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Statistical Analysis of Wedge Effect on the Seakeeping of a Planing Hull in Irregular Waves at the Onset of the Planing Region

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ABSTRACT

In the current paper, different experiments are conducted on a high speed planing craft in irregular waves, with and without a wedge. Performance and seakeeping aspects of these planing hulls in the form of trim, rise-up, and resistance in regular waves and heave, pitch, bow, and center of gravity (CG) acceleration in irregular waves are extracted in time series. Irregular waves represent sea state 3 with 12cm height and peak period of 1.66. A model length of 2.63m and 1:5 scale is considered and all data for irregular waves are scaled, as well. The deadrise angle is constant and is taken to be 24 degrees. The targeted experimental tests are conducted for four longitudinal Froude numbers of 1.0, 1.18, 1.37, and 1.57, which are all in the planing regime. The results are analyzed for the mean height of wave, significant wave height, RMS, and spectrum. The comprehensive study of wedges' effects is also presented which indicates that a wedge can decrease the motions and accelerations, exceedingly. Ultimately, the obtained results are compared against those by Fridsma (1971) and Soletic (2010) and it is demonstrated that motions and accelerations are indeed reduced.

Keywords: Planing hull; Experimental seakeeping tests; Vertical accelerations; Statistical analysis; Irregular head sea; Wedge

NOMENCLATURE

B	beam	Fr	Froude number
D_B	draft at bow	Re	Reynolds number
D_D	design Draft	U	speed
D_T	draft at transom	ZCG	CG Rise up
L	length	Z1	rise up at stern
LBP	Length Between Perpendiculars	Z10	rise up at bow
LCG	Longitudinal Center of Gravity	α	stagnation angle
LOA	Length Overall	δ(x)	boundary layer thickness
m	mass	τ	trim angle
V	volume	H1/3	significant wave height
VCG	Vertical Center of Gravity	TP	Peak Period
x	distance from transom	RMS	Root-Mean Squares
β	deadrise angle	m0	mean value
Δ	weight	**Flap and Wedge**	
τS	static trim angle	Lf	length of flap
Coefficients		g	gravity acceleration
C_V	speed coefficient	ρ	density of fluid
C_Δ	weight coefficient	L/B	length to beam ratio
		CG	Center of Gravity

1. INTRODUCTION

A ship is a complicated vessel which moves on the sea surface. The sea and ship motions display random and unpredictable surfaces. It is very unlikely to see a calm sea with no waves. Sea waves have various heights from zero to 10m and have different periods, as well. Since the waves and motions are the main cause of sea accidents, understanding and optimizing the ship motions in sea is significant which can be studied under several titles such as rational motions, slamming, propeller exiting, and green see among others, commonly known as seakeeping. Nevertheless, studying the seakeeping of planing boats is a different concern. Planing boats have non-linear response to waves with more complexity and, as a result, one cannot apply the linear models to analyze them. Many researchers have conducted different experimental, numerical and full-scale studies on them, but most of these studies have been done on mono-hull boats with no appendages. However, the main idea of the current paper is to investigate the effect of adding a wedge to the stern and determining the seakeeping all over again.

In early 70s, researchers were looking for a way to accurately predict the dynamic motions of planing boats. Martin (1976) predicted a linear behavior in head sea waves which was in agreement with Fridsma's work (1971). However, planing boats exhibit a nonlinear motion and that is why the motions must be examined along with time. Zarnikh (1978, 1979) repeated Martin's work (1976) in time series, which has become a reference for many other researchers.

Zarnikh (1978, 1979) used strip theory and von karman's (1929) added mass theory which assumed wavelengths to be large in comparison with the boats length and low wave slope. All the mentioned methods were designed for a symmetric wedge water entry. Toyama (1990) also presented a method for an asymmetric water entry.

From 1990 until now, the study of water entry of various sections, especially wedge sections, in terms of pressure distribution and induced motion analysis have been widely followed via numerical modeling (Arai *et al*. (1995), Yang and Qiu (2012), Farsi and Ghadimi (2014a, 2014b, 2015), Feizi *et al*. (2016), Ghadimi *et al*. (2012, 2013c, 2014a), Shademani and Ghadimi (2017a, 2017b, 2017c, 2017d)), analytical (Mei *et al*. (1999), Yettou *et al*. (2007), Ghadimi *et al*. (2013d, 2017b)) and experimental analysis (Judge *et al*. (2004), Yettou *et al*. (2006), Nikfarjam *et al*. (2014)). The main aim of these studies have been the utilization of the results of these studies in motion prediction of planning hulls. Meanwhile, Sebastiani *et al*. (2010) presented a method including heave, pitch and roll that separated the added mass to the left and right sides. Ghadimi *et al*. extended this method to four DOF (2013a) and six DOF (2013b) motions. Ghadimi *et al*. (2016) also presented a model for the asymmetric wedge which was able to calculate the oscillating forces of the roll, sway, and yaw, in addition to heave and pitch in calm water and regular waves. Considering the difficulties of modeling the motion of planing boats, experimental studies are considered the most viable and trustable method. Most, if not all, of these experimental methods are based on Fridsma's model test (1971). Prediction of the behavior of planing boats predictions in irregular wave is based on statistical analysis and spectrum analysis which does not calculate the vertical motions and non-linear acceleration. There have been several statistical methods utilized by different researchers, thus far. Fridsma (1971) used probability distribution function for the heave, pitch, and vertical acceleration. Zarnick and Turner (1981) further developed Fridsma's model (1971) for length (L) to beam (B) ratios of L/B = 7 - 9 in irregular waves. The concept of larger ships was born in the 1990s. Keuning and Pinkster (1995, 1997) extended the boats' length 25% and kept other properties unchanged to improve the hydrodynamic behavior with some changes in the bow shape. There were significant improvements in the resistance and motion. Later, Keuning *et al*. (2002, 2006, 2011) presented an ax-shaped bow known as ABC. The experiments conducted by Keuning *et al*. (2002, 2006, 2011) showed a substantial decrease in bow acceleration. Grigoropoulos (2010, 2011) also presented some seakeeping results for a systematic series with double chine and L/B= 4-7 in regular and irregular waves. The results corresponded to heave, pitch, and vertical acceleration at Froude numbers Fn= 0.34 – 0.68 (i.e. semi-planing condition). Recently, three different boats have been investigated in experiments by Soletic (2010), Taunton *et al*. (2011), Begovic *et al* (2012, 2014). Soletic (2010) worked on a USA coast guard ship series focusing on seakeeping issues. The ships were 47 feet long, and their heave, pitch, and vertical acceleration were measured at 5 points. At some velocities, the results were similar to that of Fridsma (1971), albeit vertical acceleration ratio and center of gravity (CG) were less than that of Fridsma (1971). Taunton *et al* (2011) also investigated four planing boats at velocities 6, 10 and 12 m/s in irregular waves. They presented a statistical analysis for minimum and maximum motions for the CG and bow. They showed that Gama distribution showed a better fit in comparison with the exponential model.

