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WIND TUNNEL AND CFD INVESTIGATION OF UNCONVENTIONAL RIGS

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Abstract. This paper presents research activities carried out by the authors to investigate aerodynamic behaviour of several unconventional saiplans in comparison to the sloop traditional solution. In particular an *"A- shaped"* mast, placed in the stern area of the yacht has been considered in single-jib and double-jib configurations. Wind Tunnel tests and performance prediction analyses have been performed in order to compare different configurations.

1. INTRODUCTION

Most of the modern small and medium sized sailing yachts are equipped with a *sloop* kind of sailplan.
This kind of sailplan is composed of a single mast, placed approximately in the middle of the boat (somewhere between 35% and 45% of LWL measured from the bow), and it consists of a *mainsail*, hoisted between the mast and the boom, and a *foresail*, jib or genoa, rigged on a forestay. Downwind sails, like *spinnakers* and *gennakers* may be added, and are set free of stays.
The sloop sailplan, very widely used because of its simplicity, has some aerodynamic and operational drawbacks, such as:

- the central position of the mast and its rigging (spreaders, shrouds etc.) produces vortexes that disturb the air flow both on the mainsail and in the air tunnel (called slot) between mainsail and genoa, reducing aerodynamic performance of the whole system of sails;
- the mast placed in the centre of the boat dramatically reduces both above and below deck comfort, which is affected by the indispensable presence of heavy structures and pillars;
- the boom and mainsail sheet and traveller, usually in the centre of the cockpit, create obstacles on the deck and possible danger for non experienced passengers;
- the tuning techniques required on the mast, the boom, the stays and the sails, need, to be effective, expensive equipment like additional tracks, sheets, vangs and the correspondent purchases;
- the reduction of the sail surface on a boomed mainsail is always a difficult manoeuvre (even with a rolling boom), and it is difficult for a single sailor, especially in heavy weather conditions.

There are many design proposals, which will be quoted later, that have been created to answer the previous questions, especially the aerodynamic ones. The most interesting solution, including major potential development, appears to be the one configured on an *"A" shaped* mast, placed in the stern area of the yacht. In this way, what was the mainsail is now transformed into another jib (in the *double jibs* configuration) or even completely removed (*single jib* configuration), with the following aerodynamic and operational advantages:

- removal of the mast interference on sails;
- elimination of the boom and of the mainsail sheet track;
- simpler sail handling while reefing and dropping the sails;
- reduction of the deck rigging;
- reduction of mast fixing structures to the hull (reinforced beams, pillars, keel reinforcements, chainplates, etc.)
- increase of usable deck surface.

It might be noticed that a mast placed astern considerably reduces the backstay arm if compared to the sloop configuration. This fact brings to an increased compression strength for the "A" shaped mast. But the problem is reduced by the fact that the compressed beams are two (instead of one) and these can be designed with fewer aerodynamic drawbacks. Furthermore, we are confident that a bit more testing in the engineering field would lead to a quick evolution of this type of mast, thus eliminating many remaining disadvantage.
Many attempts to reduce drawbacks of aerodynamic interference of the mast on sails, both in sloops and in multiple mast sailplans, have been made in the past.
On the experimental yacht Amoco Procyon by O. Harken and B. Chance an "A" shaped mast (patented as Bi-POD

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mast and built by E. Hall) was installed [9], with a central stay to hoist the mainsail onto, like a jib. That reduced mast and rig interference on the sail leading edge, thought it didn't completely remove it.
Mention should be made on the fact that the idea of this configuration already appeared in M. Curry designs back in the thirties, and later in N. & G. Sironi design, winner of the Philips award in 1971.
In other Seventies experiments (see Luna or Vendredi 13 designed by D. Carter) schooner type sail plans using only jibs without mainsails were built, with masts placed astern of the corresponding jib.
A more interesting idea of solving the aerodynamic problem by adopting an "A" shaped mast in the stern area of the boat, is still quite old: some pioneering experiments back in the fifties (see Marara catamaran by C.O. Walker), and a number of very similar patents, (among them I. Brandin, 1992, SE; K.D. Lehman 1994, DE; C. Atkinson, P.C. Sewell, K.L. Hamson 1987, CA; R. Wieland 1997, DE; H. Erler 2000, DE; A. Vallicelli, A. Nazareth, 2005, ITA were recorded).
To the authors' knowledge all these ideas, theoretically equivalent, never went beyond the hypothetical stage and have never been tested enough for reliable experimental evidence.
So far the purpose of this research, conducted by a cooperation between Mechanics Department of Politecnico di Milano and IDEA Department of Facoltà di Architettura di Pescara, was to compare through wind-tunnel tests, a traditional sloop sail plan with a (similarly sized) "A" shaped stern mast sail plan, both in the single-jib and the double-jib configuration.

