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Mainsail Planform Optimization for IRC 52 Using Fluid Structure Interaction

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ABSTRACT

Most IRC 52 based upon existing TP52 retain their original rig proportions and mainsail girths to avoid the cost and disruption of a rig change and to not disturb the finely tuned yaw balance. It is not obvious whether the mainsail proportions essentially dictated by the TP52 box rule (aggressively square topped mainsails) are actually optimal under IRC even though IRC 52 with TP52 style mainsails tend to successfully compete under IRC. To determine the answer to this question, a mainsail planform investigation was performed as collaboration between Botin Partners and Quantum Sail Design Group.

The mainsail planform investigation utilized a Fluid Structure Interaction (FSI) program developed by Quantum Sail Design Group (QSDG) known as IQ Technology (IQT) that consists of sail geometry definition, inviscid Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), Velocity Prediction Program (VPP), and shape validation (based upon VSPARS) modules. Applicability of the inviscid CFD was validated by comparison to a limited number of viscous flow solutions, i.e. RANS analysis, performed by Porto Ricerca.

Two mainsails were considered, a conventional TP52 style and an alternative that was chosen to be closer to the IRC default girth values. To maintain sail area and yaw balance, the alternative mainsail had a longer P and E. The focus of the study was exclusively on upwind performance, i.e. to maximize upwind Velocity Made Good (VMG).

Results from the study suggest that a TP52 style mainsail is not optimal under IRC. The combination of rating reduction and predicted performance advantages over a wide range of wind speeds suggest that an alternative mainsail with larger P and E with girth values closer to the IRC default values is a superior choice for an IRC 52.

NOTATION

P	Mainsail Hoist
E	Mainsail Foot Length
MHB	Mainsail Top Width
MSA	Mainsail Area
MGM	Mainsail Girth Middle (half)
MGL	Mainsail Girth Lower (quarter)
MGU	Mainsail Girth Upper (three quarter)
MGT	Mainsail Girth Top (seven eights)
MHW	Mainsail Half Width
MTW	Mainsail Three Quarter Width
MUW	Mainsail Upper Width

INTRODUCTION

While numerous IRC 52 have been optimized to sail under the IRC handicapping formula after competing under the TP52 Rule, few if any, have started the optimization process prior to their initial launch. In the winter of 2011 however an opportunity to perform a comprehensive optimization effort in the early design stages was provided with the only initial constraint being the use of an existing female mould from which a pair of TP52 had already been produced. This would ultimately prove an excellent starting point as one of these original TP52, QUANTUM RACING, would later go on to win the 2011 Audi Med Cup Series. Among the various lines of the optimization effort, the design team from Botin Partners proposed a study to identify an alternative mainsail planform that might offer upwind performance advantages under the IRC rule and that investigation is the focus of this paper.

PROBLEM STATEMENT

Most IRC 52 based upon existing TP52 retain their original rig proportions and mainsail girths to avoid the cost and disruption of a rig change and to not disturb the finely tuned yaw balance. It is not obvious whether the mainsail proportions essentially dictated by the TP52 box rule (aggressively square topped mainsails) are actually optimal under IRC even though IRC 52 with TP52 style mainsails tend to successfully compete under IRC.

To determine the answer to this question, a mainsail planform investigation was performed as collaboration between Botin Partners and Quantum Sail Design Group (QSDG). The focus of the study was exclusively on upwind performance, i.e. to maximize upwind Velocity Made Good (VMG).

BACKGROUND

Like many of the parameters controlling a TP52, mainsails are defined within the TP52 rule by a box. As an example, consider the mainsail requirements set by the 2011 TP52 Rule (Weiland, 2011):

- Mainsail Hoist (P) shall be no greater than 20.4 M
- Mainsail Foot Length (E) shall be no less than 7.0 M
- Mainsail Top Width (MHB) shall be no less than 1.25 M (Authors' note- essentially requiring TP52 to have square topped mainsails)
- Measured perpendicular to the luff at 0.5 M below the head point there shall be a maximum width (girth) of 1.50 M.
- Mainsail Area (MSA) shall be no less than 93.5 M^2 where MSA is defined by the following equation and MGL, MGM, MGU, and MGT are the Lower (quarter), Middle (half), Upper (three quarter), and Top (seven eights) girths respectively.
- Mainsail area to be calculated according to the following formula:

$$MSA=P/4*(E+MGL)/2) + (P/4*(MGL+MGM)/2) + P/4*(MGM+MGU)/2) + (P/8*(MGU+MGT)/2) + (P/8*(MGT+1.250)/2)$$

Alternatively, IRC establishes a default mainsail girth distribution as a function of mainsail foot length (E) (Seahorse Rating Ltd., 2010). The measurement points are defined as the half width of the mainsail (MHW), the three quarter width of the mainsail (MTW), and upper width of the mainsail (MUW). Unless declared as greater, MUW, MTW, and MHW are assumed to be 0.22*E, 0.38*E and 0.65*E respectively. Increases from the default girth values result in a rating assessment. Because the IRC rule is "secret", the exact consequences of deviating from the default values can only be known by running IRC trial certificates (the number of which that can be run over a given time period are strictly limited).

