



Investigation of the static trim angle effects on the hydrodynamic performance of a semi-planing catamaran in calm water and waves

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Received 19 February 2023; Received in revised form 12 February 2024; Accepted 14 September 2024

Keywords

Model test;
 Semi-Planing Catamaran (SPC);
 Static trim angle;
 Calm water;
 Wave.

Abstract

This article uses the model test to investigate the effect of static trim angle on the hydrodynamic performance of a Semi-Planing Catamaran (SPC) named AUT-SEM00. First, the resistance test results in calm water at different speeds for static trim angles of 0.00 to 4.00° are presented. The best static trim angle, hence the lowest resistance, is 2.0° at a speed of 3.78 m/s, which leads to the dynamic trim of 2.5°. Then, the model test in three regular waves in a range of static trim angles is conducted, and the results are analyzed. It has been seen that the best static trim angle, in comparison to the other trim angles, depicts up to 9% less resistance. Additionally, it is shown that the static trim angle does not significantly affect pitch motion and vertical accelerations. As far as the regular wavelength is concerned, the pitch and accelerations on the Center of Gravity (CG) and Fore Perpendicular (FP) rapidly increase as wavelength increases. There is a strong correlation between vertical acceleration and pitch motion, where both have the same tendency concerning the wavelength.

1. Introduction

Using a catamaran is very attractive due to providing a large deck area to carry cargo and passengers. Due to the hydrodynamic lift, the wetted surfaces of semi-planing hulls are reduced, and the reduction of the wetted surfaces also reduces the hulls' resistance. The Semi-Planing Catamaran (SPC) is small in size, about tens to hundreds of tons, and has a maximum Froude number (Fr) of about 1. Despite lower resistance, semi-planing vessels, compared to displacement ships, have larger acceleration in waves.

Many research studies have been conducted on the subject of catamarans. Dansig and Bunt [1] experimentally investigated the wave resistance of a catamaran in calm water in Fr of 0.2 to 0.5. They found that with a reduction of the interference ratio, the distance between two demi-hulls divided by vessel wet length, and waves generated by demi-hulls increase. Millward [2] analyzed the effect of the interference ratio and water depth on catamaran resistance using the analytical-numerical method. He found that the resistance gradually increases as the distance between demi-hulls decreases. Insel and Molland [3] investigated the

resistance components of high-speed catamarans by separating the wave-making and viscous resistance in Fr of 0.2 to 1 and the interference ratio of 0.2 to 0.5. Results showed that the viscous force, despite the wave force, is independent of the interference ratio. Also, at high speeds, the interference of the generated waves is negligible. Zaraphonitis et al. [4] conducted an experimental and numerical study on three Wiggly-shaped catamarans in Fr of 0.25 to 0.55 and the interference ratio of 0.2 to 0.4. They concluded that the largest resistance corresponds to the smallest interference ratio. They also found that by changing the demi-hull from symmetric to asymmetric, the resistance decreases due to the reduction of generated wave heights. Fang and Chan [5] investigated seakeeping parameters of high-speed wave-piercing catamarans in oblique waves using two mathematical models. Results showed that wave-piercing catamarans have lower motion in waves than conventional catamarans. Moraes et al. [6] conducted an analytical study on wave-making resistance for high-speed catamarans having U- and V-shape sections in Fr of 0.2 to

To cite this article:

A. Moghaddas, H. Zeraatgar "Investigation of the static trim angle effects on the hydrodynamic performance of a semi-planing catamaran in calm water and waves", *Scientia Iranica* (2025) 32(20): 7544. <https://doi.org/10.24200/sci.2024.61884.7544>

0.9 and an interference ratio of 0.2 to 1.0. They found that the U- or V-shaped sections do not affect the resistance for interference ratios larger than 0.6, and the effect of the interference ratio on the wave-making resistance is insignificant. Zamora et al. [7] conducted a model test on a displacement catamaran model in Fr of 0.1 to 0.55. Results showed that the resistance, trim, and height of the wave generated between demi-hulls increase as the distance between two demi-hulls increases. Dyachkov and Makov [8] conducted a numerical study on a 23-meter high-speed displacement catamaran at Fr of 0.28 and verified the results with a model test on a scale of 1:12. Then, they developed an analytical method for evaluating seakeeping (heave and pitch) of catamarans with stabilizers and also tried to develop this method for analysis in irregular waves. Sahoo et al. [9] experimentally investigated the resistance of high-speed catamarans in calm water. They suggested a regression formula for resistance force considering the distance between two demi-hulls. Lee et al. [10] conducted a study on a small catamaran in Fr of 0.2 to 0.9 and an interference ratio of 0.12 to 0.39 using both experimental and numerical methods. The results showed that decreasing the interference ratio increases the trim and sinkage of the catamaran. Souto-Iglesias et al. [11] analyzed the wave pattern of a catamaran. They concluded that the wave height between two demi-hulls, due to the interference ratio, is higher than that of two demi-hulls. Zaghi et al. [12,13] conducted experimental and numerical studies on the effect of the interference ratio on high-speed catamarans in Fr of 0.2 to 0.8 and the interference ratio of 0.17 to 0.3. The results showed that reducing the distance between two demi-hulls increases the trim angle, which means that the center of pressure moves forward and increases the sinkage of the catamaran.

Broglia et al. [14] investigated the resistance and motion in waves of a high-speed catamaran named DELFT-372 in Fr of 0.1 to 0.8 using model tests. They recorded resistance, trim, and rise-up and investigated the role of nonlinearity on motion in waves. Castiglione et al. [15] conducted a numerical study on the catamaran in regular waves in Fr of 0.3 to 0.75. The results showed that the maximum heave occurs at the resonance frequency and the maximum pitch occurs at a frequency lower than the resonance frequency. Broglia et al. [16] experimentally investigated the effect of interference ratio on high-speed catamarans in calm water and found that the resistance at the lowest interference ratio is about 30% more than the resistance at the highest interference ratio. Shahraki et al. [17] conducted a towing tank test of a multi-piece model of an INCAT wave-piercing catamaran having a range of lengths (volume) in head sea conditions. They concluded that a center bow with a longer length has a greater slamming load and a greater pitch motion. Shahraki et al. [18] surveyed methods to reduce the slamming load of a large wave-piercing catamaran using an experimental method. The results showed that as the height of the deck increases, the slamming load decreases, while the motion increases. Additionally, it showed that the maximum bow motion and the maximum slamming load occur at the same non-dimensional encounter frequency. Farkas et al. [19] conducted a numerical study on the interaction of resistance components for a 60-series catamaran in Fr of 0.30 to 0.55 and the interference ratio of 0.23 and 0.47. They concluded that in high Fr , the generated waves are of divergent type, while they are of transverse type at moderate

