 30%Tmidship bow depth shows the smallest heave motion amplitude (Table II). It can be explained that the bulky shape of the convex hull can generate a larger heave motion damping than the others. Additionally, the deeper bow might increase the vertical motion acceleration due to the streamlined and sharp bow shape. On the other side, the smallest pitch motion amplitude has been shown by the convex spline hull with 50%Tmidship bow depth. Although the sharp bow might increase the vertical motion acceleration, the deeper bow depth has reduced the pitch motion amplitude.

TABLE I
COMPARISON OF THE MOTION ROOT MEAN SQUARE IN BEAM SEA

Motion Type	Concave 30%	Concave 40%	Concave 50%
Heave Amplitude	0.478	0.478	0.477
Heave Velocity	0.361	0.360	0.360
Heave Acceleration	0.373	0.372	0.372
Roll Amplitude	5.23	5.19	5.15
Roll Velocity	0.076	0.074	0.073
Roll Acceleration	0.071	0.068	0.065
Pitch Amplitude	0.70	0.70	0.70
Pitch Velocity	0.017	0.017	0.017
Pitch Acceleration	0.027	0.027	0.027
Motion Type	Straight 30%	Straight 40%	Straight 50%
Heave Amplitude	0.478	0.478	0.477
Heave Velocity	0.361	0.360	0.360
Heave Acceleration	0.372	0.371	0.370
Roll Amplitude	5.19	5.13	5.11
Roll Velocity	0.074	0.071	0.070
Roll Acceleration	0.067	0.064	0.061
Pitch Amplitude	0.70	0.70	0.70
Pitch Velocity	0.017	0.017	0.017
Pitch Acceleration	0.026	0.026	0.026
Motion Type	Convex 30%	Convex 40%	Convex 50%
Heave Amplitude	0.477	0.477	0.476
Heave Velocity	0.359	0.359	0.358
Heave Acceleration	0.367	0.366	0.365
Roll Amplitude	5.14	5.12	5.11
Roll Velocity	0.072	0.069	0.068
Roll Acceleration	0.064	0.061	0.058
Pitch Amplitude	0.69	0.70	0.70
Pitch Velocity	0.016	0.016	0.016
Pitch Acceleration	0.025	0.025	0.025

TABLE II
COMPARISON OF THE MOTION ROOT MEANS SQUARE IN HEAD SEA

Motion Type	Concave 30%	Concave 40%	Concave 50%
Heave Amplitude	0.628	0.632	0.637
Heave Velocity	1.050	1.060	1.070
Heave Acceleration	2.125	2.143	2.161
Pitch Amplitude	2.13	2.12	2.11
Pitch Velocity	0.075	0.074	0.074
Pitch Acceleration	0.170	0.169	0.167
Motion Type	Straight 30%	Straight 40%	Straight 50%
Heave Amplitude	0.624	0.629	0.635
Heave Velocity	1.046	1.058	1.069
Heave Acceleration	2.128	2.151	2.172
Pitch Amplitude	2.15	2.14	2.14
Pitch Velocity	0.076	0.076	0.075
Pitch Acceleration	0.175	0.173	0.171
Motion Type	Convex 30%	Convex 40%	Convex 50%
Heave Amplitude	0.615	0.621	0.628
Heave Velocity	1.022	1.035	1.049
Heave Acceleration	2.065	2.093	2.120
Pitch Amplitude	2.11	2.10	2.09
Pitch Velocity	0.075	0.074	0.074
Pitch Acceleration	0.171	0.169	0.168

This behavior might be explained that the larger bow depth has increased the inertia waterplane area. The larger waterplane inertia might decrease the pitch motion amplitude. Furthermore, the larger bow depth has increased the front draught. Consequently, the deeper bow might decrease the slamming occurrence probability during the sagging wave condition. In Bow Quartering Sea, the convex spline hull type shows the smallest heave motion amplitude with 30%Tmidship bow depth.

Otherwise, the smallest pitch motion amplitude has been presented by the convex spline hull type with 50%Tmidship bow depth. This behavior is similar to the motion behavior in the Head Sea.