GENERAL SOLUTION APPROACH

The mainsail planform investigation utilized a Fluid Structure Interaction (FSI) program developed by QSDG known as IQT (described in more detail in the next section) coupled with the Botin Partners Velocity Prediction Program (VPP) with additional input from IRC trial certificates.

Two mainsails were considered, a conventional TP52 style and an alternative that was chosen to be closer to the IRC default girth values. To maintain sail area and yaw balance, the alternative mainsail had a longer P and E. The focus of the study was exclusively on upwind performance, i.e. to maximize VMG.

A series of realistic upwind sail shapes were developed using the IQT system at 6, 8, 10, 12, 14, 16, 18 and 20 knots. Upwind sail forces for both the IRC 52 and the TP52 mainsail predicted by the inviscid CFD module within IQT were integrated with the Botin Partners VPP to perform the comparative analysis. The modified VPP predicted the resulting upwind VMG with the two different mainsails. Using IRC trial certificates, the rating consequence of the two mainsail options was calculated. Over the true wind speed range, the net (speed and rating) consequence of the alternative mainsail was calculated.

To address concerns that the inviscid CFD would not correctly predict the consequences of the girth changes properly, a small subset of the inviscid CFD analysis was also analyzed using a viscous flow solver based upon Reynolds Averaged Navier-Stokes (RANS) equations. This concern was focused on the relatively short girths of the alternative mainsail behind the mast above the hounds and the possibility that separation in this region might lead the inviscd CFD results astray.

FLUID STRUCTURE INTERACTION USING IQT

High fidelity FSI simulations which integrate CFD with structural calculations via Finite Element Analysis (FEA) are a necessary tool to optimize sail structures and accurately predict flying shapes and sail forces.

The FSI program IQT provides QSDG designers with state of the art tools to allow efficient design of composite laminate sails with intelligently deployed fiber layouts, enhanced control of flying shapes, and whose aerodynamic performance is finely tuned to the specific application.

IQT has also been designed to enhance interface and data exchange with the various relevant parties (designer, builder, spar maker, and others) during all stages of the design/build process. The ability to predict structural loads throughout the sail membrane but also at all attachment points allows the sail designer to interact with yacht designers and equipment vendors in the early stages of the design/build process which enhances deck layouts and hardware specifications and reduces costs.

The IQT system consists of the following integrated modules:

- Sail/spars/boat geometry definition called QDES
- Aero-Hydro Forces/VPP
- Inviscid CFD
- Viscous CFD
- FEA
- Shape Validation based upon VSPARS (Le Pelley & Modral, 2008)

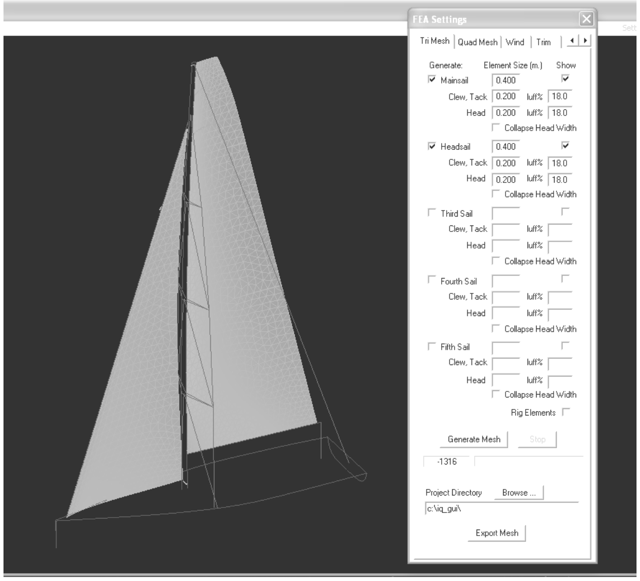
IQT was developed by QSDG's in-house technical team to retain Intellectual Property (IP) rights and facilitate efficient maintenance and future development. IQT is extremely adaptable, as an example, there are no limitations on boat configuration, rig configuration/# of sails, etc, and IQT is computationally efficient as its architecture is focused on efficient passing of information between various elements of the code, i.e. between QDES, CFD, and FEA to reduce labor intensive user intervention.

IQT predicts the following parameters as a function of user defined variable trim, sailing conditions, sail fiber material/orientation, and rig setup:

- Flying shapes and the associated aerodynamic forces
- Stress/strain in the sail membrane
- Loads and stress/strain in the rig, standing rigging, and sheets/other control lines.