Fr , and the interference of the transverse waves causes the formation of a wave trough in the stern, increasing the resistance, trim, and sinkage. Davis et al. [20] conducted an experimental study on the slamming of a 2.5 m hydro-elastic wave-piercing catamaran in a random head wave with a short center bow. The results showed that the slamming load on the hull is 25% to 135% of the catamaran's weight. The additional bending moment caused by the slamming load is 11% higher than the calm water bending moment. Lavroff et al. [21] experimentally investigated wave shock loads on wave-piercing catamarans using a multi-piece model. They concluded that slamming energy decreases along the catamaran length by a damping ratio of 0.02 to 0.06, and that the damping ratio depends on the internal friction mechanisms of the ship. Fitriadhy et al. [22] investigated the seakeeping of a round-bilge catamaran in waves using computational fluid dynamics, considering Fr , the distance between two demi-hulls ratio, and the wavelength-to-ship-length ratio. The results showed that the heave and pitch motion of a round-bilge catamaran is significantly affected by Fr and the wavelength-to-ship-length ratio. Farkas et al. [23] numerically investigated the Interference Factor (IF) for a series 60 catamaran. The results show that interference effects are more significant for narrower catamaran configurations and that the minimum of the IF curve shifts towards higher values of Fr . Also, the obtained wave elevations are significantly higher for narrower configurations. Fitriadhy et al. [24] conducted a numerical study on a V-shaped high-speed catamaran at Fr of 0.5 and 1.0. Results showed that the Response Amplitude Operator (RAO) decreases as wavelength increases for wavelengths less than 0.75 m. As the wave height increases, RAO increases, too. Lin et al. [25] investigated the seakeeping performance of a wave-piercing catamaran called CAT-I using a numerical method with Star-CCM+ software, a RANS method, and a potential flow method. It showed that, among the three methods, the RANS results highly coincided with the experimental results. Chen et al. [26] investigated the High-Order Boundary Element Method (HOBEM) for the evaluation of a high-speed catamaran performance at Fr of 0.1 to 1.0 and the interference ratio of 0.2 to 1.0. Results showed that for Fr higher than 0.5, the waves generated between two demi-hulls are of the divergent type, and the interaction caused by transverse waves is negligible. The interaction between the waves in Fr of 0.4 to 0.7 highly affects the resistance, trim, and sinkage. Shabani et al. [27] designed a bow and a wet-deck to reduce motion and loads using a multi-piece model of a wave-piercing catamaran hull. They conducted 200 model tests in head seas equivalent to wave heights of 2.70, 4.00, and 5.40 m of the full-scale ship. The results showed that increasing the height of the wet deck increases the vertical acceleration of the vessel and reduces the slamming load at a certain speed. Also, the slamming load is 18% to 105% of the ship's weight, which depends on the center bow location and the wave height. They found that reducing the speed from 38 knots to 20 knots can reduce 30% of the load caused by slamming in a regular wave. Hasheminasab et al. [28] experimentally studied the water entry of twin wedge sections as catamaran sections. This study is carried out on a set of twin wedges of 7, 15, and 20-degree deadrise angles. The results show that the effect of the distance between two demi-hulls on the peak pressure is negligible. Also, the pressure on the non-vertical side of an

asymmetry wedge is considerably lower than that on the equivalent symmetry wedge. Miao et al. [29] conducted a numerical optimization study on an S60 catamaran for resistance reduction based on a consideration of the demi-hull shape and separation. Three Free-Form Deformations (FFD)-related parameters and the separation distance of the demi-hulls are selected as four design variables, with two geometric constraints imposed. The total resistance for Fr 0.4 and 0.45 is taken as the two objective functions. Results showed that a maximum resistance reduction of 20.52% for OPT1 and 15.00% for OPT2 is achieved by the optimal catamaran designs for Fr 0.4 and 0.45, respectively. Three optimal catamaran designs are selected from the Pareto front for numerical simulations using the RANS-based solver naoe-FOAM-SJTU. The hydrodynamics of these catamarans are compared in detail to those of the initial catamaran. The total resistances of the three optimal catamarans are greatly reduced at $Fr = 0.4$, and the total resistance of OPT1 is increased a little (0.17%) at $Fr = 0.45$, due to a larger IF value. Julianto et al. [30] conducted research using the experimental method on hydrodynamics and structure of a wave-piercing catamaran considering the fluid-structure interactions. They found that keel-shaped fins and titanium and aluminum materials can make the structure of the ship more durable and resistant to waves. Liu et al. [31] conducted numerical studies of seakeeping behavior for a high-speed catamaran with a stern flap advancing in a long crest head wave. Both model-scale and full-scale simulations have been carried out in sea state 6 using an Unsteady Reynolds-Averaged Navier-Stokes (URANS) solver. Model-scale simulation results indicate that using a stern flap could reduce the catamaran's total resistance, and the effects on heave and pitch motions are obvious in sea state 6. The installation of the stern flap shows a significant effect on the reduction of vertical acceleration amplitudes, especially in reducing the occurrence of slamming impact due to the effective control of the model's trim angle. Full-scale simulations have also been conducted and compared with the model-scale results. Results show that the effects of the stern flap on heave and pitch motions are the same for both model-scale and full-scale catamarans.

Honaryar et al. [32] investigated a new phenomenon due to interference in the dynamic response of catamarans. The results of catamaran dynamic response reveal that not only does its resistance reduce substantially up to 15%, but also the trim angle diminishes by 30% as the distance between the two demi-hulls decreases in semi-planing and planing modes. Dogrul et al. [33] focused on the numerical investigation of Delft Catamaran 372, which is widely used for benchmarking. URANS analyses were conducted at $Fr = 0.3$ in regular head wave conditions. The main highlights of this study are the comprehensive validation study with the literature and the calculation of the IF through total and added resistance in waves. Motion and added resistance transfer functions were obtained for catamaran and demi-hull geometries. It is concluded that the effects of IFs in waves are highly important in catamaran forms. Almallah et al. [34] conducted a full-scale CFD simulation to investigate the pressure distributions and resultant global loads acting on the 98 m INCAT wave-piercer catamaran HSV2 Swift at a forward speed of 20 knots, validated against sea trial tests. Splitting forces are found to have a longitudinal distribution

along the catamaran hull, which causes prying moments. Peak values for LBM are examined relative to the corresponding instantaneous wave height prior to the slam event. In addition, it is found that pitch acceleration has a linear correlation with LBM slam loads. Iqbal et al. [35] numerically investigated the use of a foil-shaped center bulb in catamaran fishing vessels at Fr of 0.15 to 0.35. The results showed that the best model was found in Model 6, where the length of the center bulb was 15% greater, while the width and height were 10% smaller than the original one. Model 6 can reduce resistance by 10.68%. Wang et al. [36] performed experimental tests and numerical investigations on a planing catamaran under different displacements to analyze the resistance characteristics and mechanism of the tunnel flow. Model tests were conducted in a towing tank for Froude numbers (Fr of 0.76 to 1.93). Numerical results of pressure, comparisons of wave profile along the transom stern centerline, lift distribution on the tunnel, and components of tunnel lift are presented and compared for the analysis of tunnel flow under different displacements. The tunnel could contribute the maximum lift of about 26% of the ship weight in the case of $M = 202.9$ kg. This study would provide a better understanding of hydrodynamics and the aerodynamics of the tunnel for the planing catamaran. Farkas et al. [37] numerically investigated the interference effect for the Delft 372 catamaran. The results of analyzing the wave profile in the longitudinal center plane of the catamaran with the distance between the hulls equal to 0.233 reveal that, at a lower Fr , a larger wave crest was obtained behind the stern of the ship compared to a wave crest at a higher Fr . Kiryanto et al. [38] numerically studied the seakeeping performance of a hospital catamaran ship to handle the COVID-19 pandemic in Indonesia. They investigated a catamaran ship's performance at two Fr values of 0.23 and 0.31. They found that Fr plays a significant role in motion response, enabling the designers of the hospital ship to predict seakeeping behavior with a satisfactory approximation during the very early design stages. Sugianto et al. [39] numerically studied the effectiveness of waste collection using a monohull and catamaran fitted with a forward conveyor using OpenFOAM software. The results show that marine debris flows at two Fr values of 0.08 and 0.16 much more conveniently through the conveyor fitted in front of the catamaran model than in the monohull model. In addition, considering the front-side hull flow, the catamaran model is superior since marine debris can approach the ship easily. Sulistyawati et al. [40] conducted a comparative numerical study of monohull rounded and chine catamarans on the squat factor in shallow water by varying the water depth ratio h/T to 1.2, 1.3, and 1.5 at Fr of 0.25, 0.50, and 0.75. The analysis is also carried out on the sinkage and trim factors by varying the ship's trim with changes in LCG points and variations in speed. The overall analysis shows that the monohull has a remarkable effect on shallow water at $Fr < 0.3$. While at higher speeds, catamarans have a lower influence on the squat, sinkage, and trim factors in shallow water conditions. Windyandari et al. [41] numerically investigated the hexagonal catamaran hull form on the deadrise angle, angle of attack, and stern angle variation at $Fr = 0.30$. Results showed that the hexagonal catamaran hulls have better seakeeping performance in the beam sea. However, the conventional catamaran has

demonstrated superiority over the hexagonal catamaran in the bow quartering and head sea conditions.

