UDC 629.57:532.5

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Hydrodynamic Aspects of a High-Speed SWATH and a New Hull Form

Professional paper

The main problems of high-speed ships operating in open seas are their insufficient seaworthiness and speed loss in high sea states. Small Water-plane Area Twin-Hulls (SWATH) are characterised by excellent seaworthiness, but the hull forms of a traditional SWATH are not suited for higher speeds. A new shape of underwater gondola has been developed for a semi-planing (S/P) SWATH. Additionally, hydrofoils can be applied to this ship to provide the optimal dynamic draught and trim, to mitigate motions in rough seas, and even to carry a part of the ship weight. The relative speed of this SWATH can be beneficially increased up to the displacement Froude number 3. Several concept designs addressing naval and civil transportation needs are outlined in this paper.

Keywords: *SWATH ships, high speed vessels, hull form, hydrodynamic analysis*

Hidrodinamički aspekti dvotrupca minimalne površine vodne linije (SWATH) velike brzine i novog oblika trupa

Stručni rad

Glavni problemi brodova velike brzine tijekom plovidbe na otvorenom moru su njihova nedovoljna pomorstvena vrijednost i gubitak brzine kod visokog stanja mora. Značajka malih dvotrupaca minimalne površine vodne linije (SWATH) je njihova odlična pomorstvena vrijednost, ali oblik trupa tradicionalih SWATH-ova nije prilagođen za veće brzine. Razvijen je novi oblik podvodnog trupa (gondola) za poluglisirajuće SWATH-ove. Za takav brod se mogu dodatno rabiti i hidrokrila radi postizanja optimalnog dinamičkog gaza i trima, smirivanja gibanja na uzburkanom moru i čak da nose dio težine broda. Relativna brzina ovih SWATH-ova se može korisno povečati sve do istisninskoga Froudeovog broja 3. U ovom je članku prikazano više konceptualnih projekata ovih brodova za potrebe vojnog i civilnog prijevoza po moru.

Ključne riječi: *SWATH brodovi, brzi brodovi, oblik trupa, hidrodinamička analiza*

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Received (Primljeno): 2005-07-05
Accepted (Prihvaćeno): 2005-09-08

Introduction

The main problems of high-speed ships (with the Froude number $\mathrm{Fn} = V / (gL)^{0.5} \geq 0.5$, where V- ship speed, m/s; L – the hull length at the water-plane, m; g – gravitational constant) operating in open seas are their insufficient seaworthiness and speed loss in high sea states. A Small Water-plane Area Twin-Hull Ship (SWATH) includes two submerged hulls (gondolas) and one or more water surface piercing parts (struts) on each gondola. Such ships are characterised by excellent seaworthiness, comparable with that of vessels having deeply submerged and automatically controlled hydrofoil systems. But hydrofoil boats are not as promising as large ships due to the sharp increase in the foil system size in comparison with ship dimensions and constant speed. Other issues of hydrofoil vessels of this type are their cost and maintenance. In contrast, the SWATH type is less expensive and more reliable and can have large dimensions. Therefore, the increase in speed of SWATHs can make them an attractive option for many applications, including high-speed oceanic transportation.

However, the traditional hull forms of a SWATH are not inherently suited for higher speeds. The main reason for a low wave resistance and for a superior seaworthiness of a SWATH is the sufficiently deep immersion of the main volume of the hulls. All surface craft, including SWATHs, drastically change their sinkage and trim in the transitional speed regime. A traditional SWATH with a blunt bow approaching the free water surface in a high-speed regime becomes inefficient. The subject of this paper is a new semi-planing (S/P) SWATH configuration designed for high speeds.

A typical dependence of the SWATH dynamic trim on the Froude number, Figure 1, shows a significant reduction in the bow immersion with increasing speed. On a traditional SWATH, a positive trim (bow up) is observed at small (< 0.3) and large (> 0.45-0.5) length Froude numbers. A negative trim is not desirable; it is usually counteracted by fins or by a special shape of the gondola. The initial (static) trim is approximately an additive to the dynamic trim in the entire range of Froude numbers.