Sail/Spars/boat Geometry Definition (QDES)

Information related to the geometry and properties of the boat, spars, and sails is entered into the IQT system through the QDES module. Figure 1 shows an example of the Graphical User Interface (GUI) used to enter the information.



☑ Mainsail 0.400 ☑
Clew, Tack 0.200 luff% 18.0
Head 0.200 luff% 18.0
☐ Collapse Head Width
☑ Headsail 0.400 ☑
Clew, Tack 0.200 luff% 18.0
Head 0.200 luff% 18.0
☐ Collapse Head Width
☐ Third Sail ☐
Clew, Tack luff%
Head luff%
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☐ Fourth Sail ☐
Clew, Tack luff%
Head luff%
☐ Collapse Head Width
☐ Fifth Sail ☐
Clew, Tack luff%
Head luff%
☐ Collapse Head Width
Rig Elements ☐
-1316
Project Directory
c:\iq_gui\

Figure 1 – QDES Entry for Conventional TP52 Mainsail

Aero-Hydro Forces/Velocity Prediction Program

In normal use, the Aero-Hydro Forces/VPP module is the repository of aerodynamic and hydrodynamic force/moment matrices which form the basis of establishing the sailing conditions, i.e. boat speed, heel, apparent wind speed/angle, etc.

Present system utilizes a link to external data generally provided by yacht designer that identifies target heel moments generated by their own aerodynamics models and returns aerodynamic forces/moments (drive force, side force, heel moment, etc.) predicted by IQT CFD.

Depending upon the specific needs of the yacht designer, IQT can automatically generate a multiple point aerodynamic matrix about single trim point to maximize user efficiency. A common force/moment output format consists of an 81 points matrix at each required windspeed. This matrix is a 3 by 3 by 3 by 3 based upon +/- 0.5 knots boatspeed, +/- 2 degrees TWA, +/- 3 degrees Heel, and +/- 1 degree Leeway.

An in-house VPP is under development to allow FSI simulations to be performed on all boats without requiring input from yacht designer but instead utilizing basic information about the boat that can be obtained from various open sources.

Inviscid Computational Fluid Dynamics

The IQT system utilizes a potential flow formulation (based upon Boundary Element Method) with an integral Boundary Layer (BL) solver which is appropriate for sails where separation is not a dominant effect (upwind and tight reaching). The computational mesh is based upon quadrilateral panels as is shown in Figure 2.

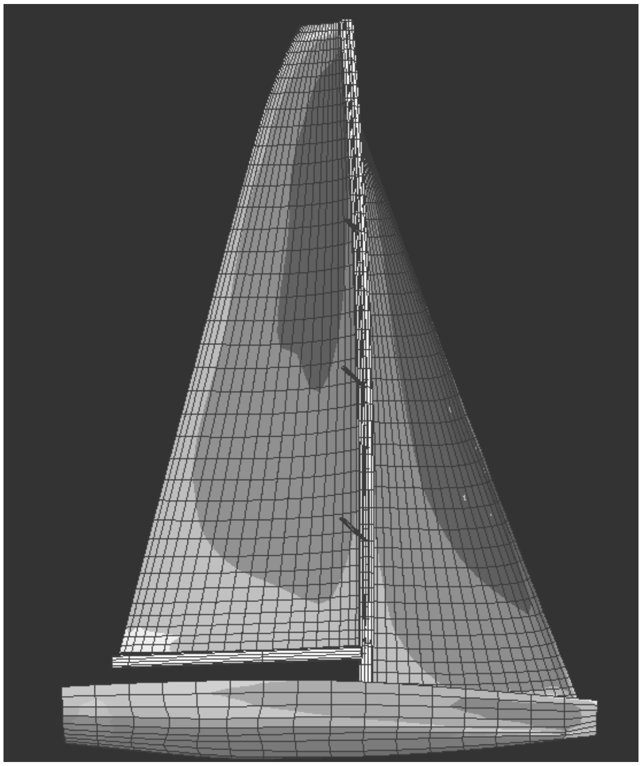


Figure 2 – Inviscid CFD Mesh

Viscous Computational Fluid Dynamics

The viscous CFD module of IQT is based upon the RANS equations. This approach is applicable to separated flows where viscous effects are a dominant feature such as highly cambered sails or when operating at wide angles of attack.

The specific implementation utilizes the open source code OPENFOAM to avoid costly licensing fees and allow customization to the FSI solution process (OPENFOAM Foundation, 2012).

The viscous CFD module is generally intended to be applied at conclusion of baseline FSI process, i.e. once a nominal flying shape has been predicted using simpler and less computationally intensive inviscid CFD.