Having considered all cited references, the effects of static trim angle on the catamaran performances of SPC have not been addressed. The goal of this study is to investigate the hydrodynamic performances of an SPC in calm water and waves using experiments. For this purpose, an SPC model, which is called AUT-SEM00, is initially tested in calm water in Fr of 0.13 to 1.02 at static trim angles of 1°, 2°, 3°, and 4°. The best static trim angle corresponding to the lowest resistance at the service speed of the craft, equivalent to Fr of 0.83, is determined. Additionally, at Fr of 0.83 and for the same range of static trim angle, motion in regular head waves in wavelength-to-length ratios between fore and aft perpendiculars of ships (L_{BP}) of 1, 1.5, and 2 are tested. The results of the conducted model tests are analyzed to show the effect of the static trim angle on the hydrodynamic performance of an SPC. The details of the geometry of the catamaran and experiments and the data generated in this study are illustrated, which can also be employed for validation of future numerical simulations.

2. A brief review of ship motion principles

A ship is moving in a regular cosine wave defined at the center of Gravity (CG) as follows:

$$\zeta(t) = \bar{\zeta} \cos(\omega_e t), \quad (1)$$

$$\omega_e = \omega_w - kv \cos \mu. \quad (2)$$

A ship model's motion in regular waves is presented in non-dimensional form as follows:

$$Non - DimPitch = \frac{\bar{\eta}_\theta}{k\bar{\zeta}}, \quad (3)$$

$$Non - DimACC = \frac{\bar{\zeta}_3}{g}. \quad (4)$$

3. Experimental set-up

3.1 Specifications of AUT-SEM00

The AUT-SEM00 selected for the analysis is a 37.50 m in length crew boat. A model of 2.250 m in length is manufactured for the model tests. Specifications of the AUT-SEM00 as an SPC in full-scale and model size are described in Table 1. Figure 1 demonstrates the geometry of the craft in the form of bodylines and sheer plan.

Table 2 depicts the AUT-SEM00 model hydrostatic properties in trim conditions. The model is manufactured from composite material with a combination of epoxy resin and glass fibers, and the master is carved using a Computer Numerical Control (CNC) machine. For this purpose, two demi-hulls are manufactured, polished, and painted. The two demi-hulls are connected with two rigid steel rods.

3.2 Model test facilities

The model tests have been conducted in the National Iranian Marine Laboratory (NIMALA). NIMALA towing tank is a large, 402 m in length, and high-speed, 19.0 m/s, tank. In this towing tank, resistance, motion in regular and irregular waves, captive model tests of the Planar Motion Mechanism type for maneuvering hydrodynamic coefficients, and propeller-open-water and propeller-behind-hull tests are conducted. Tests are performed at speeds of 0.10 to 19.0 m/s where the permissible speed fluctuation is ± 0.005 m/s. The NIMALA towing tank can perform model tests for displacement ships, semi-planing, and planing craft. A 6-

Table 1. Specifications of AUT-SEM00 ship and model.

Parameter	Unit	Ship	Model
L_{OA}	m	37.50	2.250
L_{WL}	m	34.73	2.083
B_T	m	11.21	0.672
T	m	1.81	0.109
Δ	kg	161570	34.12
ρ	kg/m ³	1025	1002
λ	-	1:1	1:16.67
P_B	kW	3152	-
V	kn or m/s	30.0 (kn)	3.78 (m/s)

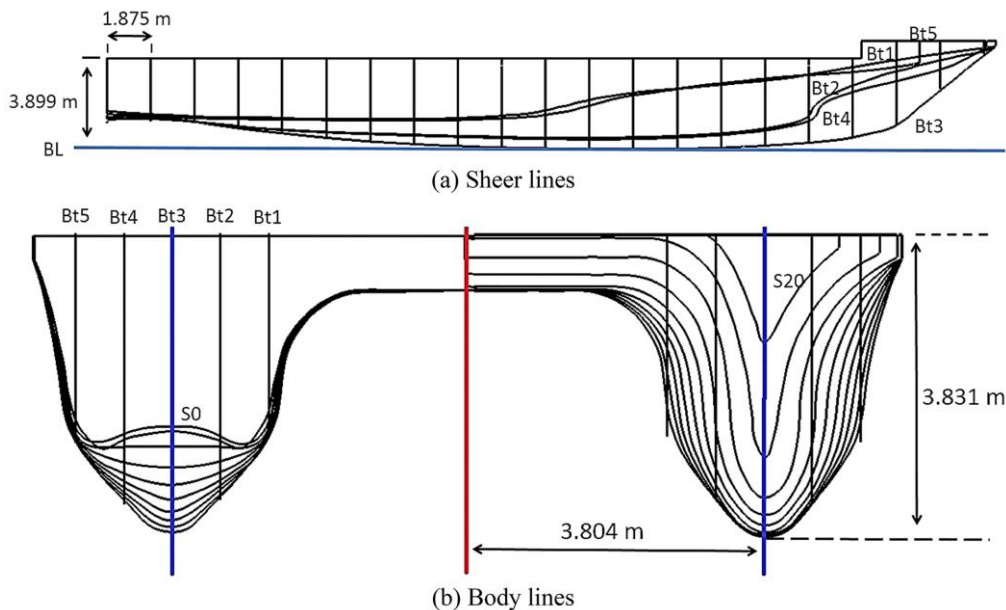


Figure 1. Geometry of AUT-SEM00 ship.

Table 2. Hydrostatic properties of the AUT-SEM00 model in trim conditions at a displacement of 34.12 kg.

No.	LCG (m)	θ_s (deg)	TF (m)	TA (m)
1	1.003	0.0	0.107	0.107
2	0.923	1.0	0.086	0.122
3	0.844	2.0	0.064	0.137
4	0.768	3.0	0.042	0.151
5	0.698	4.0	0.020	0.166

Table 3. NIMALA towing tank specifications.

L (m)	402.0
b (m)	6.0
H (m)	4.5
h (m)	4.0
Vc (m/s)	19.00
Wave-maker type	Segmented plate-type
Max H_w (m)	0.50
Wave recording system	Save probe, resistive

Segmented plate-type wave-maker generates regular and irregular waves of several spectrum types up to 0.50 m wave height. A beach-type wave damper is located at the second end of the towing tank for the fast preparation of the next test. Table 3 depicts the NIMALA towing tank specifications.

3.3 Model setup and test scenarios

The model connected to the carriage is shown in Figure 2. In this setup, the resistance of the model is measured by a 1-component load cell. The heave and pitch motion are calculated from the recorded vertical displacement at the aft and fore of the model. Also, two accelerometers are installed at the LCG and Fore Perpendicular (FP) of the model to record the vertical acceleration in the wave tests.

Two sets of model tests are performed: resistance in calm water and motion in waves. Additionally, a parametric study is conducted on the effect of the longitudinal center of gravity, say static trim angle, on the resistance and motion in waves.