TABLE III
COMPARISON OF THE MOTION ROOT MEANS SQUARE IN BOW QUARTERING SEA

Motion Type	Concave 30%	Concave 40%	Concave 50%
Heave Amplitude	0.585	0.588	0.591
Heave Velocity	0.872	0.878	0.885
Heave Acceleration	1.676	1.689	1.701
Roll Amplitude	1.71	1.59	1.47
Roll Velocity	0.029	0.026	0.024
Roll Acceleration	0.034	0.031	0.029
Pitch Amplitude	1.65	1.64	1.64
Pitch Velocity	0.057	0.057	0.056
Pitch Acceleration	0.129	0.128	0.126
Motion Type	Straight 30%	Straight 40%	Straight 50%
Heave Amplitude	0.583	0.586	0.589
Heave Velocity	0.869	0.877	0.885
Heave Acceleration	1.680	1.695	1.711
Roll Amplitude	1.55	1.43	1.31
Roll Velocity	0.026	0.024	0.021
Roll Acceleration	0.031	0.028	0.026
Pitch Amplitude	1.67	1.66	1.66
Pitch Velocity	0.058	0.058	0.057
Pitch Acceleration	0.132	0.131	0.130
Motion Type	Convex 30%	Convex 40%	Convex 50%
Heave Amplitude	0.576	0.58	0.585
Heave Velocity	0.851	0.861	0.870
Heave Acceleration	1.634	1.653	1.672
Roll Amplitude	1.44	1.30	1.18
Roll Velocity	0.024	0.021	0.019
Roll Acceleration	0.027	0.026	0.024
Pitch Amplitude	1.64	1.63	1.63
Pitch Velocity	0.057	0.057	0.056
Pitch Acceleration	0.130	0.129	0.127

The roll motion has a minimum amplitude of 0.019 degrees for the convex spline hull with 50%Tmidship bow depth. The effect of spline type and bow depth on the roll motion in Bow Quartering Sea has shown similar behavior to Beam Sea. It is indicated that the convex spline type and the deeper bow might improve the roll motion behavior.

IV. Conclusion

The seakeeping analysis of the various axe-bow hulls for the patrol boat to support the domestic surveillance activities has been made. The hull form variations have been defined with the configuration of the spline type and the bow depth. Furthermore, JONSWAP spectra have been selected as the wave spectrum of the sea environment. Otherwise, the strip theory numerical calculations of the developed axe-bow hulls' seakeeping performance have provided the results that can be adopted as a reference on their applicability to improve the patrol boat performance for the surveillance operations in Indonesia. The response amplitude results show that the convex spline type might reduce the effect of the wave excitation on all motion responses in all of heading angle conditions consisting of Beam Sea, Head Sea, and Bow Quartering Sea. Otherwise, the bow depth of 30%Tmidship presented a slight decrease of the peak-point of the heave motion RAO. The variation of bow depth does not significantly influence the peak-point of pitch and roll motion RAO in all wave heading angle conditions. Furthermore, it can also be found out that both parameters have reduced the peak-point of translational motion RAO (heave) and have shifted the curve line encounter frequency of the rotational motion RAO (roll and pitch). Regarding the motion spectral density and the root mean square results, the convex spline has also presented the lowest amplitude of all motion in all of heading angles conditions. Furthermore, the deeper bow has reduced the roll and pitch motion amplitude but has slightly increased the heave motion amplitude. It might be explained that the deeper bow may reduce the heave damping effect due to the sharp and streamlined bow shape. Based on the seakeeping behavior of the variations of the axe-bow hull, it is recommended to select the convex spline type and the bow depth of 50%Tmidship for being adopted as the axe-bow hull of patrol boat to support the surveillance activities in Indonesia territorial Sea. Otherwise, the deeper bow depth may also reduce the slamming probability occurrences due to the sagging wave. The study has shown that the convex spline type and the deeper bow depth have shown better seakeeping performance using the strip theory method. It is recommended to investigate both parameters' effects by using more advanced methods such as computational fluid dynamic analysis to complement results, especially on investigating nonlinear phenomena such as slamming and green water load on the ship motion performance for future works.

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