This module was under development during the mainsail planform investigation described here so the RANS results were performed by Alberto Porto at Porto Ricerca and are described in more detail later in the paper.

Finite Element Analysis (FEA)

The IQT system utilizes non-linear structural analysis to account for modern composite laminate material properties and large displacements common to the sail FSI problem.

The FEA model incorporates standard elements such as cables (standing rigging, luff wire in free flying sails like Code Zero), pulleys, beams (battens, mast tube, spreaders), shells, and sliders (interface between sail luff and forestay/mast).

The FEA model includes specialized membrane elements of varying types to represent sail materials and accounts for varying fiber quantity/layouts.

Figure 3 shows a representation of the triangular element FEA mesh. Results are exchanged between quadrilateral panels in aerodynamic computation with triangular elements associated with the FEA calculation. Figure 4 shows the two computational meshes side by side.

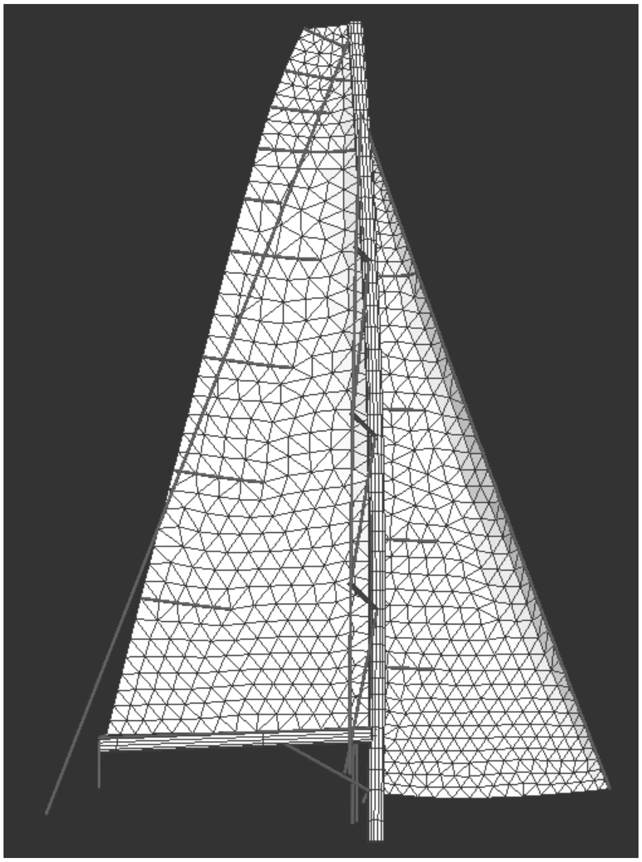


Figure 3 – FEA Mesh

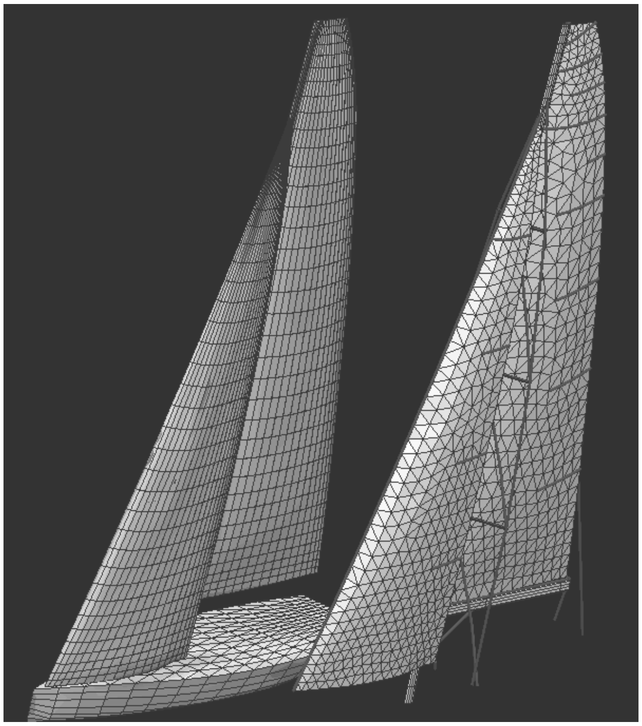


Figure 4 – FEA and Inviscid CFD Mesh

Shape Validation

Validating the results of the IQT predictions is the key to building confidence in its results and enhancing its usefulness as a design tool. Are the predicted flying shapes accurate? Are the predicted loads accurate? Does the predicted impact in the VPP match the actual performance? Is the flying shape a good one? Does the design shape and structure provide the right range of flying shapes for the design range?

