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The Influence of a Keel Bulb on the Hydrodynamic Performance of a Sailing Yacht Model

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ABSTRACT

The scope of this work has been to investigate the overall performance of a sailing yacht with a keel-bulb configuration. Experiments were carried out at the Laboratory of Ship and Matrine Hydrodynamics (LSMH) of the National Technical University of Athens (NTUA). A ¼ scaled model of a 50-ft modern sailing yacht has been tested. Experimental results referring to the drag, the side force, the dynamic C.G. rise and the dynamic trim, are presented. The performance of the model in calm water was evaluated, both with and without the bulb attached to the keel for a grid of leeway angles and three model speeds. In addition, the free surface elevation has been measured at various distances from the hull and characteristic wave cuts are presented.

1. Introduction

The investigation of the flow around racing yachts is an important issue, especially in the final design stage, where optimization of the hull form results in a competitive design. Nowadays, although the role of the numerical methods in the design of sailing yachts has significantly increased, the experimental methods have also been considerably refined since Davidson's memorable towing tank investigation (Davinson, 1936). Kirkman (Kirkman, 1979) discussed the evolving role of the towing tank in providing assistance to the designers and the appropriate means of using model tests in light of the contemporary understanding of scale effects. Especially for sailing yachts, balancing under the combined effect of aerodynamic and hydrodynamic forces and sailing in most of the cases in an inclined and yawed condition, the contribution of the experimental evidence to the prediction of their behaviour is invaluable. It is important to minimise the yaw angle in order to optimise the velocity against the wind (VMG). Furthermore, racing yachts compete in races where the winner is only a few seconds faster than the other participants. In such cases the incorporation of high technology and the adoption of innovative solutions can make the difference.

In towing tank measurements on sailing yachts, the keel is acting as lifting surface at yaw angles 3.5° – 7° which affect considerable all resistance parameters as well as the free surface. The yacht keel features a relatively large laminar region and requires special transition devices which must control both lift and drag components. Besides, modern sailing yacht designs consist of a keel-bulb configuration which has beneficial results to the overall stability of the yacht. However, the bulb tends to increases the resistance components. In addition, in some cases, the lift increases, which results to a better windward sailing.

The aim of the present work has been the experimental investigation of the hydrodynamic influence of a bulb attached to the keel of a particular yacht design. To study its performance three model speeds have been selected and various yaw (or leeway) angles were tested. Results for the side force and the drag are presented and compared for different cases. Moreover, since for a competitive sailing yacht design the free surface effect is important, measurements of wave cuts have been also taken which can be used for comparisons with various numerical approaches.

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2. The experimental setup

2.1. The tested model

A 1:4 scaled wooden model of a 50-ft modern sailing yacht, designed by Mortain and Mavrikios according to the British Oxygen Corporation (BOC) regulations has been extensively tested in the towing tank of the Laboratory for Ship and Marine Hydrodynamics (LSMH) of the National Technical University of Athens (NTUA). Both, the canoe body and the keel are made of wood to ensure precise representation of the hull form (Figure 1). In order to achieve a light model construction to enable testing at light displacements, water-resistant plywood was used to shape the transverse frames and wooden strip planks which formed the shell. The main particulars of the yacht, the keel and the tested bulb are given in Table 1.

Table 1: Main particulars of the tested yacht

Main Particulars	BOC 50-ft yacht
Length at waterline	14.87 m
Breadth at waterline	2.66 m
Design draft (canoe body)	0.415 m
Design draft (maximum)	4.065 m
Design displacement	7.175 mt
Appendage displacement	0.569 mt
Trim	Even keel
Sectional foils of Keel	NACA 64A015
Span of keel	0.8m
Rigging	Ketch
Sailing area	130 m^2
Bulb length	2.4 m
Bulb diameter	0.5 m

Source: Authors

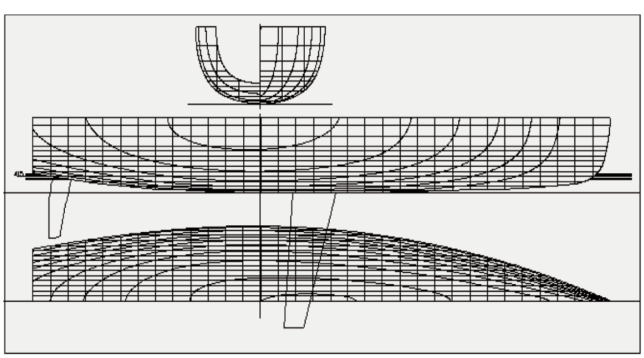

Figure 1: The lines plan of the model.