Begovic *et al*. (2012, 2014) studied a number of warped mono-hull planing boats with variable deadrise angles in calm water and regular wave. Bow acceleration coefficient for the CG for all wave frequencies and three different significant wave heights were presented. Later, total pressure distribution (Ghadimi *et al*. 2015), asymmetric 2D+t model (Ghadimi *et al*., 2017) and combination of 2D+t and pressure distribution methods (Ghadimi *et al*. 2016), were used to provide useful suggestions for predicting the vessel performance in calm water. Saltines and Sun (2010) also examined a model of the planing boat in irregular wave using boundary element (BEM) method. Their result displayed good agreement with the reported results of Fridsma (1971), albeit the calculations were performed by 2.5D method.

Recently, the study of roll motion has been pursued both in terms of determining the hydrodynamic coefficients (Tavakkoli *et al*., 2015) and the time domain simulation of that motion (Ghadimi *et al*., 2016). On the other hand, Das *et al*. (2010)

introduced a mathematical model to analyze the planning hulls, in the case of sway, roll and yaw motions. Similar study was also conducted by Tavakkoli *et al.* (2017). They studied the motions of planning hulls through considering heave, pitch and roll as coupled motions.

There have also been many in-field tests carried out concerning the seakeeping tests, mostly by Garme (2005), Jervis Bay (2002) and Pinkster (1971) from 1997 to 2005 in different sea states. Yagi (1987) also executed in-field tests about the "Jet-foil boats' seakeeping operational technique. However, there have been various methods proposed for the enhancement of the boats' general movements, bow's accelerations and the CG. Jeonghwa *et al.* (2016) also conducted various tests on a semi-hull planing boat with small deadrise angle at the stern and three different spray rails concerning the boats' performance and seakeeping. This work resulted in 11% reduction of the bow acceleration, where the accurate position of the spray rail was opted compared to the bare hull.

It is evident in the surveyed literature that the lifting appendages, which are installed at the vessel's stern such as wedge and trim tab, can eliminate the longitudinal instability of the vessel and influence the resistance (Ghadmi *et al.* 2014.b), which are important to explore. In the current article, the effects of a wedge which is installed at the vessel's stern, is experimentally investigated from the viewpoints of hydrodynamic stability and performance. Considering the fact that the influence of the wedge has not yet been experimentally studied in irregular waves, and all the experimentally conducted studies have concentrated on wedges in calm water, in the current study, the influence of this appendage in irregular waves, as a reducer of the vessel's motion, is explored. Accordingly, vessel's motion is experimentally examined with or without a wedge in calm water and irregular waves under similar seakeeping conditions. The measured parameters in these experiments include trim, rise-up, resistance in calm water, and heave, pitch, bow acceleration, and center of gravity in irregular waves with velocities 5, 6, 7, and 8 m/s, which correspond to Froude numbers Fr=1.0, 1.18, 1.37, and 1.57. The testing condition in the conducted experiments for the irregular waves is sea state 3, wave height of 12cm, and period of 1.66. Through addition of a wedge to the vessel's stern and carrying out the mentioned towing tank trials, it is aimed to demonstrate how this will also lead to the reduction of bow acceleration and the enhancement of the center of gravity**.**

2. MATERIALS AND METHODS

2.1 Problem Definition

The aim of conducting these experiments is to examine the wave effects on seakeeping and reduction of the motions and accelerations in a significant wave height and producing the peak period (T_P) and several velocities in the planing region. Since in these velocities, the boat has a hydrodynamic force almost as large as the boats weight, there will be a rise-up and a trim angle. Trim angle is defined as the angle between the water line and baseline in degrees. Rise-up is defined as the mounting of center of gravity (CG) from the waterline. In fact, one must measure the rise up at three points and the CG plays the most importance role in this regard. Wetness of the bottom of the boat, known as L_k, varies at different velocities in irregular waves and causes the boat to exhibit oscillatory behavior. Heave and pitch motions oscillate around the rise-up and trim in the calm water, respectively.

To obtain the absolute heave and trim, initial values must be known. Therefore, the tests must be initially performed in the calm water. These parameters are then recorded at constant velocity.

The boats velocity is determined from Froude number as in

$$Fr_L = \frac{U}{\sqrt{g.L}} \tag{1}$$

The most important parameter in boat's movement, is bow acceleration and center of gravity, since they exert the most pressure and cause destruction on the boat's structure. This is why these accelerations must be kept as low as possible. Accelerometers record the targeted data, as time progresses. Considering different possible behavior of the boat, all the parameters are statistically analyzed.

2.2. Physical Description of the Model Test No.1

The selected boat in the current study, is a mono-hull fiberglass planing boat with scales of 1:5 of the prototype, while length to beam ratio of L/B is 4.78. As evident in Fig. 1, this hull has a constant deadrise of 24.39 degrees, from point A to B, and a varying deadrise from 25 degrees to 40 degrees, from B to C. This hull has no longitudinal and transversal steps. The main boat characteristics are presented in Table 1. The schematic of the boat geometry is also displayed in Fig. 1.

Table 1 Considered boat's principal characteristics

CACE	SIZE
LOA	2638.31 mm
LCG	791.49 mm of transom
VCG	184.6 mm
LBP	2368.18 mm
C_Δ	0.5096
Mass	86.024 kg
V	0.08585 mm^3
D_B	186.45 mm
D_T	89.81 mm
τ_S	2.34 deg
D_D	146.57 mm
B	551.9 mm
C_v	2.15-3.44

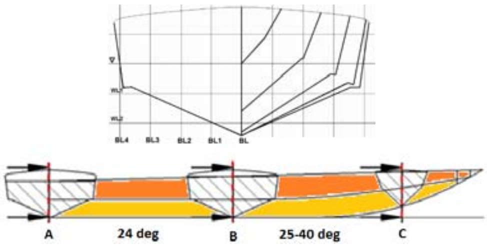


Fig. 1. Schematic of the boat (Model test 1).

