3rd HIGH PERFORMANCE YACHT DESIGN CONFERENCE

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COMPOSITE OPTIMISATION – A MINEFIELD OF OPPORTUNITIES

James Anderson, james.anderson@highmodulus.co.nz

Abstract. When optimisation routines for isotropic materials first hit the automotive industry over 10 years ago there was a flurry of activity to optimise castings, boot floor swaging patterns and panel thicknesses. Even then, many people were confused by the myriad options and assumed optimisation simply didn't work. Routines for the optimisation of composite structures still promise much but have to be used at the right stage in the projects, with the correct design variables and drivers to give useable answers. The increase in potential design variables; ply thickness, orientation, core thickness, patch size, number of plies, material thickness and even material cost – not to mention all the potential new optimisation algorithms - has given enormous potential for tailoring an optimisation problem. There are now many more ways to achieve a well optimised design, but also many more ways to get the wrong answer from an optimisation analysis. This paper provides an overview of common optimisation routines and briefly discusses the pros and cons of each. Examples of real world optimisations are given, showing both how robust solutions can be achieved and how errors can be made. Achieving robust solutions is heavily reliant on a good understanding of not only the finite element analysis process, and how composite structures work, but more importantly the optimisation processes and how composites are built. Attempting a component design without all of the above is likely to result in problems.

COMFORTABLE STRUCTURE

Dr Rozetta Payne, rozetta.payne@gurit.com
Nicolas Siohan, nicolas.siohan@gurit.com

Abstract. Interior Design is increasingly becoming more important in the design of both high performance racing yachts and slower, more comfortable cruising yachts. The drive for an improved use of internal space within a yacht presents many challenges for the naval architect, interior designer, structural engineer and the builder. These challenges can be overcome by working closely together to understand the objectives that each party wants to achieve. In this paper the main load paths, as applied to a generic yacht, are explained. Some of the common conflicts that arise when integrating with the interior comforts are also highlighted. Different approaches that can be adopted to find solutions to these conflicts are considered and comparisons between component weight and cost are drawn together for each compromise which is made.

LOW CYCLE FATIGUE OF COMPOSITE SANDWICH FOAM CORES

Rebecca Islin, risl008@aucklanduni.ac.nz
Susan Lake, susan.lake@highmodulus.co.nz
Mark Battley, m.battley@auckland.ac.nz

Abstract. This paper addresses low cycle-high elongation fatigue performance of foam core materials used in sandwich composite hull structures, particular for regions subjected to slamming loads. A testing methodology is developed based on four point loaded sandwich beams which are cycled to a prescribed displacement based on the yield deformation from pseudo-static tests. Four cores are tested, a closed cell, linear polyvinyl chloride (PVC) foam, two closed cell, cross-linked PVC foams and a styrene acrylonitrile (SAN) foam. The results from the study demonstrate significant differences between the cores, demonstrating the importance of this type of testing for evaluating cores for slamming regions of yachts. The three PVC core materials retained, or in some cases increased, the area under their post-fatigue residual strength load-deflection curves. The SAN core had a significant reduction in shear energy absorption and elongation after repeated and fatigue loading indicating that this material may not be suitable for areas which would be subject to recurring slamming events. The results of this test programme highlight the importance of using more relevant performance criteria than just static strength properties when designing for slamming regions.

HYDROELASTIC BEHAVIOUR OF SLAM LOADED COMPOSITE HULL PANELS

Mark Battley, m.battley@auckland.ac.nz
Tom Allen, tall028@aucklanduni.ac.nz
Jason Schierlink, jsch089@ec.auckland.ac.nz
Susan Lake, susan.lake@highmodulus.co.nz
Petter Pehrson, ppehrson@kth.se

