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Resistance Analysis of a Semi-SWATH Design Concept in Shallow Water

Arifah Ali[1*], Adi Maimun[1], Yasser M. Ahmed[2] and Rahimuddin[3]

1. Marine Technology Center, Department of Aeronautics, Automotive & Ocean Engineering, Universiti Teknologi Malaysia, Skudai 81310 UTM, Malaysia
2. Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, Alexandria 21526, Egypt
3. Program Studi Teknik Sistem Perkapalan, Universitas Hasanuddin, Makassar, 90245, Indonesia

Abstract: Resistance analysis is an important analytical method used to evaluate the hydrodynamic performance of High Speed Craft (HSC). Analysis of multihull resistance in shallow water is essential to the performance evaluation of any type of HSC. Ships operating in shallow water experience increases in resistance because of changes in pressure distribution and wave pattern. In this paper, the shallow water performance of an HSC design concept, the semi-Small Waterplane Area Twin Hull (semi-SWATH) form, is studied. The hull is installed with fin stabilizers to reduce dynamic motion effects, and the resistance components of the hull, hull trim condition, and maximum wave amplitude around the hull are determined via calm water resistance tests in shallow water. These criteria are important in analyzing semi-SWATH resistance in shallow water and its relation to flow around hull. The fore fin angle is fixed to zero degrees, while the aft fin angle is varied to 0º, 5º, 10º, and 15º. For each configuration, investigations are conducted with depth Froude numbers (Fr_H) ranging from 0.65 to 1.2, and the resistance tests are performed in shallow water at the towing tank of UTM. Analysis results indicate that the resistance, wave pattern, and trim of the semi-SWATH hull form are affected by the fin angle. The resistance is amplified whereas the trim and sinkage are reduced as the fin angle increases. Increases in fin angle contribute to seakeeping and stability but affect the hull resistance of HSCs.
Keywords: resistance, wave height, semi-SWATH, shallow water, fin stabilizers

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1 Introduction

Research on High Speed Craft (HSC) has increased in recent years because of the development of inland waterway transportation. The design issue of this type of vessel is strongly related to concepts in coastal engineering point. One type of HSC vessel with an innovative design is the semi-Small Waterplane Area Twin Hull (semi-SWATH), which is a combination of a SWATH and a catamaran. This design provides operations in coastal regions with improved seakeeping criteria.

Determining the hydrodynamic characteristics of a semi-SWATH in shallow water is an essential undertaking. The restriction of the distance between the hull bottom and the seabed exerts significant effects on resistance and trim changes (Senthil and Chandra, 2013). The mentioned ship criteria in shallow water condition have been discussed in the experimental work of Molland *et al*. (2003) and Millward (1996) which addressed the increase of resistance near the critical Depth Froude Number, Fr_H, due to effects of larger wave interference at the limited depths.

Both resistance and trim changes are important considerations in innovative catamaran designs as producing catamarans with both smaller resistance and good seakeeping criteria is challenging. Many catamaran vessels are installed with a pair of fins or foils to reduce rolling and pitching. Thus, thefin design requires deep evaluation because the employed design will affect the hull resistance lift force from the fin and cavitation around the fin stabilizer (Faltinsen, 2005). The discussion of the result in Chen (2013) and the theoretical text on the hydrofoil resistance by Faltinsen (2005) explained the concept of foil resistance, in which the foil contributes to the viscous resistance, the induced drag, and the wave resistance.

Wave pattern sare very critical in shallow water because a small water depth cause the flow around the hull to reach critical levels resulting in generation of high-amplitude waves. The occurrence of waves in critical conditions increases the wave resistance and, consequently, the total resistance of the hull. Several factors, including hull design, geometry, and wetted surface area, influence the flow around the hull and changes in the hull form affects the profile of the wave generated (Stumbo *et al*., 1999).

The work presented in this study is performed to predict the resistance and trim and wave pattern changes around the semi-SWATH in shallow water. The results of shallow-water experiments can provide a reliable reference for further analyses of semi-SWATH operations in inland waterways and validate numerical work.