2.3. Physical Description of the Model Test No.2 (with a wedge)

Model test 2 has a wedge appendage at the boat's stern, and is designed based on karimi *et al*'s recommendation [31], which has 5mm height and 92 mm long. The wedge's shape and positioning are displayed in Fig.2. The wedge height is calculated by boundary layer height as in

$$\delta(\mathrm{x}) = 0.37 R_e^{-1/5} \tag{2}$$

The dynamic trim angle in this model test is used to calculate the other edge of the wedge. The angle is 3 to 8 degrees for Froude numbers of 0.2 to 1.5, which gives the wedge's other edge ranging from 70mm to 140mm, hence, it is assumed to be somewhere between these values. This causes the CG to be virtually near the center of lift. The schematic of the boat with a wedge is also displayed in Fig. 2.

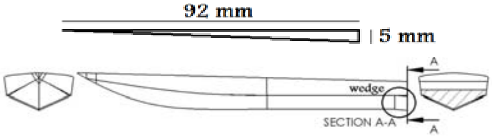


Fig. 2. Wedge positioning.

All the planned experiments are conducted by adopting the ITTC recommendations in the Persian Gulf national towing tank, which is illustrated in Table 2. It has 400m length, 6m beam, and 4 m depth. The carriage's max speed is 19m/s. Different hydrodynamic parameters can be measured. There are three sensors on the model (shown in Fig.3) to determine the dynamic trim and total resistance. The main point for determining the drag is aligned with the shaft and LCG. The angle between the shaft and the baseline is 6 degrees. For the seakeeping and resistance tests, the motions are limited to the roll, heave and pitch. Figure 3 shows a photograph of the laboratory equipment, installed on the boat.

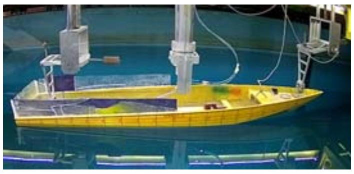


Fig. 3. Experimental setup of Persian Gulf National Towing Tank.

2.4. Parameter Measurement and Test in Calm Water

In order to measure the rise-up and heave, two potentiometers are placed in sections 1 and 10 (Fig. 4).

Table 2 Towing tank characteristics

case	size
Length of canal	400 m
Width of canal	6 m
Depth of canal	4 m
Velocity max of carrier	18 m/s
Density of towing tank water	1002 kg/m^3
Viscosity of towing tank water	9/75831E-07
Temperature of water	21^0
Length of crowbar	500 mm
Distance of between potentiometer	1901 mm
Height of towing situation	120.88 mm

Pitch and trim are calculated using Eq. (3) in which Z_1 and Z_2 are the vertical positions of the transom and bow potentiometers, respectively, while L is the distance between the potentiometers.

$$\theta = \tan^{-1}\left(\frac{Z_2 - Z_1}{L_{10-1}}\right) \tag{3}$$

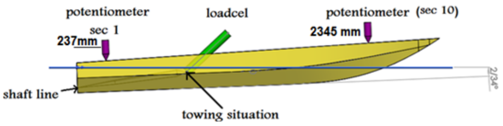


Fig. 4. Positions of the potentiometers according to Table 2.

The accelerations are measured by two G-Link-LXRS accelerometers [31] at 100Hz frequency. They are set to CG and 2014mm from the transom. The tests were conducted on two different models (No.1 without the wedge and No.2 with the wedge) in calm water. The boat's behavior is assessed at various velocities which are 5, 6, 7 and 8m/s, all in the planing region. However, since porpoising phenomenon stops the boat from moving faster, it should hence be eliminated to keep the balance. One of the main reasons behind proposing is that the CG is too close to the transom. This problem can be solved by addition of the described wedge in section 2.2.

First, the model without a wedge (model No.1) is tested. The results including the resistance and dynamic trim are shown in Table 3. Boats' water line for calculating the Froude number is equal to 2.31m, which is equal to the static draft.

Table 3 Result of the model 1 (without wedge).

V m/s	Fr$_L$	Statics trim	Rise-up at CG(mm)	Dynamics trim	R$_T$(KgF)
5	1.07	2.34	52.67	7.39	13.94
6	1.28	2.34	70.26	6.63	13.65
7	1.49	2.34	81.54	5.81	13.8
8	1.71	2.34	-	P0RPOISE	-

As observed in Table 3, the vessel exhibits porpoising (longitudinal instability) beyond 7 m/s. Due to this reason, the trim and rise up could not be computed. To overcome this problem, two approaches exist; changing the longitudinal center of gravity and/or changing the longitudinal center of vessel's hydrodynamic forces. Since the center of gravity is at 30% of the vessel's length from the transom (closer to the vessel's transom), and on the other hand, avoiding porpoising should be done without any changes to the arrangement of vessel's weights, the center of gravity cannot be displaced or altered. Therefore, the alternative approach would be to change the longitudinal center of hydrodynamic forces. This is accomplished by the added appendages to the bottom section of the vessel. In the current paper, the center of hydrodynamic force is changed via a wedge which is added to the stern, as a lifting appendage. This is done in a way that, with the help of the generated lift by the added wedge at the transom, the center of hydrodynamic force gets closer to the center of gravity.

After conducting the experiment on the model with wedge, the proposing is eliminated and resistance, rise-up, and trim are found to reduce. The obtained results are presented in table 4.

Table 4 Results of model 2 (a 5 mm wedge)

V m/s	Fr_L	Statics trim	Rise-up at CG(mm)	Dynamics trim	R_T(KgF)
5	1.07	2.34	45.13	5.22	12.17
6	1.28	2.34	57.92	4.52	12.33
7	1.49	2.34	67.62	3.65	13.2
8	1.71	2.34	70.38	2.89	15.07

Comparison of the results of the two models is presented in Fig. 5.

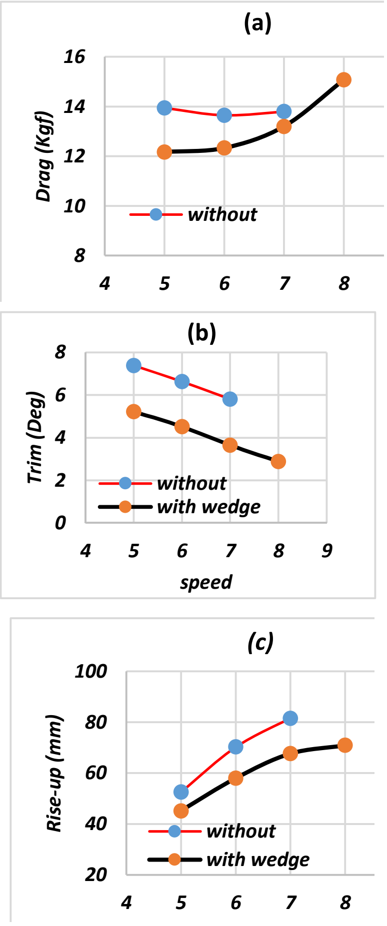


Fig. 5. Comparison of a) drag, b) trim, and c) rise-up of the two models.