The initial trim influences the residual resistance coefficients, depending on Froude numbers. An illustration of the influence coefficient (defined as the ratio of the residual resistance coefficients at non-zero and zero initial trims) is given in Figure 2 for a traditional SWATH. The negative static trim is favourable for

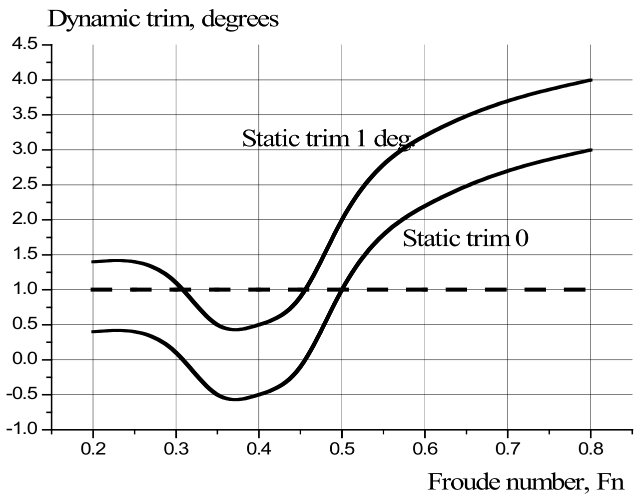
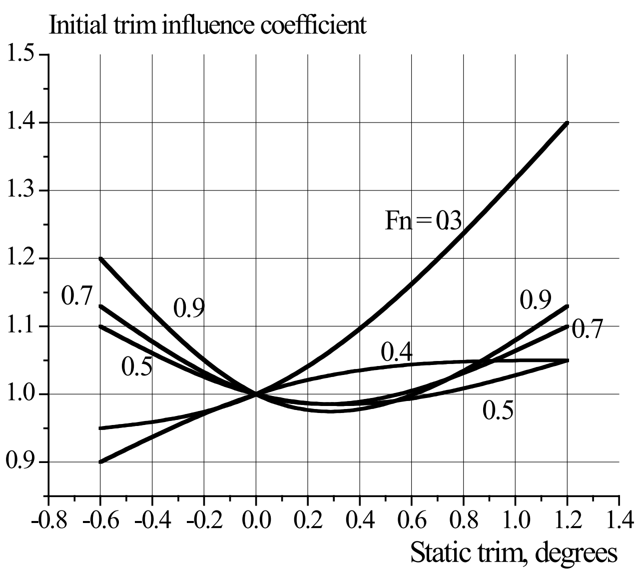


Figure 1 **Typical dependence of the SWATH trim on the length Froude number, with positive and zero static trim (positive trim corresponds to bow up)**
Slika 1 **Tipična ovisnost trima SWATH-a o duljinskom Froudeovom broju sa i bez početnog trima (pozitivni trim se odnosi na uzdignuti pramac)**

residual resistance for relatively small Froude numbers (e.g. 0.3-0.4 in Figure 2); but it is not a reasonable method of resistance reduction because sailing with a negative trim is not a good sea practice. Only small positive initial trim seems permissible for high values of Froude numbers.

A variation in the mean dynamic draught of a traditional SWATH is usually negative (draught increases), but can be positive either at very high relative speeds or if there is a significant initial trim (Figure 3). The effect of the initial draught (variation) on the residual resistance coefficients of a traditional SWATH depends on its relative speed (Figure 4). Smaller draught is obviously favourable for relatively high speeds (Fn = 0.5-0.7 in Figure 4), but this advantage remains only until the gondola is fully submerged. If draught becomes smaller than the gondola height, the residual resistance grows rapidly (e.g., the left part of the curve Fn=0.9 in Figure 4). Larger draught is favourable for Froude numbers 0.3-0.4.

Figure 2 **Example of the initial trim influence on the residual resistance coefficient C_R of a traditional SWATH**
Slika 2 **Primjer utjecaja početnog trima na koeficijent preostalog otpora C_R tradicionalnog SWATH-a**



