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ISSN 1333-1124
eISSN 1849-1391

PLANING HULL SEAKEEPING IN IRREGULAR HEAD SEAS

UDC 629.5.017/018.71

Summary

The paper presents the results of planing hull seakeeping tests in irregular seas. The tested model belongs to a small systematic series developed at the University of Naples; it is a prismatic hull very similar to the well-known Fridsma's models. The 16.7 degrees deadrise angle, length-to-breadth and load coefficient are representative of modern hull forms of pleasure boats. Tests in irregular waves have been performed at three speeds for one displacement in three sea states. The measured heave, pitch, acceleration at the centre of gravity and at bow have been analysed in the time domain and the results are presented in terms of significant values (the mean of 1/3rd highest values). They are given in tabular and graphical form. Furthermore, the obtained results are commented with respect to the state of the art in planing hull seakeeping, and compared with the available experimental data from literature. The conclusions highlight the applicability of these data in design practice, commenting on trends and the range of significant parameters.

Key words: *planing hull seakeeping, vertical motions and accelerations, irregular waves, experimental assessment*

1. Introduction

Experimental studies on planing boat behaviour in irregular waves started with well-known systematic model tests of constant deadrise prismatic hulls by G. Fridsma (1971). This work is the milestone for seakeeping considerations of planing hulls in terms of both experimental results originally presented and empirical formulae developed by Fridsma (1971), reviewed in Savitsky and Brown (1976) and Savitsky and Koelbel (1993). From these tests the effect of the deadrise angle on the vertical motions and added resistance has been pointed out and as final conclusion it has been reported that the motions follow a distorted Rayleigh distribution, while accelerations follow an exponential distribution. Moreover, Savitsky and Brown considered the nonlinearity of the phenomenon and the effect of the meaningful parameters at different relative speeds. Since then, few systematic papers on planing hull seakeeping were published, e.g.: Zarnick and Turner (1981) studied the motions and added resistance of a very high length-to-breadth (L/B) hull form in waves; Klosinski and Brown (1993 a, b) investigated the effect of L/B and longitudinal centre of gravity (LCG) position. Keuning (1995) introduced an enlarged ship concept (ESC) for improving the seakeeping characteristics of a planing craft. Gregoropoulus et al. (2010, 2011) presented seakeeping results for a systematic series of double-chine wide-transom hull form with warped planing surface in regular and irregular waves at F_N = 0.34 and 0.68. Recently, three systematic series of planing hulls were presented: by Soletic (2010), by Taunton et al. (2010, 2011) and by Begovic et al. (2012, 2014). In each of these last three papers, some new results with respect to Fridsma's results are highlighted. Soletic's paper focused on the seakeeping of US Coast Guard (USCG) systematic series from Kowalyshyn and Metcalf (2006) and Metcalf et al. (2005), relative to four models based on MLB 47 foot USCG boat. These models have warped bottoms with small deadrise variation (from 16.61 to 22.51 deg) and one model has 20-25.1 deadrise at stern and section 5, respectively. The varying parameter is L/B while displacement is constant. Heave, pitch and vertical accelerations on five positions along the hull were measured in irregular waves covering the same relative speeds and significant wave height as Fridsma's (1971) work. An interesting result is the range of typical values of the ratio of vertical accelerations along the boat and centre of gravity (CG) acceleration. Taunton et al. (2010, 2011) presented a series of four monohedral hulls, where L/B ranged from 6.25 to 3.77 corresponding to $L/V^{1/3}$ from 8.70 to 6.25 and the constant deadrise angle of 22.5 degrees. All tested models had radii of gyration k_{55}=0.16L. For this systematic series, there are resistance data, motions and accelerations at three speeds (model speeds=6, 10 and 12 m/s) in irregular waves. The results are given in terms of statistical distribution parameters. These authors confirmed that the Rayleigh distribution can be used for motions but pointed out that accelerations are better fitted by the gamma distribution instead of the exponential one. In Begovic et al. (2012, 2014), a series of one monohedral and three warped hull forms developed by the systematic variation of the deadrise angle along the hull was studied in calm water and regular waves. In practice, the deadrise angle variation along the hull length is empirically designed with an after part characterized by almost constant deadrise of 10 – 16 degrees and a progressive increase up to 25-30 degrees or more at bow sections. In this series developed at the University of Naples (DII) the warping of hulls has been mathematically defined as linear variation of chine from transom to 0.8L from stern, with a characteristic section at 0.25L with 16.7 degrees deadrise identical in all four models. The 16.7 deg deadrise angle, L/B and load coefficient are representative of modern hull forms of pleasure boats. The seakeeping results in regular head waves have shown that high deadrise angles benefit only the higher order harmonics of the acceleration response. The ratio of acceleration at bow and CG was given for all wave frequencies and 3 tested speeds confirming the results of Soletic in a wide range of encounter frequencies.

