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On Small-Size Motor Yachts with Round-Bilge Hulls

Review paper

In this paper multi-hull small-sized motor yachts with rounded bilge hulls were examined as alternative options for enough high speed: catamarans without and with under-water foils, as well as outriggered boats without and with foils. Besides, a twin-hull motor yacht with decreased water-plane area was examined too. Restriction of speed, as a result of avoiding hard chine, was examined; necessary power and seakeeping levels of the examined yachts were estimated too. It has shown that the examined yachts are compatible (from the energy point of view) with today's dominant planing monohulls for defined ranges of speed; the examined multi-hulls are better from the seakeeping point of view than the comparable monohulls.

Keywords: *catamarans, motor yachts, multihulls*

O motornim jahtama malih dimenzija i trupa okruglog uzvoja

Pregledni znanstveni rad

Kao alternativna mogućnost za slučaj dovoljno visokih brzina ispitivane su sljedeće višetrupne motorne jahte malih dimenzija s trupom okruglog uzvoja: katamarani bez i s podvodnim krilcima kao i višetrupne barke bez i s krilcima. Pored toga, također je ispitivana dvotrupna motorna jahta sa smanjenom površinom vodne linije. Procijenjeno je ograničenje brzine kao posljedica izbjegavanja izlomljenih poprečnih presjeka. Također je procijenjena i potrebna snaga kao i razine pomorstvenih svojstava ispitivanih jahti. Pokazalo se, da su ispitivane jahte kompatibilne (sa stanovišta energije) s današnjim dominirajućim glisirajućim jednotrupcima unutar određenog raspona brzina, dok su se sa stanovišta pomorstvenih svojstava ispitivani višetrupci pokazali boljim od usporedivih jednotrupaca.

Ključne riječi: *katamarani, motorne jahte, višestrupci*

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Introduction

Today, the motor yachts of various displacement and purpose are one of the most developing parts of the shipbuilding market. A lot of various yachts are monohulls; that means inherent problems in insuring the transverse stability. Also, very often the monohull motor yachts have hard chine hulls, which means an inherent problem of bottom slamming in waves. But, some motor yacht types are free from the noted disadvantages of monohull planing boats.

It seems evident that a defined useful accommodation area is one of the main initial demands on a yacht. Also, for the defined area a minimal possible displacement and building price are desired.

Besides, an enough high level of seaworthiness is needed for any motor yacht as a sufficient part of comfort level and safety. It is a more important characteristic of small-sized yachts, which are more sensitive to an even small wave action.

As it is well known, high deck area, higher or high seakeeping, high level of safety are the advantages of multi-hull ships and boats (for example [1]). Therefore, some types of multi-hull motor yachts were examined.

The peculiarity of the investigation was to avoid of hard chine hulls because of their evident disadvantage: high possibility of bottom slamming in waves. But such decision leads to an initial restriction of design speeds: the speeds must be lower than the planing speed regime.

Two ways of the problem decision were examined: speed restriction for avoiding the planing regime, and under-water foil application for full unloading of the vessels at full speed (but there is the usual problem of towing resistance hump at the time of hull extraction from water).

Hard chine hulls have the energy advantage at displacement Froude numbers greater than 3. Thus, the preliminary estimation of possible displacement of yachts with the desired deck area was needed.

Froude number less than 3 corresponds to the transient regime of speeds; hulls with bigger aspect ratio are preferable for the regime of speeds. Evidently, a greater length means a larger longitudinal bending moment in waves and a bigger plating value per unit of volume displacement, i.e. the hull structure weight is a natural limit of the hull length.

There is another speed restriction for hulls of high aspect ratio: hull length Froude number ($Fn = v/(gL)^{0/5}$, where L – hull length) must be no more than 1.0-1.25. A higher value means very intensive generation of wave jets by the hull, and a corresponding growth of towing resistance. The restriction allows the defining of a minimal hull length of the needed displacement. And again, the displacement must be previously estimated.