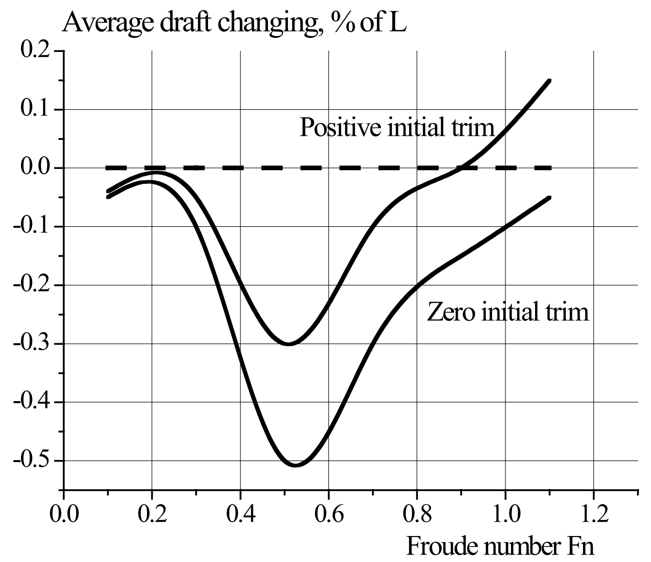
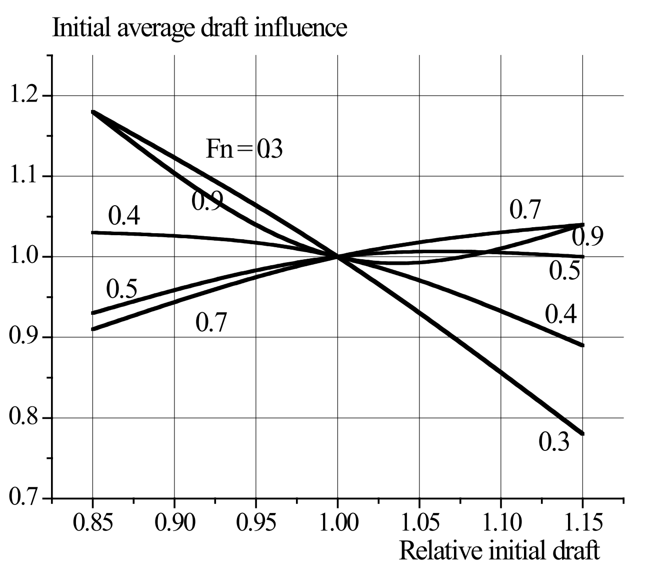


Figure 3 **Example of the mean dynamic draught variation of a SWATH**
Slika 3 **Primjer dinamičkoga srednjeg gaza SWATH-a**

Figure 4 **Example of the mean static draught influence on residual resistance coefficients of a traditional SWATH (constant displacement)**
Slika 4 **Primjer utjecaja početnoga srednjeg gaza na koeficijente preostalog otpora tradicionalnog SWATH-a (konstantna istisnina)**



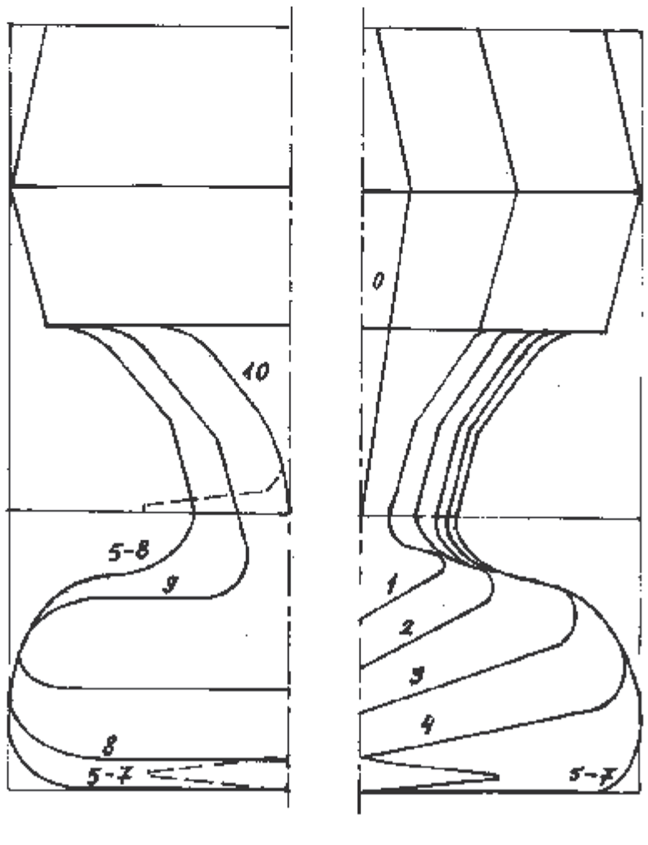
A partial exit from water of a blunt bow of the traditional SWATH gondola, occurring at high Froude numbers due to variations in the dynamic trim and/or draught, leads to several adverse effects: the increase in the wave-making resistance, the appearance of the wave-breaking resistance, the flow separation on a hull (accompanied by the resistance growth), and the increase of the longitudinal moment exerted on a hull. Besides, pitch and heave motions increase in rough seas if the gondola crosses the water surface. Therefore, traditional shapes of underwater hulls are not acceptable for a high-speed SWATH.