2.2. Selection of turbulence stimulators

Ship model tests use turbulence stimulators to compensate for the violation of Reynolds similarity and enforce laminar-turbulent transition in models roughly at the same location as in full scale. Joubert and Matheson (Joubert & Matheson, 1970) studied the effect of stimulators on the boundary layer characteristics past a model in a wind tunnel. It is common to use empirical rules to correlate the size of the stimulator with its position from the forward end of the body as well as with the model speed. In conventional resistance towing tank tests, the results from this procedure can be assumed reliable, as the size of the stimulator affects only a small area near the bow. The forced transition leads to the recovery of the desired turbulent flow and influences mainly the total skin friction component.

There are cases, however, where this standard procedure is not applicable because the turbulence stimulators disturb drastically the flow-field. For instance, in towing tank measurements on sailing yachts, where the keel, acting as lifting surface at yaw angles 3.5° - 7°, affects considerable all resistance parameters.

There are two conditions that must be satisfied by the turbulence stimulation devices in order to have the desired effects. Firstly, their geometrical properties should be selected in such a way that steady turbulence is stimulated leading ideally to equivalent velocity profiles to those of the fully turbulent flow. Secondly, their height should be not present high parasitic drag, leading to overestimation of the resistance force. Combination of these two conditions results in a range of geometrical values that can be selected for the stimulation, when a speed range is considered for testing.

Trip wires, which are commonly used in Laboratory for Ship and Marine Hydrodynamic (LSMH) of NTUA, have low parasitic drag and work sufficiently for a wide range of ship model types. However, they are unreliable in cases where lifting surfaces exist, such as the keel of a sailing yacht. In fact, the rapid change of the pressure about the trip wire affects the local pressure and changes drastically the lift and drag characteristics. Sand strips on the other hand, are expected to trigger turbulence without causing significant local picks of the pressure and, therefore, they exhibit a rather smooth behaviour. Since it is generally difficult to estimate their parasitic drag, it is desirable for keep it near to a minimum value (Mishkevich, 1995). Based on previous experimental and numerical investigations with regard to the effect of turbulence stimulators on a sailing yacht model, we concluded to use sand strips (Figure 1, 2) on the keel and trip wire on the canoe hull of the model (Liarokapis, Sfakianaki, Perissakis and Tzabiras, 2010; Tzabiras, 2008).

The significant influence of turbulent stimulators placed at the same location near the leading edge of the keel with and without the bulb is shown in Figures 2 and 3. In Figure 2, the drag force is plotted with respect to the yaw angle for the carriage speed of 2m/sec corresponding to a Froude number equal to 0.32. As expected, the cases without stimulators present the lower drag values. The label "tape" corresponding to a 6 mm tape has almost the same influence with the used wire of 0.5 mm. Evidently, the higher drag is observed when turbulence stimulators are applied on both the keel and the bulb. However, the most important differences appear when the side force is compared, Figure 3. In general, the absence of turbulence stimulators on the keel is associated with a noticeable increase of the side force. The use of wires seems to cause higher lift and lower drag with respect to the tapes due to the different level of the caused disturbance on the flow field. When the bulb is included, the side force becomes higher for the same actual length of the keel, owing to the annihilation of the tip vortex.

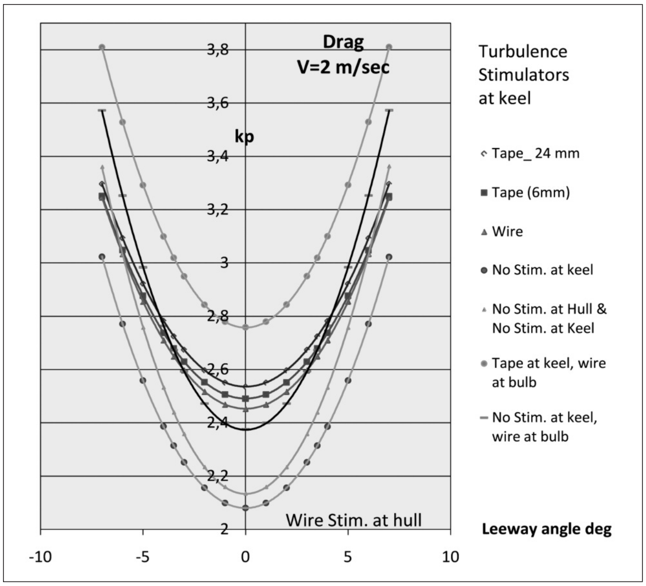

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Figure 2: Resistance (Kp) against leeway angle Vm= 2 m/s.