This paper focuses on the behaviour of a monohedral model from the mentioned systematic series. The model was tested at one displacement in irregular waves at three speeds. The aim of the study was to cover the range of speeds and wave heights applicable to pleasure craft for which the values of speed and wave heights considered in Fridsma's paper are too high. Furthermore, the obtained experimental results are compared to all available data from literature, and comments on the differences are included.

2. Model design

The monohedral model is characterized by a constant deadrise angle along the hull with the chine parallel to the base line. The tested model has a 16.7 deg deadrise angle along the prismatic part of 1.5m in length, it was fitted with faired bow to allow the transition to the planing regime and, the same as in Fridsma's models, the bow shape is meant to isolate the only effect of the deadrise angle. The model of an overall length of 1.9 m has the L/B ratio equal to 4, the typical value for motor yachts and small HSC passenger ferries. The main characteristics are given in Table 1.

Table 1 Principal characteristics of monohedral hull

L_{OA}	m	1.90
$L_{A\text{-}B}$	m	1.50
$B_C = B_{OA}$	m	0.424
T_{AP}	m	0.096
β	deg	16.7
Δ	N	353.00
C_Δ	-	0.471
Static trim	deg	1.66
LCG	m	0.721
VCG	m	0.157
r_{44}	% B_C	0.2745
r_{55}	% L_{OA}	0.2847

The model has been built with a transparent bottom and deck to allow visual identification of wetted surface in calm water, as it can be seen from Fig. 1.

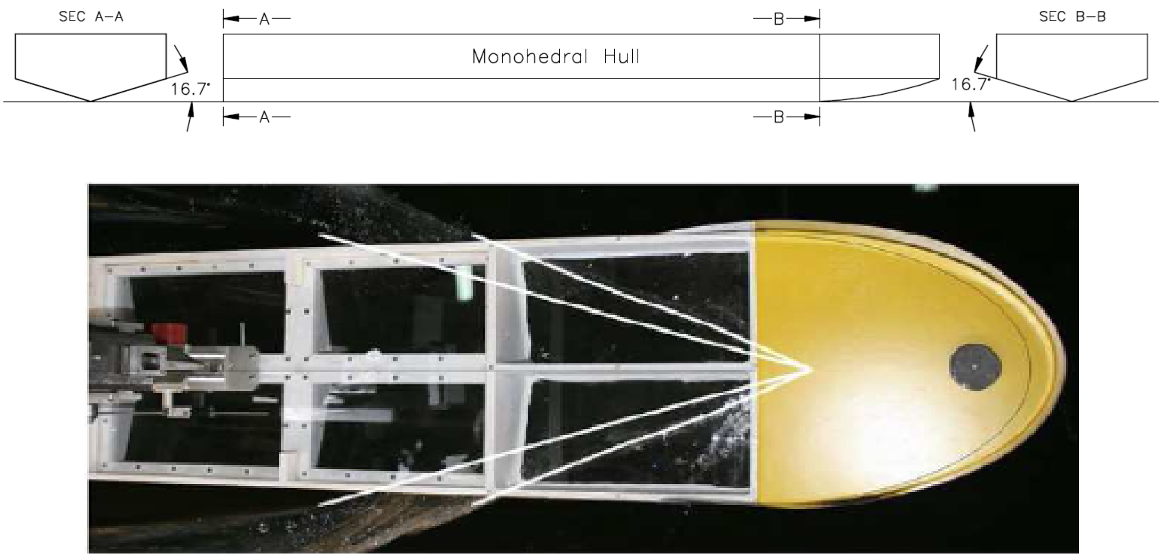

Fig. 1 Monohedral hull form

3. Experimental setup

All tests were performed in the Towing Tank (135x9x4.2 m) of the University of Naples Federico II. Irregular wave tests were performed with a model displacement of 353 N and at model velocities of 1.952, 2.44 and 3.4 m/s corresponding to C_V values: 0.96, 1.196 and 1.66. In Table 2, the summary of hydrodynamic regimes is given together with the full scale speeds considering the model characterized by the 1:10 scale ratio. In the last column, the $v/L^{0.5}$ is given to compare our speed range with the well-known Fridsma's results ($v/L^{0.5}$ = 2,4,6). It can be seen that we are covering the semiplaning and the beginning of the planing regime which is very often the service speed range of pleasure boats in rough waters, voluntarily reduced to preserve the comfort aboard.

