Tank Tests with a Scaled Model of a BOC-50 Sailing Yacht Model in Calm Water and in Regular and Random Head Waves

Dimitrios Liarokapis, Konstantina Sfakianaki, Giannis Papantonatos, and Gregory Grigoropoulos
National Technical University of Athens, Athens, LSMH, Greece

Abstract: In this paper the performance of a BOC-50' sailing yacht model in calm water and in realistic sea states is investigated experimentally. A scaled model of the hull form with the keel-bulb configuration has been tested in the towing tank of the LSMH of NTUA. During the tests the calm water resistance and the dynamic responses, including the added resistance in waves were recorded. Results referring to the resistance, the side force, the CG displacement, the pitch as well as the vertical accelerations of the model at the bow, the CG and the stern are presented. Moreover, by using a Velocity Prediction Program the polar and the stability diagram of the tested sailing yacht were calculated. Useful conclusions about the dynamic behavior of the model were obtained.

Key words: Added resistance in waves, sailing yacht experiments.

Nomenclature

A	wave amplitude
B_{WL}	waterline breadth
F_n	Froude number
k	wave number
L_{WL}	waterline length
R_{CW}	resistance in calm water
R_{AW}	added resistance in waves
SF_{CW}	side force in calm water
SF_{AW}	added side force in waves
T_{CB}	draft of canoe body
T_{MAX}	maximum draft (incl. appendages)
t	trim
V	speed
β	wave heading angle (180° for head waves)
Δ	Design displacement
Δ_{APP}	Appendage displacement
λ	wave length
ω_p	peak frequency of the spectrum

1. Introduction

The evaluation of the hydrodynamic behavior 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. Kirkman 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 [1]. 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 [2].

Contrary to a conventional hull, sailing yachts, balance under the combined effect of aerodynamic and hydrodynamic forces and sail in most of the cases in an inclined and yawed condition. Thus, the contribution of the experimental evidence to the prediction of their behavior is invaluable. The dynamic performance is strongly connected to the wind and wave conditions, as well as the vessels velocity. Thus, accurate and reliable predictions of the added resistance in natural waves are necessary, especially for racing yachts which participate in long races where the winner is only a few seconds faster

Corresponding author: Liarokapis Dimitrios, Mechanical Engineer, research fields: towing tank and underwater flow measurements.

than the other participants.

On the way to investigate the dynamic performance of a $\frac{1}{4}$ scaled model of a 50-ft modern sailing yacht in waves, a series of tests have been carried out in regular and random waves. The performance of the model in waves was evaluated, for three heeling and leeway realistic angle combinations. The presented experimental results refer to the RAO curves for heave, pitch and three points along the hull (the bow, the midship section and the stern), as well as added resistance and added side force in regular and random head waves.

2. Hull Form Description

A 1:4 scaled wooden model of a 50-ft modern sailing yacht, designed by Mortain and Mavrikios according to the BOC (British Oxygen Corporation) regulations has been constructed at the LSMH (Laboratory for Ship and Marine Hydrodynamics) of the NTUA (National Technical University of Athens).

The main particulars of the tested yacht are given in Table 1. Both, the canoe body and the keel are made of wood to ensure precise representation of the hull form (Fig. 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 were used to sheathe the model. The experimental evaluation of the behavior of the model in calm water was presented by Grigoropoulos and Perissakis [3].

Based on previous experimental and numerical investigations with regard to the effect of turbulence stimulators on a sailing yacht [4], we concluded to use two different kinds of turbulent stimulators, one for the keel and one for the canoe body and the bulb.

A trip wire (with a mean diameter of 1.8 mm) was fitted on the canoe body at a distance of 23 cm aft of the bow, a sand strip of 6 mm width was fitted on the keel at a distance of 2 cm aft of the leading edge and a

Table 1 Main particulars of the racing yacht tested.

Main particulars	BOC 50-ft yacht
Length at waterline, L_{WL}	14.870 m
Breadth at waterline, B_{WL}	2.660 m
Design draft of canoe body, T_{CB}	0.415 m
Design maximum draft, T_{MAX}	4.065 m
Design displacement, Δ	7.175 mt
Appendage displacement, Δ_{APP}	0.569 mt
Trim, t	Even keel
Keel	NACA 64A015
Rigging	Ketch
Sailing area	130 m ²

Fig. 1 Lines plan from BOC 50-ft hull form.