Referring to statistical data, usually the foiled vessels have a moderate relative speed (displacement Froude number no more than about 4.0). It can be supposed that a higher relative speed means some problems in avoiding the foil cavitation. Therefore, it is natural to have a restriction of foiled vessel speeds.

A selection of the examined types of small-sized motor yachts was carried out on the basis of general information concerning the specificity of various multi-hull ships [1].

1 Selection of the examined types of yachts

Air cushion vessels and WIGs were excluded from the examined type list: both of them can not ensure a high level of seaworthiness at small displacement. Besides, the vessels of the first type are too noisy, and small-sized WIGs have small useful area referring to overall dimensions.

The possibility of catamaran application as small-sized motor yachts is confirmed practically. Especially "wave-piercing" catamarans differ from other ship types by a high relative area of deck, high performance at high enough speeds, and developed seakeeping. Higher speeds can be ensured by added underwater foils; the same foils can be used for the motion control.

The usual ships with small water-plane area, SWA ships, are not effective for the transient regime of speeds. But a novel SWA ship type, the so called "semi-planing" SWA ship, has also shown as a high-speed motor yacht.

All noted boat options were designed at zero approximation (concept designs were carried out) for a correct comparison of the main characteristics.

It must be noted that some triple-hull boats can be designed today as small-sized motor yachts. And the triple-hull boats with identical hulls were excluded from the research because these ships can compete with corresponding catamarans at hull length Froude numbers not greater than 0.7 [2], but the needed upper level of permissible Froude numbers is about 1.0 for the transient regime of speeds. Triple-hull boats with various hulls (a bigger main hull and two smaller side hulls, "outriggers") were included in the list of examined yachts; the outriggered yachts were examined without and with under-water foils for full hydrodynamic unloading at full speeds and for motion control.

Therefore, the following types of small-sized motor yachts were examined:

- "wave-piercing" catamaran without foils;
- "wave piercing" catamaran with foils
- outriggered boat without foils;
- outriggered boat with foils;
- "semi-planing" SWA boat.

All boats were designed for the same useful deck area, design draught, and range at economy speed.

2 Estimation of displacement and speed restrictions

It seems evident that the living, service and auxiliary areas of a small-sized motor yacht will be arranged in the upper platform, which connects the hulls. Such a case means a minimal value of the useful deck area; it was defined as 12 m^2. But, it seems very possible that the main engine room will be arranged in the platform, if the boat displacement is small enough, i.e. the width of the hulls is small enough. Such a case means a bigger value of the useful deck area, it was supposed equal to 150 m^2.

It seems evident that the inter-deck distance of a motor yacht can be no less than 2.5 m, which means the platform inner volume about 400 m^3 for the area of 150 m^2.

Referring to statistical data, the average mass of one cubic meter of any inner volume (with the equipment) of an aluminium boat is about 35-40 kg. This means that the platform mass of the noted volume is from 10.5 up to 16 t.

Usually, the platform mass is about 75% of metal catamaran hull mass, which means that the total mass of the equipped hull of the examined catamarans makes from 14 up to 21 t.

Referring to statistical data of multi-hull boats, the mass of equipped hull is about 40% of full displacement, which means that the displacements of examined multi-hull yachts range from 35 up to 55 t.

The previously noted speed restriction by the hull displacement Froude number from 3.0 (without foils) to 4.0 (with foils) allows the estimation of rational (from the energy point of view) speeds of yachts of the defined displacements. Then, the speed restrictions can be defined by the following equations:

$$Fn_v = 0.515\ V_S / (gW_1^{1/3})^{0.5} = 3.0 \text{ for boats without foils,}$$
$$Fn_V = 0.515V_S / (gW^{1/3})^{0.5} = 4.0 \text{ for boats with foils;}$$

where V_S – speed in knots; W_1 – minimal hull (volume) displacement in m^3; W - boat full displacement in m^3.