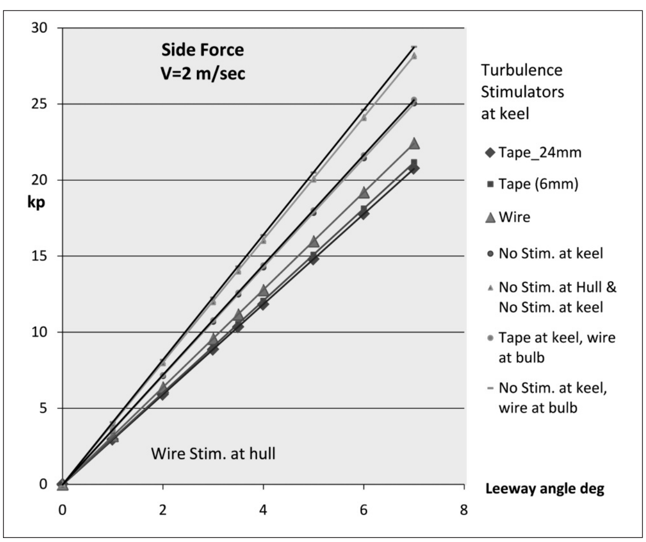

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Figure 3: Side Force (Kp) against leeway angle Vm= 2 m/s.

In order to compare the results for the total forces as presented in the sequel, it was decided to apply a standard configuration of turbulence stimulators, as follows. A trip wire (with a mean diameter of 1.8mm) was fitted on the canoe body at a distance of 23 cm from the bow, a sand strip of 6mm was fitted on the keel (tape) and a trip wire of 0.5 mm on the bulb, The keel stimulator was placed at a distance of 2 cm from the leading edge, while the diameters of trip wire diameter were calculated through the standard software used at the LSMH for ship models, according to the Reynolds number and the position of the installation.

2.3. Experimental apparatus

The LSMH of NTUA possesses a four-component balance yacht dynamometer specially designed for its towing tank (Figure 4) by Wolfson Unit. The dynamometer is capable of measuring drag, side-force, yaw moment, roll moment, heel, trim and heave.

The model was attached to the dynamometer at the LCG, via a pivot, which allowed the vertical motion (heaving) and the rotation around the lateral axis through the attaching point (pitching). The model was restrained in surge, sway, yaw and heel. The drag along the yacht's track down the tank, the side force, vertical to the drag, the yaw moment and the roll moment were recorded. At the same time the vertical motion of the centre of gravity and the trimming angle of the model were measured from the attitude of the model relative to the dynamometer. Although these data have no direct use for any performance estimate, as explained by Campbell and Claughton (Campbell and Claughton, 1987), they can provide some qualitative insight into the hydrodynamic behaviour of the yacht. Furthermore, the model was restrained at preset angles of heel and leeway, selected for performance prediction.

Sailing yacht measurements resolve two critical issues on the experimental procedure. The first issue is the accuracy of the dynamometer positioning relatively to the water surface. The yacht dynamometer is attached to the tank carriage through two parallel rails. A fully adjustable rig connecting the dynamometer with the towing tank carriage was devised. The constructed rig allows for 6-degrees of freedom adjustments and by using modern measuring techniques e.g. (laser, etc) the experimentalist can accurately align the dynamometer parallel to the water surface.

The second issue is associated with the position of yacht model relatively to the longitudinal axis of the towing tank. A possible misalignment affects the measurement of resistance and side forces. The alignment procedure proposed by the manufacturer suggested rotating the model till both the side force and drag is minimized (resistance versus side force squared diagram). Following this procedure, it was noticed that a fairly small misalignment (less than 0.5 degree) with respect to the tank longitudinal axis leads to substantial side forces, which results in a considerable misrepresentation of the lifting phenomenon. Another source of misalignment is inherent to the model as a result of the construction asymmetries mainly of the keel and its installation to the hull but also of the hull itself. To overcome the problem, special software was developed to calculate the exact upright position of the model by involving the measurements in both positive and negative yaw angles. The main objec2tive is to calculate

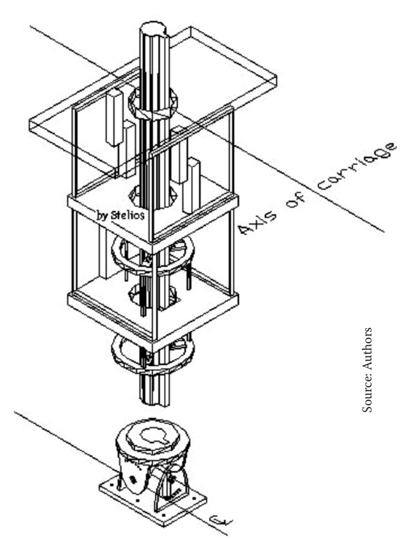

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Figure 4: The yacht dynamometer of LSMH/NTUA.

the yaw (or leeway) angle at which the side force vanishes and the drag presents its minimum value employing a least square fitting among the measured data. According to the measured values at low yaw angles, a second degree polynomial was adopted for the drag force with respect to the yaw angle at a given speed, while the side force was represented by a straight line.