Drag of the considered models (with and without the wedge) are compared in Fig. 5a. As observed in this figure, drag is lower in the case of the vessel with a wedge. One of the advantages of using a wedge is its capability in the initial skiing speed, where the pressure resistance is at its maximum. Because of the presence of a wedge and the lift generation, portion of the vessel rises above the water and the vessel starts skiing. When the planing hull rises above the water, the pressure resistance subsides and as a result, the vessel's resistance reduces, as well. Figure 5b indicates that trim of the model with wedge is lower than the trim of model without a wedge. This is due to the fact that, during the skiing stage, since lift, due to the presence of wedge at the stern, increases, the bow section gets closer to the water and consequently the vessel's trim reduces. When the bow gets closer to the water, as shown in Fig. 5c, the vessel's rise up also reduces. Overall, one may then conclude that a vessel, equipped by a wedge, has the following advantages:

1. The vessel starts skiing earlier.
2. The vessel has lower resistance at the start of the skiing stage.
3. As hydrodynamic forces get closer to the center of gravity, the vessel's porpoising diminishes.

After conducting the intended tests in calm water and eliminating the longitudinal instability from the planing hull, as a desirable achievement, the influence of wedge installation must be examined in irregular waves and subsequently, the vessel's seakeeping performance in calm water and irregular waves will be compared. The conducted experiments in irregular waves are described in subsection 2.6 and the results are presented in section 3.

2.5. Uncertainty

Based on recommendation of ITTC (2011), the useful range of dynamometer must usually be at least 1.5 times of the maximum expected resistance in a series of experiment in which the utilized load cell is capable of measuring 400 N that is 20 times of the maximum measured resistance. Selection of a suitable range in the dynamometer calibration is very important. If the measurement is expected to be carried out with precision and high speed, the range of dynamometer is very critical. In these experiments, the error involved in load cell measurement (resistance measurement) is less than 0.2% of the maximum value of the resistance. Considering the fact that maximum resistance is 24 kgf (kilogram force), the error is equal to 4.8%. The associated error in constructing the model hull is 1 mm in 1 m which is equal to 0.005%. Another factor of determining the final error is the slope of the towing tank. Since the length of the towing tank is 400 m, to preserve the horizontal direction, a metal is installed alongside the towing canal which shows water level and the error associated with water level measurement is about 0.01%. Also, the iterative error associated with measuring the drag is equal to 0.1%. The towing angle is 24 degrees with respect to the horizon and under this condition and considering the vessel's trim, the impact of towing rod on the vessel's body is impossible. Another type of error is related to the equipment calibration. Ultimately, based on the fact that maximum speed is equal to 10 m/s, the uncertainty of the measured resistance is about 2.5%.

2.6. Experimental Set-up in the Case of Irregular Wave

Both models require seakeeping tests. To conduct these experiments, some background work must be accomplished. All tests must be conducted in regular wave with significant periods and H1/3 at velocities of 5,6,7 and 8 m/s corresponding to Fn=1, 1.18, 1.37, and 1.57. The aim is to calculate the following parameters at every moment:

1- Heave in mm (Z)
2- Pitch
3- Bow and stern acceleration according to g (ACG- A_{bow})

It is essential to balance the models, statically and dynamically. Vertical and horizontal positions of the CG, initial metacentric height, and inertia moments around the CG must be determined, as well. I_{zz} can be measured on the oscillating table, displayed in Fig. 6.

Fig. 6. Measuring moment of inertia using the oscillating table.

By measuring T_z, I_{YY} can be calculated as in

$$I_{YY} = I_{ZZ} = \frac{Wa^2 T_Z{}^2}{4\pi L} \tag{4}$$

where W [N] is the model's weight, 2a [m] is the distance between the weights, L is the length of weights, and T_z [s] is the oscillation period.

The longitudinal center of gravity is 791 mm from the transom and radius of gyration of the planing hull is 25% of the main vessel's water-line.

The targeted tests must be conducted in head sea condition, and while conducting the tests, the models should have no transversal motions. The models are allowed to exhibit surge motion. This implies that the models can move forward with a certain speed or can be still. In Fig. 3, one can see the mechanical leverage in order to record the vessel's behavior in wave and calm water. Sea state is set according to jonswap spectrum (Fig. 8) represented by ITTC 1984 which is recommended for the fetch-limited sea [32].

The experimental wave maker is a piston type which, through vertical upward and downward movement and based on particular equations, each of which represents a particular wave spectrum, generates wide range of waves. This wave maker is capable of producing waves in deep and shallow waters and is located at the end of the towing tank. The distance between the wave maker and towing tank front is 400 m. This waver maker is capable of generating regular waves with wave height of 0.50 m and wave length of 0.2 to 15 m, and irregular waves with wave characteristic height of 0.50 m and wave frequency of 0.6 to 18 rad/s. The irregular wave spectrums include Jonswap and Bretschneider spectrum. The wave maker can only produce 2D waves in straight Head sea direction. The wave corresponding appendages include the wave measuring sensors which is capable of measuring the wave amplitude. This sensor is connected to the data processor via an amplifier and measures the time series of the wave amplitude. Another utilized appendage is a wave absorber. In order to avoid the return of generated waves and their resulting interferences, two stationary and one moving wave absorbers are used in the towing tank. These wave absorbers are capable of absorbing 80% of wave energy via the plates installed on them.

To ensure that the generated waves in the towing tank are of jonswap type, a time series of the generated waves is obtained. The wave height testing mechanism is illustrated in Fig. 7 and the required Jonswap spectrum for generating the irregular wave is displayed in Fig. 8.

Fig. 7. Testing mechanism for wave calibration.

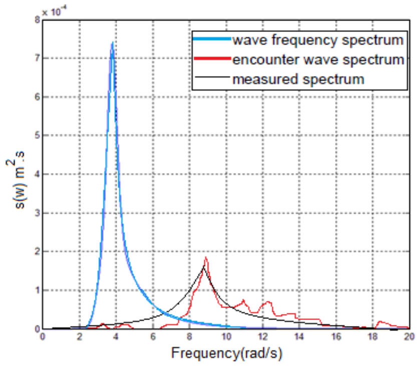


Fig. 8. Jonswap spectrum for the required irregular wave.