Therefore

$$V_S = 18.25*W_1^{1/6} \text{ for boats without foils,}$$
$$V_S = 24.3*W^{1/6} \text{ for boats with foils.}$$

Table 1 contains the results of the estimations (it was additionally supposed that one outrigger displacement is equal to 10% of the boat full displacement).

Table 1 **Upper limits of rational speeds (in knots) for various displacements of motor yachts with smooth hulls**
Tablica 1 **Gornja granica prihvatljivih brzina (u čvorovima) za različite istisnine motornih jahti s glatkim trupom**

Displacement, t	Twin-hull boats		Outrigger boats	
	Without foils	With foils	Without foils	With foils
35	29.5	44	22.5	44
45	30.5	46	23.5	46
55	31.7	47.5	24.3	47.5

It can be noted that the twin-hull yachts without foils can be applied for speeds up to 30-32 knots, outriggered ones – 22-24 knots; the foiled yachts can be applied for speeds 44-48 knots, depending on the displacement.

The second previously noted restriction of the hull length Froude number allows the estimation of the minimal length of hulls and outrigger of yachts without foils from the condition:

$$Fn = 0.515V_S / (gL)^{0.5} = 1.0;$$

The minimal length is $L = 0.022*V_S^2$.

The calculation results are shown in Table 2.

Table 2 **Minimal hull (outrigger) length (in meters) of yachts without foils**
Tablica 2 **Najmanja duljina (u metrima) trupa (plovak) jahti bez krilaca**

Displacement, t	Twin-hull yachts (hull length)	Outriggered yachts (Outrigger length)
35	19.2	11.2
45	20.5	12.2
55	22	13

It can be seen that catamaran hulls must have the water-plane length no less than 19-22 m and the outrigger length of the triple-hull yachts must be no less than 11-13 m, depending on the boat displacement.

3 Selection of the main dimensions

For a practically constant mass of the upper-water platform and for the constant design draught (for these calculations), the difference of the hull structure mass of yachts is defined by the hull number, dimensions and shape. It can be supposed that a bigger surface of hulls with small water-plane area is the reason of their relative bigger part in the hull structure mass. On the contrary, small dimensions and displacement of the outriggers mean a slightly smaller mass of the outrigger hull structure. But, in such a case the main hull will be longer than the catamaran hulls, and therefore the end result of the hull mass comparison cannot be defined previously.

If the design draught is 1 m, and a hull minimum width no less than 2 m, then the main dimensions and weight displacement parts of the examined yachts correspond to the values shown in Table 3. It is evident, that the "achievable" deadweight can be equal about 4-5 t, but only if the catamaran yacht (without foils) displacement will be about 45 t, and outrigger yacht (without foils) displacement about 40 t.

It must be noted that the power and main the engine mass of the examined catamarans are considerably bigger in comparison to the power of outrigger yachts, but the full displacement difference is not so big, as it could be previously supposed.

The shape difference of "wave-piercing" hulls does not affect the performance in still water, thus the characteristic was predicted as for common catamarans.

As an alternative option of a SWA yacht for high speeds, a novel type yacht of about 50 t displacement was proposed (power 2 x 1.1 kWt), see Figure 1.

Figure 1 **Possible exterior of a "semi-planing" SWA vessel as a motor yacht**
Slika 1 **Mogući vanjski izgled "poluglisirajućeg" SWA plovila kao motorne jahte**

Table 3 **Main dimensions of the examined yachts without foils**
Tablica 3 **Glavne dimenzije ispitivanih jahti bez krilaca**

Displa-cement, t	Length, m	A hull beam, m	Relative length	Block coeff.	Empty ship, t	Power, kWt	"Achievable" deadweight, t
Catamarans							
35	23	2.0	8.85	0.4	35.5	2×0.55	-5
45	25	2.0	8.85	0.45	40	2×0.75	5
55	28	2.0	9.27	0.5	45	2×1.0	10
Outrigger yachts (the main hull)							
35	27	2.5	8.9	0.4	34	0.6	1
45	30	2.5	9.1	0.45	34	0.75	9
55	32	2.5	9.06	0.5	38	1.0	17

The following was supposed: two CPP propellers for each yacht, the range 1,000 nm and the economy speed of about 12 knots, if the corresponding power is no less than 35% of the power of one main diesel engine. If not so, the economy speed was supposed equal to the speed at 35% power of one diesel engine.