1 New hull form

Some research efforts have been devoted to the study of unconventional SWATH hull forms with reduced pitch moment at high speeds [1]. In contrast to this approach, a positive pitch moment can actually be utilised to reduce the wetted area of a SWATH, and consequently its towing resistance. To achieve these goals, the increase in the dynamic trim should be accompanied by the decrease in the dynamic draught, so the dynamic wetted area will be smaller than the static value.

A special shape of the SWATH gondolas has been developed with a purpose to operate at high speeds [2]. Hull lines of the new form provide minimal drag at high speeds, when trim and draught change significantly. An example of the new hull form is shown in Figure 5. The optimal dynamic trim and draught of the ship are ensured by a control hydrofoil system which can also be applied for the motion mitigation in rough seas.

Figure 5 **Example of the new SWATH hull form**
Slika 5 **Primjer novog oblika trupa SWATH-a**



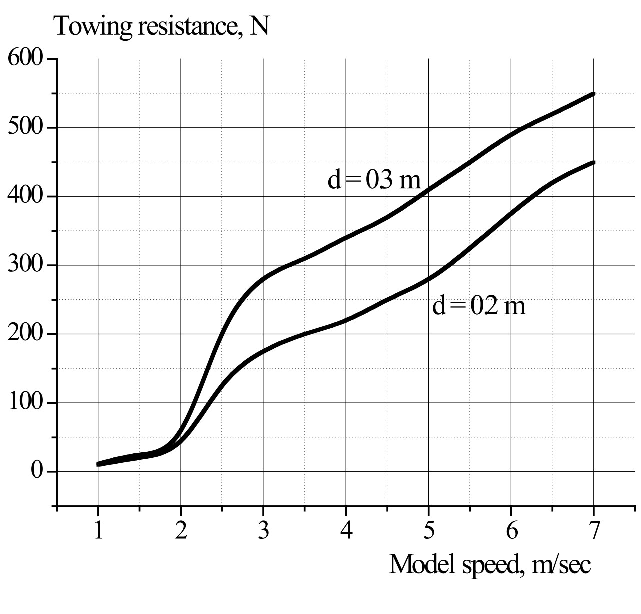
1.1 Resistance

Table 1 **Main characteristics of the towed model**
Tablica 1 **Glavne značajke tegljenog modela**

Design draught, d,m	0.3	0.2
Displacement, W, cub. m	2 x 0.175	2 x 0.130
Waterline length, L_{WL}, m	3.6	3.6
Hull relative length, $l = L / W^{1/3}$	6.44	7.1
Overall beam, B_{oa}, m	1.6	1.6
Gondola beam, B_g, m	0.3	0.3
Strut beam, B_{st}, m	0.2	0.2
Wetted area, S_w, sq. m	6.43	5.0
Bow foil area, S_f, sq. m	0.027	0.027
Mass centre height, Z_m, m	0.3	0.25

Characteristics of the tested model are given in Table 1. The towed model was free to sink and to pitch. Turbulence stimulation by wires was applied at the first station of each hull. The model total towing resistance is shown in Figure 6. The residual resistance coefficient of the model with larger draught is presented in Figure 7, where it is also compared with the same coefficient of a common SWATH model. The new hull shape demonstrates lower residual resistance at the upper range of tested speeds. The relative wetted area of the new-shape gondola at rest is only slightly larger than the wetted area of a traditional hull form. Therefore, the new hull form can ensure higher achievable speeds in comparison with a traditional SWATH. The achievable speed of the new-shape SWATH can reach the displacement Froude number of about 3.