To evaluate the data from the sailing yacht dynamometer several tests we carried out using also the classical (one component) dynamometer of LSMH. All experiments were performed at the upstream position, both with and without the keel and with the keel-bulb configuration. The results confirmed that both dynamometers produce the same output. In the following graph the drag is plotted against the velocity both with and without the keel for the two dynamometers. Evidently the data obtained by the classical dynamometer are lying on the curves of the sailing yacht dynamometer (Figure 5).

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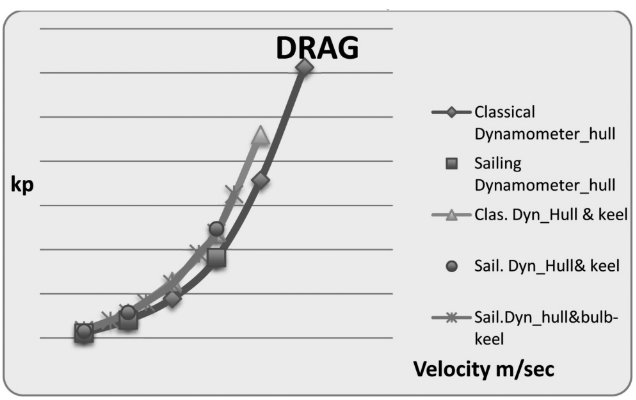

Figure 5: Comparison of the Dynamometers.

The wave pattern was measured by the well established wave probes which are the commonly used instruments for this kind of measurements. The time history of the free surface elevation at specific transverse locations was recorded at various distances and the corresponding wave cuts were represented. For our measurements we used two kinds of wave probes, the resistance and the acoustic type.

— The resistance wave probe, which although is a low cost, reliable and relatively accurate instrument, has considerable limitations mainly due to the fact that it is an intrusive method. Thus, it is not feasible to position these wave probes on the path of the model.

— The acoustic wave probe, which measures the distance to the wave surface by sound propagation. Steep and very fast moving waves can be measured with a relative velocity of 15 m/s, and frequency response of 100Hz. The acoustic probes, due to their non intrusive nature, where used for measuring wave elevation near the hull.

3. Analysis and presentation of the results

The performance of the model in calm water was evaluated, both with and without the keel and with the keel-bulb configuration for upright position in a variety of leeway angles. During the experiments, the draught of the hull was decided to be kept constant, in order to study the hydrodynamics changes when the bulb was fitted on the keel. Moreover, the model was tested at three speeds (0.5, 1 and 2 m/s) and at four leeway angles (0, 3.5, 6, 7 degrees) on both tacks.

3.1. Resistance tests

When installing the dynamometer and the model in the towing carriage, there are some unavoidable sources of misalignment. Special software has been developed which finds the “zero-angle” position of the model by involving the measurements in both tracks since, even a small fraction of a degree in the alignment of the dynamometer may induce reasonable errors in the measured forces. The main objective is to calculate the yaw (or leeway) angle at which the side force vanishes and the drag presents its minimum value employing a least square fitting among the measured data. According to the measured values at low yaw angles, a second degree polynomial was adopted for the drag force with respect to the yaw angle at a given speed, while the side force was represented by a straight line.

The measured values for the drag and side forces are presented in Figures 6 and 7, respectively. The forces are given in Kp, while all configurations are included, i.e. the bare hull, the hull with the keel and the hull with keel and bulb. For each combination, the results are drawn for two model speeds, i.e. 1 and 2 m/s, with respect to the leeway angle. As expected, the drag increases drastically as the speed becomes higher. The corresponding drag values are given in Table 2, while the percentage differences between configurations are presented in Table 3, which also includes results for the low speed of 0.5 m/s. In the last column of this Table, the standard deviation represents the uncertainty between the adopted least square curve for the mean values and the measured data. It is evident that, for a constant speed, the percentage difference of the drag between the hull-keel and the bare hull cases increases substantially with the leeway angle. This behaviour is due to the drag of the lifting surface of the keel, which is essentially more sensitive to yaw. Since the corresponding non-dimensional coefficient becomes higher at low speeds, the effect of the keel explains also the reduction in the percentage difference when the speed increases at constant yaw. It is also noticeable that at low speeds the drag of the bare hull is almost constant with respect to the leeway angle, while it is more drastically affected at the high speed of 2 m/s. In this speed the wave making resistance component is considerable and the wave formation is influenced by the yaw angle. The addition of the bulb leads to an almost constant increase of the resistance of about 11% at the speed of 1 m/s where the wave resistance is negligible. Therefore the non-dimensional drag coefficient of the bulb appears practically constant at all yaw angles. This is also true for the speed of 2 m/s up to the leeway angle of 5 deg. In this case, the slight percentage increase at higher angles may be associated with the influence of the bulb on the wave formation as discussed in the next section. At the speed of 0.5 m/s the yaw angle influences apparently the total resistance changes. However, it should be noted that the corre-