Per ITTC recommended standard, the minimum number of encounters for the displacement boats is equal to 50 and for better observations, it is set to 100 to 200. Although 75 is recommended for High Speed Marine Vehicles [33], in the current tests, wave encounter is set equal to 100 and is repeated 8-12 times [34].

As pointed out earlier, the model scale is 1:5. The

$H_{1/3}$ and peak period (T_P) for the model and the ship are presented in Table 5.

3. RESULTS AND DISCUSSION

3.1. Results of a Sample Test

The heave, pitch, bow acceleration, and CG acceleration are measured. The recorded rise-up and trim must be omitted from the heave and pitch in the calm water. Results of a sample test are presented in Fig. 9, while Fig. 10 displays the measured values of heave, pitch, accelerations, and added resistance.

Table 5 Wave parameters for different velocities for the jonswap spectrum.

Fr_L	$H_{1/3model}$(cm)	$T_{p\text{-}model}$(s)	$H_{1/3ship}$ (cm)	$T_{p\text{-}SHIP}$(s)
1	12	1.66	60	3.71
1.18	12	1.66	60	3.71
1.37	12	1.66	60	3.71
1.57	12	1.66	60	3.71

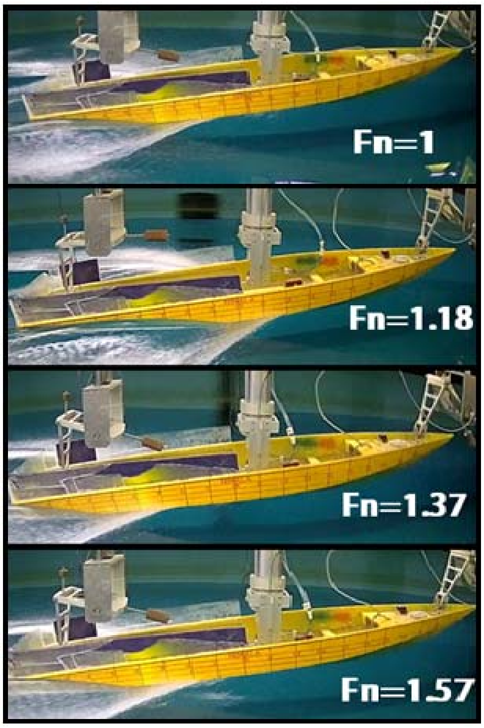


Fig. 9. Samples of the conducted tests.

Figure 9 shows the trim behavior at bow, and water spray for Froude numbers Fr= 1.0, 1.18, 1.37, and 1.57. Since the considered wave is irregular and at each moment, the wave impacts the vessel with a particular height, the vessel's position is not predictable and it cannot be examined through a time series. The standard method for investigating motions in irregular wave is through spectrum approach and interpretation of motions at a particular moment is not possible through the generated plots. For example, trim and water spray for different Froude numbers in Fig. 9 do not follow a specific trend. This issue can be further corroborated in Fig. 10.

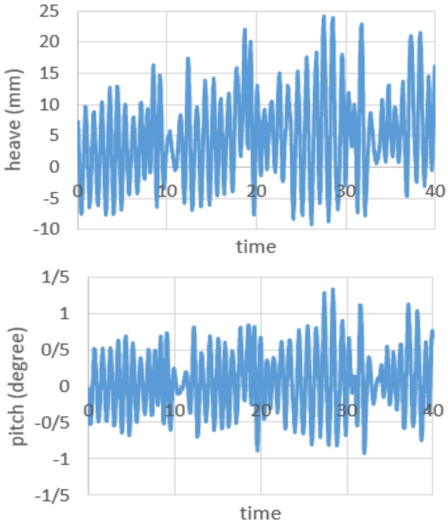


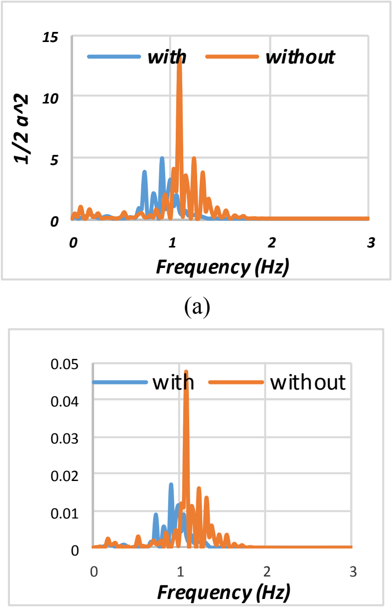
Fig. 10. Heave and pitch at V=6m/s for Model test No.1 (without a wedge) in 40s.

In Fig. 10, vessel's motions at 6 m/s speed are demonstrated as a time series. As evident in this figure, motion variation exists at each moment and no interpretation can be offered for the motion in time. As a result of this, statistical methods are suggested as alternative approach for describing the vessel's motions in irregular waves

3.2. Comparison of the Results

3.2.1. Heave and Pitch

The first study is conducted on heave and pitch. Waves hit the boat for approximately 40 seconds. Since heave and pitch motions in irregular waves are semi-linear, the heave and pitch spectrums can be used for the statistical analysis. Comparisons of the results of the two models are displayed in Figs. 11, 12 and 13.



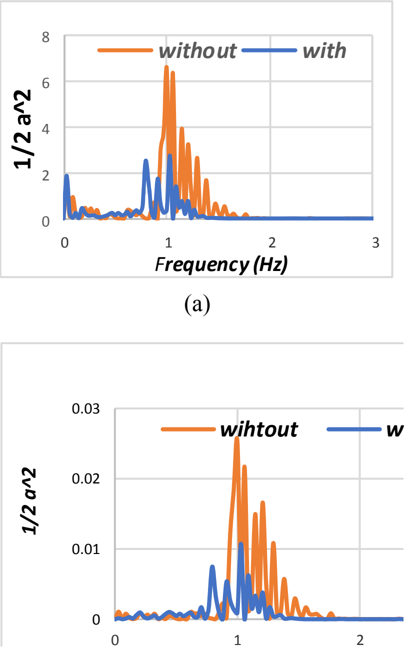
(a)

(b)

Fig. 11. Comparison of the heave and pitch spectrums, with and without the wedge models at V=5 m/s: a) heave, b) pitch.

Figure 11 displays the frequency spectrum for heave and pitch motions of the vessel at 5 m/s speed. As observed in these plots, the model equipped by a wedge shows lower heave and pitch that the model without the wedge. With regard to Fig. 11a, it can be stated that, when a lift is exhibited by the vessel's transom through the presence of a wedge at each moment, the bow section returns to the water. This implies that the trim of the bow section reduces which causes a decrease in the distance of the vessel from the water surface, to some extent. Consequently, the vessel's motions subside, too. In Fig. 11b, trim in frequency spectrum of the model with wedge is lower than that of a model without a wedge.