3.3.1. Resistance tests

As far as resistance tests are concerned, following the ITTC recommendations [42], tests are performed in the range of 5% less than the minimum speed to 5% more than the maximum speed of the ship. Table 4 shows the model test scenario in calm water. Altogether, 45 test runs are performed in calm water.

Table 4. Model test scenario in calm water.

Static trim Angle (deg)	Fr	V_K (ship)	V (model)
From 0.0° to 4.0° at the step of 1.0°	0.13	4.75	0.60
	0.14	5.00	0.63
	0.28	10.00	1.26
	0.42	15.00	1.89
	0.56	20.00	2.52
	0.70	25.00	3.15
	0.84	30.00	3.78
	0.98	35.00	4.41
	1.02	36.75	4.63

Table 5. Model test scenario of motion in regular waves at a speed of 3.78 m/s.

Run #	θ_s (deg)	H_w (m)	T (sec)	λ/L_{pp}
1	0.0	0.0418	1.16	1.00
2		0.0626	1.42	1.50
3		0.0834	1.63	2.00
4		0.0418	1.16	1.00
5	1.0	0.0626	1.42	1.50
6		0.0834	1.63	2.00
7		0.0418	1.16	1.00
8	2.0	0.0626	1.42	1.50
9		0.0834	1.63	2.00
10		0.0418	1.16	1.00
11	3.0	0.0626	1.42	1.50
12		0.0834	1.63	2.00
13		0.0418	1.16	1.00
14	4.0	0.0626	1.42	1.50
15		0.0834	1.63	2.00

3.3.2. Motion in waves

The model test in waves is performed in regular head waves. Wave profile, pitch motion, acceleration at the CG, and acceleration at the FP are recorded. To prepare the model for testing in waves, the pitch radius of gyration (r_z) is set to 0.25LPP. Also, to measure the vertical acceleration of the model, two accelerometers are employed, one on the FP and the other one on the longitudinal CG. Figure 3 shows a photo of the model on the moment of inertia table.

ITTC has several recommendations for the model tests of ships in waves as follows: the wavelength should be at least in the range of 0.50 L_{PP} to 2.00 L_{PP} and the ratio of wave height to wavelength must remain constant at about 1/50 [43]. The model test scenario in waves is shown in Table 5. All tests in waves are conducted at a speed of 3.78, equal to 30 knots, for the ship.

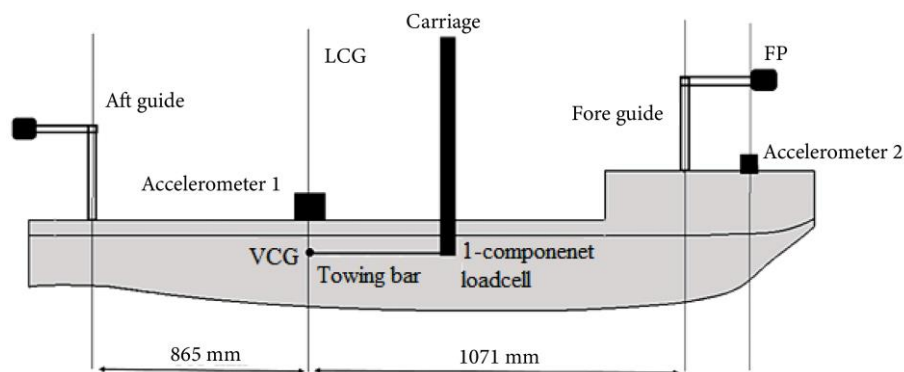
**Figure 2.** Model setup and measuring equipment.



Figure 3. Measuring and setting up the moment of inertia of the model.

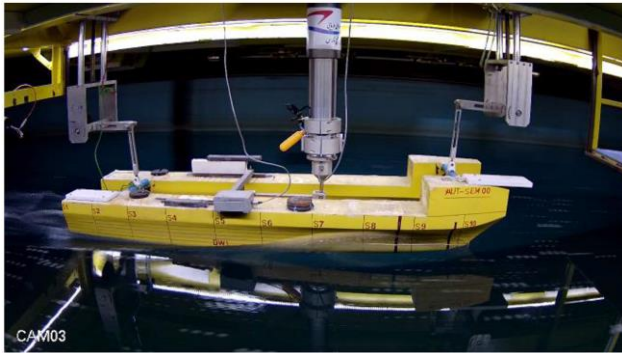


Figure 4. The resistance test at a speed of 4.41 m/s and 0.0° static trim angle.

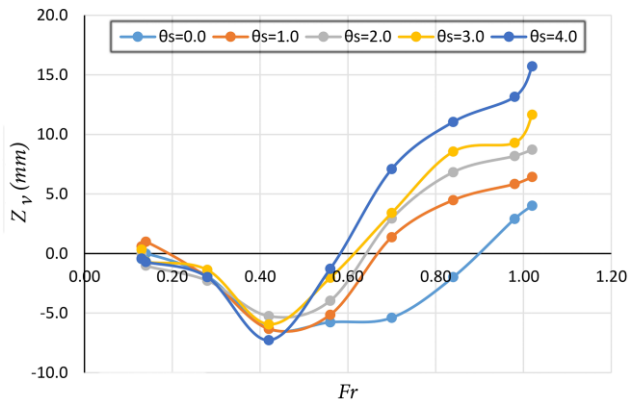


Figure 5. Rise-up versus Fr in a range of static trim angles.

4. Results and discussions

4.1 Resistance in calm water

Following the test scenario of Table 4, more than 45 runs are performed. The rise-up, dynamic trim, and resistance are recorded. Figure 4 shows a photo of the AUT-SEM00 model in the calm water test at a static trim angle of 0.0° and a speed of 4.41 m/s.

Table 6 shows the model test results in calm water in a range of static trim angles and speeds. Also, the uncertainty of results is presented according to ITTC recommendation [44].

Figures 5 and 6 show the rise-up and dynamic trim as a function of Fr for a range of static trim angles.

As can be seen in Figure 5, the rise-up has two trends where it reduces from zero to a considerable negative value

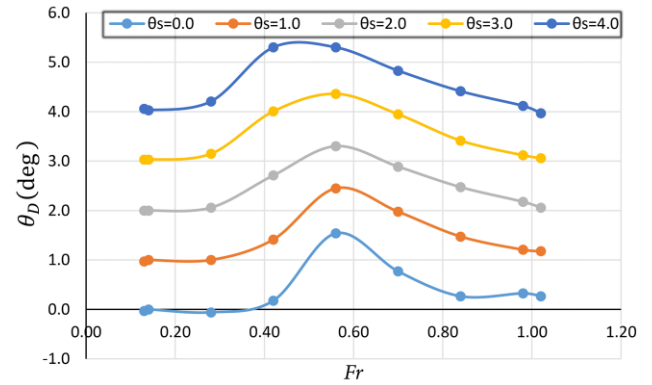


Figure 6. Dynamic trim versus Fr in a range of static trim angles.

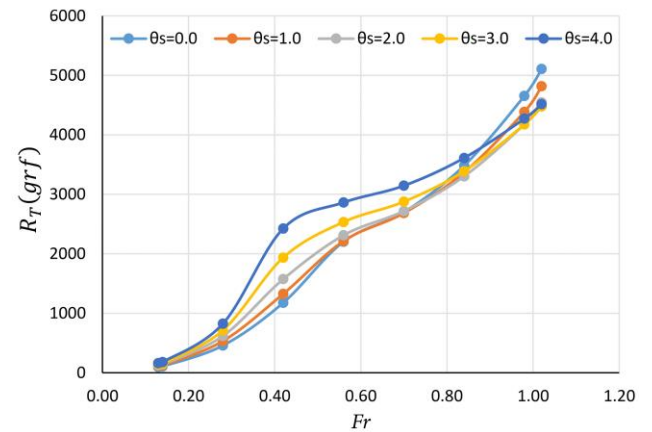


Figure 7. Resistance versus Fr in a range of static trim angles.