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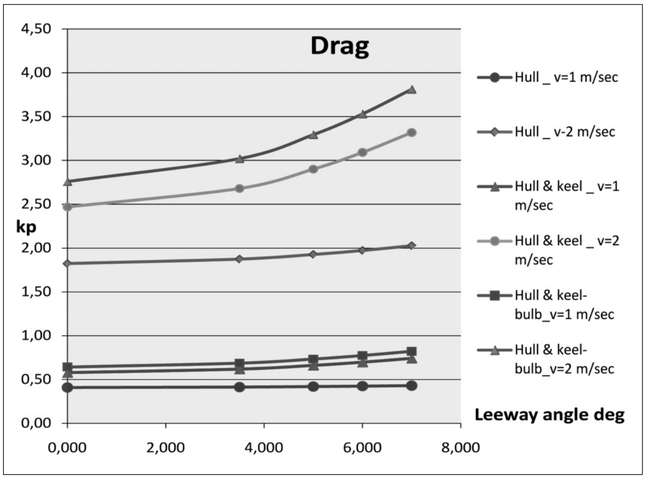

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Figure 6: Resistance against Leeway angle.

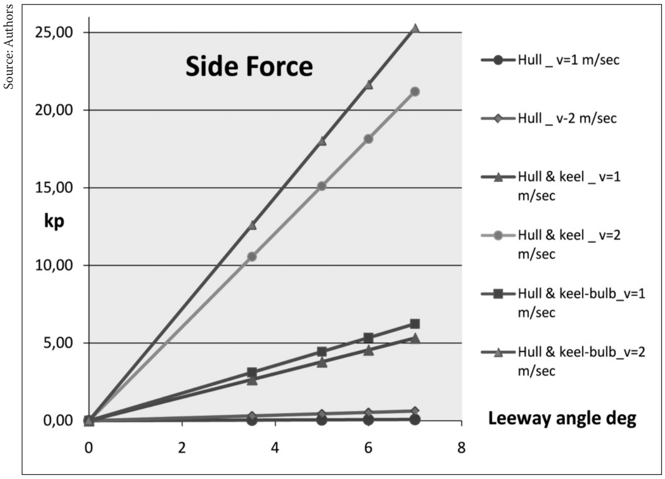

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Figure 7: Side Force against Leeway angle.

sponding Reynolds number is reduced while the turbulence stimulators have been selected for the speed range between 1 and 2 m/s. Therefore, extended laminar flow areas may appear affecting decisively the measured forces.

The side force, Figure 7, exhibits different behaviour than the drag. Actually it is generated by the keel and becomes significantly higher than the drag as the leeway angle increases. The bare hull is essentially a non-lifting body and presents very low side forces for both speeds at all tested angles. Therefore, the comparison with the keel configurations is rather meaningless. This is clearly shown in Tables 4 and 5 where the values and the percentage differences of the side forces are depicted. The presence of the bulb increases considerably the side force at all speeds and yaw angles when compared to the hull-keel case, Table 5. Although the bulb behaves also as anon-lifting body, its presence removes the tip vortex formation which is responsible for a local lift reduction. Besides, the percentage difference between the hull-keel-bulb and hull-keel configurations is substantially higher than the corresponding differences of drag (almost doubled) at all speeds. This performance improves the efficient route of the yacht.

In conclusion, the drag and the side force increases when the bulb is fitted on the keel. This is apparent in Figure 8, where the non-dimensional drag coefficient CD is plotted versus the side (lift) coefficient CL. These coefficients are defined as

$$CL = \frac{F_S}{1/2\rho S v^2} \qquad CD = \frac{F_D}{1/2\rho S v^2}$$

where F_s, F_D stand for the side and drag force respectively, S is the totally effected surface and v the model speed. As observed in Figure 6, the keel-bulb configuration produces higher CD

Table 3: Percentage differences of Drag.

Hull&Keel vs Bare Hull						
Speed (m/s)	0	3.5	5	6	7	Standard deviation (SEE) (Kp)
0.5	39.28%	54.95%	71.81%	85.45%	103.7%	0.002
1	41.66%	49.63%	57.75%	64.62%	72.32%	0.003
2	35.45%	43.03%	50.57%	56.74%	63.74%	0.007
Hull&Keel&Bulb vs Hull&KeeL						
Speed (m/s)	0	3.5	5	6	7	Standard deviation (SEE) (Kp)
0.5	5.12%	7.55%	9.52%	11.27%	12.61%	0.002
1	11.07%	11.16%	11.04%	10.88%	10.93%	0.003
2	11.79%	12.72%	13.55%	14.17%	14.79%	0.015

Source: Authors

Table 2 : Measured Drag vs speed and leeway angle.