2 The resistance characteristics of multihull vessel in shallow water condition

The semi-SWATH adapts similar resistance components

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***Corresponding author Email:** arifah2@live.utm.my

compared to other types of multihull vessel. The changes of waves properties in shallow water condition are described according to the behavior of fast ship in limited water depth.

2.1 Resistance components of multihull vessels

Analysis of the fundamental resistance of multihull vessels is based on the force derivation of monohull vessels. Normal and tangential forces generated from the vessel operation are considered based on the direction of motion. The factor differentiating the derivation of force between monohulls and multihulls is the interference response between the hulls (Insel and Molland, 1991).

The resistance breakdown usually applied in experiment includes residual and frictional resistance components. Division of these components in resistance analysis can show the dominant resistance at a certain speed and condition. Residual resistance can be divided into wave-making resistance and viscous pressure resistance, while frictional resistance refers to the effect of hull motion in viscous fluid (Couser *et al*., 1997). The parameters affecting frictional force value are the hull's wetted surface area, surface roughness, and water viscosity.

The wave resistance of a ship is affected by the energy density of the propagated wave (Whittaker and Doyle, 2001). Vessel motion causes formation of different wave patterns according to the vessel speed. In shallow water, changes in trim and sinkage modify the pressure distribution around the hull, which strongly influences wave formation in shallow water. The residual resistance in shallow water is contributed to by the water depth effect on the wave pattern generated around the hull. The aspect of wave resistance was more highlighted than friction resistance based on the significance of wave effect in shallow water (Sahoo and Doctors, 2003) and the wave resistance enlargement in shallow water condition was currently discussed by Mousaviraad *et al.* (2015).

The interference resistance coefficient of a multihull also affects the resistance components. While some interferences increase the total resistance, others reduce it. The total resistance (R_T) of multihull vessels, including those with a semi-SWATH, is presented by Eq. (1), where R_F is the frictional resistance, R_W is the wave-making resistance, β is the viscous interference factor, k is the hull form factor, and τ is the wave-resistance interference factor.

$$R_T = \left(1+\beta k\right) R_F + \tau R_W \tag{1}$$

2.2 Wave pattern in shallow water condition

A critical concern of hydrodynamic assessment in shallow water conditions is waves generated by the vessel and wake wash. Wake wash is one of the effects contributed by wave energy around the hull. Assessment of wake wash involves many physical criteria, including the wave pattern generated under different operational speeds and wave propagation to the far field.

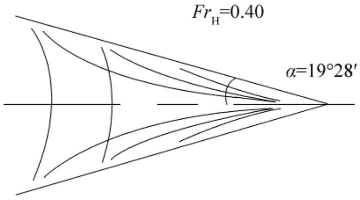
Brizzolara and Bruzzone (2003) revealed the influence of limited water depth to the increase of fast ship wave resistance, which is more significant in longer generated waves. The limited depth in shallow water makes the phenomena becomes critical with the influence of generated wave characteristic and dynamic behavior of the vessel. Whittaker and Doyle (2001) discovered that the generated wave pattern of vessels depends on Depth Froude number, Fr_{H}, which is calculated as in Eq. (2) and related to the wave celerity, c in Eq. (3).

$$Fr_{\mathrm{H}} = \frac{V}{\sqrt{gh}} \tag{2}$$

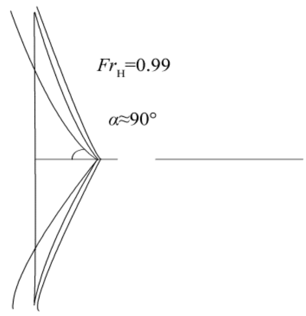
$$c = \sqrt{gh} \tag{3}$$

where V is the vessel speed, g is the acceleration due to gravity, and h is the water depth.