Abstract. The effects of stiffness on hydroelastic responses of composite marine hull panels subjected to water slamming loads have been experimentally characterised. Panels included a very flexible single skin laminate, a medium stiffness sandwich panel and a very stiff sandwich panel. Panels were tested at a deadrise angle of 10º for a range of water impact velocities from 0.5 to 7m/s in a Servo-hydraulic Slam Testing System. Results demonstrate that the panel stiffness has a significant effect on the responses of slam loaded composite panels. Flexible panels had reductions in the local velocity at the centre of the panel relative to the water, reducing peak pressures at the panel centre. Pressures increased near to the chine edge of the panel, possibly due to reductions in the local deadrise angle due to panel deformation. Such effects were particularly noticeable when the loading rate was of similar order to the first natural frequency of the panel. The implications of the effects of panel stiffness on effective pressure and panel structural response on composite structural design are discussed.

V-SPARS: A COMBINED SAIL AND RIG SHAPE RECOGNITION SYSTEM USING IMAGING TECHNIQUES

D.J. Le Pelley, d.lepelley@auckland.ac.nz
O. Modral, o.modral@auckland.ac.nz

Abstract. Measurement of flying sail shapes is an extremely useful technique both for design and for use whilst racing. Until now, no simple method of measuring highly curved downwind sails has been found. In this paper, a method called Visual Sail Position And Rig Shape (V-SPARS) is presented which addresses this issue. The system uses deck mounted cameras to look up at stripes marked on the sails and has the ability to correct for large perspective effects. In addition, the rig deflection is measured from the displacement of target points and is combined with the sail shapes to give a global position of the sails and rig above the deck. This paper represents a validation of the system for many different types of sails and, through the results of wind tunnel experimentation, shows a number of ways in which the system can be used. Conventional upwind sail testing has been carried out in a wind tunnel using V-SPARS to accurately measure the sail stripes and simultaneous rig position. The system has been used with downwind sails to capture the highly curved shapes and global locations of a gennaker flying from a bowsprit.

A WEB SERVICE FOR YACHT DESIGNERS

Matteo Ledri, matteo.ledri@esteco.com
Mauro Poian, mauro.poian@esteco.com
Rosario Russo, rosario.russo@esteco.com
Enrico Nobile, nobile@univ.trieste.it

Abstract. Several web-based software packages are available now a days following a trend known as "software as a service," or "cloud computing." The earliest were e-mail programs, but they now include services to create and manage content and even whole operating systems. These services don't require time-consuming upgrades because the service provider maintains them. This paper presents the application of such approach to develop a software for yacht design. First a web portal (sail4web) has been developed: it includes a series of tools addressed to yacht designers, such as a velocity prediction program. In the second phase the robustness of the system has been tested on a wide set of boat configurations. Finally additional features, such as advanced post-processing and import-export facilities, have been implemented in order to assess and improve sailing yacht performances. Sail4web is completely Web-based so designers can use it with any type of computer, operating system and browser. Users can get to their accounts and their own database from different computers. The standard VPP (Velocity Prediction Program) model is based on aerodynamic and hydrodynamic force approximations (by means of empirical functions, like the well-known IMS (now named ORC International) sail coefficients, or the Delft polynomial for residuary resistance calculation). Built-in facilities make the VPP model customizable if better insight and precision is needed. For high-level applications the VPP can be coupled with CFD solvers, or may use external data (like those coming from wind tunnel or tank tests). The computed or imported aero and hydro matrices are automatically fitted with a response surface in order to be used by the VPP solver. A case study is presented, showing the capabilities of the service applied to a racing yacht design project.