Frequency spectrum of the vessel's motions at 6 m/s is presented in Fig. 12.



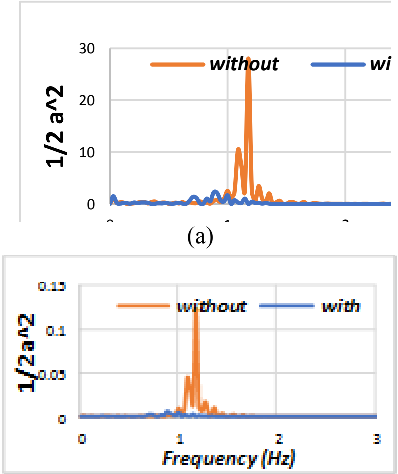
(a)

(b)

Fig. 12. Comparison of the heave and pitch spectrum, with and without the wedge models at V=6 m/s: a) heave, b) pitch.

In Fig. 12, similar trend is observed as in Fig. 11, i.e. model's motions with a wedge are lower than that of a model without a wedge. Accordingly, same occurrence is observed for 7 m/s speed in Fig. 13. The effect of a wedge is quite evident at all considered speeds. Meanwhile, the moment of inertial and center of gravity do not vary in both models, which implies that the presence of the wedge is indeed the cause of change in hydrodynamic behavior of the vessel and subsequently the reduction of motion.

Another observation which can be made in Figs. 11, 12, and 13 is the fact that frequency spectrum of the vessel equipped with a wedge is lower than that of the vessel without a wedge. In fact, through a small change in vessel's transom, the frequency spectrum of the vessel can be changed.



(a)

(b)

Fig. 13. Comparison of the heave and pitch spectrum, with and without the wedge models at V=7m/s: a) heave, b) pitch.

Comparison of the heave and pitch can be made from two viewpoints; significant wave height and mean wave height. Significant and mean wave height results or $H_{1/3}$ are presented in Tables 6 and 7, respectively.

Table 6 Statistical analysis of significant height for heave and pitch.

Speed m/s	$H_{1/3}$ Heave without wedge mm	$H_{1/3}$ Heave with wedge	$H_{1/3}$Pitch without wedge deg	$H_{1/3}$Pitch with wedge
5	28.769	21.59	1.70	1.2
6	27.1345	18.35	1.65	1.04
7	35.03	18.07	2.25	0.952

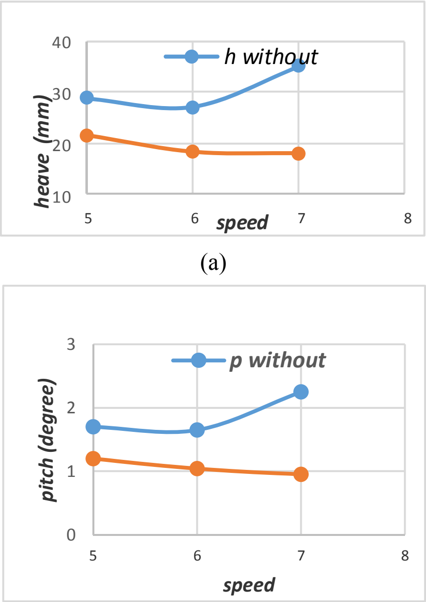
Table 7 Statistical analysis of mean wave height for heave and pitch.

Speed m/s	Mean Heave without wedge mm	Mean Heave with wedge	Mean Pitch without wedge deg	Mean Pitch with wedge
5	6.38	4.9	0.392	0.27
6	8.13	6.21	0.4	0.32
7	10.781	6.1	0.631	0.41

All the presented results indicate that heave and pitch are lower in the presence of the wedge.

Heave and pitch motions for $H_{1/3}$ are compared in Fig. 14. As evident in this figure, as the speed increases, the difference between the plots becomes larger which is indicative of the fact that there is a direct relation between the speed and heave and pitch motions. With an increase in speed, lift at the transom increases which causes a decrease in the speed of water entry of the vessel, which in turn brings about a reduction in motions.

Recorded and analyzed data in sea waves indicates that density probability of wave amplitude is in good agreement with Gaussian normal function. Comparison of the computed heave and pitch for the two models and the predicted probability function from



(a)

(b)

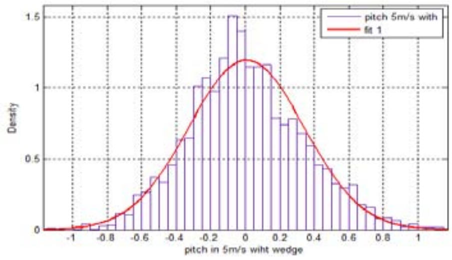
Fig. 14. Comparison of the heave and pitch motions, with and without the wedge models different speeds of V=5 to 7m/s: a) heave, b) pitch.

$$p(\varsigma)=\frac{1}{\sigma\sqrt{2\pi}}\exp(-\frac{(\varsigma)^2}{2\sigma^2}) \qquad (5)$$

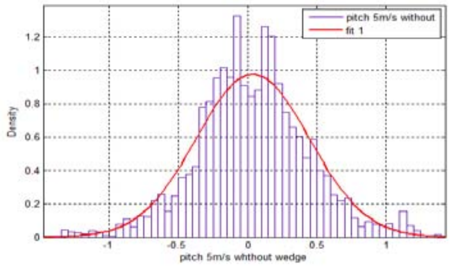
are presented in Fig. 15. In Eq. (5), σ is the variance, ς is the wave amplitude. Irregular waves in the sea can be categorized by two points of views. From one point of view, an irregular wave generates a layer of water surface, but from another view point, the amplitudes of the irregular waves have maximum and minimum peaks which are called maximum and minimum points, respectively. In this paper, heave and pitch motions of the vessel in irregular wave are investigated, based on the first view point. Registration and their analyses indicate that probability density function for the occurrence of irregular wave amplitude follows the Gaussian normal function. This is quite visible in Figs. 16 and 17.

In Fig. 15, Gaussian normal function in both models for pitch motion at 5 m/s is in complete agreement with probability distribution for both conditions. This shows that, the claim for time series approach is true, as initially stated.

In Fig. 16, similar to Fig. 15, the probability distribution follows the Gaussian Normal probability function, but it is noteworthy that the peak of density values in the vessels with a wedge is lower than that of the vessel without a wedge. This shows that motion of the wedged vessel is lower than that of a vessel without a wedge.