2. EXPERIMENTAL TESTS

2.1 Test arrangements and measurements setup

Two complete scaled models for both single rigged yacht and traditional sloop yacht have been built and tested in the Politecnico di Milano Twisted Flow Wind Tunnel. Figure 1 shows an overview of the P.d.M. facility: it is a closed circuit facility in a vertical arrangement having two test sections, a 4 x 4m high speed low turbulence and a 14 x 4m low speed boundary layer test section.
A peculiarity of the facility is the presence of two test sections of very different characteristics, offering a very wide spectrum of flow conditions, from very low turbulence and high speed in the contracted 4 x 4m section (I_u<0.15%, V_{max}=55 m/s), to earth boundary layer simulation in the large wind engineering test section (14m wide, 4 m height, 36 m length).
With reference to the present tests, these have performed in the boundary layer test section which allows for testing large scale models (typically 1:10 -1:12 for IACC yacht model) with low blockage effects at maximum speed of 15 m/s. For more details on the facility please refer to [1] [2].
The yacht model, consisting of yacht hull body (above the waterline) with deck, mast, rigging and sails, is mounted on a six component balance, which is fitted on the turntable of the wind tunnel. The turntable is automatically operated from the control room enabling a 360° range of headings.

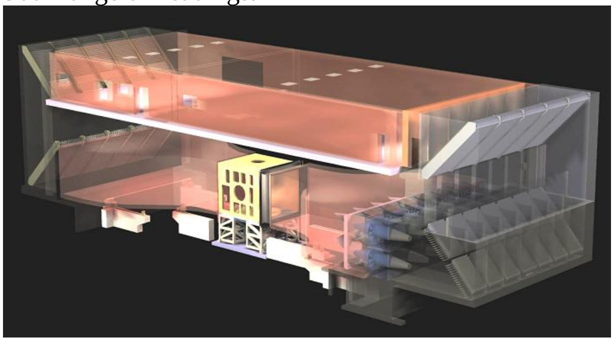

Figure 1. Politecnico di Milano Wind Tunnel

A high performance strain gage dynamic conditioning system is used for balance signal conditioning purposes. The balance is placed inside the yacht hull in such a way that the X axis is always aligned with the yacht longitudinal axis while the model can be heeled with respect to the balance. Yacht deck layout has been reproduced in details with particular reference to sheet winches, allowing all the sails to be trimmed as in real life. The sheet trims are controlled by the sail trimmer who operates from the wind tunnel control room.
Data acquisition was performed by means of National Instruments Data Acquisition Boards and suitably written programs according to Matlab standards. The data acquisition software calculates the forces and moments using the dynamometer calibration matrix. During the test sailplan forces are shown in a virtual panel designed on the computer screen in real time so that the sail trim can be optimised because the effects of trimming the sails on the driving and heeling forces can be directly appreciated.
The raw data, in terms of time histories and mean values, are stored in files that are used for the detailed data analysis.
In order to correlate force measurement readings and the sail shape and in order to provide input data for CFD calculations, an in-house photogrammetric measuring system has been developed to recover flying shapes during tests.

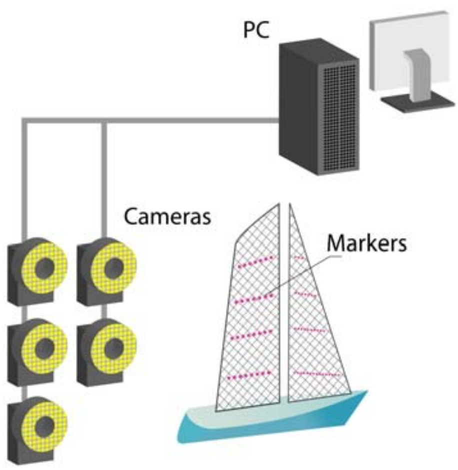

Figure 2. Flying shape measurement system layout

The photogrammetry based technique is relatively fast during the tunnel occupancy phase and in principle it requires only three digital images be recorded from useful points. In order to overcome difficulties arising from sails overlapping, especially in downwind configurations, and in order to be able to have at least three useful points in each part of the sails the system is equipped with eight cameras.

For the present tests this system is composed of five cameras, filming reflective targets placed on sails in sync, and a PC equipped with acquiring and processing custom-made software.

Cameras have resolution of 1392 x 1040 pixels, greyscale 1/2" CCD sensor, 17 fps (frames per second). Each of them mounts an optical zoom and a high intensity infrared (830 nm) LED illuminator, triggered to simultaneously flash with cameras frame rate. Custom-made software performs real time blob detection and stores images sourced from cameras on a hard disk. As a result of this routine a table with the 2D blob detected coordinates is available for post process. Cameras have been previously calibrated using a custom built calibration frame.

The 3D marker points coordinate for each sail are then obtained by means of a DLT (Direct Linear Transformation) algorithm, reaching marker position with an uncertainty equal to 0.5 mm. Marker coordinates are obtained as mean of their position over a 20[sec] acquisition period with 17 Hz acquisition rate.

This 3D points array is later used for surface modelling as well as to extract the trim parameters as explained in [4]. Figure 3 shows an example of measurements during the tests.

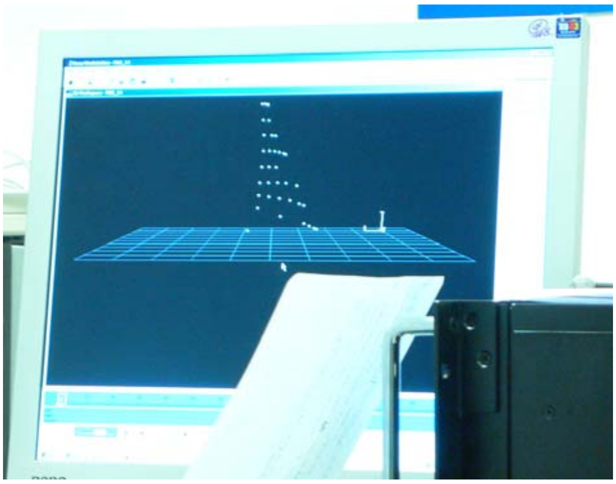

Figure 3. Sails flying shape detection process

2.2 Sailplan tested configurations

The traditional sloop yacht rig used as a reference is a Comet 51'a Vallicelli Yacht Design & Co 51 feet IMS cruiser-racer sailing yacht, winner of 2007 IMS Italian Championship (fig. 4).