Fig. 2 The yacht dynamometer of LSMH/NTUA.

trip wire of 0.5 mm diameter was fitted on the bulb. The width of the sand strip was selected to result in the same resistance of the overall configuration in the upright condition as the suitable trip wire. Sand strips lead to a better reproduction of the full scale phenomenon in the inclined conditions, than the trip wire [4].

3. Experimental Apparatus

3.1 Sailing Yacht Dynamometer

The LSMH of NTUA possesses a four-component balance yacht dynamometer specially designed for its towing tank (Fig. 2) by Wolfson Unit. The dynamometer is capable of measuring drag, side-force, yaw moment, roll moment, roll, pitch 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 overall resistance, the side force, the yaw moment, the heel moment as well as the vertical motion of the centre of gravity and the trimming angle of the model were

recorded. Although these data have no direct use for any performance estimate, as explained by Campbell and Claughton [5], they can provide some qualitative insight into the hydrodynamic behavior of the yacht. Furthermore, the model was restrained at preset angles of heel and leeway, selected for performance prediction.

3.2 Adjustable Rig Dynamometer

In sailing yacht measurements, it is critical to ensure accurate positioning of the dynamometer 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.

Another critical issue is associated with the position of yacht model relatively to the longitudinal axis of the towing tank. This leeway angle affects the measurement axes of resistance and side force. The alignment procedure proposed by the manufacturer suggested rotating the model till both the side force and the drag is minimized (resistance versus side force squared diagram). From the results it can be noticed that fairly small leeway angles (less than 1 degree) from the carriage's track direction result in substantially high side forces, which lead to 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. Thus, a contemporary analytical method to calculate the exact upright position was developed.

The basic principle of the software, developed by Tzabiras and Sfakianaki at the LMSH is as follows: Referring to model asymmetries, and provided that

these asymmetries are small, the physical zero leeway angle could be arbitrary defined at zero Side Force. However a second correction should take place, considering the angle between the main axis of the dynamometer and the axis of the motion of the carriage. Both problems are encountered by assuming an overall correction angle of the position of the dynamometer and recalculating the resistance and side force according to the new corrected axis. The assumed correction angle should satisfy the following rule of thumb: the recalculated resistance must be minimum and at the same time the recalculated side force must be zero.

3.3 Accelerometers

Three strap-down accelerometers with 0-10 g range recommended for use in the 0.1 to 100 Hz band were fitted along the model at the FP, the LCG and the AP, to record the vertical accelerations. In order to investigate the form of the acceleration time histories, sampling at 100 Hz was performed. However, the data did not reveal any indication of sharp-down impact accelerations necessitating the use of special data acquisition and analysis techniques. Thus, a sampling frequency of 20 Hz was used in the tests.

4. Test Procedure

The actual sea doesn't take the form of a series of uniform waves, of constant height and length, proceeding in a steady and reliable sequence. Typically, the sea comprises a myriad of waves, of all different sizes, lengths and directions, jumbled together as a result of wind generated disturbances of different intensities, locations and directions.

The towing tank on LSMH (Fig. 3) consists of a single direction wave maker, capable of producing head waves with frequency between 0.3 to 1.2 Hz, and maximum amplitude of 35 cm. In our case, we decided to investigate the model behavior at small yaw angles relative to the upcoming waves. In reality, in most of the cases the waves are encountered at the same heading angle as the wind. Thus, following the ORC VPP [6], when the yacht sails at speeds comparable with those of the tests and at a 40-45 degrees angle relative to head waves, the estimated added resistance is a small portion of the overall resistance. However, there are cases that head waves are coming as an existing swell or during the maneuvering of a sailing tack. In these cases the added resistance in waves should be taken into account.

Fig. 3 The towing tank of LSMH/NTUA.

The performance of the model both in calm water and head waves was evaluated for the upright position and in a set of leeway angles. To be more specific, the model was tested at:

- Two speeds: 1;
- m/sec ($Fn = 0.17$) and 1.5 m/sec ($Fn = 0.24$), at sea condition 1 and 2, respectively;
- three leeway angles: 0, 2 and 4 degrees with associated heeling angles: 0, 10 and 20 degrees, respectively.