Table 2 Tested speeds and hydrodynamic regimes

v_{MODEL}	v_{SHIP}	C_V	F_{r-L}	F_{r-V}	$v/L^{0.5}$
m/s	kn				kn/ft$^{0.5}$
1.952	12.00	0.096	0.571	1.084	1.520
2.44	15.00	1.196	0.713	1.355	1.900
3.40	20.90	1.66	0.994	1.888	2.647

The test setup is shown in Fig. 2; the model is towed at a constant speed, connected to a towing carriage by a mechanical arm R47 positioned at 0.535 m from the stern. In this setup, the model is free to heave and pitch and is restrained for all other motions. Two accelerometers Cross Bow CXL04GP3-R-AL were mounted on the model, one close to the bow (1.62 m from the stern) and another one at the LCG position (0.72 m from the stern). Encounter head waves were measured by two ultrasonic wave gauges BAUMER UNDK 301U6103/SI4, one aligned with the R47 and another one 3.5 m ahead of the R47. All the data were sampled at 500 Hz in a LabView home-made software.

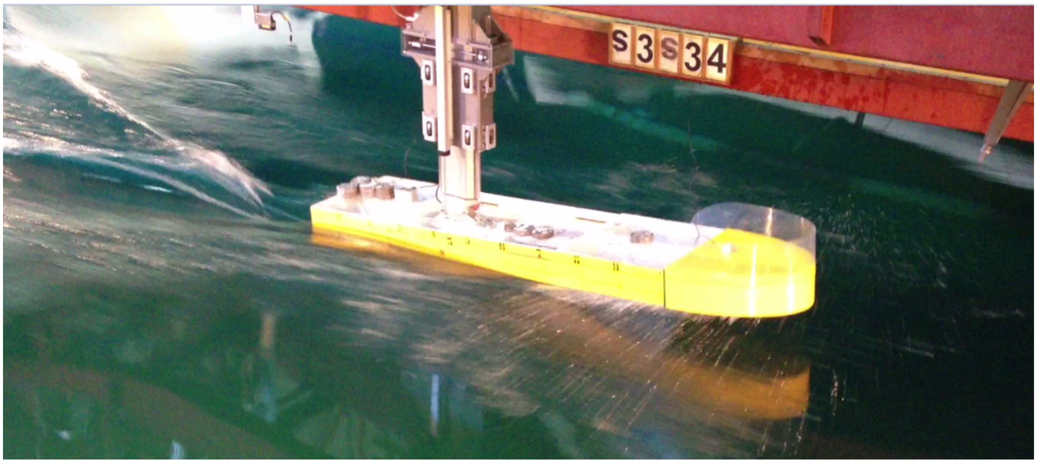

Fig. 2 Experimental setup at University of Naples Towing Tank

The sea state is described by the JONSWAP spectrum, with a peak parameter of 3.3. The target sea states are given in Table 3. The 4th, 5th and 6th column give the values of significant wave height $H_{1/3}$, peak period T_P and zero-crossing period T_Z, respectively, for full scale considering a 1:10 model. It can be seen from the last column of Table 3 that the ratios $H_{1/3}/B_C$ are significantly lower than those tested by Fridsma (0.22, 0.44 and 0.66). As the aim of the study was to obtain data on realistic service and weather conditions, the tests were performed in the range of sea states the boat is expected to operate, while the sea states applying Fridmsa's $H_{1/3}/B_C$ ratios would be too severe, with continuous water on deck and unsustainable accelerations. It should be said that the choice of the JONSWAP spectra is according to the ITTC Recommended Procedures and Guidelines indicating that "In the absence of specific wave spectrum data the ITTC should be used for open ocean and the JONSWAP spectrum should be used for fetch-limited seas."

Table 3 Target JONSWAP spectrum parameters

Sea State	$H_{1/3MODEL}$	$T_{P-MODEL}$	$H_{1/3-SHIP}$	T_{P-SHIP}	T_{Z-SHIP}	$H_{1/3}/B_C$
	m	s	m	s	s	
SS1	0.040	1.000	0.40	3.16	4.65	0.09
SS2	0.060	1.174	0.60	3.62	5.46	0.14
SS3	0.074	1.333	0.74	4.16	6.20	0.17

According to the ITTC Recommended Procedures and Guidelines for irregular waves the minimum number of encounters for displacement vessels to be tested is 50, testing more than 100 is standard and more than 200 is considered excellent practice. The ITTC High Speed Marine Vehicles Committee reports that "If only RMS of motions and accelerations are required, 75 wave encounters will give a sufficient accuracy". To obtain a sufficient number of encounters, more than 200, the runs were repeated 8-10 times, depending on the model speed, merging all data in one time series as can be seen in Fig. 3. The typical theoretical-encounter spectrum analysis is given in Fig. 3.