Figure 6 **Towing resistance of the model tested at two draughts**
Slika 6 **Otpor tegljenja modela izmjeren za dva gaza**



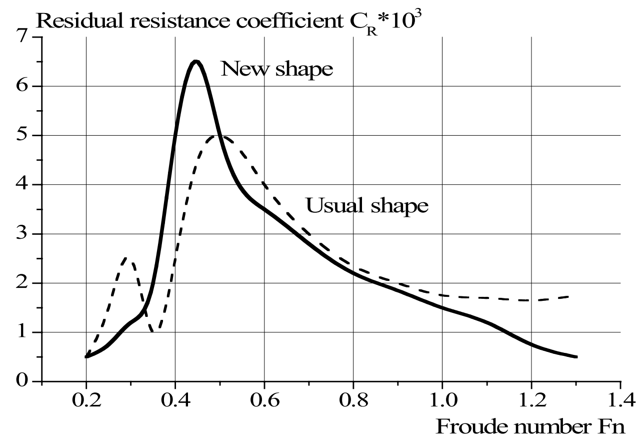


Figure 7 **Residual resistance coefficient of the model tested at two draughts**
Slika 7 **Otpor tegljenja modela izmjeren za dva gaza**

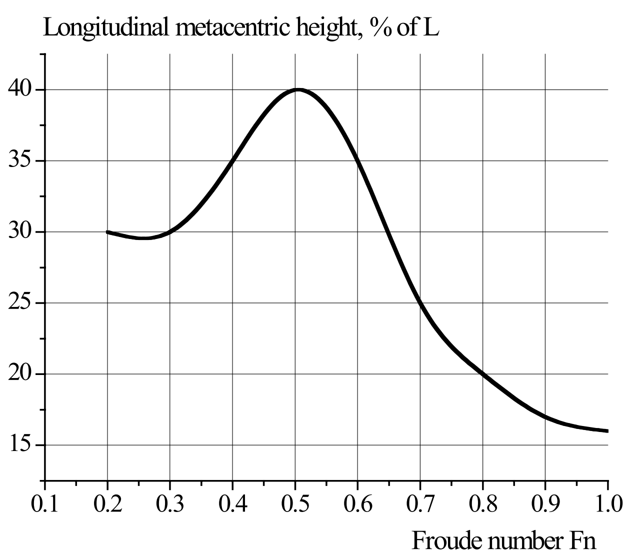
1.2 Hydrofoil control system

As noted above, the main objective of the control hydrofoil system is to ensure the optimal draught and trim. An additional purpose is the motion mitigation. The proper placement for the T-foil systems on the proposed ship is at the hull ends. The hydrofoil aspect ratio of 1.5-2 is recommended for this ship type to minimise vibrations and the probability of fatigue damage. The hydrofoil profiles should be chosen to maximise their lift-drag ratio under requirements for cavitation avoidance and strength. The hydrofoil area should be at least 5% of the ship water-plane area at rest.

1.3 Seakeeping

One of the specific features of the new hull form is a considerable reduction of the longitudinal metacentric height with increasing speed (Figure 8). The relative water-plane area is also small. This means that the natural pitch period is large, which is favourable for longitudinal motions. A model with the new gondola shape was tested in regular head waves. The results for heave and pitch amplitudes are shown in Figures 9 and 10, respectively. As any other SWATH, the new hull-shape model is characterised by reduced motions with increasing speed. Besides, viscous damping plays a significant role in sharp resonances typical for SWATH response amplitude operators. These experimental results on sea-keeping allow us to estimate pitch and heave amplitudes for various ships of the proposed type.

Figure 8 **Example of the longitudinal metacentric height of the proposed SWATH**
Slika 8 **Primjer uzdužne metacentarske visine predloženog SWATH-a**



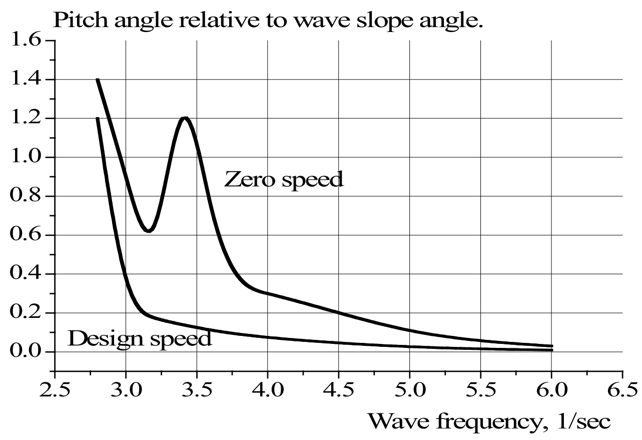


Figure 9 **Response amplitude operator of pitch in head waves**
Slika 9 **Operator amplitude odziva kod posrtanja na valovima u pramac**