K-SPLINE: A NEW CURVE FOR ADVANCED HULL MODELLING

Kevin Cudby, msg@kevincudby.com

Abstract. The k-spline is introduced and the underlying equations presented. These equations yield four parameters, including the area coefficient. The k-spline is inherently smooth and convex, which reduces the need for heuristic computing. The k-spline equations facilitate input parsing, which permits a user-friendly interface. A family of light displacement sailboat hulls is presented which have k-spline sections, a k-spline centreplane curve, and an overhanging transom stern. These hulls are modelled by applying a metasurface to a framework of transverse sections and longitudinal curves. These variants are created by manipulating longitudinal parameter curves which define some of the k-spline parameters. The area coefficients do not change between variants. A practical application is demonstrated, in which the underwater shape of a sailboat hull can be modified, without affecting its hydrostatic characteristics in the upright condition. All variants have practically identical displacement, LCB, and LCF, in the upright condition. In the heeled condition, the waterlines and the position of the centre of flotation differ between variants. The overhanging stern leads to a small but usually negligible impact on upright displacement, LCB, and LCF, between variants. When the hull has an immersed transom stern, manipulating the k-spline parameters does not affect the upright displacement, LCB, and LCF. It is proposed that such a family of hull shapes allows a designer to investigate potential performance differences using computational fluid dynamics and/or tank testing. This is only one of numerous possible applications for the k-spline. The k-spline has been implemented in an advanced hull modelling application.

EXPLORING AUTOMATIC EVOLUTIONARY YACHT SAIL DESIGN

Vicente Díaz Casás, vdiaz@udc.es
Fernando López Peña, flop@udc.es
Richard J. Duro, richard@udc.es

Abstract. In this work an environment for the automatic aerodynamic optimization of sails and its associated methodology is presented. The proposed approach automatically explores the design space and derives a set of design parameters defining the shape of the model providing the best performance. The system makes use of macro-evolutionary techniques that operate using the evaluation of the efficiency of individual sails by means of fluid dynamic simulators. The participation of the designer is limited to the initial definition and creative stages where the problem, its characteristics, targets, and constraints are determined. After a detailed description of the environment, some test results on a Tornado class sail are presented.

WIND TUNNEL AND CFD INVESTIGATION OF UNCONVENTIONAL RIGS

Fabio Fossati, fabio.fossati@polimi.it
Sara Muggiasca, **Fabrizio Martina, A. Nazareth**
A. Vallicelli , I. Viola

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.

OPTIMISATION OF SPAN-WISE LIFT DISTRIBUTIONS FOR UPWIND SAILS

Peter Richards, **pj.richards@auckland.ac.nz**
T. Junge, timm.junge@euroavia.de
H. Hansen, hansen@friendship-counsulting.com
D.J. Le Pelley, d.lepelley@auckland.ac.nz
F. C. Gerhardt, fger003@aucklanduni.ac.nz

Abstract. Wind tunnel experiments using a Real-Time Velocity Prediction Programme to investigate the optimal trim of a VO70 model under various simulated true wind speeds are reported. The results illustrate that the decision made depend upon the particular apparent wind direction and true wind speed. It is suggested that these can be sub-divided into three broad bands: low wind speeds where the total drag is minimised and the trim that provides the maximum thrust coefficient is chosen, moderate wind speeds where the heel angle has a strong effect and the optimum choice includes a reduction in lift coefficient and centre of effort height and strong winds where the heel angle and hence heeling moment is limited to the maximum acceptable value and the optimum loading distribution is strongly constrained by this limit. Extended Lifting Line Theory is used to further investigate the detailed loading distribution on an AC90 mainsail. The result illustrate the way in which the optimal distribution changes with varying conditions.

LIFTING LINE METHOD FOR MODELLING COVERING AND BLANKETING EFFECTS FOR YACHT FLEET RACE SIMULATION

Thomas Spenkuch, ts305@soton.ac.uk
Dr. Stephen Turnock, srt@soton.ac.uk
Dr. Matteo Scarponi, ms1004@soton.ac.uk
Prof. Ajit Shenoi, r.a.shenoi@soton.ac.uk