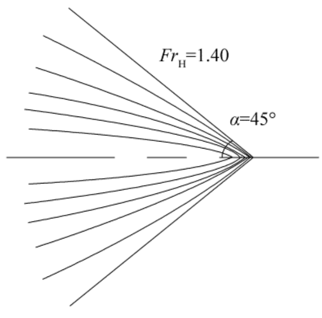
The critical condition occurs when Fr_{H} approaches or is equal to 1.00. At this point, the vessel reaches the critical speed, and the wave propagation angle (α in Fig. 1) approaches 90º and moves nearly perpendicularly to the vessel array. The wave patterns obtained at subcritical (Fr_{H}<1.0), critical, and supercritical (Fr_{H}>1.0) speeds are shown in Figs. 1(a)–(c). The wave pattern generated by vessel motion in calm water affects the resistance components, causing the resistance in shallow water to be larger than that in deep water at a similar speed. The ratio between the wave resistances in shallow water and deep water exceeds 15 at the critical speed and small water depth over vessel length, h/L, values (Faltinsen, 2005).



(a) at subcritical speed



(b) At critical speed



(c) At supercritical speed (Senthil and Chandra, 2013)

Fig. 1 Effect of shallow water on wave patterns

2.3 Effect of trim and sinkage on hull resistance

The trim motion of HSCs in shallow water is an important consideration. Restricting the distance between the hull bottom and seabed changes the fluid velocity and pressure around the hull as shown in Fig. 2 and causes sinkage and large trims (Jachowski, 2008). The experimental work done by Kazerooni and Seif (2014) on the squats of the ship in shallow water conditions addressed the grounding risk due to the excessive hull sinkage for the limited underkeel clearance.

These changes influence the resistance component of the vessel. The trim condition affects the flow on the hull surface and consequently changes the pressure distribution around it. In a previous analysis of the trim effect on the resistance of a semi-SWATH, the wave-making resistance was found to increase when the vessel is trimmed by stern at small-angle conditions rather than at even-keel conditions (Iakovatos *et al*., 2014). Each hull form is known to exert a specific response in terms of resistance due to the prevailing trim condition.

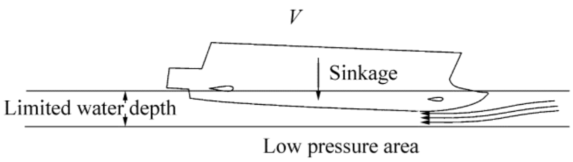


Fig. 2 Effects on limited depth on trim and sinkage

3 The experimental resistance test in shallow water condition

The resistance of the semi-SWATH is predicted in experiments performed in shallow water. The resistance test is prepared according to ITTC standards but features several limitations because of differences in the performance of the semi-SWATH in comparison with those of other types of hulls in shallow water. Because of these limitations, some procedures including testing of the hull without fin stabilizers and testing of the hull with different water depths, were not performed to simplify the experiment. The attachment of the fin stabilizers to the hulls and the motion prediction system restrict the resistance test for hulls without the stabilizers. Excessive motion at smaller water depths can lead to grounding. The experimental results are analyzed based on the obtained resistance curves and wave heights.

3.1 Effect of trim and sinkage on hull resistance

The semi-SWATH model used in this study is shown in Fig. 3; the model features a fixed fin at the fore of the hull and an adjustable fin at its aft. Based on Rahimuddin (2013), this arrangement provides good seakeeping of the hull in calm water and wave conditions. The dimensions of the model are shown in Table 1 and main dimensions of fin stabilizer are in Table 2. The buoyancy of the hulls is provided by the submerged torpedo-like body below water surface.