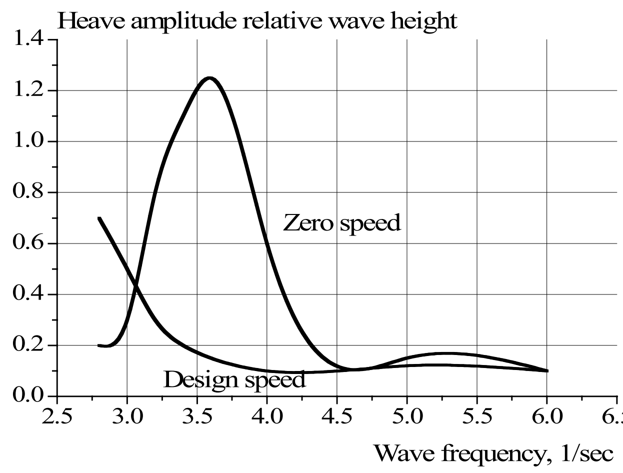


Figure 10 **Response amplitude operator of heave in head waves**
Slika 10 **Operator amplitude odziva kod poniranja na valovima u pramac**

2 Possible realisations of an S/P SWATH

2.1 Small-sized passenger ferry or motor yacht

An example of a relatively small variant of the new-hull SWATH is a ferry for 50 passengers, which can also be designed as a high-safety motor yacht. This ship will have the length of 15 m, beam of 7 m, depth of 4.5 m, displacement of 25 t, living area of 50 sq. m, and engine power of 2x370 kW for the design speed of 30 knots. Living compartments, a wheelhouse, and engine rooms are arranged in the above-water platform. Power transmission to propellers can be either mechanical or hydraulic. The ship can move even if one or both hulls are flooded. Figure 11 shows an artist's impression of a motor yacht. The living rooms can be transformed into one large cabin on a passenger ferry.

Comparable mono-hull ships can operate only in the Sea State below 2 (3%-exceeding wave height of 0.75 m). The proposed new shape of a SWATH can have the speed of up to 30 knots in the Sea State 3 (wave height of 1.25 m) with a high level of comfort (Figure 12). For the 3%- exceeding vertical acceleration level of 0.25g, this ferry can ensure the speed of 22 knots without any motion mitigation system, and higher speeds are achievable with a control hydrofoil system.

Figure 11 **Example of a small motor yacht**
Slika 11 **Primjer male motorne jahte**

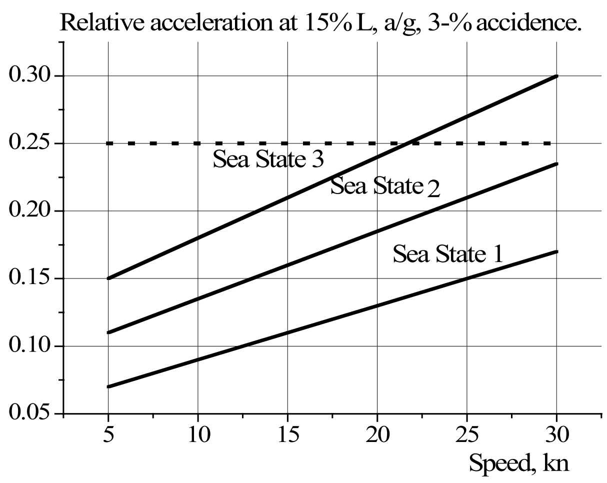


Figure 12 **Relative vertical acceleration *a/g* at 15%*L* from FP, 3% accidence**
Slika 12 **Relativno vertikalno ubrzanje *a/g* na 15%*L* od prednje okomice, 3% premašaja**

2.2 Fast corvettes

Currently, the main tendency in the development of surface combat ships is the increase in their speeds [3]. The new-shape SWATH can ensure high speed and high seaworthiness for combat ships, such as patrol and attack corvettes (Table 2). An external view of the patrol corvette is shown in Figure 13. The proposed attack corvette can ensure the use of helicopters in waves up to the Sea State 5 (Figure 14). Pitch amplitudes within 4 degrees define possible speeds for the helicopter operation without