(sinkage) and then it increases, which becomes positive (rise-up). The above trends are repeated for five different static trim angles. This consistency of the rise-up trends indicates that a similar pressure field is generated around the model hull at a given Fr, disregarding the static trim. The maximum sinkage is about -7 mm which is considerable compared to the model draught. At Fr greater than about 0.6, a rise-up occurs which rapidly increases as Fr increases. It becomes 12 mm at a static trim angle of 4.0° which is significant. As far as the static trim angle effects on the rise-up are concerned, it governs the rise-up as much as that at Fr=0.84; the rise-up is -2 mm and +12 mm at static trim angles of 0.0° and 4.0°, respectively.

The dynamic trim versus Fr has a similar trend in different static trim angles. At a given Fr, the dynamic trim difference is almost the static trim difference. The dynamic trim is negligible for low Fr, up to 0.30. A rapid increase happens where the highest dynamic trim occurring at Fr of 0.56. Then, it rapidly decreases. At Fr=0.84, for all cases of static trim angle, the dynamic trim is larger than the static trim angle by up to one degree.

Figure 7 shows the resistance of the model in calm water as a function of Fr for different static trim angles.

Figure 7 shows that at Fr about 0.45, the trend of the resistance curve changes, and a hump appears. Referring to Figure 5, it can be seen the highest sinkage occurs at the same Fr. A trend change happens after Fr about 0.45, and the sinkage becomes rise-up at Fr about 0.60. This phenomenon can be due to the hydrodynamic lift, which decreases the wetted surface, and as a result, the trend of the resistance is changed.

Table 6. Model test results in calm water in a range of static trim angles and speeds.

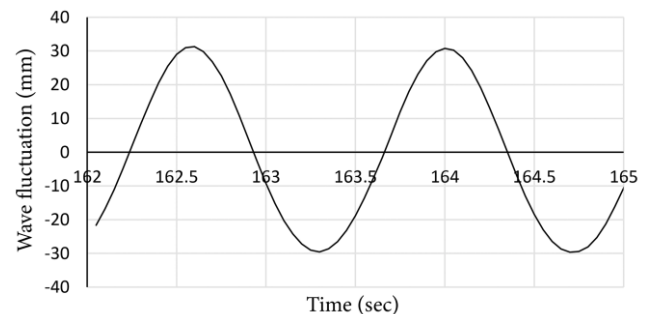
θ_s (deg)	Fr	V (m/s)	R_T (grf)	Up (%)	Θ_D (deg)	Ut (%)	Z_v (mm)	Ur (%)
0.0	0.13	0.60	98	0.2568	-0.0	1.02	-0.5	1.17
	0.14	0.63	108	0.2430	0.0	0.60	0.00	0.98
	0.28	1.26	459	0.3035	-0.1	0.49	-1.9	0.49
	0.42	1.89	1178	0.1898	0.2	0.30	-6.3	0.33
	0.56	2.52	2205	0.1698	1.5	0.22	-5.8	0.77
	0.70	3.15	2701	0.1670	0.8	0.18	-5.4	0.07
	0.84	3.78	3484	0.1647	0.3	0.15	-2.0	0.04
	0.98	4.41	4656	0.1631	0.3	0.13	2.9	0.67
	1.02	4.63	5109	0.1628	0.3	0.14	4.0	0.90
	0.13	0.60	111	0.2399	1.0	1.08	0.6	1.26
1.0	0.14	0.63	123	0.2277	1.0	0.65	1.0	1.03
	0.28	1.26	534	0.2735	1.0	0.52	-2.0	0.52
	0.42	1.89	1327	0.1841	1.4	0.33	-6.3	0.36
	0.56	2.52	2215	0.1697	2.5	0.24	-5.1	0.82
	0.70	3.15	2685	0.1670	2.0	0.20	1.4	0.08
	0.84	3.78	3371	0.1649	1.5	0.17	4.5	0.04
	0.98	4.41	4389	0.1634	1.2	0.14	5.8	0.70
	1.02	4.63	4818	0.1630	1.2	0.15	6.4	0.99
	0.13	0.60	126	0.2245	2.0	1.19	0.0	1.33
	0.14	0.63	139	0.2149	2.0	0.71	-1.0	1.08
2.0	0.28	1.26	620	0.2493	2.1	0.57	-2.3	0.57
	0.42	1.89	1575	0.1778	2.7	0.35	-5.3	0.39
	0.56	2.52	2312	0.1691	3.3	0.26	-4.0	0.88
	0.70	3.15	2720	0.1669	2.9	0.21	2.9	0.08
	0.84	3.78	3303	0.1651	2.5	0.18	6.8	0.04
	0.98	4.41	4178	0.1636	2.2	0.15	8.2	0.75
	1.02	4.63	4546	0.1632	2.1	0.16	8.7	1.05
	0.13	0.60	144	0.2117	3.0	1.28	0.3	1.42
	0.14	0.63	154	0.2063	3.0	0.77	-0.7	1.13
	0.28	1.26	715	0.2306	3.2	0.62	-1.4	0.62
3.0	0.42	1.89	1937	0.1723	4.0	0.37	-5.9	0.42
	0.56	2.52	2535	0.1678	4.4	0.28	-2.0	0.97
	0.70	3.15	2877	0.1663	4.0	0.22	3.4	0.09
	0.84	3.78	3390	0.1649	3.4	0.19	8.6	0.05
	0.98	4.41	4175	0.1636	3.1	0.15	9.3	0.83
	1.02	4.63	4476	0.1633	3.1	0.17	11.7	1.14
	0.13	0.60	164	0.2015	4.1	1.38	-0.4	1.50
	0.14	0.63	182	0.1948	4.0	0.84	-0.7	1.25
	0.28	1.26	827	0.2153	4.2	0.65	-2.0	0.66
	0.42	1.89	2426	0.1684	5.3	0.40	-7.3	0.45
4.0	0.56	2.52	2863	0.1664	5.3	0.30	-1.3	1.04
	0.70	3.15	3145	0.1655	4.8	0.24	7.1	0.09
	0.84	3.78	3612	0.1644	4.4	0.21	11.1	0.05
	0.98	4.41	4273.1	0.1635	4.1	0.17	13.2	0.88
	1.02	4.63	4517	0.1632	4.0	0.19	15.7	1.24

As far as the static trim angle is concerned, the low static trim angle triggers low resistance in the first area. However, in the second area, the lowest resistance belongs to static trim angles of 3.0° and 4.0° , and the highest is for 0.0° , at $Fr=1.0$. The best static trim angle for the AUT-SEM00 at a speed of 3.74 m/s ($Fr=0.84$) is 2.0° , which has the lowest resistance. In this condition, the dynamic trim is 2.5° which is acceptable regarding crew comfort.

4.2 Motion in waves

The second set of model tests is conducted in regular head waves to record model motion as a function of wave characteristics in a range of static trim angles. According to the test scenario of Table 4, more than 15 runs are performed. The time series of wave profile, pitch motion, and acceleration at CG and FP are recorded.

As samples, Figure 8 presents a time series of the wave, and Figures 9-11 present time series of pitch and acceleration at CG and FP at Run #2.

**Figure 8.** Time series of the wave profile at Run #2.

The regular wave is recorded in the towing tank about 50 m from the wave-maker. According to Figure 9, its profile is quite regular and repeats the same wave amplitude in each period.