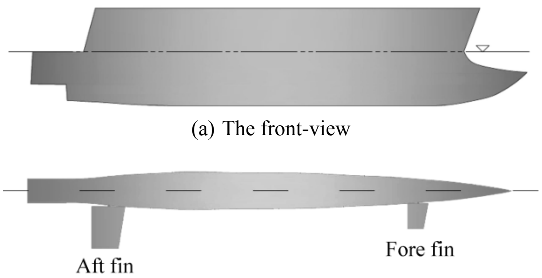


Fig. 3 The illustration of the hull form of the semi-SWATH model

Table 1 Main dimensions of the semi-SWATH full scale and model with scale factor 10:1

Particular	Full scale	Model
Overall length/m	23.90	2.39
Length of waterline, L_{WL}/m	21.11	2.11
Overall breadth/m	8.0	0.8
Hull spacing between centerlines/m	6.4	0.64
Shallow water draft/m	1.6	0.16

Table 2 Main dimensions of the fins stabilizer model with NACA 0015 section type

Parameter	Fore	Aft
Length of span/m	0.12	0.185
Length of chord/m	0.096	0.16
Position from C.G./m	0.7	0.924
Aspect ratio	1.25	1.15

3.2 Shallow water towing tank

The semi-SWATH model is tested in the Marine Technology Center of Universiti Teknologi Malaysia (MTC UTM). The tank size has been identified with the given dimension: length=120 m and width=4 m and the shallow water platform installed near the end of the towing tank is 18.75 m long. Such a length allows the vessel to reach steady-state conditions during testing. The model is tested at water depth-based scaled speeds ranging from about 0.94 to 1.74 m/s over Fr_H ranging from 0.65 to 1.2. During the tests, the separation distance between the demihulls is held constant at an S/L value of 0.30 according to the practical range for catamaran service, $0.20<S/L<0.40$.

The water was considered shallow when the shallow water depth-to-draft ratio, h/T value was in the range of 1.2 to 1.5 (Vantorre, 2001). The water depth, h, in this experiment is 21.5 cm based on the range of h/T. The h/T value for this experiment is 1.35. The wave height generated by the semi-SWATH during operation is recorded according to the method applied in Ghani and Rahim (2008). Resistance and trim were recorded by a data acquisition and analysis system at the towing carriage. The measured total resistance is converted to the non-dimensional total resistance coefficient, C_T, using Equation 4, and the residual resistant coefficient, C_r, is obtained from Eq. (5) by substituting the C_f value calculated by Eq. (6).

During the resistance test, characteristics of the wash generated by the hull is measured in terms of wave amplitude according to the method applied in Nasirudin (2007). Longitudinal wave cuts were measured by two wave probes with a specific *y*/*L*, as shown in Fig. 4, where y is the transverse distance of the probe from the tank centerline. Probe 1 measures near-field waves, while probe 2 measures far-field waves. Wave heights are recorded by LabView software integrated with the wave probes, a signal conditioning unit, and a computer.

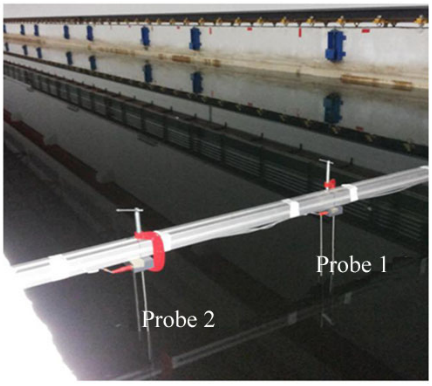


Fig. 4 Installation of wave probes on the towing tank (*y*/*L* is 0.3 at probe 1 and 0.9 at probe 2)

$$C_{T_m} = \frac{R_{T_m}}{\frac{1}{2}\rho U^2 A} \tag{4}$$

where ρ is the water density, U is the model speed, and A is the wetted surface area of the hull

$$C_r = C_{T_m} + C_f \tag{5}$$

$$C_f = \frac{0.075}{\left(\log_{10} Re - 2\right)^2} \tag{6}$$

where Re is the Reynolds number of the fluid

4 Results and discussion

In this work, the fin angles are varied to 0, 5, 10, and 15 degrees based on Fitriadhy (2007) who considered the effective fin angle for high speed to dynamic motion of the tested Semi SWATH.