DRAG (Kp)					
Hull	Leeway angle (deg.)				
Speed (m/s)	0	3.5	5	6	7
0.5	0.112	0.111	0.110	0.110	0.109
1	0.408	0.413	0.419	0.424	0.430
2	1.822	1.873	1.926	1.972	2.027
Hull & Keel	Leeway angle				
Speed	0	3.5	5	6	7
0.5	0.156	0.172	0.189	0.204	0.222
1	0.578	0.618	0.661	0.698	0.741
2	2.468	2.679	2.900	3.091	3.319
Hull & Keel-Bulb	Leeway angle				
Speed	0	3.5	5	6	7
0.5	0.164	0.185	0.207	0.227	0.250
1	0.642	0.687	0.734	0.774	0.822
2	2.759	3.020	3.293	3.529	3.810

Source: Authors

Table 4: Measured Side force vs speed and leeway angle.

SIDE FORCE (Kp)					
Hull	Leeway angle (deg.)				
Speed (m/s)	0	3.5	5	6	7
0.5	0	0.013	0.019	0.023	0.027
1	0	0.038	0.054	0.065	0.076
2	0	0.312	0.446	0.536	0.626
Hull & Keel	Leeway angle				
Speed	0	3.5	5	6	7
0.5	0	0.785	1.122	1.348	1.575
1	0	2.647	3.786	4.548	5.313
2	0	10.563	15.108	18.150	21.202
Hull & Keel-Bulb	Leeway angle				
Speed	0	3.5	5	6	7
0.5	0	0.975	1.394	1.675	1.957
1	0	3.107	4.444	5.339	6.237
2	0	12.601	18.023	21.651	25.293

Source: Authors

Table 5: Percentage differences of Side force.

Hull & Keel vs Bare Hull		
Speed (m/s)	Difference %	Standard deviation (SEE) (kp)
0.5	5733	0.025
1	6890	0.059
2	3286	0.097
Hull & Keel & Bulb vs Hull & Keel		
Speed	Difference%	Standard deviation (SEE)
0.5	24.25	0.014
1	17.39	0.058
2	19.30	0.184

Source: Authors

coefficient for the same *CL* (Tinoco, 1993).

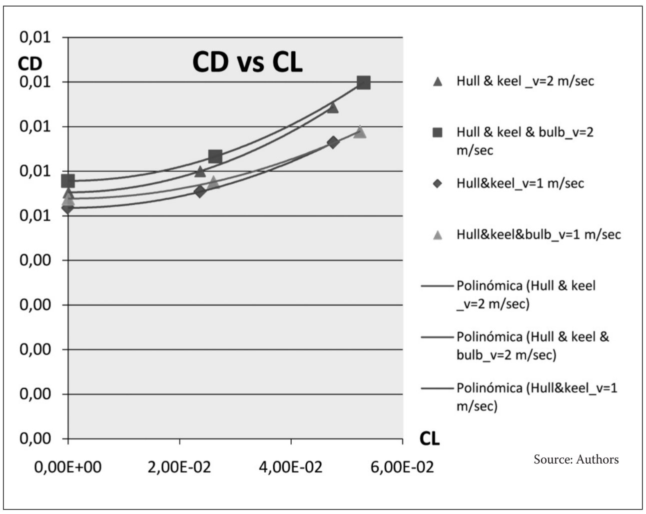

Figure 8: CD against CL.

The side force plotted versus drag in Figure 9, shows the advantage of the addition of the bulb on the original keel. Between two yachts sailing at the same speed and presenting equal side and drag forces, the more competative is the one with the ability to sail at a lower leeway angle. This is particularly important when the yacht sails windward. It is apparent from Figure 9 that for equal side force and drag the comparison of the two cases demonstrates that the yacht with the bulb, sails at a lower leeway angle. Therefore, the presence of the bulb not only lowers the centre of gravity of the yacht (improving stability), but also increases its ability to sail windward. This effect is more intense at low Reynolds numbers and at small yaw angles.

In order to study the effect of the bulb on sinkage at various speeds, the CG rise is plotted against speed in Figure10 at zero yaw. As observed, the difference among the three curves (hull, hull-keel, hull-keel-bulb) is practically negligible, showing that the main contribution to sinkage is due to the hull wetted surface.

Finally, the effect of the trim on the resistance at zero yaw was investigated. In Figure 11, it is observed that a small trim by bow or stern increases resistance. The higher values were noticed for one degree trim and when the transom is partially submerged. The minimum values of Drag both with and without the keel were observed at even keel.