Abstract. An approach is presented that can be used to enhance the realism of yacht fleet race simulations. The wake of an upwind sailing yacht is represented as a single heeled horseshoe vortex (and image) system. At each time step changes in vortex strength are convected into the wake as a pair of vortex line elements. These subsequently move in accordance with the local wind, self-induced velocity and velocity induced by the presence of the wakes of other yachts. An empirical based decay factor is used to eventually remove the far wake. A synthesis of sail yacht wake representations based on detailed 3D Reynolds Averaged Navier-Stokes (RANS) Computational Fluid Dynamics (CFD) calculations with wind tunnel test results are used to capture the initial strength of the combined main-jib vortex system and its vertical height. These were based on a typical upwind sail arrangement for a range of heel angles and in-line calculations for a pair of yachts separated by three boat lengths. This paper details the basis of the validated CFD results for a yacht at heel and the analysis of the CFD results to provide an approximate single line vortex method for the yacht. The developed algorithm will eventually run within the Robo-Race which is a real-time yacht race strategy analysis tool based on MATLAB®-Simulink® developed at the University of Southampton.

THE EFFECT OF HEEL ANGLE AND FREE-SURFACE PROXIMITY ON THE PERFORMANCE AND STRUT WAKE OF A MOTH SAILING DINGHY RUDDER T-FOIL

Jonathan R. Binns j.binns@amc.edu.au
Paul A. Brandner p.brandner@amc.edu.au
Julien Plouhinec plouhiju@ensieta.fr

Abstract. The use of hydrofoils for sailing yachts is becoming more prolific. However its use in mainstream sailing classes has only become standard for the Moth dinghy class. The Moth class uses a twin T-Foil design, one on the centreboard for primary support and one on the rudder for additional support and control. The rudder T-Foil forms the basis of an experimental study carried out at the Australian Maritime College towing tank facility described here. Lift and drag data is presented for upright and heeled configurations considered indicative of windward sailing conditions. Force variation with respect to angle of incidence, depth of submergence and onset flow speed is presented using elliptical lift distribution parameters for easy design use. In addition deflection of the strut run-up was attempted to produce additional lift. Finally, a windward sailing condition prone to ventilation has been identified.

CFD-BASED HYDRODYNAMIC ANALYSIS OF HIGH PERFORMANCE RACING YACHTS

Len Imas, Len.Imas@stevens.edu
Gregory Buley, Greg.Buley@cdicorp.com
Bryan Baker, bryan@farrdesign.com
Britton Ward, britton@farrdesign.com

Abstract. Advances in Navier-Stokes solver technology have enabled naval architects and hydrodynamicists to implement high fidelity CFD models as a means of analyzing complex flows around high performance racing yachts. As a consequence, recent research activity in this area has increased and the associated results have contributed to enlarging the boundaries of the design spaces being explored. This paper will present selected examples from a research study based around tow tank tests and CFD simulations of a canonical high-performance racing yacht. The geometry configuration studied was fully appended with rudders, keel/bulb and a dagger-board. Simulations were performed under a multitude of sailing conditions covering both lifting and non-lifting flow regimes. Topics covered will address (i) validation against tow tank measurements; (ii) efficient performance of large-scale computations; and (iii) numerical issues related to (a) mesh generation, (b) solution, discretization, and free surface capturing algorithms, (c) turbulence modelling, (d) rigid body dynamics and sail force models.

TACKING SIMULATION OF SAILING YACHTS WITH NEW MODEL OF AERODYNAMIC FORCE VARIATION

Yutaka Masuyama, masuyama@neptune.kanazawa-it.ac.jp
Toichi Fukasawa, toichi@neptune.kanazawa-it.ac.jp

Abstract. A mathematical model for the tacking manoeuvre of a sailing yacht is presented as the extension of research by the same authors. In the previous paper the authors have proposed the equations of motion expressed by the horizontal body axes system. The calculation method was applied to a 34-foot sailing cruiser and the simulated result indicated good agreement with the measured data from full-scale tests. However, the modelling of aerodynamic force variation during tacking was insufficient due to lack of information about the sail forces. In this report, the authors performed full-scale measurement of sail forces during tacking manoeuvres using a sail dynamometer boat *Fujin*. The *Fujin* is a 34-foot sailing cruiser, which has a measurement system to obtain the sail forces and shapes, and boat attitude simultaneously. From the results of full-scale measurement a new model of aerodynamic force variation for the tacking manoeuvre was proposed. The equations of motion were also reanalyzed to easily execute the numerical simulation. Using this calculation method, the tacking simulations were performed and compared with the measured data for two full-scale boats. The simulated results indicated good agreement with the measured data. This simulation method provides an effective means for assessment of tacking performance of general sailing yachts.