The fuel supply for these yachts without foils is about 3.5-4.5 t, i.e. the minimal deadweight is about 4-5 t.

After that, the value was compared with the difference between the varied displacement and the defined displacement of the empty yacht, i.e. with the "achievable" deadweight, see Table 3.

For options with full unloading by underwater foils, it was supposed that the foils would be rotated ones, i.e. they would not act on the yacht towing resistance at the economy speed. The hydrodynamic quality of the foils was supposed equal to about 10. The calculations have shown that the catamaran yachts will have approximately the same power for higher achievable speeds, 10-12 knots (own mass of foil system was estimated as about 2-2.5 t, and the displacement growth as about 3.5-4 t.). The results are close to the statistical data on practiced application of additional foils on built high-speed catamarans.

However, it must be noted that the cost of building a foiled catamaran will be 25-30% higher compared to the costs of building a catamaran without foils. Thus, it means that the issue of the foil application has to be discussed in detail prior to the option selection by a yacht customer.

Foiled outrigger yachts must have a sufficiently greater power relative to the displacement (because of a lower level of initial speeds). The difference between the full displacement of foiled catamarans and foiled outrigger yachts is negligible (at this design stage). It might happen that a more detailed design will show a bigger difference in the full displacement of the compared yachts.

4 Comparison of performance and seaworthiness

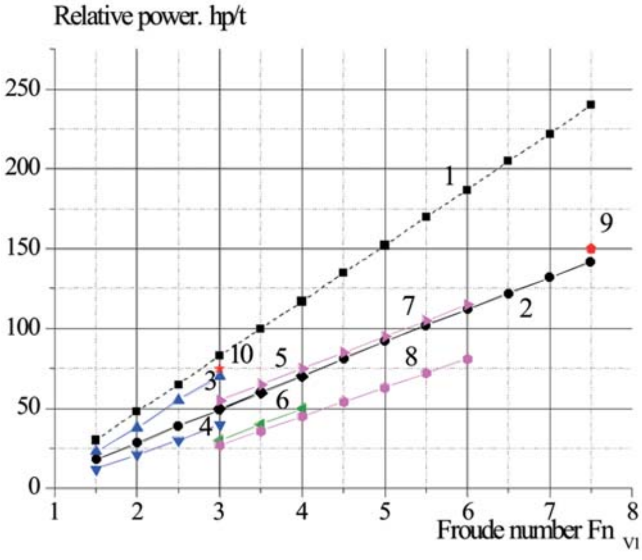
The previously noted restriction of speeds was defined by the rejection of the hard chine shape, and it is the reason of application fields of the "wave-piercing" catamarans without foils and the same outrigger vessels by absolute speeds. It means, that higher (noted) speeds are favourable for catamaran application, lower speeds – for outrigger vessels.

Foiled options (with full hydrodynamic unloading) are equivalent from the performance point of view (for the same foil systems, which were not examined in the shown calculations).

A more general comparison with wide statistical data, Figure 2, has shown that the examined yachts are in the average region of values of corresponding vessels.

Figure 2 **Relative power (per one ton of full displacement): 1,2 – monohulls, upper and lower values; 3,4 – catamarans; 5,6 – foiled boats; 7,8 – boats on air cushion; 9 – "wave-piercing" trimaran as a development of the same catamarans; 10 – "semi-planing" SWA boat**

Slika 2 **Relativna snaga (po toni pune istisnine): 1,2 – jednotrupci, gornja i donja granična vrijednost; 3,4 – katamarani; 5,6 – barke s krilcima; 7,8 – barke na zračnom jastuku, 9 – trimaran „sjekač valova“ razvijen iz istovrsnog katamarana; 10 – „poluglisirajuća“ SWA barka**



It seems evident that the relative power of the proposed "semi-planing" SWA boat is bigger than that of the comparable catamarans. It must be compensated by higher seakeeping.

