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ABSTRACTS

Experimental and numerical prediction of foiling monohull dinghy performance

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The rise in interest in large foiling yachts, such as those in the America's Cup, has spurred a corresponding interest in foiling applications in monohull sailing dinghies, both for boats designed specifically for foiling, and through retro-fit foil kits. The present study considers the assessment of foil systems for such boats, and specifically the prediction of the necessary foil performance of t-foils with and without flaps. Towing tank and wind tunnel experiments are used alongside numerical simulations. The accuracy of different simulation approaches is examined and the corresponding sensitivity of the predicted boat speed to the numerical method adopted is identified. Results are presented via two case studies, predicting performance for a foiling International Moth, and for a Europe dinghy retro-fitted with hydrofoils.

Benchmark data for the numerical simulation is obtained using two approaches. The main lifting foil for a moth dinghy with flap was tested at full-scale in a towing tank at a range of speeds, trim angles and flap angles. Results are compared with published experiment data for a similar moth foil. In a complementary set of tests, the rudder of a Europe dinghy was tested in a wind-tunnel, initially in the original design condition, and subsequently with a T-foil rudder designed for a retro-fit foiling solution.

A range of numerical techniques of varying levels of complexity, fidelity, and numerical intensity were then used to predict the performance of the foils. The techniques adopted include 2D predictions using XFOIL allied to a simple correction for 3D effects, a numerical lifting line theory, a fully 3D panel code and RANS CFD. The data from these simulations is used in two ways. The data is first used to examine the accuracy of the different simulation techniques by comparison of predictions with the measured data. The simulated data is then deployed in a 5-DOF Velocity Prediction Program (VPP) in order to predict the performance of a foiling moth and a concept design for a foiling Europe over a windward-leeward course, in order to illustrate the sensitivity of the predicted boat performance to the choice of foil simulation technique.

Conclusions are drawn regarding the accuracy of the simulation techniques, and the pros and cons of wind tunnel and towing tank testing of T-foils are discussed. The VPP study demonstrates the trade-offs which may be exploited in the design process when computational resource is limited: between a small number of high fidelity simulations with high numerical intensity and a large number of moderate-fidelity simulations which are computationally less intensive.

Hydrodynamics of Three Slender Models Resembling Polynesian Canoe Hulls

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Towing tank tests were carried out on three slender models in order to obtain more information on the hydrodynamics of such shapes, and in particular, how the shapes could generate side force when operating at a leeway angle. Slender hulls are of much interest for multi-hull vessels. There is increased interest in such vessels at present due to the use of wing-sail multi-hulls in the recent America's Cup races in San Francisco and Bermuda, although the AC yachts use foils to generate a lot of the side force, and only at low speeds are the hulls in the water. On the other hand, ancient Polynesian multi-hull vessels did not appear to have keels, and so the side-force had to be generated by the hulls. The authors speculates that the earliest vessels had rounded hulls (from trees) and were probably used mainly for sailing downwind. However, with time, it would have been realised that sail powered vessels could also manoeuvre across the wind, and then the importance of side force as well as drag would have begun to be appreciated. Modern Polynesian multi-hull vessels often have one or both hulls which are Vee-shaped in cross-section. Hence, it appeared that evolution may have caused a change in shape from circular to Vee, presumably because such shapes

are better able to generate side force. A CFD study with ANSYS-CFX using three different hulls was carried out as suggested by the first author and it showed that sharper Vee sections were better at generating side-force than a rounded hull. The purpose of the present tests is to investigate whether such behaviour could also be observed in physical testing. Three models were manufactured and were tested in the Towing Tank at Newcastle University in July and August 2013. One set of tests were carried out with fixed sink and trim, and the August tests had free sink and trim, with a thrust moment applied which approximated the sail force at part height up the mast. It was found that there was good agreement between the CFD and tank test results, and indeed that the hypothesis that narrower Vee shaped hulls would generate more side-force when at leeway than a rounded hull was proved.

The Un-restrained Sailing Yacht Model Tests – A New Approach and Technology Appropriate to Modern Sailing Yacht Seakeeping

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Over the recent years the Wolfson Unit has seen a greater impetus from yacht designers and their clients to quantify and compare the seakeeping qualities of their sailing yacht design choices. Modern high performance yachts, fitted with a wide range of appendages generating lift and creating large moments, provide a number of complex challenges for designers.