UNSTEADY AERODYNAMIC PHENOMENA ASSOCIATED WITH SAILING UPWIND IN WAVES

Frederik C. Gerhardt, fger003@aucklanduni.ac.nz
Richard G. J. Flay, r.flay@auckland.ac.nz
Peter Richards, pj.richards@auckland.ac.nz

Abstract. Velocity Prediction Programs (VPPs) based on a steady-state equilibrium between aero- and hydrodynamic forces continue to be important tools when assessing the performance of yachts during the design process. Over the last decade a number of Dynamic Velocity Prediction Programs (DVPPs), which also allow study of the dynamic characteristics of the boat, have been developed. Most DVPPs are based on numerically solving the equations of motion of the yacht according to Newton's second law with the aerodynamic forces being calculated from quasi-steady theory. This paper discusses whether this assumption of quasi-steady aerodynamics can be justified and also analyses the error introduced by such a quasi-steady analysis. Unsteady potential flow theory is used to predict the pressure distribution on an aerofoil-like, two-dimensional "slice" of a mainsail carrying out harmonic oscillations both perpendicular to, and along the direction of the incident flow. Such types of motion occur when a yacht pitches or rolls in waves. Theoretical pressure distributions are compared to wind tunnel measurements on an oscillating, rigid mainsail model of 3.2 metre span and 0.447 metre chord length. Experiments were carried out at reduced frequencies ranging from $k = 0$ to $k = 0.8$, as the mainsail of an International America's Cup Class yacht sailing upwind in waves typically encounters reduced frequencies in this range. It is found that predictions based on unsteady theory match the measured pressure distributions much better then quasi-steady predictions. This leads to the conclusion that, if the performance of the yacht is to be predicted on a time-scale shorter then the pitching period, this can be achieved best with an unsteady aerodynamic model. In the paper no attempt is made to investigate the influence of the flexibility of the sails, sail interaction, three-dimensional effects or phenomena related to dynamic stall.

THE DEVELOPMENT AND USE OF SAILING SIMULATION FOR IACC STARTING MANOEUVRE TRAINING

Jonathan R. Binns j.binns@amc.edu.au
Karsten Hochkirch Hochkirch@FRIENDSHIP-CONSULTING.com
Frank De Bord fdebord@chesmarinetech.com
Ian A. Burns iab@ianburns.com

Abstract. Sailing simulation has rapidly evolved over the last twenty years to be a useful tool in design optimisation, design evaluation, human factor analysis and beginner sailor training. The research work detailed in this paper explains a systematic approach to the development of a sailing simulation system suitable for use by elite sailor in the preparation of starting manoeuvres. An advanced velocity prediction programme was used to simulate the steady state force balance based on towing tank and wind tunnel experiments. The dynamic terms in the equations have been estimated by a systematic series of full scale tests of increasing complexity. The final simulation was incorporated into existing race analysis software permitting its use by professional sailors without the need for learning additional software skills.

HIGH FIDELITY CFD SIMULATIONS IN RACING YACHT AERODYNAMIC ANALYSIS

J.B. Braun, jbb@prg.northsails.com
Len Imas, limas@stevens.edu

Abstract. Advances in hybrid approaches comprising advanced mesh generation techniques, Navier-Stokes solver technology, and structural dynamic modeling of membranes, have enabled sail designers and research aerodynamicists to implement high fidelity aerodynamic and fluid-structure interaction (FSI) simulation models of yacht and sail aerodynamics. This paper will describe recent trends in aerodynamic CFD analysis of racing yachts where the simulations are extended to include other geometry interacting with the sail such as the hull, mast and boom for example. The aerodynamic interaction effects between the various components will be presented and discussed through relevant examples.