With dearth of two boat testing opportunities, shape validation via other means is critical issue. Starting in the spring of 2011, QSDG began a unique program to acquire real time information on the actual flying shapes of sails and correlating them directly with real world boat performance. Onboard the TP52 QUANTUM RACING a dedicated PC was installed below decks, along with three VSPARS high-definition cameras, two for the mainsail (mounted into the cockpit sidewalls) and one for the headsail, recessed into the foredeck

This PC was wired into the boat's network so it receives all of performance data, such as boatspeed, windspeed, true- and apparent-wind angles, heel, forestay load, performance percentages based on polars and it time stamps each picture so that afterwards all of the boats performance data can be correlated to any picture.

When the VSPARS system is active, the cameras take a picture every three seconds and digitize them, saving the pictures, sail-shape analysis, and the boat's performance data to a folder associated with the specific sail. An example of such an image of the mainsail is shown in Figure 5.


2011-10-05
15:30:50
AWA: 16
TWS: 8
Btspd: 7
Heel: 14

Figure 5 – Flying Shape Capture in VSPARS

The VSPARS software computes the sail's camber depth, location of maximum camber along the chord, twist, entry angle, exit angle, headstay sag, mast bend, and sag at each draft stripe in the sail.

During post race evaluation, utilizing images only from periods where the boat is known to be performing at its optimum, a library of fast shapes can be obtained. These fast shapes are overlaid directly with the IQT predicted flying shapes to allow the sail designer to refine the critically important FSI trimming process to match optimum settings in specific environmental conditions. An example is shown in Figure 6. Lessons learned in this process close the loop between IQT predictions and real world experience.

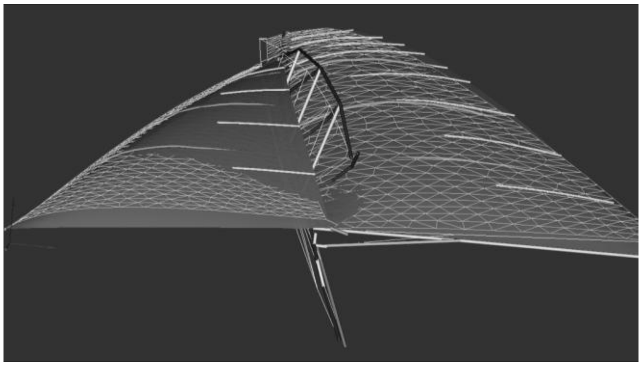


Figure 6 – Flying Shape Comparison in IQT-Predicted vs. Actual

IQT has undergone substantial validation efforts for the TP52 style mainsail and broad variety of jibs with excellent correlation between computations and measurements and it is anticipated that this effort will be the focus of a future paper.

Basic IQT System Operation

For each windspeed, the following steps are undertaken to develop the baseline sail shape and subsequent aerodynamic force/moment matrix:

- Step 1: Define input conditions using QDES and export to FEA/CFD
    - Sail design geometry and material properties
    - Rig geometry and material properties
    - Boat geometry
- Step 2: Using FEA, user adjusts rig to establish at-dock tune
- Step 3: Aerodynamic loads are calculated and results are then automatically available in appropriate format for FEA
- Step 4: FEA applies aerodynamic loads and sail-rig interaction loads to predict flying shape of sail(s) and results are then automatically available in appropriate format for CFD
- Step 5: Re-run CFD and compare integrated forces and moments to targets identified by VPP analysis for the design condition
- Step 6: Trim sails as required
- Step 7: Repeat Steps 4-6 until solution converges and then produce final results

MAINSAIL PLANFORM INVESTIGATION

Sail Geometries- Design Shape

Two mainsails were considered, a conventional TP52 style and an alternative IRC 52 style that was chosen to be closer to the IRC default girth values. To maintain sail area at the TP52 rule minimum of 93.5 M^2 (per the TP 52 MSA formula) and yaw balance, the alternative mainsail had a longer P and E.

	TP52	IRC 52
P	20.40	21.000
E	7.200	7.340
HB	1.250	0.700
MGT	2.241	1.870
MGU	3.251	2.970
MGM	4.790	4.700
MGL	6.070	6.100

Table 1 – Mainsail Geometries

Three different jibs were used over the windspeed range, C1, C2, and C3. All had the same edge lengths but differed in shape details. Mast rake varies across the windspeed but is fixed at a particular windspeed

Figure 7 show the TP52 and IRC 52 mainsails side by side:

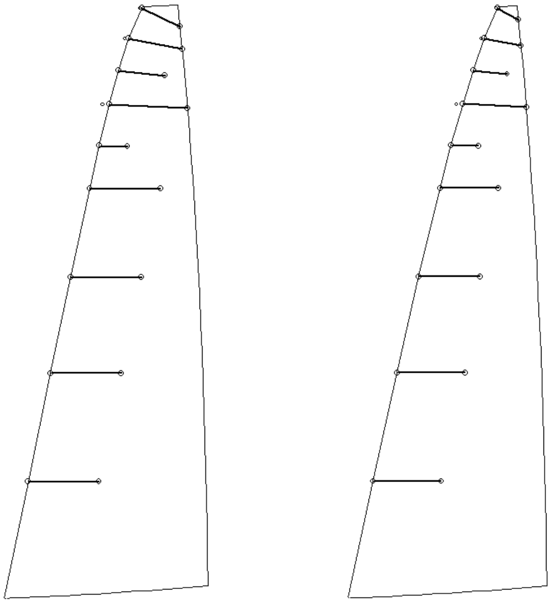


Figure 7 – Conventional TP52 and IRC 52 Mainsails

The TP52 and IRC 52 mainsails studied as part of this investigation had similar fiber quantity/layout although the exact arrangement near the head varied between the two sails given the relatively large differences in proportions near the top of the sail. Figure 8 shows the fiber layout for both mainsails near the head.

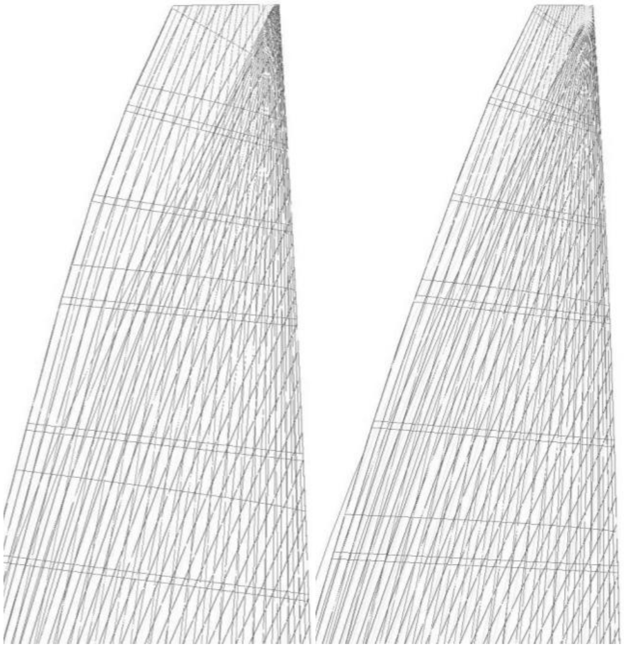


Figure 8 – Fiber Layout for TP52 and IRC 52 Mainsails

Trimming Process- Flying Shape

In concert with Botin Partners, it was agreed to develop models of optimally trimmed sails at intervals of every 2 knots between 6 and 20 knots.

As described previously, at each windspeed, the trim of the sails is iterated upon until the maximum drive force at the target heel moment is achieved. In the case of the conventional TP52 mainsail, the trim was also checked against available experimental results from the VSPARS work performed on QUANTUM RACING.

The trim at windspeeds up to 16 knots might be described as essentially full power with only changes in outhaul and sheet tension required to achieve the target heel moments and with only minor backwinding of the mainsail. It was not until windspeeds reached 18 and 20 knots where substantial changes in trim were required to depower the sails. In this context, depowering was achieved by increasing twist, dropping the traveler, changing jib lead angle, etc. In this condition the mainsail becomes fairly twisted with a slight amount of backwind caused by the interaction with the jib. Trim in this condition is a gentle balance between jib and mainsail trim. Just like real life, too much jib trim creates too much backwind in the mainsail and will cause the helm to unload and reduce the rudder angle. Whereas a jib that is too eased and a mainsail with little to no backwind may look pretty, but will cause high heel angle, excessive helm and a lack of driving force. To achieve this result often required several iterations where drive force is maximized while not exceeding the target heel moment.

Examples of the differences in trim and predicted pressure coefficient are shown in Figures 9 and 10 reflecting the simple act of easing mainsheet a few inches. The backwinding of the eased mainsail is clearly visible on the right hand side of Figure 9 when compared to the fully trimmed mainsail on the left hand side.