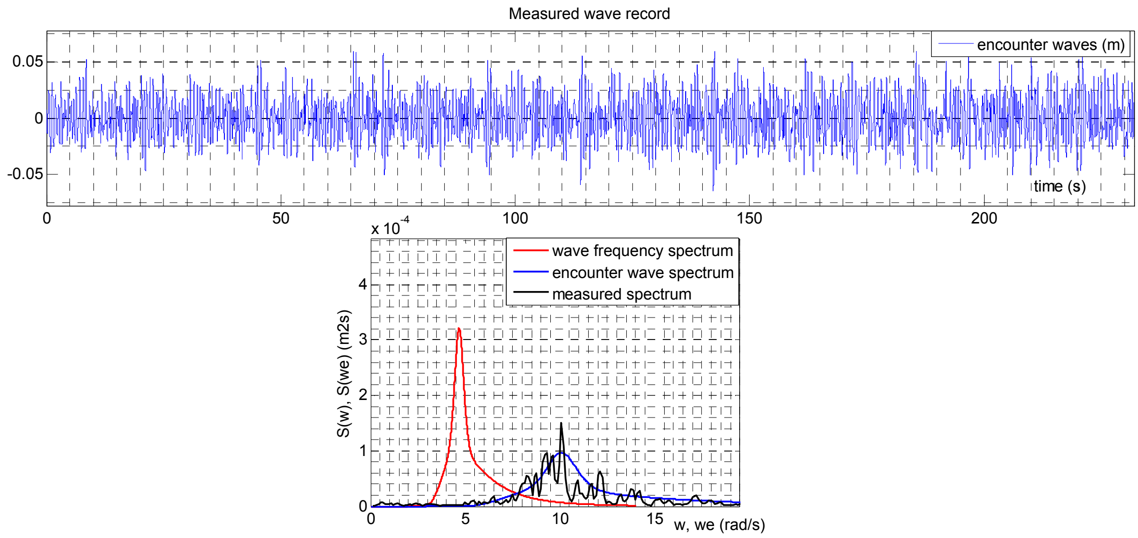

Fig. 3 Typical JONSWAP spectrum registration, in this case at speed $v = 2.44$m/s

For each speed the measured results at three sea states are given in Tables 4, 5 and 6 and in Figures 4, 5, 6 and 7. They are given as significant values (mean of 1/3rd highest values). Heave is given in a non-dimensional form divided by the significant wave height. Pitch is given in degrees and accelerations are given in a non-dimensional form divided by g.

Table 4 Results at model speed of 1.95 m/s

$H_{1/3}/B_C$	**0.088**	**0.135**	**0.169**
$\eta_{3\text{-}1/3}/H_{1/3}$	0.129	0.324	0.625
$\eta_{5\text{-}1/3}$, deg	0.279	1.081	2.258
a_{CG}/g	0.020	0.074	0.156
a_{BOW}/g	0.075	0.197	0.352

Table 5 Results at model speed of 2.44m/s

$H_{1/3}/B_C$	**0.087**	**0.136**	**0.160**
$\eta_{3\text{-}1/3}/H_{1/3}$	0.124	0.287	0.573
$\eta_{5\text{-}1/3}$, deg	0.320	1.059	2.030
a_{CG}/g	0.032	0.077	0.160
a_{BOW}/g	0.119	0.252	0.402

Table 6 Results at model speed of 3.4 m/s

$H_{1/3}/B_C$	**0.084**	**0.134**	**0.148**
$\eta_{3\text{-}1/3}/H_{1/3}$	0.123	0.278	0.535
$\eta_{5\text{-}1/3}$, deg	0.314	1.070	1.771
a_{CG}/g	0.047	0.114	0.176
a_{BOW}/g	0.157	0.349	0.464