4.1 Trim and sinkage of the semi-swath in shallow water

Figs. 5 and 6 show the measured trim and sinkage at fin angles of 0º, 5º, 10º, and 15º. Validation of changes in the sinkage pattern of a vessel is important in shallow water analysis. Fig 6 shows that the sinkage pattern agrees with available results of SWATH sinkage in shallow water based on Bertram (1994). In this Fig. 7, the sinkage is represents by ΔT, and changes in the sinkage pattern between this work and the reference are compared for Fr_H <1.2.

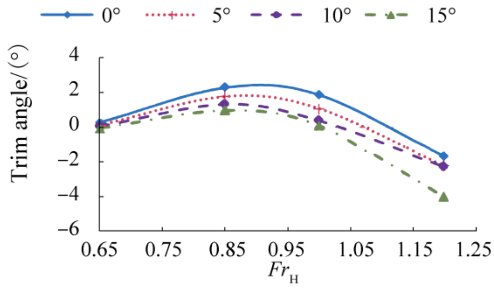


Fig. 5 The trim angle of the semi-SWATH in shallow water

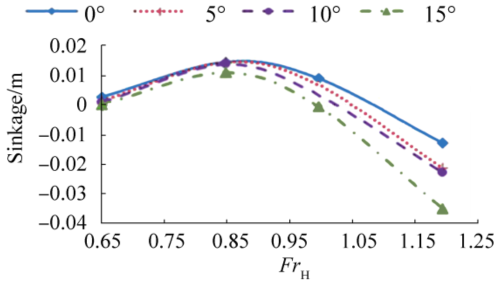


Fig. 6 Sinkage of the semi-SWATH in shallow water

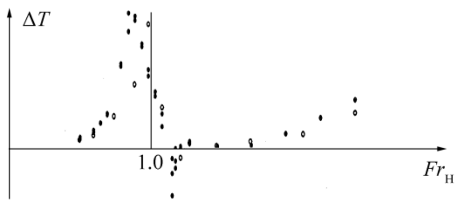


Fig. 7 Sinkage versus depth Froude number of a SWATH in shallow water obtained from Bertram (1994)

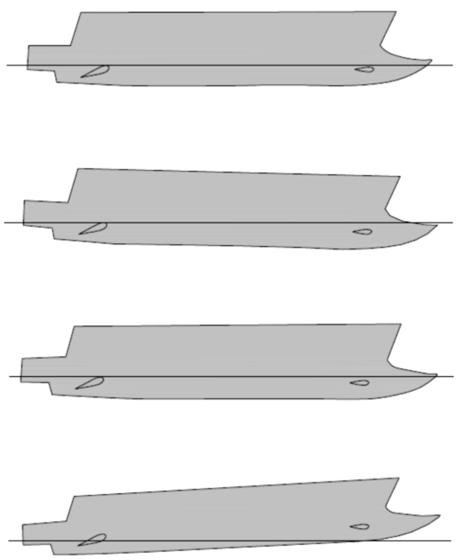


Fig. 8 The hull conditions of the semi-SWATH with the aft fin angle of 15º at different speeds

The maximum trim and sinkage are obtained at high subcritical speeds over Fr_H values ranging from 0.8 to 1.0.

The literature indicates that the sinkage reaches 0 at critical speed and becomes nearly constant after reaching a maximum value at supercritical speed. However, the sinkage of the semi-SWATH is not constant at supercritical speed, and values increase with increasing Fr_H. This result shows that the motion response of the semi-SWATH in shallow water differs from that of other vessels because of the effects of the fin stabilizer and hull form.

Fig. 8 presents changes in the hull condition at each speed studied according to the measured trim angle and sinkage. The semi-SWATH tends to reach planning hull characteristics at high speed (Begovic, 2015), leading to a change in L_{wL}/B value (Molland *et al*., 2008). The aft fin angle of 15º contributes to the most stable hull condition except at the supercritical speed, where the hull experiences large trim by stern.