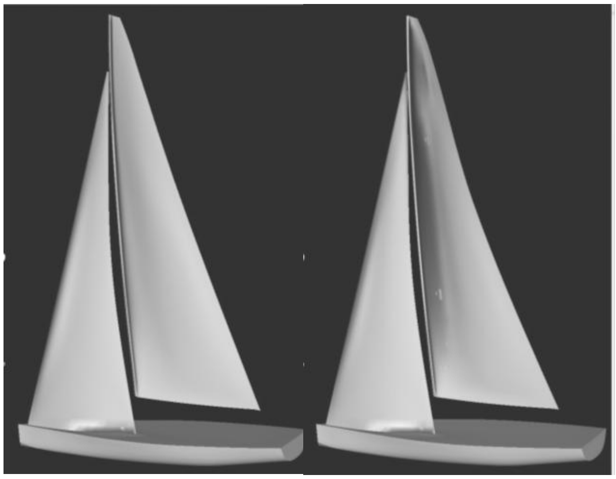
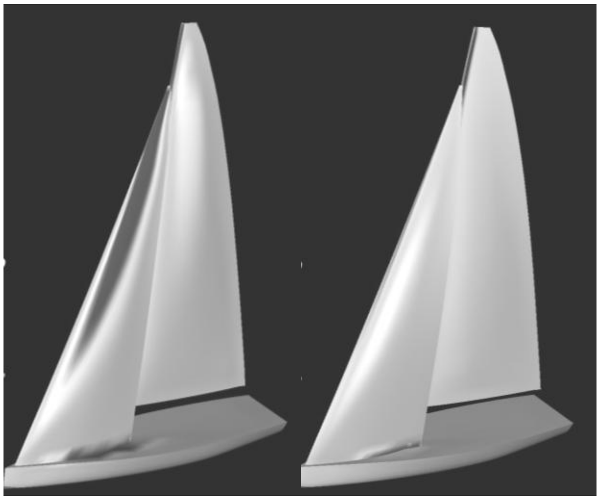


Figure 9 – Full and Depowered Trim: Simple Example

Figure 10 – Full Power and Depowered Trim: Simple Example

The increased twist in the eased mainsail leech can be easily observed on the right hand side of Figure 10.

As mentioned previously, to obtain maximum driving force and keep the heel moment down at the target level requires a combination of depowering of both mainsail and jib. These differences are highlighted in Figure 11 showing pressure coefficient for two trimmed cases at 10 knots and 20 knots true windspeed.



10 knots- full power **20 knots- depowered**

Figure 11 – Full Power and Depowered Trim

In the case of the fully powered trim at 10 knots, both the mainsail and jib are adjusted to achieve a fairly high camber ratio, the sheets are trimmed tight, the mainsail traveler is near centerline, and the jib in-hauler is pulled fairly close to centerline. This results in a relatively low angle of attack such that the luffs of both sails are fairly highly loaded.

In the case of the depowered trim at 20 knots, both the mainsail and jib are adjusted to achieve a relatively low camber ratio, the sheets are eased slightly, the mainsail traveler is dropped slightly, and the jib in-hauler is adjusted outboard a bit. This results in a relatively higher angle of attack such that the luffs of both sails are more lightly loaded resulting in a reduced heel moment.

Integration with Botin Partners VPP

Once upwind baseline optimal trims were obtained for 6, 8, 10, 12, 14, 16, 18, and 20 knots, each baseline trim was run through a macro that produces an upwind aerodynamic force/moment matrix predicted by the IQT inviscid CFD module consisting of 81 points based upon the following parameters: +/- 0.5 knots boatspeed, +/- 2 degrees TWA, +/- 3 degrees Heel, and +/- 1 degree Leeway. For each of these 81 points, the sail trim is the constant baseline shape. This approach is repeated for each individual windspeed until a 648 point (8 by 81) upwind aerodynamic model is produced for integration with the Botin Partners VPP.

The Botin Partners VPP is highly flexible and since late 2007, when the first QUANTUM RACING TP52 was designed, joint efforts have been carried out by both technical groups to help integrate the IQT aero outputs and the VPP's specific needs for a custom TP52 aerodynamics model.

As heel and rudder angles have a huge impact on the TP52's performance, the VPP in this analysis was used just to equilibrate some of the forces and moments, in order to make sure the sail trim was adjusted to targets heel and rudder angles (as in real life). This was a very efficient way of approaching the problem, as the boatspeed differences were only due to the aerodynamic inputs and not the hydrodynamic differences (as heel, rudder and leeway were the same for both cases).

RANS Comparison

Before committing to VPP results based upon the inviscid CFD, a RANS study was undertaken to address concerns that the inviscid CFD would not correctly predict the consequences of the girth changes. This concern was focused on the relatively short girths of the IRC 52 mainsail behind the mast above the hounds and the possibility that separation in this region might lead the inviscid CFD results astray. The RANS study focused on only a small subset of the inviscid CFD analysis.

The RANS analysis was performed on a mesh of approximately 7 million cells using a K-Epsilon turbulence model. Grid and turbulence model sensitivity was studied by doubling mesh density and exercising a different turbulence model before undertaking the final set of runs. Force and moment results from the sensitivity study showed less than a 1% delta.

Quantitative comparison between the inviscid and viscous CFD results show that the trends were predicted by the IQT CFD module correctly even though the absolute values did not match the presumably more accurate viscous CFD results. This provided confidence in proceeding with the mainsail planform investigation using the complete set of inviscid CFD results. Typical examples of the RANS results produced by Porto Ricerca for the two mainsails are shown in Figure 12.