Figure 4.

Wind tunnel tests were performed using a 1:10 scaled model of this yacht where a mainsail with the maximum IMS rule allowed roach and 100% non overlapping jib have been used (fig.5).

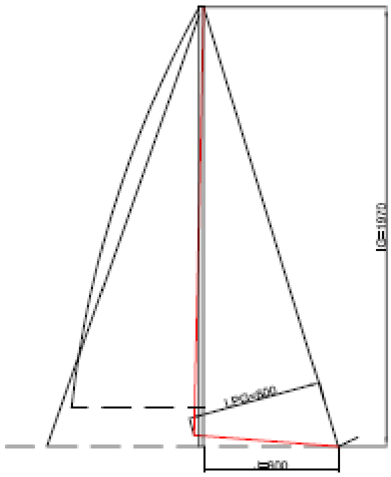

Figure 5. Standard sloop configuration

A second 1:10 scaled model of the same yacht equipped with the non conventional rig has been built. As already explained in the introduction the non-conventional configurations investigated are characterised by an "A" shaped stern mast without mainsail in single-jib and double-jib configurations.

Figure 6 shows the layout and the principal dimension of the non-conventional rig in the single jib configuration. Figure 7-8 refer to two jib non-conventional sailplan respectively with non overlapping and overlapping configurations. Sailplan codes are defined according to table.1:

Table. 1 Sailplan codes

Std	Standard main+jib
Mono	Single jib
WO overlap	2 jibs with overlap
Overlap	2 jibs without overlap