Assessing seakeeping behaviour and performance in a seaway is, indeed, important during the design process since the motions cause unsteady effects on the yacht hydrodynamic characteristics, for instance on the lift generating capabilities of the appendages. Hence it may not be justifiable to assume during the optimisation process that the yacht outperforming other design candidates in calm water would also perform well in waves.

Therefore, the Wolfson Unit developed an innovative experimental model testing approach that would be an improvement over existing methods, simulating the 6 degrees of freedom motions and accelerations.

The unique un-restrained sailing test approach uses a mast mounted air screw device to simulate the aerodynamic propulsion from the sails allowing a scaled model of the yacht to be tested at a range of conditions, sea states and wave directions (from head seas to following waves). These tests can be used as a comparative tool to assess controllability and seakeeping characteristics of multiple configurations (e.g. hull shape, appendages, inertias) by quantifying induced motions and providing an estimate of added resistance in waves. Non-linearity attitudes such as surfing can be investigated.

Free-running model testing is a technique frequently used in the development of power vessels, but little adoption is made in the sailing yacht world. Furthermore dynamic and seakeeping studies are at present challenging for computational fluid dynamics based tools, encouraging an experimental based approach.

This paper introduces an un-restrained model testing method on sailing yachts. Discussion will also be made on how this new method can be implemented in design decisions and add value during the design and performance evaluation process for sailing yachts.

Maneuver Simulation and Optimization for AC50 Class

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The stability and the dynamic behaviour is an integral part of designing hydrofoil supported sailing vessels, such as the America's Cup (AC) 50 class. The foil design and the control systems have an important influence on the performance and stability of the vessel. Both foil and control system design also drive the maneuverability of the vessel and determine maneuvering procedures. The AC50 class requirements lead to complex foil control systems and the maneuvering procedures become sophisticated and multifaceted.

Sailing and maintaining AC50 class yachts is a complex, expensive and time-consuming task. A dynamic velocity prediction program (DVPP) for the AC50 is therefore developed to assess the dynamic stability of different foil configurations and to simulate and optimize maneuvers. The goal is to evaluate certain design ideas and maneuvering procedures with this simulator so that sailing time on the water can be saved.
The paper describes the principal concepts of developing a AC50 model in the DVPP FS-Equilibrium. The force components acting on the yacht are defined based on physical principles, computational fluid dynamics (CFD) simulations and experimental investigations. The control systems for adjusting the aero- and hydrodynamic surfaces are modelled. Controllers are utilized to simulate the human behaviour of performing sailing tasks. Maneuvers are then defined as sequences of crew actions and crew behaviours.
In the paper examples of utilising the DVPP in preparation for the 35th America's Cup in Bermuda are described. The DVPP is for example used to investigate the effect of different boat set-ups on stability and handling during maneuvers. With the sailing team, maneuver procedures are developed and tested. Procedures such as dagger board and rudder elevator movement and crew position are investigated and evaluated to minimize the distance lost during tacking and gybing. The DVPP is also employed for trajectory optimization during maneuvers.

Application of System-based Modelling and Simplified-FSI to a Foiling Open 60 Monohull

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The increasing number of foiling yachts in offshore and inshore races has driven engineers and researchers to significantly improve the current modelling methods to face new design challenges such as flight analysis and control (Heppel, 2015). Following the publication of the AC75 Class Rules for the 36th America's Cup (RNZYS, 2018) and since the brand new Open 60 Class yachts are all equipped with hydrofoils, the presented study will propose a system-based modelling coupled with a simplified FSI (fluid-structure interaction) method that leads to better understand the dynamic behavior of monohulls with deformable hydrofoils.
The aim of the presented paper is to establish an innovative approach to assess appendage behavior in a dynamic VPP (velocity prediction program). For that purpose, dynamic computations are based on a 6DOF mathematical model derived from the general non-linear maneuvering equations (Horel, 2016). The force model is expressed as the superposition of 7 major force components expressed at the center of gravity of the yacht: gravity, hydrostatic, maneuvering, damping, propulsion (wind), control (rudders, daggerboard, foils …) and wave (Froude-Krylov and diffraction phenomenon).
As test cases, course keeping simulations are performed on an Open 60 yacht with control loops to simulate the wing trimmer, helmsman and foil trimmer when finding the optimal foil settings is needed. In first hand, IMOCA's polar diagrams are used as reference.
In calm water and in waves, the influence of foil's shapes (foil with shaft pointing downward and tip pointing upward, foil with shaft pointing upward and tip pointing downward) and stiffness (non-deformable, realistic, flexible) on the global behavior of the yacht is presented.