4.2 Resistance components of the semi-swath in shallow water

A comparison of the total resistance (R_T) for each condition is shown in Fig. 9. Fins apparently exert different resistance effects over the range of Froude numbers investigated. At supercritical speed, where Fr_H is greater than 1.0, increases in resistance are less obvious than those at subcritical and critical speeds. The wave pattern changes, and no transverse waves exist at supercritical speed (Kirkegaard *et al*., 1998). Increases in aft fin angle lead to larger R_T, which increases with 0.5–3.5 N increments for each 5-degree increase in fin angle. The resistance curve shows that resistance increases gradually with increasing Depth Froude number until a maximum point known as the hump speed at critical speed (Fr_H=1). Thereafter, the resistance becomes approximately constant with further increases in Fr_H. Small differences in resistance are also observed for each case at similar speeds.

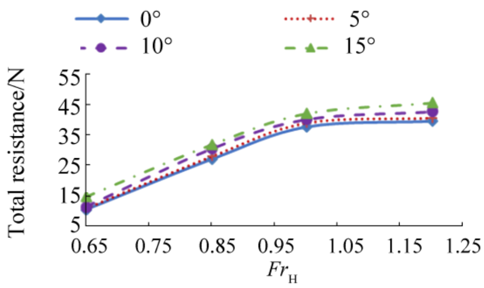


Fig. 9 Resistance curve of the semi-SWATH in shallow water at different aft fin angles

The residual resistance coefficient (C_r) of the semi-SWATH is calculated based on the measured total resistance and plotted in Fig. 10. The fin angle produces significant effects on changes in the hull resistance component with increasing Froude number. As the speed reaches the critical speed region, the hull produces the maximum C_r for each case; C_r values then decrease after the critical speed. This result reflects the significant effect of hull-generated waves at the critical speed region.

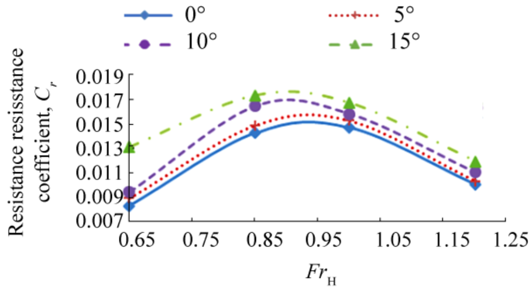


Fig. 10 Resistance curve of the semi-SWATH design in shallow water at different aft fin angles

Changes in resistance can also be related to the sinkage and trim condition in shallow water. Variations in sinkage and trim conditions at different aft fin angles represent changes in the wetted surface area and immersed hull volume, which can affect the resistance components. The sinkage and trim condition also influence the pattern of flow through the bow of the hull and underkeel, further causing changes in the resistance components (Jurgens and Jager, 2006).

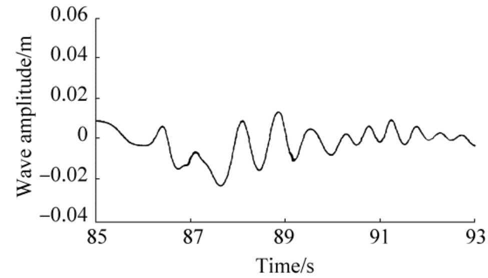
Differences in sinkage for each of the cases shown in Fig. 8 reveal that changes in distance between the keel and seabed produce alterations in the physical characteristics of water flow and affect the pressure distribution on the hull. The aft fin angle exerts different effects on the trim and sinkage of the hull. Positive increases in fin angle produce larger lift forces and restoring moments, promoting better seakeeping criteria for the hull in shallow water. However, forces generated from large installation fin angles also increase the induced drag and consequently the resistance around the hull. This may be influenced by the pressure distribution on the surface of the foil (Liang *et al*., 2012).