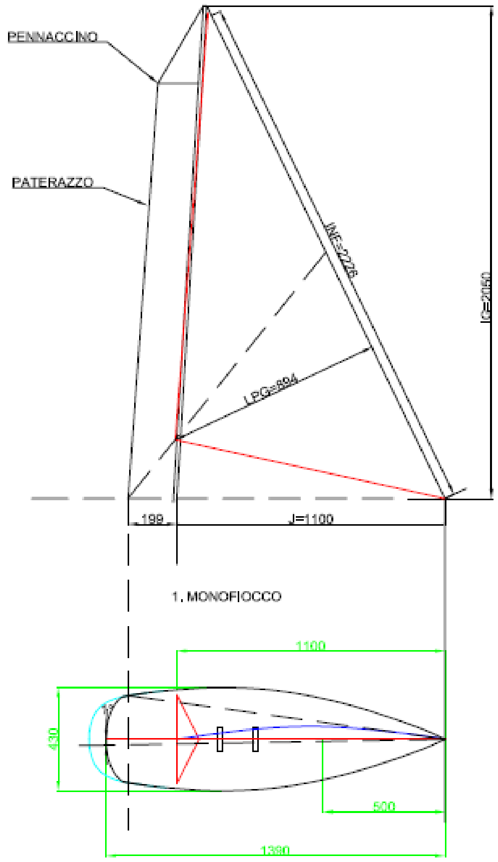

Figure 6. Single jib configuration

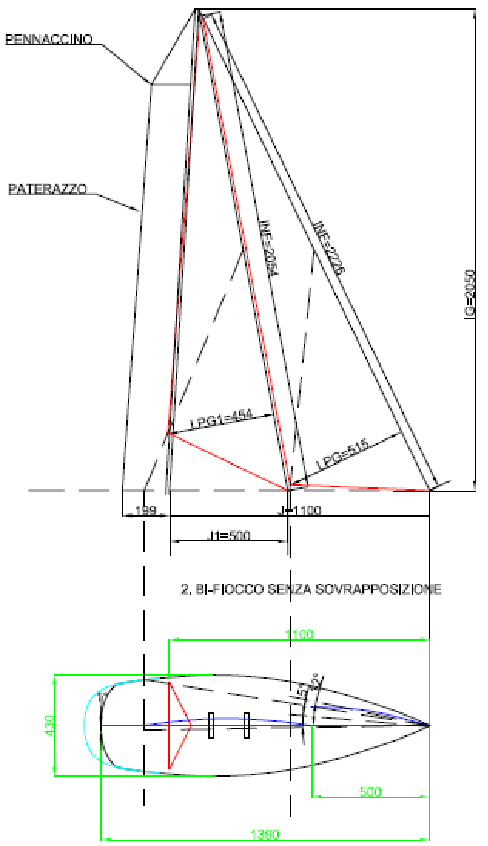

Figure 7. Double jib without overlap configuration

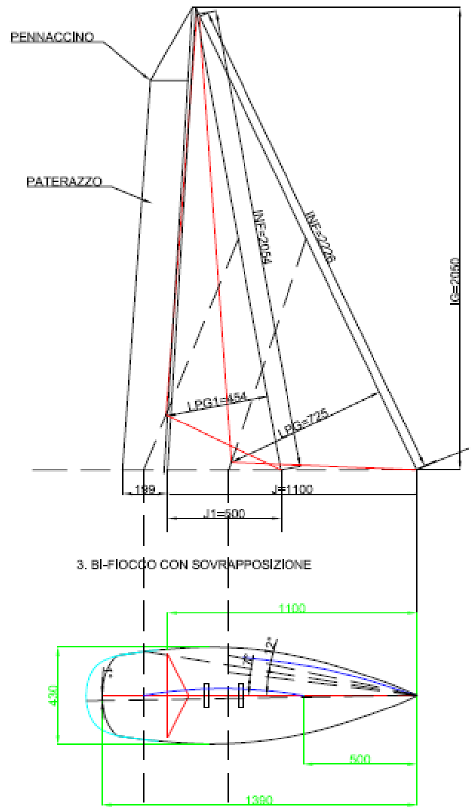

Figure 8. Double jib with overlap configuration

Picture 9 shows the "A shaped" mast model and deck layout during setup.

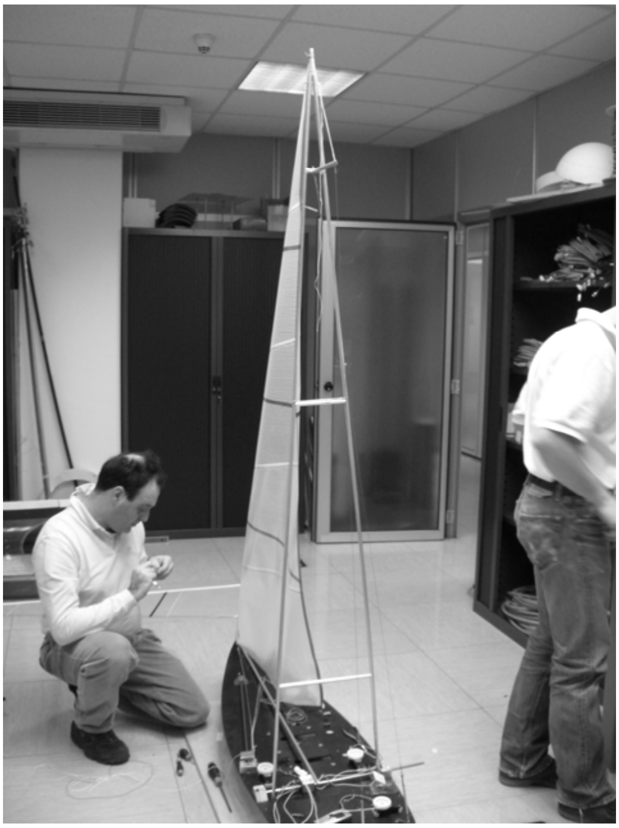

Figure 9. "A" shaped rig model setup

Figure 10. Double jib with overlap configuration during the test

Figure 11. Double jib without overlap configuration during the test

Figure 12. Single jib configuration during the test

Figure 13. Standard sloop configuration during the test

Figures 10-13 show the different sailplan configuration during wind tunnel tests. The wind tunnel was operated at a constant speed after the wind speed profile and wind twist have been properly tuned considering the desired targets.

3.2 Sailplans testing procedure

Apparent wind angles were chosen to be 22°, 27°, 32° and 42° which cover the upwind range. Tests were conducted in upright condition. For each apparent wind angle tested the first task was to determine the maximum driving force potentially achievable At the same time the influence of the sails trimming changes was observed using the data acquisition program that visualizes the forces acting on yacht model in real time.
Trimming the sails to obtain optimum sailing points proved to be the most challenging task of the testing process. Attempts were made to carry out the job as systematically as possible. Firstly, the maximum drive point was found by trimming the sails to the best using the cameras views, the tufts on the sails and the force measurements output data. From there, the heeling force would be reduced to simulate the trim of the sails for windier conditions. In real life windy conditions, to keep the optimum heeling angle, heeling force has to be reduced by the crew.
The sail trimming routine adopted was obviously different depending on the sailplan configuration: with the standard sloop the trimming procedure was to choose the mainsail traveller position (initially quite high up to windward) and then to vary the incidence and the twist of the mainsail to power or de-power it, by over-trimming or easing the main traveller and main sheet. The genoa was initially trimmed in order to provide the maximum driving force and was fixed when varying the mainsail shape.
With the unconventional sailplan the depowering procedure was not so trivial: as can be seen in figure 10-12 the aft jib in double-jib configurations and jib in single-jib is equipped with a sort of boom which can be moved on a traveller placed on the mast directly, avoiding any additional fitting on the deck, while trimming of the fore jib in the double jib configurations was performed primarily by adjusting the jib sheet car position.
The heeling moment is also measured in wind tunnel tests and can be used to determine the centre of effort position of the rig: The centre of effort height, Ceh, is obtained by dividing the roll moment by the heeling force component in the yacht body reference system.
At the end, some runs were performed on the bare hull and rigging (without sails) for both yacht models at different apparent wind angles and in different heeling conditions in order to measure windage. These values are subtracted from each of the measured data points in order to produce the sail force coefficients.