Table 2 **Characteristics of a corvette-type S/P SWATH**
Tablica 2 **Značajke poluglisirajućeg SWATH-a kao korvete**

Ship type	Patrol corvette	Attack corvette
The full displacement, t, aprx.	400	1 200
Full speed, knots	45	55
Armament, t	50	100
Useful area of decks, sq. m, aprx.	600	1 500
Overall dimensions, m	40x16x9	55x28x12
Design draught, m	3	4
Main engine (GT) power, MW	2x8.5	GT2x22
Design Sea State, Beaufort scale	4-5	5
Helicopter weight, t	1x16	1 x 16
Range, nm / Economy speed, knots	3 000 / 15	2 500 / 17
Endurance, days	15	15
Operability coefficient in Northern Atlantic, %, aprx.	75	85

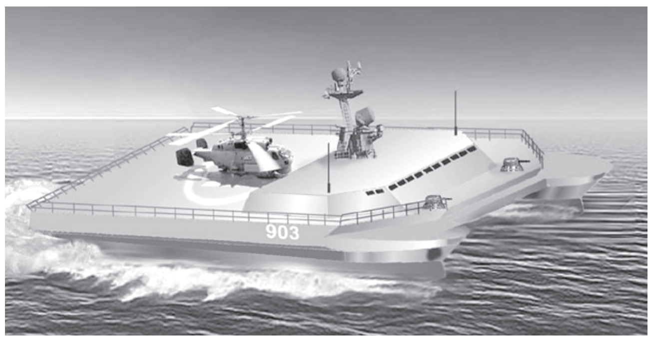
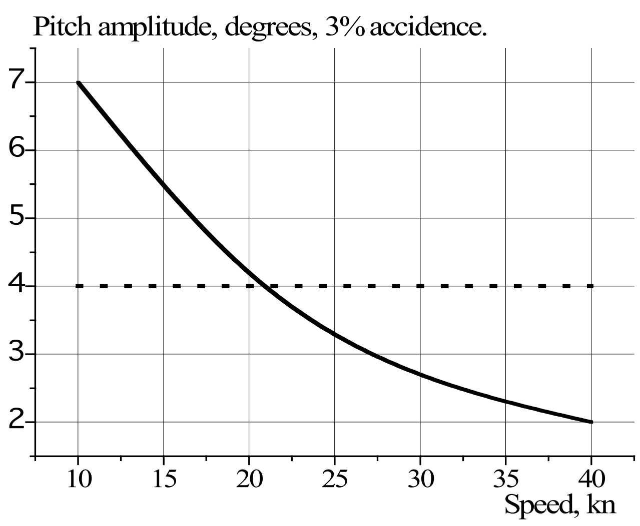


Figure 13 **External view of a patrol S/P SWATH corvette**
Slika 13 **Vanjski izgled poluglisirajuće ophodne SWATH korvete**

Figure 14 **Pitch amplitude in head waves of a patrol SWATH corvette**
Slika 14 **Amplituda posrtanja na valovima u pramac ophodne SWATH korvete**



any automatic system of landing: from 20 to 40 knots inclusive. There is no other ship type that can provide such a level of speed and sea-keeping at so small displacement.

2.3 Fast containership

As shown in [2], the displacement of a SWATH with a new hull shape is excluded from above by the power of existing gas turbines. For example, a fast containership of this type (Figure 15) can carry a payload of 1 000 t at full speed of 60-65 knots over the range (at this speed) of 500 nm. Such a container-carrier can be an alternative to the Japanese design of a Techno-Super-Liner, which was intended for similar initial data [4]. The proposed S/P SWATH, which is based on already conducted model tests, can ensure the required characteristics and sufficiently high seaworthiness.