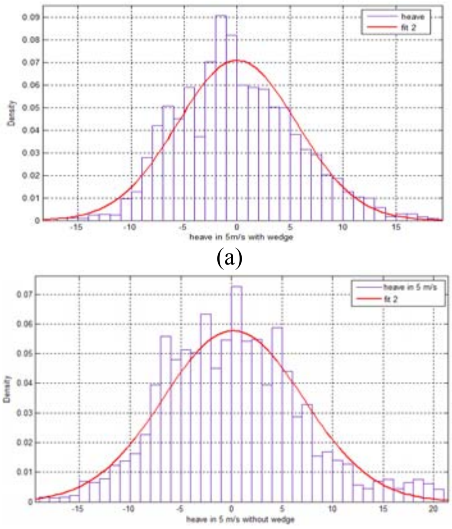


(a)



(b)

Fig. 15. Probability function and pitch at V=5 m/s a) with wedge, b) without wedge.



(a)

(b)

Fig. 16. Probability function of heave in V=5 m/s a) with wedge, b) without wedge

3.2.2. Acceleration

Acceleration is the most important parameter in seakeeping analysis, since it causes the most damage on the crew and the boat itself. Accelerations are measured at the CG and bow. They have high influence on the hull and structure design and they are comparative with the pressures at the bottom. The mean values, RMS, $A_{1/3}$, and $A_{1/10}$ for the model tests, with and without the wedge, are presented in Tables 8 and 9. Figures 17 illustrate a comparison between the CG and bow accelerations, considering the RMS and spectrum of the accelerations at different velocities. As evident in these figures, there is considerable decrease in the acceleration, in the presence of the wedge.

Table 8 CG acceleration.

Speed (m/s)	$H_{1/3}$/b	A_{CG}/g without wedge RMS	A_{CG}/g with wedge RMS	$H_{1/3}$ without	$H_{1/3}$ with
5	0.2	0.173	0.174	0.74	0.74
6	0.2	0.216	0.1848	0.92	0.76
7	0.2	0.2188	0.1936	1.12	0.88
8	0.2	0.3654	0.2001	1.64	0.90

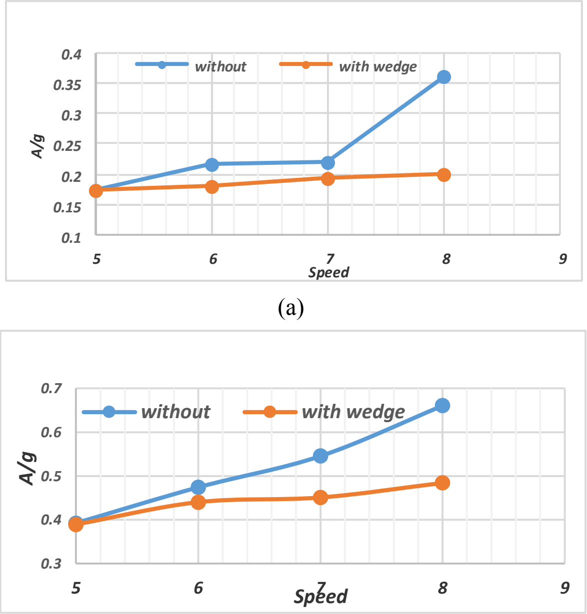
Considering the fact that accelerations in irregular waves, have completely nonlinear behavior, they do not follow the natural wave spectrum and no spectral description can be extracted from them.

Table 9 Bow acceleration.

Speed (m/s)	$H_{1/3}/b$	A_{BOW}/g without wedge RMS	A_{BOW}/g with wedge RMS	$H_{1/3}$ without	$H_{1/3}$ with
5	0.2	0.3019	0.3895	1.478	1.6
6	0.2	0.4741	0.4403	2.18	2
7	0.2	0.5454	0.4506	2.36	2
8	0.2	0.6606	0.4842	2.75	2.1

Hence, the significant wave height and the mean wave height are two parameters that define the acceleration at the bow and center of gravity. The significant acceleration height is the average of the 33% highest acceleration, which is an appropriate parameter for defining the acceleration in irregular waves.

As evident in Fig. 17, accelerations of the hull equipped by a wedge are lower than those without a wedge, at all speeds. When the wedged hull exhibits a lower trim than the hull without a wedge, its water entry distance reduces and as a result, the vessel is not allowed to have an increase in speed. Therefore, in this condition, the vessel with a wedge enters the water with a lower speed than the vessel without a wedge and its acceleration reduces. This condition can be extended to the center of gravity and bow, as well.



(a)

(b)

Fig. 17. Comparison of bow acceleration at different velocities a) in CG b) in bow.

All the computed bow accelerations are larger than the CG accelerations. This is due to the fact that bow motion is larger than the CG motion.

3.3 Comparison of the Results of the Current Paper and Other Studies about Irregular Wave

For better assessment of the results of the models' heave and pitch, some other experimental works are utilized. To this end, similar non-dimensionalized boats are selected and examined. It appears that the most important experiment belongs to Fridsma (1971), which is related to seakeeping of the planing craft in irregular wave. These experiments are conducted at three significant speeds ($V/L^{0.5}$): 2, 4 and 6 (V in knots and L in feet) for three deadrise angles of 10, 20, and 30 degrees. Other than Fridsma, Soletic (2010) conducted different experiments on a USCG Systematic Series of High Speed Planing Hulls for the sea state of 2 and 3. Schematics of the hulls considered by Fridsma (1971) and Soletic (2010)] are displayed in Fig. 18 and some of their results are presented in Table 10. The results of the conducted tests in the current study are also presented in Table 11.

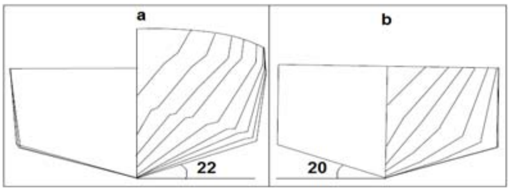


Fig. 18. a) Soletic model (2010) with 22 degrees deadrise and b) Fridsma model (1971) with 20 degrees deadrise.