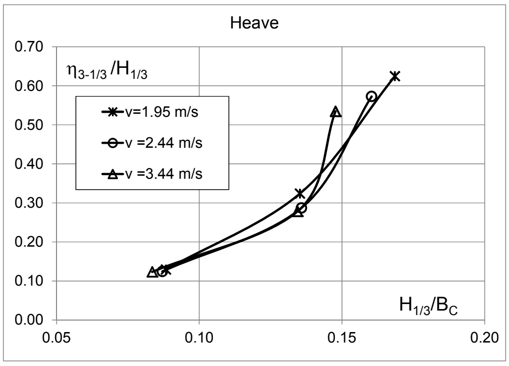

Fig. 4 Non-dimensional heave response

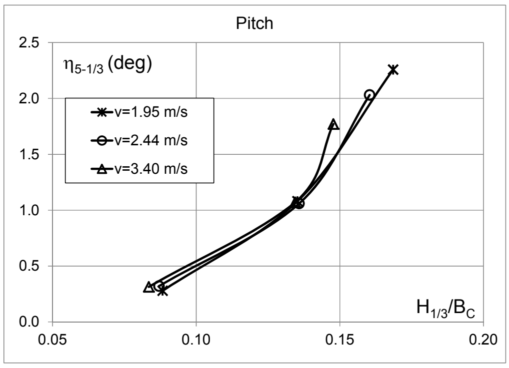

Fig. 5 Pitch response

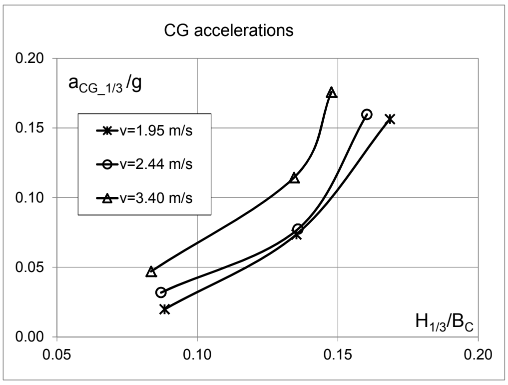

Fig. 6 Accelerations at CG

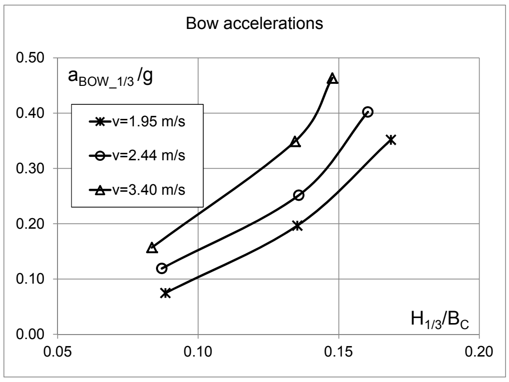

Fig. 7 Bow accelerations

From the reported results at the tested speeds and sea states it can be noted that heave and pitch do not vary a lot with speed. These results should not be seen as a typical trend but as a particular case in relation to the tested speeds. In Table 2, the different hydrodynamic regimes are reported and it can be seen that the planing regime starts at the highest tested speed. So it can be expected that at low wave heights the planing hull form will perform better in the planing speed regime. It is clearly different at the highest H/B value, where the difference for the highest speed is becoming very important. As regards the accelerations both at CG and at bow, the trend of higher acceleration with an increase in speed is always appreciable, at all sea states.

4. Comparison with experimental data from literature

To have a better understanding of our results a comparison of all available experimental data derived from the literature, is carried out. Available data from literature are considered without commenting on the effect of the hull form, experimental results from different authors are presented for different sea states and relative speeds to show the trends and range of significant parameters.

All three deadrise angle Fridsma's models were used as reference. Taunton's (2011) models were not considered as they are very light and with a significantly different pitch gyration radius. Soletic's model Variant_1 is not a monohedral hull like other models but its characteristics are almost the same as the DII hull and it considers higher speeds and more severe sea states. Variant_2 is the same model but with a different LCG position and therefore has different running trims at the tested speeds. The summary of models' characteristics is given in Table 7.

Table 7 Main characteristics of planing hulls

	Fridsma_10	Fridsma_20	Fridsma_30	Soletic_1A	Soletic_1B	DII
L, m	1.143	1.143	1.143	1.950	1.950	1.900
B, m	0.229	0.229	0.229	0.430	0.430	0.424
L/*B*	5.00	5.00	5.00	4.57	4.57	4.48
Δ, kg	7.16	7.16	7.16	34.5	34.5	36.2
C_Δ	0.60	0.60	0.60	0.44	0.44	0.471
τ, deg	4	4	4	3.5-4.9-3.6	2.1-3.8-3.2	4
β, deg	10	20	30	16.7-22.81	16.7-22.81	16.7

In Fridsma (1971) the experimental data are presented as mean values of motions and accelerations and characteristic values of distorted Rayleigh and exponential distributions. As reported by the author, to obtain the mean of 1/10th highest motions, the motions at the point of 90% have to be multiplied by 1.22. As regards the acceleration, described by the exponential distribution, the 1/Nth highest acceleration is defined as

$$a_{1/N} = \overline{a}\,(1 + \ln N)$$

leading to: $a_{1/3} = 2.09\,\overline{a}$ and $a_{1/10} = 3.30\,\overline{a}$

Fridsma's results presented here are re-elaborated in this way. Soletic reports his results directly as the mean of the 1/10th highest values but there is no data for vertical acceleration at bow. Therefore, the comparison is done by considering the 1/10th highest values of the heave, pitch and accelerations at CG for 6 models, each at two relative speeds ($v/L^{0.5}$ =2 and 4) as shown in Figs. 8, 9 and 10 and summarised in Tables 8, 9 and 10.

Table 8 Results for Soletic (2010) planing hulls

SOLETIC	$H_{1/3}/B$	$V/L^{1/2}$	$\eta_{3\text{-}1/10}/H_{1/3}$	$\eta_{5\text{-}1/10}$	$a_{CG\text{-}1/10}$
V1 _ V/ $L^{1/2}$ =2	0.2378	2	1.343	9.78	0.67
	0.4756	2	1.444	19.87	1.31
V1 _ V/ $L^{1/2}$ =4	0.2378	4	1.355	10.17	1.78
	0.4756	4	1.603	14.84	2.87
V2_ V/ $L^{1/2}$ =2	0.2378	2	1.220	9.19	0.39
	0.4756	2	1.378	16.46	1.07
V2_ V/ $L^{1/2}$ =4	0.2378	4	1.170	8.87	0.94
	0.4756	4	1.588	14.40	3.01