Furthermore, the model was tested for a series of regular waves, at the speed of 1 m/s and for frequencies in the 0.3-1.0 Hz range with a step of 0.1 Hz.

All experiments were performed with the keel-bulb configuration.

5. Analysis and Presentation of the Results

5.1 Calm Water Testing

To experimentally investigate the performance of the hull form in calm water, the model of the BOC sailing yacht was towed at a constant speed of 1 and 1.5 m/sec along the basin. Added resistance is defined as the difference between the mean resistance in waves and the calm water resistance.

The resulting side force and resistance versus heeling and leeway angle are presented in Figs. 4 and 5, respectively. The resistance measured for the lowest speed of 1 m/s with 2 degrees yaw angle and 10 degrees heeling angle was 0.648 Kp, while for 4 degrees yaw angle and 20 degrees heeling angle at the same speed was 0.701 Kp. Respectively, for the highest speed of 1.5 m/s with 2 degrees yaw angle and 10 degrees heeling angle, the resistance was measured at 1.449 Kp, while for 4 degrees yaw angle and 20 degrees heeling angle was 1.659 Kp.

Similarly, for the speed of 1 m/s and the same conditions, the side force was measured at 1.817 Kp and 3.132 Kp, while for the speed of 1.5 m/s, it was measured at 4.112 and 7.080 Kp respectively.

Fig. 4 Resistance vs. leeway angle.

Fig. 5 Side-force vs. leeway angle.

5.2 Regular Waves

The experimental results for the model of BOC 50-ft sailing yacht for regular waves are presented in Figs. 5-9. Best fit curves have been drawn on the figures to demonstrate the trends. All tests refer to two (2) degrees leeway angle with ten (10) degrees heel and to a model speed of 1m/sec (Froude 0.17).

The measured RAO values of added resistance and added side force in waves versus the frequency are presented in Figs. 6 and 7 respectively. The maximum added resistance R_{AW} is at 4.3 rad/sec for this model. It decreases with the circular frequency for higher frequencies. The added side force SF_{AW} has small values, comparable with the uncertainty of the measuring equipment, while it increases substantially for frequencies higher than 3.7 rad/sec. The RAO responses of heave and pitch are presented at Figs. 8 and 9. At low frequencies (around 0.4 Hz) the RAO of heave is 0.55 while it decreases to zero at high frequencies

Fig. 6 Added resistance $R_{AW}/(A^2)$ vs. circular frequency, at $v = 1.0 \text{ m/sec}$.

Fig. 7 Added side force $SF_{AW}/(A^2)$ vs. circular frequency, at $v = 1.0 \text{ m/sec}$.

Fig. 8 Heave/A vs. circular frequency, at $v = 1.0$ m/sec.

Fig. 9 Pitch/(k*A) vs. circular frequency, at $v = 1.0$ m/sec.

Fig. 10 $\text{Acc} * L_{WL} / (g * A)$ vs. circular frequency, $v = 1.0$ m/sec.

(around 1.0 Hz). On the other hand, the RAO of pitch decreases also with frequency from 0.95 at 0.4 Hz to zero at 1.0 Hz, as expected.

In Fig. 10 the RAO responses of the accelerometers at the bow, the LCG and the stern are presented. The maximum accelerations at all three positions along the model appear at approximately 4 rad/sec.

5.3 Irregular Head Waves

The BOC 50-ft sailing yacht model was tested in two Bretschneider spectra. The spectra, denoted as Spec_1 and Spec_2, are presented in Fig. 13. The characteristics of each spectrum are given in Table 2.

The spectra of the heave and pitch responses of the model are depicted in Fig. 11 for Spec_1. The spectra of the vertical accelerations along the model, for Spec_1 and Spec_2, respectively, are depicted in Fig. 12.

The experimental results of the mean added resistance R_{AW} and mean side force SF_{AW} in waves, for the two spectrums tested are given in Table 3.

It is obvious that the added side forces in both spectra are very small compared to the respective values in calm water. Their accurate measurement is limited by the uncertainty in the experimental measurement.

In contrary, the added resistance is significant in both spectra. In this respect, it is reminded that the tested sea conditions correspond to nearly head waves (2-4 degrees leeway angles) for both spectrums.