3. EXPERIMENTAL RESULTS

Using the aerodynamic driving force and aerodynamic heeling moment Fx and CMx component in the yacht body reference system the corresponding coefficients have been obtained as follows:

$$C_x = \frac{F_x}{\frac{1}{2}\rho S V_a^2} \qquad CM_x = \frac{M_x}{\frac{1}{2}\rho S H_{mast} V_a^2} \qquad (1).$$

where

- Fx is the driving force
- Mx is the heeling moment
- S is the actual sail area
- H_{mast} is the mast height from the deck
- V_a is apparent wind speed
- ρ is air density

The apparent wind speed V_a is evaluated according to:

$$V_a = \sqrt{(-V_t \cos\gamma)^2 + (V_t \sin\gamma)^2} \qquad (2).$$

where γ represent the true wind angle (yaw angle) and V_t is the wind tunnel flow velocity corresponding to the mean dynamic pressure at each run. All tests have been performed in upright condition and apparent wind speed has been measured at 10m height full scale.
Figures 14-16 show test results in terms of envelope curves (maximum drive force coefficient C_x versus heeling moment coefficient C_{Mx}). The comparison is shown for each of the sailplan tested at different apparent wind angles.

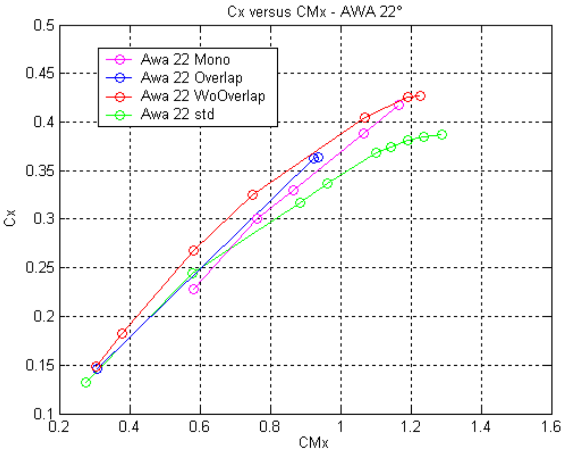

Figure 14. Cx versus CMx coefficients for each sailplan at 22° AWA

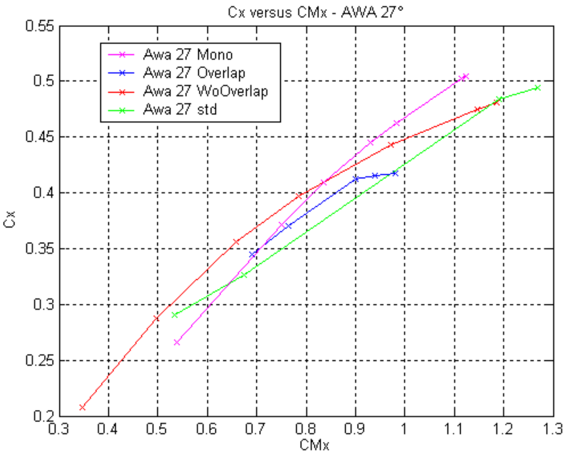

Figure 15. Cx versus CMx coefficients for each sailplan at 27° AWA

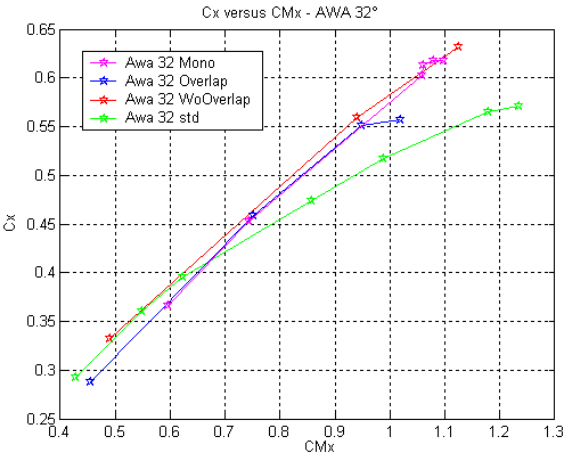

Figure 16. Cx versus CMx coefficients for each sailplan at 32° AWA

From a pure aerodynamic point of view the relative performance of different rigs can be compared by comparing the driving force at similar apparent wind angles and heeling moment. From these figures unconventional rigs seem to perform better than the standard sloop configuration.

It must be borne in mind that the force generated by a rig is the combination of area and coefficients. These effects can be properly taken into account by the driving force area coefficient versus heeling moment area coefficient curve i.e. the respective coefficients multiplied by the sailplan area. With reference to scaled models the situation is summarised in fig. 17.

As can be seen at closer AWA unconventional solutions are better than the standard sloop and in particular the two jib configuration with overlap seems to be able to produce higher driving force (at dynamic pressure =1) at the same heeling moment.

In figures 18-19 the centre of effort height in model scale (from the deck) is reported versus heeling force coefficient with reference to close hauled apparent wind angles.