4.3 Wave height of the semi-SWATH in shallow water

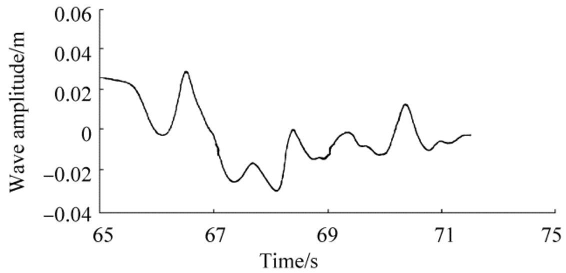
As the wave pattern generated in shallow water influences the resistance of the semi-SWATH, the characteristics of waves generated from the vessel are analyzed. In this work, the wave pattern near the hull is highlighted because of the strong effect of near-field waves in this location.

The wave patterns near the hull with aft fin 0º captured by wave probe 1 are shown in Figs. 11–13 with respect to its speed. The wave heights captured at the area around the hull and the region behind the hull stern are shown. The figures reveal that the wave pattern differs at every Depth Froude number. The wave period is large at subcritical speed and decreases at critical speed. The wave period begins to increase at supercritical speed. The sharp pattern of the wave amplitude curve at Fr_H =1.00 indicates the significance of wave formation at critical speed.

According to Ghani and Rahim (2008), wave patterns can be analyzed in terms of the maximum and minimum wave amplitudes over a range of positions around the hull. The maximum and minimum wave amplitudes detected by probe 1 were plotted against the Froude number and are presented in Figs. 14–15, respectively. Probe 1 indicates that waves are generated near field near the hull. In general, the maximum wave amplitude (H_{max}) recorded at probe 1 is obtained at critical speed, and this value becomes constant at supercritical speed. The minimum wave amplitude (H_{min}) increases until the critical speed and then decreases until the supercritical speed.