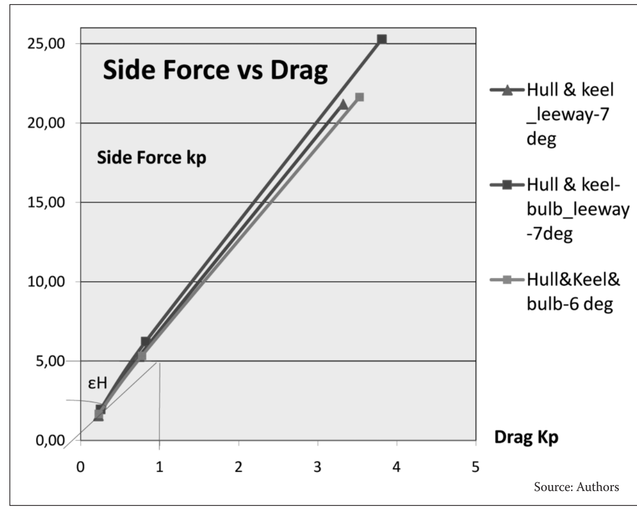

Figure 9: Side Force versus Drag.

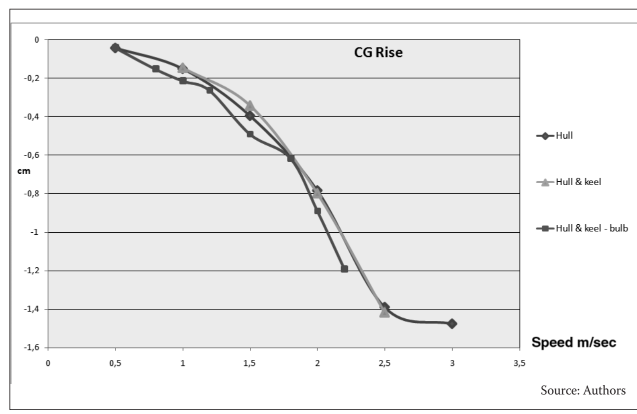

Figure 10: Heave against model speed.

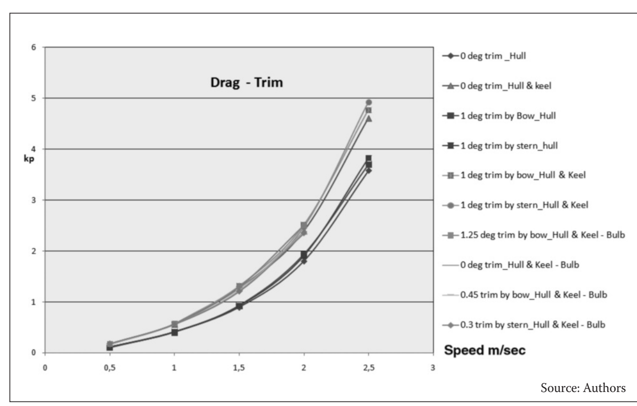

Figure 11: Drag against Trim.

3.2. Wave patterns

Measurements of wave profiles at various distances from the longitudinal axis of the tank were taken at the one side of the tank using both resistance wave probes. Again, the model was tested at three speeds (0.5, 1 and 2 m/s) and at three leeway angles (0, 3.5, 7 degrees) on both tacks. The main purpose of these set of measurements was to explore the influence of the keel and keel-bulb configurations on the wave formation as well as to provide data for comparison with CFD methods. Experimental free-surface data are particularly useful for wave resistance calculations (Dumez & Cordier, 1997) and for validation of numerical prediction codes (Brizzolara, Bruzzone, Cassela, Scamardella and Zotti, 1999).

Representative plots are shown in Figs. 12 to 13 where the wave cut along the tank at a distance of 0.64m from the longitudinal axis of the tank is plotted for the leeway angles of 0 and 7 degrees and a model speed of 2 m/s. The positions of the bow, keel and stern are also marked on the horizontal axis. Figure 12 shows that the differences of the three model cases appear at the area of the keel but they are rather small since the keel produces zero lift and the bulb is located well beneath the free surface. The same picture is observed in the windward side of the yacht. On the contrary, noticeable changes on the wave formation are apparent at the leeward side. The negative pressures generated on the suction side of the keel cause a deeper trough after the keel which is followed by a significant increase of the wave crest about the stern of the yacht. Since the bulb increases lift, the differences between the hull and the hull-keel-bulb cases are larger. These changes imply that at high speeds and yaw angles the phenomena are more intense and affect accordingly the side and drag forces.