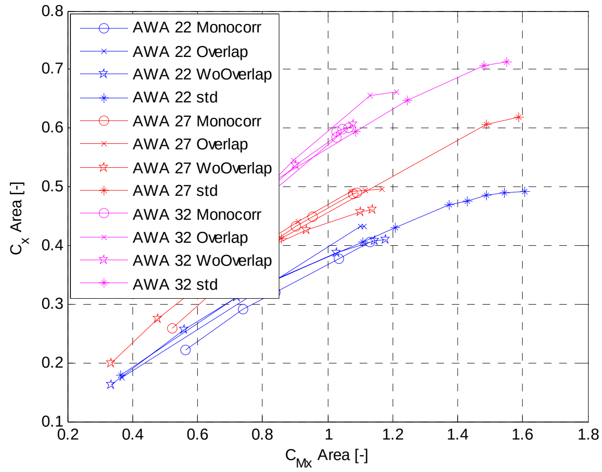

Figure 17. driving force area coefficient versus heeling moment area coefficient

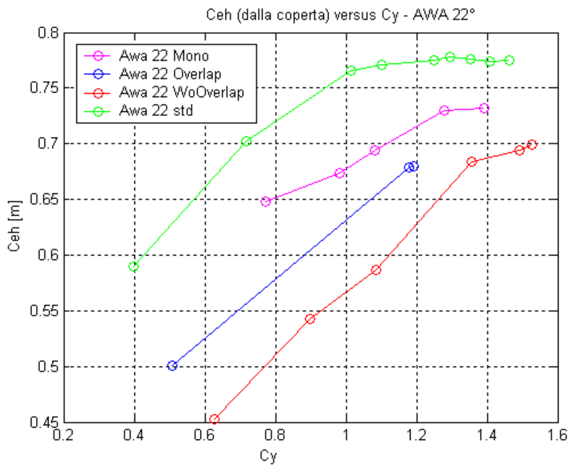

Figure 18. Center of effort height versus heeling force coefficient for each sailplan at 22°AWA

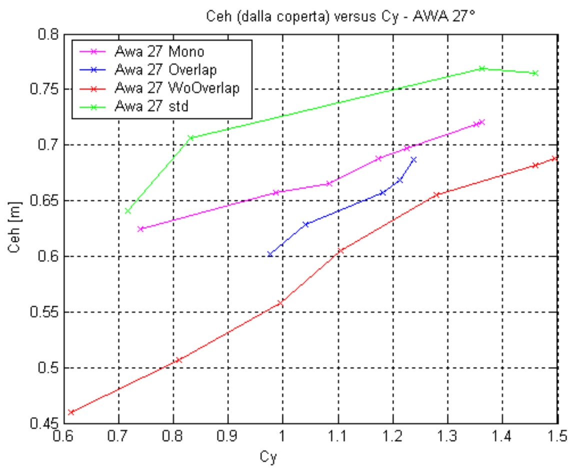

Figure 19. Center of effort height versus heeling force coefficient for each sailplan at 27°AWA

As can be seen unconventional configurations have aerodynamic centre of effort which are lower than the

standard sloop and in particular the two jibs without overlap sailplan has the lowest values.
More information can be extracted from the wind tunnel data by transforming them into lift and drag coefficients and, because both the induced drag and quadratic profile drag vary with the square of lift, it is informative to plot the variation of drag coefficient with the square of the lift coefficient.
As an example, in Figure 20 the drag coefficients against lift coefficient squared for each run performed at 22° AWA is reported for each sailplan configuration. As can be seen for reduced values of C_L the drag increases linearly following a straight line. This linear increase is primarily attributable to the induced drag.
The effective height H_{eff} which is a measure of the efficiency of the rig can be determined from the slope of the straight line applying simple aerodynamic theory according to the following equation:

$$Heff = \sqrt{\frac{SailArea}{\pi Slope}} \qquad (3).$$

Figure 20 reveal that unconventional rigs have lower slopes than the traditional one leading to an higher effective height of the sailplan.

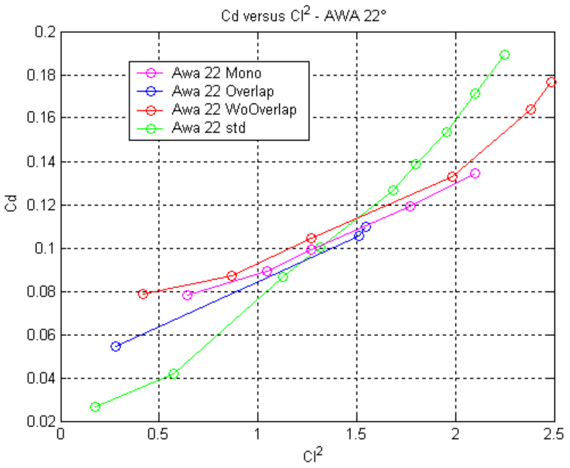

Figure 20. drag coefficient versus squared lift coefficient

4. CFD SIMULATIONS

In order to gain further understanding of the sailplans aerodynamic behaviour numerical simulations have been carried out using RANS methods. In particular computational modelling has been carried out using the Fluent CFD code with the realizable k-ε turbulence model. A numerical model of each tested sailplan, including hull and rigging, has been carried out and put in the numerical model of the wind tunnel (figure 21). The boundary conditions were set to give a wind velocity profile similar to that in the wind tunnel.
Numerical simulation have been performed at 22° apparent wind angle and, for each sailplan considered, the flying shape corresponding to maximum drive force has been used in order to generate the numerical mesh.