Table 9 Results for Fridsma (1971) planing hulls

	$H_{1/3}/B$	$\eta_{3\text{-}1/10}/H_{1/3}$	$\eta_{5\text{-}1/10}$	$a_{BOW\text{-}1/10}$	$a_{CG\text{-}1/10}$
Fridsma_10deg_ V/ $L^{1/2}$ = 2	0.444	1.1678	12.712	4.752	1.089
	0.667	1.1084	15.909	7.194	1.749
Fridsma_10deg_ V/ $L^{1/2}$ = 4	0.222	0.7584	5.673	6.798	2.211
	0.444	1.2447	10.834	11.352	3.432
	0.667	1.1852	14.298	14.058	4.851
Fridsma_20deg_ V/ $L^{1/2}$ = 2	0.222	0.8243	7.247	2.706	0.462
	0.444	1.0991	12.993	3.861	0.858
	0.667	1.1852	17.434	5.874	1.419

	$H_{1/3}/B$	$\eta_{3\text{-}1/10}/H_{1/3}$	$\eta_{5\text{-}1/10}$	$a_{BOW\text{-}1/10}$	$a_{CG\text{-}1/10}$
Fridsma_20deg_ $V/L^{1/2} = 4$	0.222	0.7199	5.356	5.445	1.485
	0.444	1.2173	11.200	7.755	2.343
	0.667	1.2127	14.469	10.197	3.465
Fridsma_30deg_ $V/L^{1/2} = 2$	0.444	1.1458	13.725	2.739	0.495
	0.667	1.2200	18.471	4.455	0.792
Fridsma_30deg_ $V/L^{1/2} = 4$	0.222	0.7034	4.404	3.498	0.792
	0.444	1.3024	10.943	5.94	1.287
	0.667	1.2493	14.103	7.887	2.178

Table 10 Results for DII planing hull

	$H_{1/3}/B$	$\eta_{3\text{-}1/10}/H_{1/3}$	$\eta_{5\text{-}1/10}$	$a_{BOW\text{-}1/10}$	$a_{CG\text{-}1/10}$
DII_ $V/L^{1/2} = 1.52$	0.088	0.177	0.386	0.093	0.027
	0.135	0.463	1.499	0.279	0.110
	0.169	0.820	2.896	0.461	0.211
DII_ $V/L^{1/2} = 1.90$	0.087	0.163	0.417	0.150	0.040
	0.136	0.378	1.426	0.349	0.111
	0.160	0.765	2.587	0.516	0.212
DII_ $V/L^{1/2} = 2.65$	0.084	0.152	0.396	0.197	0.059
	0.134	0.341	1.329	0.443	0.146
	0.148	0.756	2.341	0.588	0.234