Table 10 Results of the experiments by Fridsma (1971) and Soletic (2010).

model	$H_{1/3}/B$	$\eta_{3\text{-}1/10}/H_{1/3}$	$\eta_{5\text{-}1/10}$ deg	$A_{bow\ 1/10}$	$A_{CG\ 1/10}$	L/B	C_Δ
Fridsma	0.22	0.8	7.24	2.7	0.46	5	0.6
Fridsma	0.22	0.72	5.35	5.4	1.48	5	0.6
Fridsma	0.22	0.7	4.4	3.4	0.79	5	0.6
Soletic	0.23	1.34	9.7	-	0.67	4.5	0.4
Soletic	0.23	1.35	10.17	-	1.78	4.5	0.4

Table 11 Results of the conducted tests in the current paper.

model	$H_{1/3}/B$	$\eta_{3\text{-}1/10}/H_{1/3}$	$\eta_{5\text{-}1/10}$ deg	A_{bow} a/g 1/10	A_{CG} a/g 1/10	L/B	C_{Δ}
Without wedge	0.22	0.3	4.46	1.87	0.94	4.8	0.51
With wedge	0.22	0.22	3.8	2.3	0.94	4.8	0.51
Without wedge	0.22	0.3	4.4	2.78	1.14	4.8	0.51
With wedge	0.22	0.2	3.34	2.54	0.96	4.8	0.51

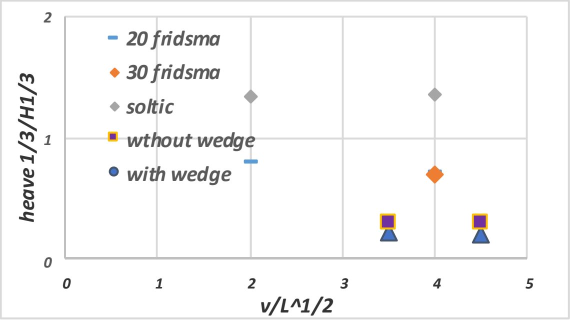


Fig. 19. Comparison of the computed heave motion against the experimental results of Fridsma (1971) and Soletic (2010).

In Fig. 19, in which all the parameters are non-dimensionalized, a comparison is presented between the computed heave motion in the current study and the reported results of Fridsma (1971) and Soletic (2010). In all the presented works, it is quite apparent that motions in the case of the wedged hull (current study) are lower than those without a wedge. This is indeed a verification of the fact that wedge installation has desirable effect and that addition of a wedge can be instrumental in hull optimization.

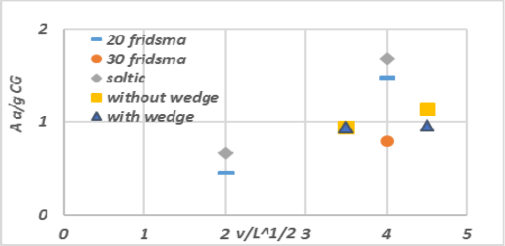


Fig. 20. Comparison of the computed CG acceleration against the experimental results of Fridsma (1971) and Soletic (2010).

Comparison of the CG acceleration computed in the current study against those by Fridsma (1971) and Soletic (2010) is presented in Fig. 20. For the designated velocity range, the result of the current study offers the lowest CG acceleration among all the cited work. On the other hand, Fig. 20 shows that, with an increase in the velocity, the accelerations generally increase, which is due to the increase in vertical speed at which the bottom of the vessel impacts the water. Therefore, utilization of a wedge in this particular case, also improves the vessel's performance in waves. All the stated conclusions can also be extended to the bow acceleration, which is presented in Fig. 21.

As evident in Figs. 19, 20, and 21, the obtained motions and accelerations in the case of wedged hull in the current study is lower than those reported by Fridsma (1971) and Soletic (2010) which involve a hull without a wedge. Based on the obtained results, one may conclude that in general, when the speed increases, the bow and CG accelerations increase, but heave and pitch decrease. It should be noted that all velocities are measured at the onset of the planing region (i.e. at Froude numbers larger than 1 and 1.18).

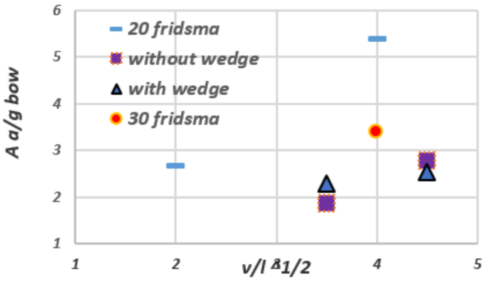


Fig. 21. Comparison of the computed bow acceleration against the experimental results of Fridsma (19 71) and Soletic (2010).

4. CONCLUSIONS

In the current paper, two planing boats with 2.63m length, 0.55m beam, and 24 degrees deadrise angle, are experimentally investigated, with and without a wedge, in calm water and irregular waves in three different sea states. In order to select the wedge, boundary layer height and dynamic trim are considered. According to Karimi *et al* (2013), the wedges height should be at least half of the boundary layer height. In order to measure the absolute heave and pitch in irregular waves, calm water tests are necessary to extract the rise-up and trim. Afterward, heave and pitch are eliminated from the recorded rise-up and trim in calm water. Tests are conducted at four different velocities of 5, 6, 7 and 8m/s corresponding to Froude numbers of Fn=1, 1.18, 1.37, 1.57. In calm water condition, the resistance, rise-up, and trim are measured which are shown to be lower in the presence of a wedge. Boat's proposing which is the most important obstacle to reach higher velocities, is diminished in the presence of a wedge. Subsequently, seakeeping parameters are measured in sea state 3 with 12cm of height and Tp=1.66s. Accordingly, the bow and CG accelerations, heave, and pitch are measured. All these parameters are oscillatory and need to be and are analyzed, statistically. Based on the obtained results, one may conclude that all of the important parameters in design procedure are reduced. Therefore, it is quite apparent that one can improve a planing boat performance by selecting an appropriate wedge.

Overall, based on the obtained results, the followings may be considered as the highlights of the findings in the current study:

1. Trim of the tested model equipped by a wedge is less than that of the model without a wedge. This is due to the added lift in transom section of the vessel.
2. Rise-up of the model with a wedge is lower than that of the model without a wedge, and this is again due to the lift in the transom area.
3. Through the help of a wedge, porpoising phenomenon diminishes and the vessel becomes longitudinally stable.
4. Addition of the wedge to the stern of the tested model, leads to the reduction of heave and pitch motions, which is due to the trim reduction in the bow section, which in turn reduces the motions.
5. Addition of the wedge to the stern of the tested model, leads to the reduction of bow and CG accelerations, which is due to the reduction of the speed at which the vessel's bow section enters the water.

Addition of a wedge to Fridsma's model (1971) and comparison of its test results with that of the model without the wedge can be considered as future studies. These results would be helpful in improving the vessel's motion which can be then extended to a real planing hull.

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