CLOSE COUPLING OF A CFD SAIL MODEL WITH A VPP

Stuart Norris, s.norris@auckland.ac.nz
Peter Richards, pj.richards@auckland.ac.nz

Abstract. Meaningful simulation of yacht sails is dependent on the geometry and boundary conditions being a faithful representation of reality. In this paper a CFD model of a yacht has details of the geometry and the boundary conditions being controlled by a Velocity Prediction Program integrated with the flow solver. The inlet velocity profile is determined by the calculated boat speed, whilst the computational mesh is deformed to allow for the heeling of the yacht predicted by the VPP. The computational method is described, and the method is demonstrated with a calculation of the speed polar for an IACC yacht.

THE USE OF ANSYS CFX IN AMERICA'S CUP YACHT DESIGN

Nick Hutchins, nick.hutchins@emiratesteamnz.com

Abstract. The design of a state of the art racing yacht of the type used in the America's cup requires the use of state of the art design tools. Emirates Team New Zealand made extensive use of Ansys CFX in the design of NZL 84 and NZL 92, the IACC version five yachts raced in the 32nd America's Cup in Valencia 2007. This paper discusses that work. Particular attention is paid to the design of the keel bulb. In this case Ansys CFX was used to compute the drag of candidate shapes. These results were then analysed using a VPP and further generations of improved candidates were developed using genetic optimisation. A second major area of study involved sail shapes. The RANS analysis of the shapes is discussed, along with the process used to integrate this into the design and sailing program. Initial shapes were taken from both design software and sail vision photos from the yachts. Using Ansys CFX, the shapes were then analysed and the performance compared in the VPP. Results were then fed back into the sailing program and developments tested on the yachts with the aid of real time sail shape analysis. The last point is the development of the software with respect to free surface calculations and our experience with this in both IACC version 5 and the new AC90 class.

A NUMERICAL INVESTIGATION INTO THE HYDRODYNAMIC PERFORMANCE OF A FIN WITH A SCALLOPED LEADING EDGE

Wim M. van Rees, w.v.rees@marin.nl
Len Imas, Len.Imas@stevens.edu

Abstract. The hydrodynamic effect of adding tubercle bumps to the leading edge of a fin with a high aspect ratio planform, inspired by the protuberances at the leading-edge of humpback whale fins, has been investigated parametrically. CFD simulations were performed on two sets of fins, each set having a different thickness to chord ratio. Within each set, planforms having three different tubercle distributions as well as a baseline planform with a straight leading edge, were considered. This paper will present a discussion on the resulting lift/drag characteristics between the two leading edge types. Flow regimes covering a broad angle of attack range including both pre- and post-stall at Reynolds numbers on the O(10^6) are considered. Secondly, a discussion on the sensitivity and validity of the numerical solution to the employed turbulence models will also be presented.

NUMERICAL INVESTIGATIONS OF THE EFFECTS OF WINGLETS ON IACC YACHT DRAG COMPONENTS

Michal Orych, michal.orych@flowtech.se
Heng Ran, heng.ran@sspa.se
Lars Larsson, lars.larsson@chalmers.se

Abstract. A computational study of an America's Cup Class keel has been carried out to improve the understanding of the effects of the winglet geometry on yacht drag components. A potential flow panel code together with a coupled thin turbulent boundary layer method was used. Systematic variations of the geometrical parameters were first carried out for chord length, span, taper ratio, dihedral and sweep angles. The calculations covered a wide range of leeway angles in upright and heeled conditions for each parametric variation. The study was extended to analyze possible interactions between the winglets and the free surface and its influence on the optimum winglet geometry. The largest impact on the efficiency was associated with the chord length, span and taper ratio which to a large extent influence both the induced and friction drag. The calculations indicate that optima with respect to the varied parameters can be found for a given side force. In most cases a reduction of the induced drag involves a frictional drag increase. The positive effects of the winglets are easier to achieve at higher keel loadings when the induced drag is significant. Free surface interaction is more distinct at large heel angles and may affect the winglet design. The study shows that a very detailed analysis is necessary to design winglets that will improve a yacht's overall performance. The design can be supported efficiently by the presented numerical methods, preferably supplemented by optimization routines to reduce the effort and time spent on processing the results.