Considering the time series of pitch motion at Run #2, as shown in Figure 9, it is almost a regular motion. It oscillates

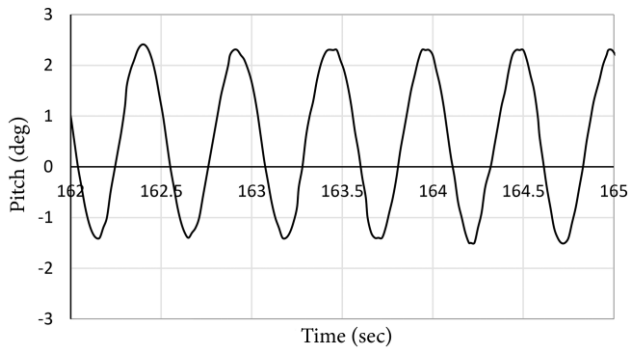


Figure 9. Time series of pitch motion at Run #2.

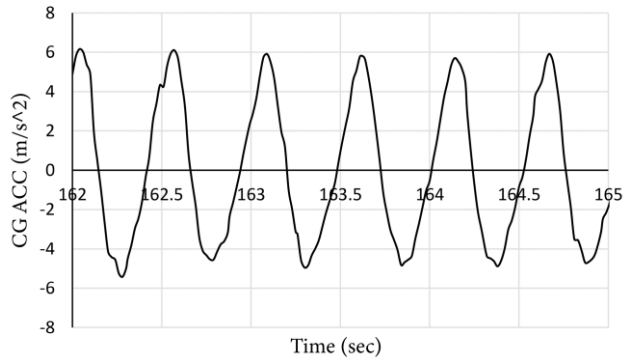


Figure 10. Time series of vertical acceleration of CG at Run #2.

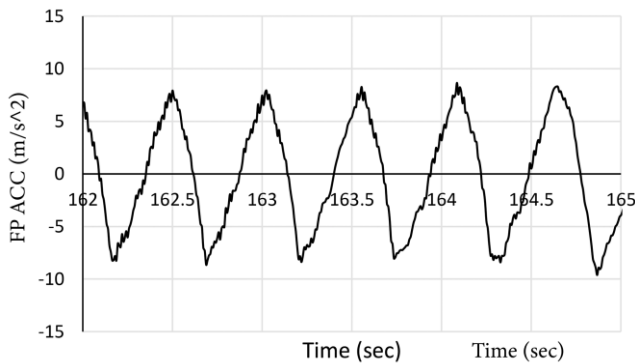


Figure 11. Time series of vertical acceleration of FP at Run #2.

about the dynamic trim angle recorded in calm water, say 0.3° . For the considered case, the pitch amplitude is 1.9° and the period of the oscillation is 0.53 seconds, which is the encounter wave period. The same behavior is seen for the pitch motion in the rest of the test runs.

Figures 10 and 11 show the time series of the vertical acceleration at CG and FP at Run #2. Both accelerations are almost repeating in consecutive periods, and their mean values are almost zero.

Figures 10 and 11 are clearly non-sinusoidal where their peaks are very sharp. At CG, the upward acceleration is slightly sharper than the downward on their peaks. The oscillation period of accelerations is the encounter period, as expected. The same behavior is seen in the rest of the test runs. The average amplitude of accelerations of the considered case on CG and FP are 5.2 and 8.2 m/s^2 , respectively.

The model test results in waves for a range of static trim angles are presented in Table 7. The results show that the pitch amplitude and acceleration on CG and FP significantly

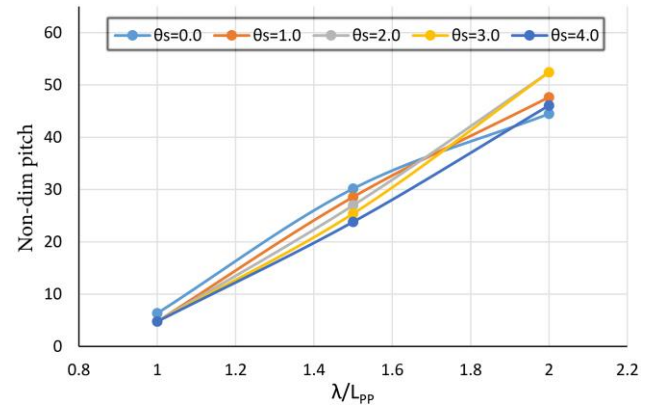


Figure 12. Non-dimensional pitch versus λ/L_{pp} in a range of static trim angles.

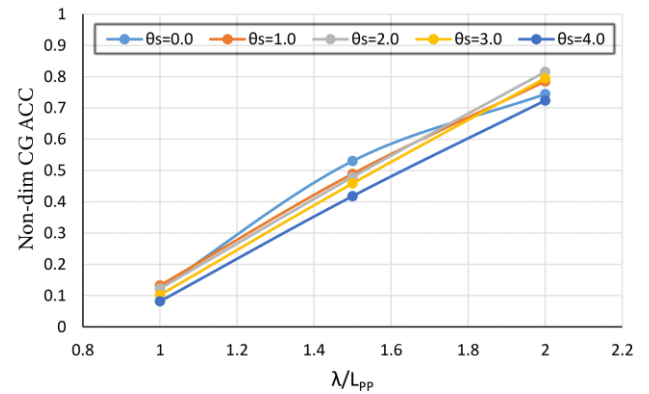


Figure 13. Non-dimensional CG acceleration versus λ/L_{pp} in a range of static trim angles.

increase as λ/L increases. Additionally, it is observed that the acceleration on FP is larger than on CG, as expected. As far as the static trim angle effect is concerned, there are considerable differences between results in different static trim angles. However, no clear tendency for both pitch motion and acceleration is detected.

Equations (Eqs. (3) and (4)), non-dimensional pitch, non-dimensional CG accelerations, and non-dimensional FP accelerations are depicted in Figures 12 to 14.

Figures 12 to 14 show that none of the pitch, CG acceleration, and FP acceleration are in the resonance peak condition for the considered range of wavelength. Additionally, the trends of the above three curves are almost the same and are rapidly increasing. Overall, it is seen that the static trim angle interference on pitch and acceleration trends is marginal. It can be seen that the amplitude of CG acceleration has not reached the gravity acceleration, while the amplitude of FP acceleration is well beyond the gravity acceleration.

5. Conclusions

A study on the hydrodynamic performances of a high-speed Semi-Planing Catamaran (SPC) using model tests is performed. The focus is on the effects of the static trim angle on the craft performance in calm water and waves. For this purpose, resistance, trim, and rise-up in calm water and pitch motion and vertical acceleration in regular waves are recorded and analyzed. The following are concluded from the considered case:

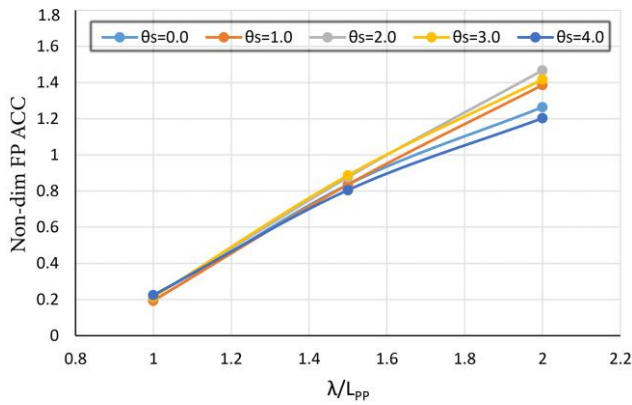


Figure 14. Non-dimensional FP acceleration versus λ/L_{PP} in a range of static trim angles.

Table 7. Model test results in waves in a range of static trim angles.