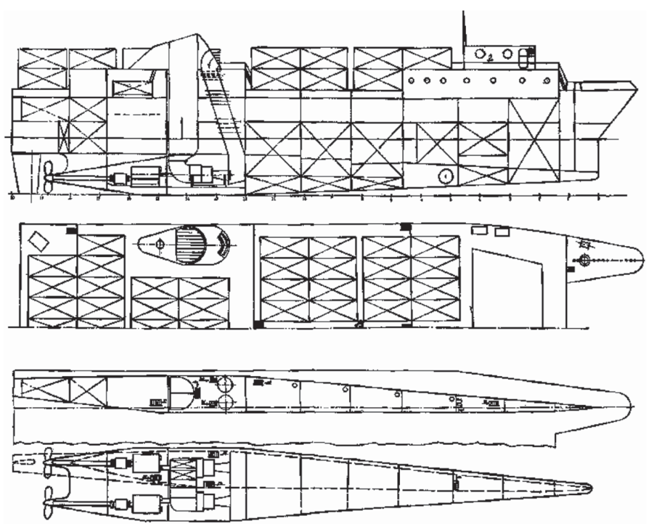


Figure 15 **A short-range fast container-carrier**
Slika 15 **Brzi brod za prijevoz kontejnera maloga dosega**

2.4 Fast frigates

Table 3 **Characteristics of a frigate-type S/P SWATH**
Tablica 3 **Značajke poluglisirajućeg SWATH-a kao brze fregate**

Payload, t	200	400
Usable area of decks, sq. m, aprx.	3 000	4 000
Full displacement, t, aprx.	3 000	5 000
Engine power, MW	4x22	4x50 / 4x65
Full speed, knots, aprx.	55	50 / 65
Design Sea State, Beaufort scale	6	6
Number of helicopters	2	2
Endurance, days	14	10
Operability coefficient in North Atlantic, %	93	95

Fast frigates can also be designed with the proposed shape of gondolas (Figure 16). These battle ships should use gas turbines for the maximum available power. Two options of these frigates were examined, with payloads of 200 t and 450 t. General characteristics of these ships are given in Table 3.

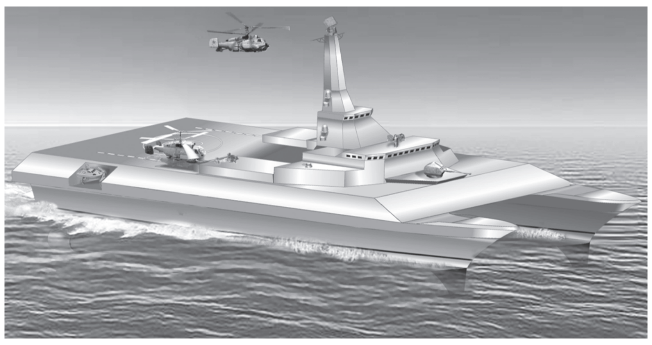


Figure 16 **External view of an S/P SWATH frigate**
Slika 16 **Vanjski izgled poluglisirajuće SWATH fregate**

Conclusions

Based on the conducted model tests, it is shown that the application of the new hull form can increase the speed of a SWATH up to the displacement Froude number 3 with a sufficiently high seaworthiness level. Combat ships of this type can ensure higher speeds for the same (contemporary) engine power per ton of displacement. Estimations made for the new SWATH are given in Figure 17 over data available for traditional ships [4].

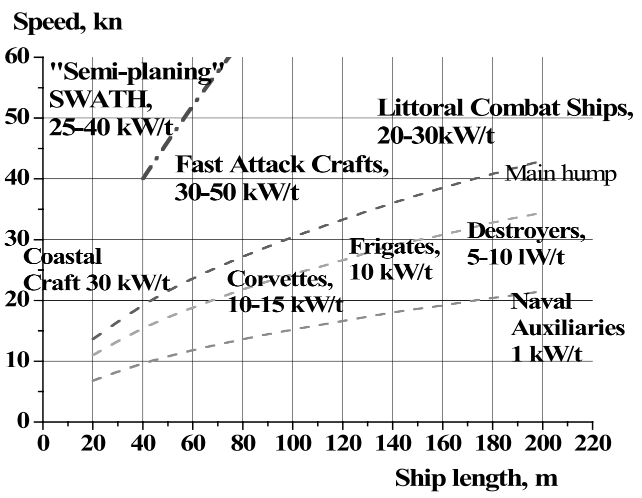


Figure 17 **The achievable speeds and corresponded relative power of the new S/P SWATH (in the upper left part of the figure). Other data are adopted from [4]**
Slika 17 **Postizive brzine i odgovarajuća relativna snaga poluglisirajućeg SWATH-a (u gornjem lijevom dijelu slike). Drugi su podaci uzeti iz [4]**

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