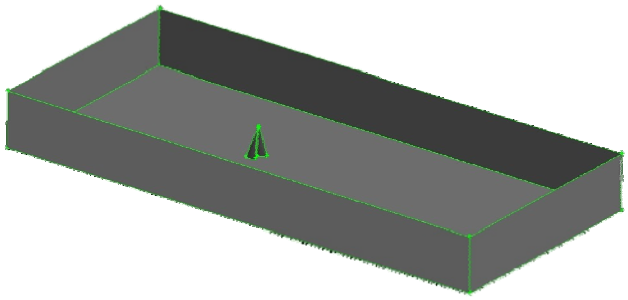

Figure 21. Leeward Cp contours in upright condition

Due to the limited space available, only a few results concerning the double jib configuration will be reported here. As an example, Figures 22-23 show the flow velocity vectors coloured by magnitude normalised to the free stream incoming flow in a plane perpendicular to the mast at 25% of mast height from the deck.
As can be seen the double jib configuration without overlap reveals some separation occurring on the leeward side of the aft jib resulting in drag increase and less driving force production as outlined by the experimental tests.

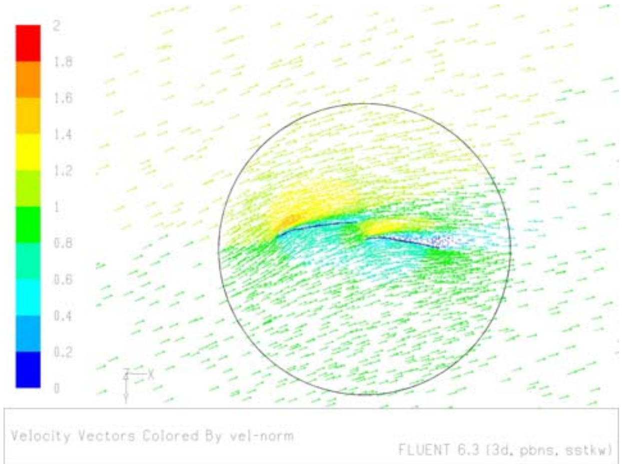

Figure 22. Double jib without overlap velocity vectors

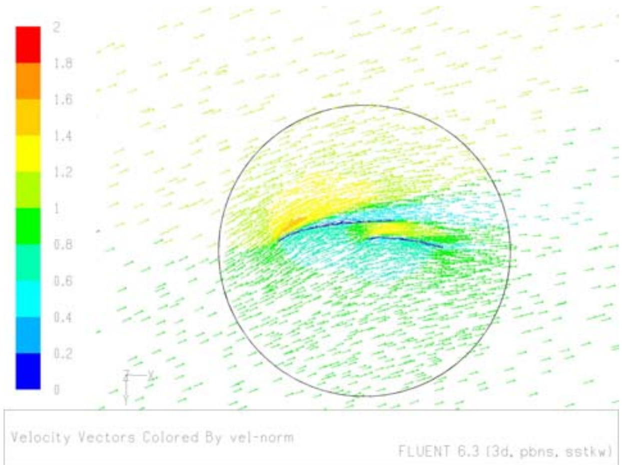

Figure 23. Double jib with overlap velocity vectors

5. FULL SCALE YACHT PERFORMANCE ANALYSES

Using aerodynamic data available from wind tunnel tests, some performance prediction at full scale have been carried out by means of the Wolfson Unit Windesign VPP code [6]. This code, besides its own internal aerodynamic modelling, allows users to define an aerodynamic experimental file containing experimental data typically from wind tunnel experiments or other source. In this case the aerodynamic input requires parasitic drag coefficient C_{DO}, maximum lift coefficient and effective height at each apparent wind angle. Sailplan centre of effort height is also required.
Bare hull and rigging coefficients obtained by means of wind tunnel windage tests have been used in order to provide windage aerodynamic model input.
Several performance simulation have been performed with reference to the Comet 51 hull considering the following design scenarios:

- Full scale standard and unconventional rig as tested in the wind tunnel
- Full scale standard and unconventional rig with the same mast heights
- Full scale standard and unconventional rig with the same total sail area

In the following tables full-scale sailplan main dimensions are reported for each of the abovementioned design scenario.

Table. 2 Dimensions for "as tested" configurations

	Mast Height	JIB 1 Area	JIB2 Area	Total Area
Standard	19.7			120.5
Mono	20.5	99.5	0	99.5
WO overlap	20.5	57.3	46.6	103.9
Overlap	20.5	80.7	46.6	127.3

Table. 3 Dimensions for equal mast height configurations

	Mast Height	JIB 1 Area	JIB2 Area	Total Area
Standard	19.7			120.5
Mono	19.7	96.5		96.5
WO overlap	19.7	55.6	44.9	100.5
Overlap	19.7	78.3	44.9	123.2

Table. 4 Dimension for equal area configurations

	Mast Height	JIB 1 Area	JIB2 Area	Total Area
Standard	19.7			120.5
Mono	25.93	120.5	0	120.5
WO overlap	24.3	65.7	54.8	120.5
Overlap	19.18	76.7	43.8	120.5

For each design scenario performance prediction have been carried out in 4-20 Knots true wind speed.

Figure 24 shows a comparison in terms of optimal VMG in close hauled condition between standard sloop and unconventional rig with reference to both single and double jib configurations. In particular figure 24 refers to full scale case with the same sails tested in the scaled model.