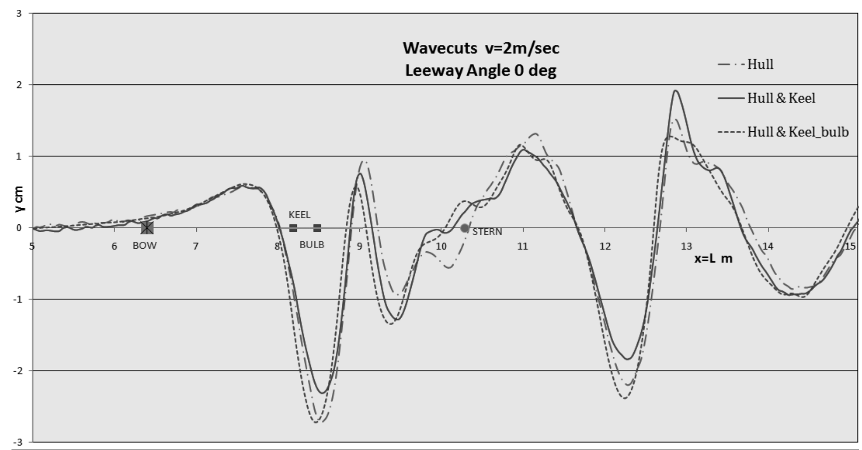

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Figure 12: Wavecut at V= 2m/s, Upright condition.

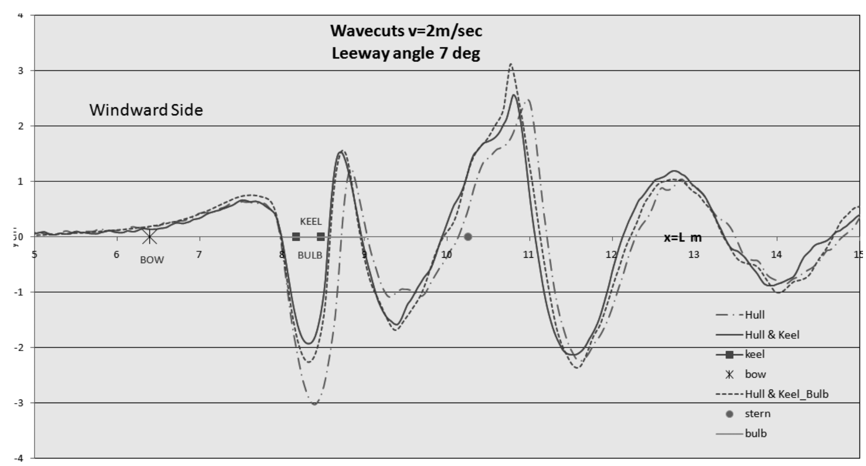

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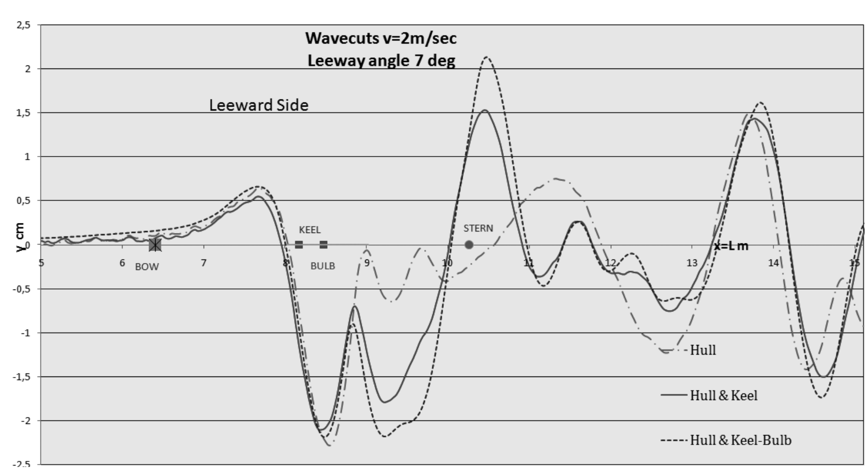
Figure 13: Wavecut at Windward side, V=2m/s.



Source: Authors

Figure 14: Wavecut at Leeward Side, V=2 m/s.

4. Conclusions

The scope of this work was to investigate the overall performance of a sailing yacht with a keel-bulb configuration advancing in calm water. The experimental results referring to the drag, the side force, the GS rise, the dynamic trim and the wave pattern for three model speeds were presented. It was found that the kind of turbulence stimulators affects significantly both the drag and side and a careful selection is necessary in this respect. All experiments were performed using a trip wire on the hull and the bulb and sand strip on the keel of the model.

In general, the experimental results derived in the towing tank of LSMH of NTUA are in satisfactory agreement with other published data. In leeway angles 3.5°-7° the keel significantly affects the hydrodynamic performance as it is apparent from the comparisons of side and drag forces. Besides it affects the wave formation about the yacht especially at high speeds implying also a considerable influence on these forces. The addition of a bulb to the keel seems to have beneficial results in some cases.

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