STRONGLY COUPLED VPP AND CFD RANSE CODE FOR SAILING YACHT PERFORMANCE PREDICTION

Yann Roux, yann@k-epsilon.com, **Mathieu Durand** mathieu@k-epsilon.com
Alban Leroyer , alban.leroyer@ec-nantes.fr, **Patrick Queutey** patrick.queutey@ec-nantes.fr
Michel Visonneau, michel.visonneau@ec-nantes.fr
Jérémie Raymond, jeremie.raymond@ec-nantes.fr, **Jean Marie Finot**, jmfinot@finot.com
Frédéric Hauville, frederic.hauville@ecole-navale.fr, **Aji Purwanto**, aji.purwanto@numeca.be

Abstract. During the design phase of a high performance sailing yacht, naval architects use tools such as VPPs (Velocity Prediction Programs). A VPP solves the equations of motion of the boat using hydrodynamic and aerodynamic force models and allows determination of the speed and the attitude of a sailing yacht. Solving the equations of motion is relatively simple but estimating aerodynamic and hydrodynamic forces is more complex and extremely costly since each boat configuration requires a set of forces that may be derived from more or less accurate empirical, numerical or experimental methods. In general at the beginning of the design phase, architects use empirical methods (quick but not so accurate) to obtain a first result. Then the databases are enriched using computed and/or experimental data around the operating points estimated by the empirical method. Recent developments in RANSE based CFD software FINE™/Marine enable us to reduce the number of steps in performing complete modelling of a sailing yacht in motion. The software is able to simulate the speed and the attitude of a sailing boat by solving the Unsteady Reynolds Averaged Navier-Stokes equations with free surface in 6 DOF (here 5 solved DOF with an imposed zero yaw motion) and by towing the vessel using an aerodynamic wrench computed by the software ARAVANTI. Both air and water flow fields are solved with the help of an Interface Capturing Method. Thus, the boat accelerates and adopts an attitude (angle, drift, trim and sink) and a speed that balance hydrodynamic and aerodynamic forces. This development is part of a long term collaboration aiming at modelling a full scale boat in motion subject to hydro and aero-elastic forces. As an illustration, a validation campaign on calm water of the RANSE code and recent results obtained with this new type of VPP applied to an AC 90 boat type will be presented.

PERFORMANCE PREDICTION OF THE OLYMPIC VARIANT TORNADO CLASS CATAMARAN

Richard G.J. Flay, r.flay@auckland.ac.nz
Stuart Norris s.norris@auckland.ac.nz
Katherine A. Halliburton, Katherine_h30@hotmail.com
Daniel A. Jowett, Jowett.daniel@gmail.com
Natasha Erriu, nerriu@unica.it

Abstract. This project is part of a collaboration between the Yacht Research Unit at Auckland University, and the University of Cagliari in Sardinia to develop procedures for determining the performance of high performance catamarans. The Tornado catamaran was used as the subject for these investigations and the aim of this research was to write a velocity prediction program for the Olympic variant Tornado class catamaran yacht. To do this both the aerodynamic and hydrodynamic coefficients for lift and drag force must be found. Mathematical models and formulae from previous research were used in order to develop a model the hydrodynamics of the yacht. To develop a model the aerodynamic performance, a 1/5th scale model of the yacht was tested in the Twisted Flow Wind Tunnel at the University of Auckland, and the forces and moments acting on the yacht, caused by the wind, were measured. By combining information from these two models it was possible to find equilibrium conditions for the yacht, and thus its speed. A VPP was then written in the Matlab programming language with inputs being the true wind speed and direction with the output being the yacht speed. The results of the analysis give yacht speeds that are higher than those obtained in previous velocity predictions, and this is expected due to the improved sail configuration used in the present Tornado class rules, compared with the sail planforms used in the previous velocity predictions.