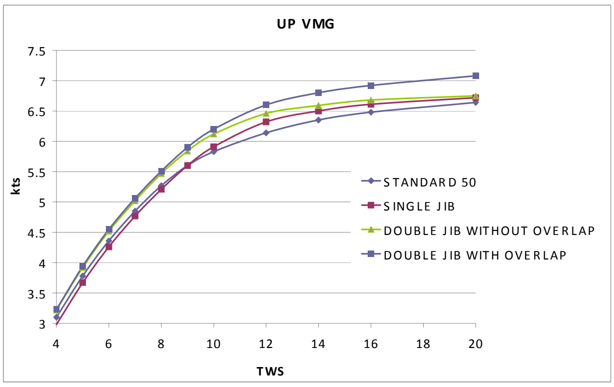

Figure 24. VMG as a function of true wind speed for various "as tested" configurations

The results obtained confirm that the double jib configuration performance is better than the standard sloop up to 10 knots TWS, while the single jib performance is pretty similar to sloop configuration. In windier conditions all the unconventional rig solution are faster and in particular the double jib with overlap gives the best performance.
Figure 25 shows the same comparison in terms of optimal VMG with reference to the same mast height design scenario. The result in this case are very similar to the previous one.

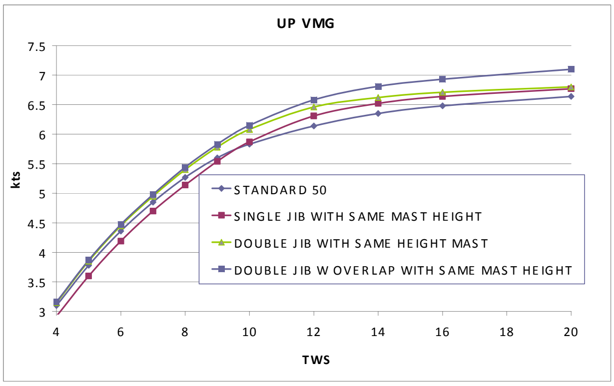

Figure 25. VMG as a function of true wind speed for various equal mast height configurations

Finally figure 26 shows the results for the different rigs with the same total sail area. In this case the standard sloop and double jib configuration with overlap are very similar within the low wind speed range, while at higher true wind speeds the unconventional yacht is faster. The better performance in windier condition is basically due to the lower heel angle associated with the equilibrium condition (see figure 27), allowing for a lower heel resistance component and lower hydrodynamic resistance. In fact, looking at figure 17 we can see that in the depowered region of the curves the unconventional and standard configuration are pretty similar from an aerodynamic point of view and the difference in yacht performance arise from the hydrodynamic behavior.

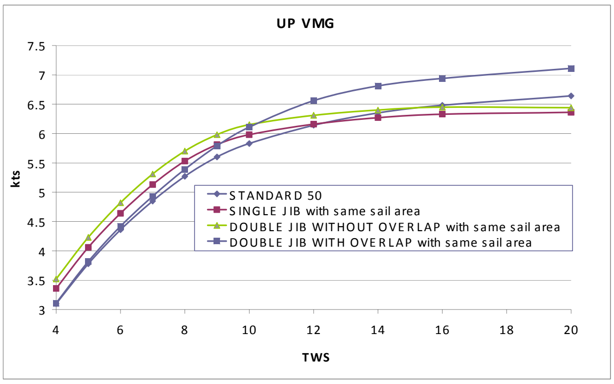

Figure 26. VMG as a function of true wind speed for various equal sail area configurations

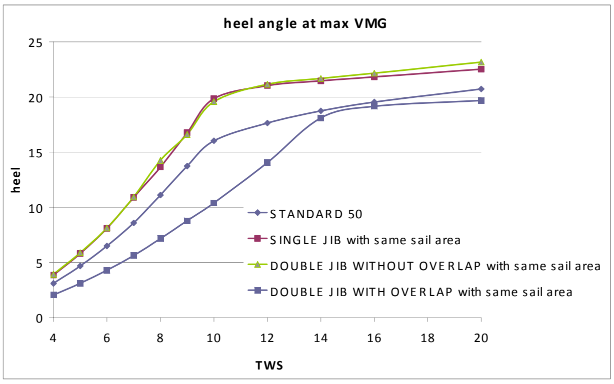

Figure 27. Heel angle at optimum VMG

With reference to the double jib configuration without overlap, we can say that a good behavior is generally outlined on the whole wind speed range: in particular its performance is very good in the low wind speed but it's not so bad also in windier condition.

6. CONCLUSIONS

In the present paper an unconventional rig has been investigated in comparison with a standard sloop rig by means of wind tunnel tests. The traditional sloop yacht rig used as a reference is a Comet 51'a Vallicelli Yacht Design & Co 51 feet IMS cruiser-racer. Several unconventional configurations have been tested, all characterised by an "A" shaped stern mast without mainsail in single-jib and double-jib configurations.
Aerodynamic data available from experiments have been used to perform some performance prediction at full scale by means of a VPP code. Both experimental tests and VPP calculation show that the double jib configuration with overlap gives the best performance and also the same configuration without overlap gives better results in comparison with the standard sloop solution.
Numerical investigation have been carried out using RANS simulation in order to better understand the aerodynamic differences resulting from the experimental tests. Simulation results put in evidence a slat effect in the overlapping jibs configuration leading to more attached flow on the aft jib allowing for an higher pressure drop on the sailplan.

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