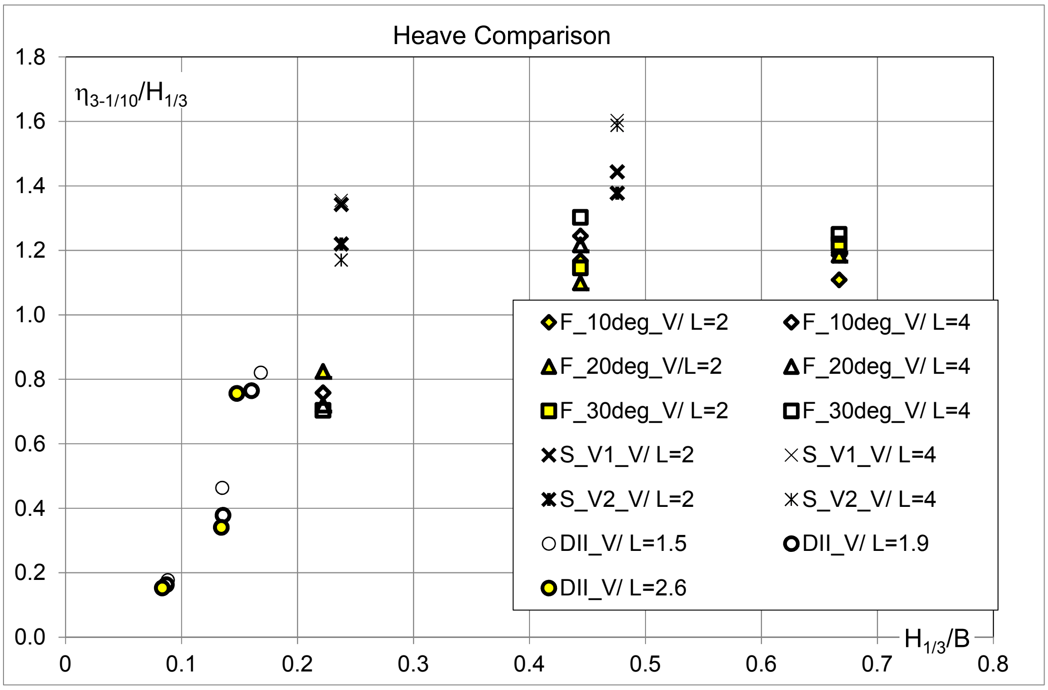

Fig. 8 Comparison of 1/10th highest heave response

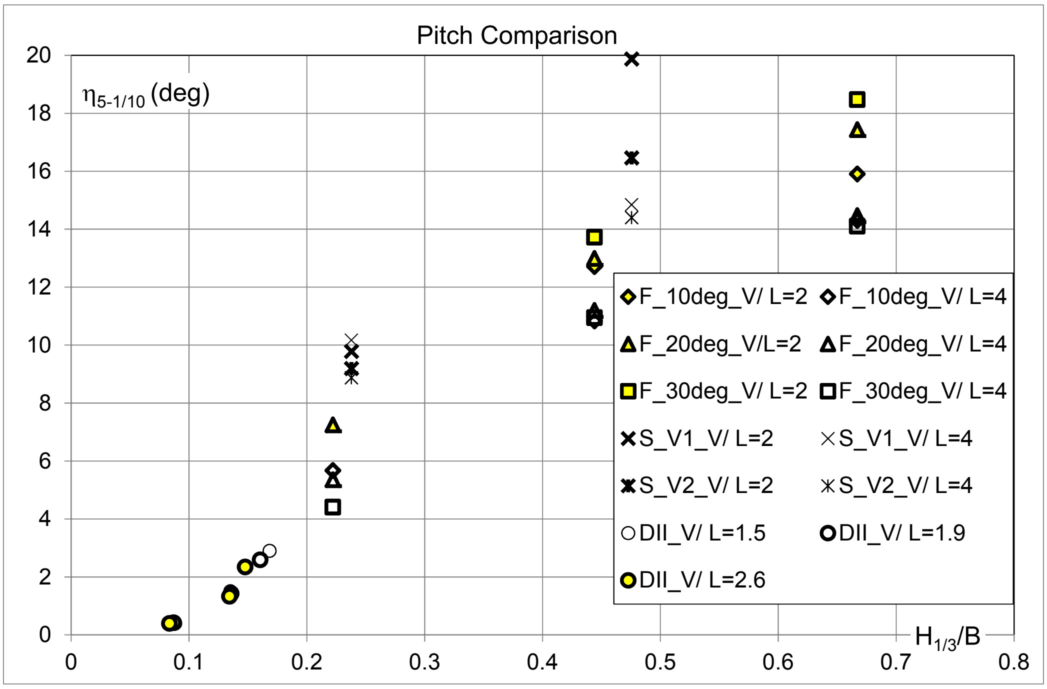

Fig. 9 Comparison of 1/10th highest pitch response

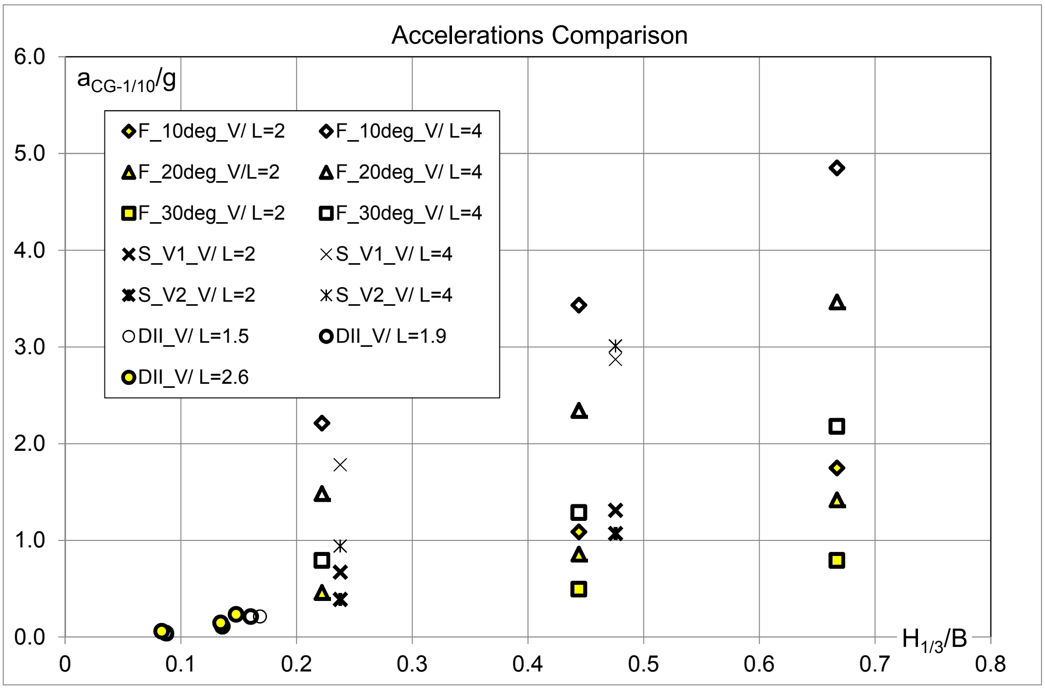

Fig. 10 Comparison of 1/10th highest accelerations at CG

From Figs. 8, 9 and 10 can be seen that DII results cover well the range of significant wave heights where no results were available. They give an important piece of information about the threshold where responses start to be significantly influenced by boat speed. Figs. 8 and 9 clearly demonstrate the grouping of data according to the relative speed without appreciable effect of the hull form. In Fig. 10, the effect of the deadrise angle on the CG acceleration at a higher speed has been demonstrated by Fridsma's results. From all diagrams it can be seen that Fridsma's data are always lower than Soletic's and in some cases the differences are up to 40%. The reason for such a huge difference should be primarily seen in the modality of performing the experiments and the experimental data analysis rather than in the properties of the models. In this case it seems reasonable to suppose that Fridmsa's data are less accurate, as the original publication says "data were recorded simultaneously on oscillograph paper and analogic magnetic tape". Soletic reports the acquisition frequency of 125 Hz, which represents the minimum for the measurement of a high speed boat in waves to be reliable.

5. Conclusions and future work

This work focuses on the experimental prediction of motions in irregular head waves of a small pleasure boat operating in the Mediterranean Sea. As the boat performance profile is primarily to provide and preserve the comfort aboard, a voluntary reduction in speed is very often necessary. Therefore, the sea states and speeds chosen for the presented investigation are meant to be more representative of the realistic service and environmental conditions.

The considered $H_{1/3}/B_C$ = 0.09, 0.14 and 0.17 are lower that the values commonly used and proposed in literature by Fridsma and other authors, who investigated conditions appropriate for the study of the phenomenon but not always applicable in the design practice. The results for vertical motions and accelerations at a speed range corresponds to the pre-planing and the beginning of the planing regime, i.e. F_{rV} = 1.084, 1.355 and 1.888, covering