MEASUREMENT AND SIMULATION OF PRESSURE DISTRIBUTION ON FULL SIZE SAILS

William Graves, wsgraves@mit.edu
Todd Barbera, t.barbera@comcast.net
J.B. Braun, jbb@prg.northsails.com
Len Imas, limas@stevens.edu

Abstract. Technological advances in wireless networking equipment and atmospheric pressure sensors have enabled the measurement of the pressure distribution across full size sails in normal operation. The pressure measurements may be generated separately on the windward and leeward sides, and on other parts of the rig. Pressure maps of the entire sail can be produced in real-time to provide a detailed time-dependent picture of the pressure distribution, showing the fluctuations and deviations from nominal values due to any changes of the rig, boat motion, or wind. This information is useful in the design process, where sail designers and research aerodynamicists can quantify real-world, full-scale measured differences against computer simulations or alternative sail shapes. It also can be used by sail trimmers to set the best sail shape rapidly and in changing conditions. The pressure sensors are small and lightweight, allowing them to be applied in high density across the entire sail. Laptop software collects and analyses the data, displaying the pressure values and logging the data for post-analysis. This paper provides a description of the technologies used to implement the wireless pressure measurement system, presents examples of the data obtained, and compares the measured results with CFD simulations.

THE EFFECTS OF STAYSAILS ON YACHT PERFOMANCE

D.J. Le Pelley, d.lepelley@auckland.ac.nz
L. Kjellberg, leif.kjellberg@gmail.com
R.G.J. Flay, r.flay@auckland.ac.nz

AAbstract. A staysail can be defined as any supplementary sail flown between the mast and primary genoa or spinnaker to enhance aerodynamic performance. Much of the time, huge expense and effort is put into improving the performance of the flying sails with little thought to staysail design and position. Wind tunnel experiments were carried out in the University of Auckland's Twisted Flow Wind Tunnel on a range of staysails operating under typical flying sails. Flow visualisation of interesting concepts was carried out. The analogy of the staysail as a turning vane that improves the flow over the other sails was investigated. Independent supports were used to determine the load contribution of the staysail to the overall loading of the sail combination. A range of clew heights of the staysail were investigated. A significant gain in driving force of around 10% on average and up to 17% has been demonstrated by correct selection and placement of staysails. Staysail area is not a key factor, with the smallest staysail testing giving one of the largest improvements. Masthead staysails and sailing triple-headed were both found to have a significant performance benefit over a conventional medium sized staysail.

DEVELOPMENT OF A THREE-DIMENSIONAL INVERSE SAIL DESIGN METHOD

Julien Pilate, julien_pilate@hotmail.com
Frederik C. Gerhardt, fger003@aucklanduni.ac.nz
Richard G. J. Flay, r.flay@auckland.ac.nz

Abstract. A code which generates the camber shape of a sail from a desired sail plan-form, sail twist distribution and surface pressure map has been written. This is an iterative 3D inverse sail design code. The method initially uses inverse thin aerofoil theory, applies this to the desired pressure map and creates an initial sail shape. A theory which gives a relationship between the change in the pressure map and the change in the sail camber was developed and is described. The code applies that theory to the difference between the desired pressure map and the pressure map of the initial sail shape. The calculated camber difference is added to the initial shape to give an improved shape with a pressure distribution closer to the desired one. This process is repeated until the generated sail produces the desired pressure map. Validation tests were performed by generating a pressure distribution from a known sail shape using a VLM code, and then the method described in the paper was used to find the shape from the pressure distribution. The sail shape was successfully obtained in as few as five iterations, with a maximum error of only about 0.2 % of the sail chord, which is acceptable in sail design practice.