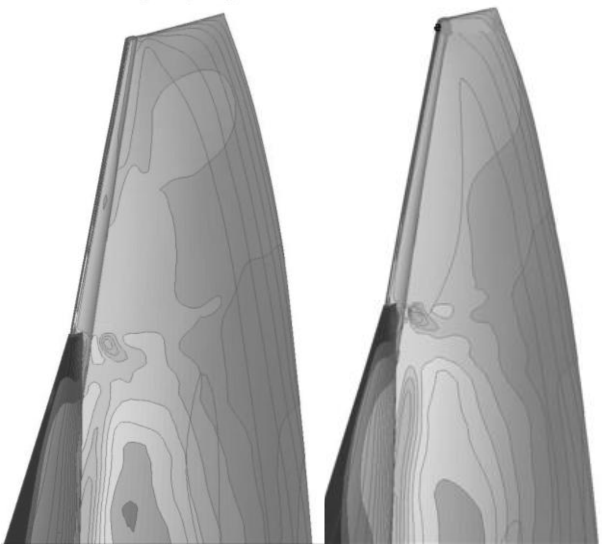


Figure 12- Typical RANS results for the TP52 and IRC 52

RESULTS

Results from the mainsail planform investigation are shown in Figure 13. The plot shows the upwind performance benefit derived from the VMG benefit alone and the VMG + IRC Rating benefit where a negative value signifies an IRC 52 mainsail advantage over the TP52 mainsail.

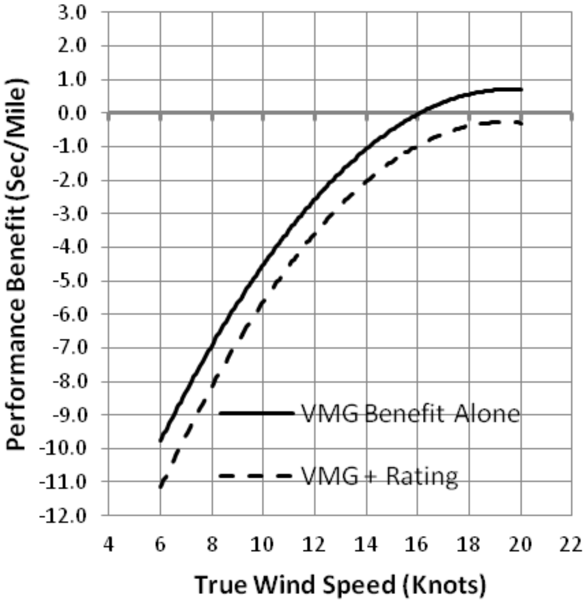


Figure 13 – VMG & VMG + IRC Rating Benefit of IRC 52 Mainsail as Function of True Windspeed

The upwind performance benefit is predicted to vary across the true windspeed range. The maximum VMG benefit is predicted at the lowest windspeeds and the advantage diminishes to near zero at 16 knots. Above 16 knots the disadvantage is quite small. The upwind VMG benefit is always less than 0.1 kts. The greatest upwind VMG benefit is realized at the lower windspeeds because the IRC 52 mainsail produces greater drive force at a given side force/heel moment in these conditions.

In addition to the predicted upwind VMG benefit, the IRC rating for the IRC 52 mainsail was reduced from 1.383 to 1.381 (.002). This provided an additional benefit ranging from approximately 1.4 seconds/mile at 6 knots to approximately 1 second/mile at 20 knots. As shown in Figure 13, the VMG + IRC Rating benefit of the IRC 52 mainsail is realized across the entire true windspeed range studied here.

CONCLUSIONS

High fidelity FSI simulations which integrate CFD with FEA are a powerful tool to accurately predict flying shapes and sail forces which can ultimately be integrated with a VPP to predict performance consequences of sail planform variation and modifying other design shape parameters.

The ability to predict flying shapes and performance consequences and making adjustments to the design shape with real time feedback allows the sail designer to optimize sail shapes for particular application and wind range well before the boat ever hits the water saving valuable program time and money.

QSDG has committed significant resources to develop and implement a comprehensive FSI simulation environment to develop specific sail designs and interface with various parties during all phases of the design/build process.

The collective capabilities of IQT have reached a state of maturity where it is being routinely applied to real world problems.

The mainsail planform investigation concluded that TP52 mainsail proportions are not optimal under IRC and identified an alternative mainsail that provided upwind VMG advantages between 6 and 14 knots and virtually no disadvantage at wind speeds in excess of 16 knots.

ACKNOWLEDGEMENTS

First, the Authors would like express their appreciation to the QSDG technical team responsible for developing IQT, Pablo del Castillo and Joan Subirats. Second, the Authors would like to offer their thanks to Alberto Porto at Porto Ricerca for performing the RANS solutions.

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