θ_s (deg)	Run no	η_θ (deg)	$\eta_{CG\ ACC}$ (m/s ²)	$\eta_{FP\ ACC}$ (m/s ²)
0.0	1	0.4	1.2	1.9
	2	1.9	5.2	8.2
	3	2.8	7.3	12.4
1.0	1	0.3	1.3	1.9
	2	1.8	4.8	8.2
	3	3.0	7.7	13.6
2.0	1	0.3	1.2	2.1
	2	1.7	4.7	8.6
	3	3.3	8.0	14.4
3.0	1	0.3	1.0	2.1
	2	1.6	4.5	8.7
	3	3.3	7.8	13.9
4.0	1	0.3	0.8	2.2
	2	1.5	4.1	7.9
	3	2.9	7.1	11.8

- The resistance of SPC in calm water shows a rapid increase as Fr increases. However, two trends are distinguished. The first trend is for Fr up to 0.42, where the resistance increases with a high slope, while the second trend occurs for Fr 0.45 to 1.0, which has a low slope in comparison to the first trend. Additionally, the static trim angle of 2.0° depicts the lowest resistance at the service speed;
- There are considerable differences between results in different static trim angles, as far as motion in waves is considered. However, no clear tendency for both pitch motion and acceleration is detected for the studied case. The non-dimensional test results in waves show that as λ/L increases, pitch and vertical acceleration rapidly increase.

By evaluating the effect of static trim angle on the resistance and running attitude of an SPC in calm water and waves, the following issues can be considered for future studies:

- Investigating the effect of weight change and geometry change on the performance of SPC in calm water and waves.

Nomenclature

$\bar{\zeta}$	Wave amplitude
ω_w	Wave frequency
ω_e	Encounter frequency
Fr	Froude number
k	Wave number
V	Speed (m/s)
V_k	Speed (knot)
μ	Wave direction
$\bar{\eta}_i$	Motion amplitude of the i th motion
ε_i	The i th phase-lag
$\bar{\xi}_3$	Average amplitude of vertical acceleration
g	Gravity acceleration
L_{WL}	Waterline length
λ_w	Wave length
L_{OA}	Overall length
B_T	Maximum transom beam
T	Draft
Δ	Displacement
ρ	Water density
λ	Scale factor
P_B	Braking power
L_{CG}	Longitudinal center of gravity
TF	Bow draft
TA	Stern draft
θ_s	Static trim angle
l	Tank length
b	Tank width
H	Tank height
h	Tank depth
V_c	Carriage speed
$or L_{BP} L_{PP}$	Length between perpendicular
T	Wave period
H_w	Wave height
R_T	Total resistance
θ_D	Dynamic trim
Z_v	Rise-up
η_θ	Pitch motion amplitude
$\eta_{CG\ ACC}$	CG acceleration amplitude
$\eta_{FP\ ACC}$	FP acceleration amplitude
U_p	Resistance uncertainty
U_t	Trim uncertainty
U_r	Rise-up uncertainty

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-for-profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

First author: Conceptualization; Formal analysis; Investigation; Methodology; Software Supervision; Writing – review & editing.

Second author: Data curation; Formal analysis; Validation; Writing – original draft.

References

- Dancig, A.A. and Bunt, E.A. "Wave interference effects on a double-hull ship model as measured by gravity dynamometer", *Int. J. Mech. Sci.*, **32**(8), pp. 653-676 (1990). [https://doi.org/10.1016/0020-7403\(90\)90008-7](https://doi.org/10.1016/0020-7403(90)90008-7)
- Millward, A. "The effect of hull separation and restricted water depth on catamaran resistance", *Int. J. Trans. R. Inst. Nav. Archit.*, **134**, pp. 341-349 (1992).
- Insel, M. and Molland, A.F., *An Investigation into the Resistance Components of High-Speed Displacement Catamarans*, Royal Institution of Naval Architects, pp. 1-20 (1992).
- Zaraphonitis, G., Spanos, D., and Papanikolaou, A. "Numerical and experimental study on the wave resistance of fast displacement asymmetric catamarans", *Proc. 2nd Int. Euro Conference HIPER* (2001).
- Fang, C. and Chan, H. "Investigation of seakeeping characteristics of high-speed catamaran in waves", *Journal of Marine Science and Technology-Taiwan*, **12**(1), pp. 7-15 (2004). <https://doi.org/10.51400/2709-6998.2215>
- Moraes, H.B., Vasconcellos, J.M., and Latorre, R.G. "Wave resistance for high-speed catamarans", *Int. J. Ocean Eng.*, **31**(17-18), pp. 2253-2282 (2004). <https://doi.org/10.1016/j.oceaneng.2004.03.012>
- Souto, I.A., Zamora, R., Fernandez, D., et al. "Catamaran wave resistance and central wave cuts for CFD validation", *12th International Congress of the International Maritime Association of the Mediterranean (IMAM), Maritime Transportation and Exploitation of Ocean and Coastal Resources*, **1**, pp. 157-165 (2005).
- Dyachkov, V. and Makov, J. "Seakeeping of a fast displacement catamaran", *Int. J. Transport*, **20**(1), pp. 14-22 (2005). <https://doi.org/10.3846/16484142.2005.9637990>
- Sahoo, P.K., Salas, M., and Schwetz, A. "Practical evaluation of resistance of high-speed catamaran hull forms-Part I", *Int. J. Ships Offshore Struct.*, **2**(4), pp. 307-324 (2007). <https://doi.org/10.1080/17445300701594237>
- Lee, S.H., Lee, Y.G., and Kin, S.H. "On the development of a small catamaran boat", *Int. J. Ocean Eng.*, **34**(14-15), pp. 2061-2073 (2007). <https://doi.org/10.1016/j.oceaneng.2007.02.011>
- Souto-Iglesias, A., Zamora-Rodríguez, R., Fernandez-Gutiérrez, D., et al. "Analysis of the wave system of a catamaran for CFD validation", *Int. J. Exp. Fluids*, **42**(2), pp. 321-332 (2007). <https://doi.org/10.1007/s00348-006-0244-4>
- Zaghi, S., Broglia, R., and Di Mascio, A. "Experimental and numerical investigations on fast catamarans interference effects", *Int. J. Hydrodyn.*, **22**, pp. 528-533 (2010). [https://doi.org/10.1016/S1001-6058\(09\)60250-X](https://doi.org/10.1016/S1001-6058(09)60250-X)
- Zaghi, S., Broglia, R., and Di Mascio, A. "Analysis of the interference effects for high-speed catamarans by model tests and numerical simulations", *Int. J. Ocean Eng.*, **38**(17-18), pp. 2110-2122 (2011). <https://doi.org/10.1016/j.oceaneng.2011.09.037>
- Broglia, R., Bouscasse, B., Jacob, B., et al. "Calm water and seakeeping investigation for a fast catamaran". *11th International Conference on Fast Sea Transportation FAST* (2011).
- Castiglione, T., Stern, F., Bova, S., et al. "Numerical investigation of the seakeeping behavior of a catamaran advancing in regular head waves", *Int. J. Ocean Eng.*, **38**, pp. 1806-1822 (2011). <https://doi.org/10.1016/j.oceaneng.2011.09.003>
- Broglia, R., Jacob, B., Zaglul, S., et al. "Experimental investigation of interference effects for high-speed catamarans", *Int. J. Ocean Eng.*, **76**(2014), pp. 75-85 (2014). <https://doi.org/10.1016/j.oceaneng.2013.12.003>
- Shahraki, J., Thomas, J., and Amin, V. "Center bow design for wave piercing catamarans", *12th International Conference on Fast Sea Transportations FAST'12*, Netherland (2013). <https://doi.org/10.13140/RG.2.1.3840.2406>
- Shahraki, J., Davis, M., Shabani, B., et al. "Mitigation of slamming of large wave-piercing catamarans", *30th Symposium on Naval Hydrodynamics*, Hobart, Tasmania, Australia (2014).
- Farkas, A., Degiuli, N., and Martić, I. "Numerical investigation into the interaction of resistance components for a series 60 catamaran", *Int. J. Ocean Eng.*, **146**(August), pp. 151-169 (2017). <https://doi.org/10.1016/j.oceaneng.2017.09.043>
- Davis, M.R., French, B.J., and Thomas, G.A. "Wave slam on wave piercing catamarans in random head seas", *Int. J. Ocean Eng.*, **135**, pp. 84-97 (2017). <https://doi.org/10.1016/j.oceaneng.2017.03.007>