(a) Fr_H =0.65



(b) Fr_H =0.85

Fig. 11 Changes wave pattern captured by wave probe 1 at subcritical speed

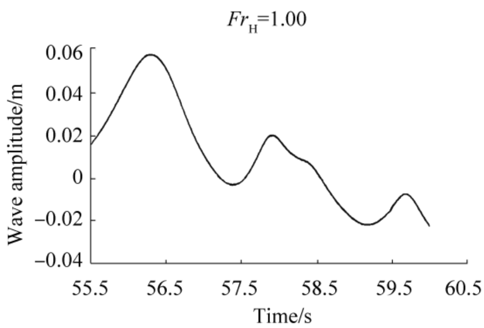


Fig. 12 Changes in wave pattern captured by wave probe 1 at critical speed

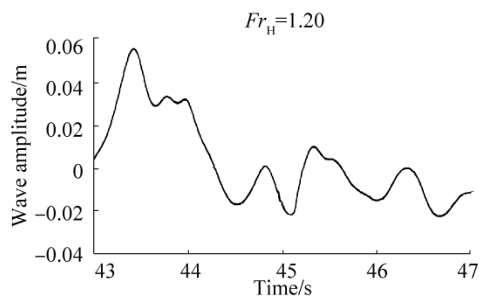


Fig. 13 Changes in wave pattern captured by wave probe 1 at supercritical speed

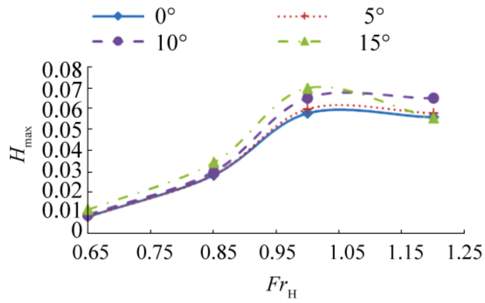


Fig. 14 Maximum wave amplitude recorded at probe 1

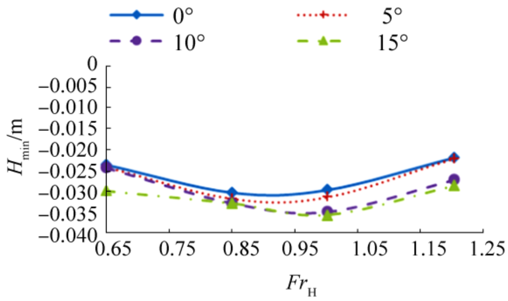


Fig. 15 Minimum wave amplitude recorded at probe 1

Changes in wave amplitude with speed can be affected by many factors. The effect of limited depths in shallow water strongly influences the pressure gradient and, consequently, the wave pattern generated around the hull. Changing the distance between the hull keel and seabed at different speeds alters the pressure around the hull, resulting in differences in the characteristics of the generated waves. The wave celerity significantly contributes to the changing of the wave pattern. At critical speed, the wave speed increases until the maximum celerity. Strong interference between the transverse waves generated by the vessel can occur at critical speed (Molland *et al.*, 2008). Sufficient time is required for the wave energy to dissipate at critical speed if the strong wave interference effect persists (Glamore, 2005).

The fin stabilizer may be claimed to affect the maximum and minimum values of the wave amplitude. Although the changing patterns of the maximum and minimum wave amplitude are not perfectly similar between each case, the influence of fin angle on the pattern of generated waves can be predicted and analyzed. Under the condition of a 15-degree aft fin angle, H_{max} is highest for both probes at subcritical and critical speeds. The H_{max} is then reduced dramatically at supercritical speeds and becomes smaller than the H_{max} of the semi-SWATH design with fin angles of 5º and 10º. Similar to the maximum amplitude, the H_{min} at probe 1 is highest for the waves generated by the semi-SWATH design with a 15-degrees aft fin angle.

Comparison of the resistance and both H_{max} and H_{min} of the hull at different fin angles is beneficial to predict the factors contributing to the total resistance. The fin stabilizer influences the total resistance in term of the generated waves and the induced drag, which similar with the result of Chen (2013). The pressure point of the hulls is shifted due to the existence of fins that alters the wave systems based on the angle configuration (Ram *et al*., 2014). Furthermore, the induced drag from the fin stabilizer is dependent on the angle of attack, which is according to the ship's initial pitch angle and the relative fluid velocity with respect to the fin stabilizer (Radhakrishnan *et al*., 2011).

Wave energy can be related to the amplitude of waves generated from the hull (Molland *et al*., 2008). The high resistance observed in the case of the 15-degree aft fin angle is contributed by the energy produced from wave formation around the hull and fins at subcritical and critical speeds, where transverse and divergent waves present high amplitude. At supercritical speed, the generated wave pattern is not the dominant factor contributing to high resistance. The phenomena of supercritical speed are not fully achieved by semi-SWATH at Fr_H=1.20 compared to theory due to the low dissipation of transverse wave energy. This gives effect on the hull resistance at supercritical speeds as well as the planing hull condition.

5 Conclusions

Resistance tests of a semi-SWATH design in shallow water is performed to achieve the shallow water resistance and wave pattern of semi-SWATH with effect of Fr_H and fin stabilizer. The fin stabilizer affects the Semi SWATH resistance by 1) changing of trim condition and 2) changing of the induced resistance by the fins according to the hull trim condition. The H_{max} and H_{min} of the hull reaches maximum values at a critical speed, and Fr_H =1.0 for most of the cases studied. These values are reduced at supercritical speeds. The results are in agreement with shallow water theory as the wave in supercritical speeds is affected only by divergent waves and effects on hull resistance are reduced.

The effects of fin angle on the resistance, trim, sinkage, and wave generation of the semi-SWATH are defined. Changes in sinkage and trim angle are reduced by increasing the fin angle except at supercritical speed. Trim changes at supercritical speed cause increases in resistance. Similar to the total resistance, the amplitude of waves generated be the semi-SWATH also increases with increasing fin angle. The fin angle and significant trim and sinkage of the hull contribute to increases in semi-SWATH resistance in restricted water depths.

Further research on fin stabilizer designs must be carried out to investigate wave interference phenomena between the fin and hull. Studies in this field could include prediction of the wave interference factor to determine its relation to wave height and performance of the shallow water resistance test at different h/T.

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