a range of speeds and wave heights for which there were no results in literature. The value of 0.5g of bow acceleration has been considered a limit for a pleasure boat and it has been reached at the highest speed and sea state. The ratio a_{BOW}/a_{CG} for all speeds and all sea states is about 2. It should be noted that after the study by Soletic, Begovic et al. (2014) and these experiments, this ratio should be considered to be more reliable than in previous findings. The future work will continue with the experiments at higher speeds and an analysis of the best statistical distribution for accelerations and motions will be made with respect to the presented results.

NOMENCLATURE

A – wave amplitude, m	a – acceleration, m/s^2
$\overline{a}$ – mean acceleration, m/s^2	$a_{1/3}$ – mean of 1/3rd highest acceleration, m/s^2
$a_{1/N}$ – mean of 1/Nth highest acceleration, m/s^2	
B – beam, m	B_C – beam at chine, m
C_V – Froude number based on breadth $C_V = \frac{v}{\sqrt{g \cdot B}}$	
C_Δ – load coefficient = $C_\Delta = \frac{\Delta}{\rho \cdot g \cdot B^3}$	
F_{rL} – Froude number based on waterline length $F_{rL} = \frac{v}{\sqrt{g \cdot L}}$	

F_{rV} – volumetric Froude number $F_{rV} = \frac{v}{\sqrt{g \cdot \nabla^{1/3}}}$	
g – acceleration of gravity, 9.80665 m/s^2	
$H_{1/3}$ – significant wave height, defined as mean value of 1/3rd highest waves, m	
$H_{1/3}/B_C$ – ratio of significant wave height to beam on chine	
L_{OA} – length over all, m	$L_{A\text{-}B}$ – length of clear part of models, m
LCG – longitudinal position of the centre of gravity from transom, m	
r_{44} – roll radii of gyration, m	r_{55} – roll radii of gyration, m
T – draught, m	T_{AP} – draught at aft perpendicular, m
T_P – peak period of sea state, s	T_Z – period of zero crossing, s
v – speed, m/s	∇ – displacement volume, m^3
VCG – vertical position of the centre of gravity, m	
β – deadrise angle, deg	Δ – displacement, N
λ – wave length, m	η_3 – heave displacement, m
$\eta_{3-1/3}/H_{1/3}$ – non dimensional heave response defined as mean of 1/3rd highest heave peak to trough heights divided by significant wave height	
η_5 – pitch displacement, deg	
$\eta_{5-1/3}$ – 1/3rd highest pitch response peak to trough, deg	
$\eta_{5-1/10}$ – 1/10th highest pitch response, deg	

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Submitted: 14.02.2014

Accepted: 17.9.2014

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