21. Lavroff, J., Davis, M.R., Holloway, D.S., et al. "Wave impact loads on wave-piercing catamarans", *Int. J. Ocean Eng.*, **131**, pp. 263–271 (2017).
<https://doi.org/10.1016/j.oceaneng.2016.11.015>
22. Fitriadhy, A., Razali, N., and Aqilah Mansor, A. "Seakeeping performance of a rounded hull catamaran in waves using CFD approach", *Int. J. Mechanical Engineering and Sciences*, **11**(2), pp. 2601–2614 (2017).
<https://doi.org/10.15282/jmes.11.2.2017.4.0238>
23. Farkas, A., Degiuli, N., and Martic, I. "Numerical assessment of interference resistance for a series 60 catamaran", *The VII International Conference on Computational Methods in Marine Engineering, CIMNE*, pp. 1016–1027 (2017).
<https://doi.org/10.1016/j.oceaneng.2012.06.008>
24. Fitriadhy, A., Adam, N., Amalina, N., et al. "Seakeeping prediction of deep-V high-speed catamaran using computational fluid dynamic approach", *Int. J. SINERGI*, **22**(3), pp. 139–148 (2018).
<https://doi.org/10.22441/sinergi.2018.3.001>
25. Lin, C.T., Hsieh, C.W., Lu, L., et al. "Investigation of the seakeeping performance of twin hull vessels by different computational methods", *J. Taiwan Society of Naval Architect and Marine Engineering*, **37**(3), pp. 127–136 (2018).
26. Chen, X., Zhu, R., Chuan Song, Y., et al. "An investigation on HOBEM in evaluating ship wave of high-speed catamaran ship", *J. Hydrodyn.*, **31**(3), pp. 531–541 (2019).
<https://doi.org/10.7/s42241-018-0092-8>
27. Shabani, B., Lavroff, J., Holloway, D.S., et al. "Center bow and wet-deck design for motion and load reductions in wave piercing catamarans at medium speed", *Int. J. Ships and Offshore Structures*, **16**, pp. 1–17 (2019).
<https://doi.org/10.1080/17445302.2019.1708043>
28. Hasheminasab, H., Zeraatgar, H., Moradi, H., et al. "Experimental study on water entry of twin wedges", *Proceedings of the Institution of Mechanical Engineers, Part M, J. Engineering for the Maritime Environment*, **234**(3), pp. 707–720 (2019).
<https://doi.org/10.1177/1475090219889236>
29. Miao, A., Zhao, M., and Wan, D. "CFD-based multi-objective optimization of S60 Catamaran considering demi-hull shape and separation", *Int. J. Applied Ocean Research*, **97**, 102071 (2020).
<https://doi.org/10.1016/j.apor.2020.102071>
30. Julianto, R.I., Muttaqie, T., Adiputra, R., et al. "Hydrodynamic and structural investigations of catamaran design", *Int. J. Procedia Structural Integrity*, **27**, pp. 93–100 (2020).
<https://doi.org/10.1016/j.prostr.2020.07.013>
31. Liu, L., Wang, X., He, R., et al. "CFD prediction of stern flap effect on Catamaran seakeeping behavior in long crest head wave", *Int. J. Applied Ocean Research*, **104**, 102367 (2020).
<https://doi.org/10.1016/j.apor.2020.102367>
32. Honaryar, A., Ghiassi, M., Liu, P., et al. "A new phenomenon in interference effect on catamaran dynamic response", *Int. J. Mechanical Sciences*, **190**, 106041 (2021).
<https://doi.org/10.1016/j.ijmecsci.2020.106041>
33. Dogrul, A., Kahramanoglu, E., and Cakıcı, F. "Numerical prediction of interference factor in motions and added resistance for Delft catamaran 372", *Int. J. Ocean Eng.*, **223**, 108687 (2021).
<https://doi.org/10.1016/j.oceaneng.2021.108687>
34. Almallah, I., Ali-Lavroff, J., Holloway, D., et al. "Slam load estimation for high-speed catamarans in irregular head seas by full-scale computational fluid dynamics", *Int. J. Ocean Eng.*, **234**, 109160 (2021).
<https://doi.org/10.1016/j.oceaneng.2021.109160>
35. Iqbal, M., Budiarto, U., Hidayat, K.Z., et al. "The influence of foil-shaped center bulb geometry into catamaran fishing vessels resistance", *IOP Conf. Series: Materials Science and Engineering*, **1034**, (2021).
<https://doi.org/10.1088/1757-899X/1034/1/012030>
36. Wang, H., Zhu, R., Zha, L., et al. "Experimental and numerical investigation on the resistance characteristics of a high-speed planning catamaran in calm water", *Int. J. Ocean Eng.*, **258**, 111837 (2022).
<https://doi.org/10.1016/j.oceaneng.2022.111837>
37. Farkas, A., Degiuli, N., Tomljenović, I., et al. "Numerical investigation of interference effects for the Delft 372 catamaran", In *Sustainable Development and Innovations in Marine Technologies*, pp. 67–74, CRC Press (2022).
<https://doi.org/10.1177/14750902231197886>
38. Kiryanto, K., Santosa, A., Samuel, S., et al. "Sea-keeping analysis of hospital catamarans for handling COVID-19 patients on remote islands with a numerical approach", *Int. J. Advanced and Applied Sciences*, **9**(8), pp. 128–135 (2022).
<https://doi.org/10.21833/ijaas.2022.08.016>
39. Sugianto, E., Chen, J.H., and Permadi, N.V.A. "Effect of monohull type and catamaran hull type on ocean waste collection behavior using Open FOAM", *Water* **2022**, **14**, (2022).
<https://doi.org/10.3390/w14172623>
40. Sulistyawati, W., Sudjasta, B., and Waskito, D.Y. "Comparison of shallow water effect on a monohull and chine catamaran", *IOP Conf. Series: Earth and Environmental, IOP publishing* (2022).
<https://doi.org/10.1088/1755-1315/972/1/012046>
41. Windyandari, A., Sugeng, S., Sulaiman Ridwan, M., et al. "Seakeeping behavior of hexagonal catamaran hull form

as an alternative geometry design of flat-side hull vessel”, *Int. J. Applied Engineering Science*, **21**(4), pp. 1016–1030 (2023). <https://doi.org/10.5937/jaes0-41412>

42. ITTC “Recommended procedures and guidelines”, *Testing and Extrapolation Methods high-speed Marine Vehicles Resistance Test*, 7.5-02-05-01, Revision 01 (2002).
43. ITTC “Recommended Procedures and Guidelines”, *Seakeeping Experiments*, 7.5-02-07-02.1, Revision 04 (2014).
44. ITTC “Recommended Procedures and Guidelines”, *General guideline for uncertainty analysis in resistance tests*, 7.5-02-02-02, Revision 02 (2014).

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