Table 2 Wave spectrum parameters (model scale).

Parameters	H_s m	ω_p rad/sec	V_M m/sec
Spec_1	0.156	2.25	1.0
Spec_2	0.146	2.75	1.5

Table 3 R_{AW} , SF_{AW} and their percentages versus R_{CW} and SF_{CW} , respectively (head waves).

Leeway - Heel Angle	2°-10°		4°-20°	
	R_{AW}	SF_{AW}	R_{AW}	SF_{AW}
Spectrum	kp	kp	kp	kp
Spec_1	0.248	0.027	0.225	0.048
R_{AW}/R_{CW} , SF_{AW}/SF_{CW} (%)	28	1.5	25	1.5
Spec_2	0.411	0.071	0.345	0.023
R_{AW}/R_{CW} , SF_{AW}/SF_{CW} (%)	22	1.7	18	0.3

Fig. 11 Heave and pitch spectra vs. circular frequency for Spec_1 at $V_m = 1.5$ m/sec.

Fig. 12 Spectra of the accelerations along the model of the yacht vs. circular frequency for Spec_1 at $V_m = 1.5$ m/sec.

Fig. 13 Experimental wave spectra vs. circular frequency.

Table 4 Added resistance ($\beta = 140^\circ$).

Leeway - Heel Angle	$2^\circ - 10^\circ$	$4^\circ - 20^\circ$
Speed	R_{AW}	R_{AW}
m/sec	kp	kp
1.0	0.064	0.060
1.5	0.043	0.040

5.4 ORC VPP Results

The added resistance in waves using the documentation of the ORC VPP [6] is based on the wind speed that is necessary to sail the yacht at the speeds that correspond to the tested ones. The VPP assumes an angle of approximately $\beta = 140^\circ$ and it is presented in Table 4.

Unfortunately, the VPP could not provide results for encounter angles higher than 140° , i.e. at 180° , as it was the tested case, for direct experimental verification of its results.

6. Conclusions

For frequencies less than 4 rad/sec the RAO of added side force is negligible or even negative (see Fig. 4). The random waves tested possessed $\omega_p = 2.25$ and 2.75 rad/sec, i.e. they were within the above frequency range. This result is also reflected in the respective values given in Table 3.

Regarding the comparison of the experimental results with those derived using the VPP, the latter are only indicative. Actually, it was not possible to tow

the model in the NTUA tank at wave encounter angles other than 180° , while the VPP provides results for encounter angles of 140° at most. Although the experimental leeway angles have been accounted for in the VPP, it provides quite low R_{AW} values, corresponding to oblique waves, while head waves used in the tank are the worst case.

On the contrary, the RAO of added resistance in the above frequency range is measurable, in compliance with the added resistance in the tested spectra derived in Table 4.

Acknowledgements

The authors wish to express their gratitude towards the European Commission for funding the MARINELIVE project (contract No. 264057) within the FP7-REGPOT-2010-1 frame. Thanks are due to Mr John Trachanas, technical staff for contributing to the execution of the experiments in the towing tank.

References

- [1] Kirkman, K. L. 1979. "The Evolving Role of the Towing Tank.", *Proc. 4th Chesapeake Sailing Yacht Symposium*, SNAME, 129-55.
- [2] Davinson, K. S. M. 1936. "Some Experimental Studies of the Sailing Yacht." *Trans. SNAME* (44): 288-334.
- [3] Grigoropoulos, G. J., and Perissakis, S. G. 1998. "Experimental Investigation of the Performance of a BOC 50-ft Sailing Yacht in Calm Water." *Intl. Conf. The Modern Yacht*, Portsmouth.
- [4] Liarokapis, D., Sfakianaki, D., Perissakis and Tzabiras,

- G. 2010. "Experimental Investigation of the Turbulence Stimulator on a Sailing Yacht Model." Intl. Conf. Black Sea, Varna, Boulgaria.
- [5] Campbell, I., and Claughton, A. 1987. "The Interpretation of Results from Tank Tests on 12-m Yachts." *Proc. 8th Chesapeake Sailing Yacht Symposium*, SNAME, 91-107.
- [6] VPP ORC 2012. Offshore Racing Congress.