Some general statistical data on vertical acceleration in head waves are shown in Figure 3.

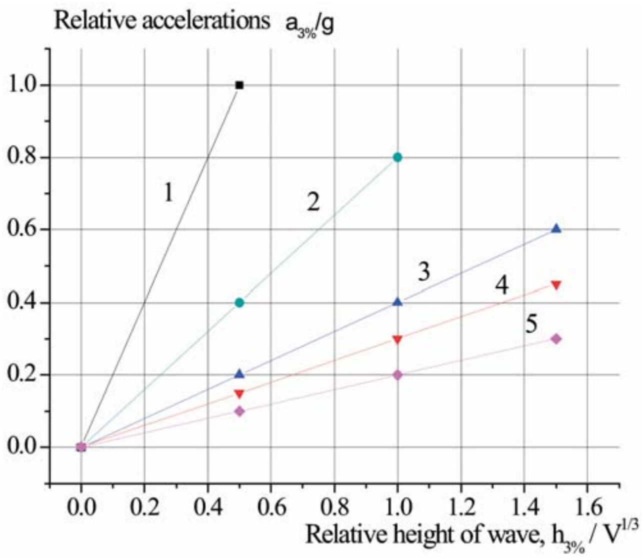


Figure 3 **Relative vertical acceleration at the mass centre: 1 – monohull plane boats; 2 – air cushion boats; 3 – "wave-piercing" catamarans; 4 – SWA boats; 5 – boats with deeply submerged and automatically controlled foils**

Slika 3 **Relativno vertikalno ubrzanje središta mase: 1 – jednotrupne glisirajuće barke; 2 – barke na zračnom jastuku; 3 – katamarani „sjekači valova“; 4 – SWA barke; 5 – barke s duboko uronjenim i automatski upravljanim krilcima**

The general data allow the estimation of the same acceleration of the examined vessels of the noted displacement, see Table 4: all yachts without foils will have approximately the same accelerations as "wave-piercing" catamarans, all foiled vessels – as foiled boats with automatic control. The acceleration level of 0.2 g was assumed as the desired level.

Table 4 **Designed wave height for vertical acceleration at the mass centre (maximum 0.2 g)**

Tablica 4 **Projektna valna visina za vertikalno ubrzanje težišta mase (najviše 0,2 g)**

Yacht type	"Wave-piercing" catamaran and outrigger vessel	Foiled yachts	"Semi-planing" SWA yacht
Design wave height, m	About 1.7	About 3.0	About 2.3

Therefore, multi-hull yachts with full hydrodynamic unloading by foils can ensure high comfort level from the acceleration point of view in Sea State 4 and slightly higher. The same yachts without foils – Sea State 3 and slightly higher, the "semi-planing" SWA, boat will have approximately average seakeeping characteristics.

5 Conclusion, recommendations

The carried out research of multi-hull high-speed small-sized yachts with round bilge hulls has shown the possibility and specificity of such vessel designing by the example of ship line with constant useful area of living deck and range at economy speed. Two types of yachts, "wave-piercing" catamarans and the same outrigger vessels, were designed conceptually, their performance and seakeeping characteristics were estimated.

It has been shown that these types without foils are not competitors with respect to speeds, each type is recommended for its own region of absolute speeds. The difference in seakeeping is small enough too.

The proposed "semi-planing" SWA boat with attitude control by foils is slightly worse from the performance point of view, but sufficiently better from the seakeeping point of view.

The same yachts with automatically controlled foils can have sufficiently higher seakeeping compared to the same boats without foils, but added price of the foil system is about 25-30%.

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