6DOF behavior of an offshore racing trimaran in an unsteady environment.

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While in recent years the use of hydrofoils has experienced a substantial growth, traditional design tools such as Velocity Prediction Programs (VPP) have proven inadequate to help architects and engineers with

performance trade offs which now include specific stability issues related to these foils. The quest for performance also demands a better account of the unsteadiness of the environment in which the offshore yachts evolve. Time-domain analysis and system-based modeling allow for an improved understanding of the controllability and dynamic stability of given geometries, enabling to adapt and refine the design. This paper presents such a dynamical unsteady model, based on the superposition of several loads components, computed from either numerical, empirical or analytical models. A test case and its results are presented to show the reliability and efficiency of the developed numerical tool, by comparing response amplitude operators of a reference hull form with experimental and numerical data. Finally, the paper outlines two 6DOF dynamic simulations of an offshore trimaran. The first case shows a simple bearaway maneuver and compares two sail tuning strategies, while the second one presents the yacht evolution in unsteady wind demonstrating how in varying conditions the boat may reach attitudes that widely differ from the steady ones.

Sailboat Routing with Multiple Objectives for Sailing Races

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Sailboat routing consists in computing the best route for a sailboat taking into account the characteristics of the ship and environmental data such as weather forecast. In the context of sailing races, the best route computation is usually based on the isochrone algorithm, a sub-optimal solution to optimize the time to destination (TtD) criterion by computing a route as a sequence of waypoints. In this paper, we propose to compute a set of possible routes by considering two criteria : the time to destination and the stress. The time to destination is evaluated according to weather forecast and boat polar diagrams. The stress function is a combination of human and environmental factors. The set of possible routes are then obtained by using an iterative multiple objective optimization algorithm. Isochrone algorithm is used for initializing the set of routes. Then mutation operators are used to explore alternative solutions. Applied to realistic test cases, our search strategy allows to obtain routes with very different characteristics in terms of time to destination and stress values, asserted by experimented sailors. Concerning the main objective of minimizing time to destination, we are competitive with commercial softwares such as MaxSea or Adrena.

A Comparative Study of Program FloSim Results against SYRF Wide Light Project Data

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In November, 2015, the Sailing Yacht Research Foundation (SYRF) published the tank test data from their “Wide Light Yacht Project” for the hydrodynamics of a modern, high performance, semi-planing yacht. This comprehensive data set, comprising canoe body with and without appendages in upright, heeled and yawed conditions, provides an important validation base for CFD codes; previously, such data were not readily accessible mainly due to proprietary issues. The SYRF report includes a number of comparative results from commercial CFD codes, the RANS program Star-CCM+ results in general showing the best correlations with the measured data, albeit with some significant departures.
In this paper, we present results computed using an advanced Boundary Element Code, FloSim, these calculations being compared against the test matrix of “Wide Light” measured data and also Star-CCM+ calculated results. Times for computer model preparation and case execution are discussed together with computer requirements.
An outline of the FloSim method is presented; it is an unsteady code with a coupled integral boundary layer analysis for viscous effects such as skin friction resistance and boundary layer displacement effect. Its time-stepping procedure has free convection and rollup of vortex wake elements providing non-linear lift

properties and includes a number of modeling techniques for treating "real world" effects, such as flow separation and wave breaking. The free surface wave development uses a non-linear mixed Eulerian-Lagrangian treatment at each time step. For the higher speed cases in the SYRF data set that have a breaking bow wave crest, FloSim's Wave-Breaker treatment is applied to convert excessive energy in the bow wave to a "dead-weight" pressure applied on the free surface; this effectively attenuates downstream wave amplitudes consistent with the loss of energy at the breaking crest.
FloSim, already used in America's Cup and Volvo racing yacht analyses, was developed specifically to bridge the gap between basic potential flow panel methods and RANS codes, with the objective of providing accurate, practical solutions on a laptop computer within a reasonable turnaround time and cost. In essence, the results presented so far in this paper demonstrate these objectives have been achieved. The comparisons of FloSim's essentially "low-order" results against test data and Star-CCM+ RANS calculations, provide a measure of tradeoff between calculation accuracy versus cost and turnaround time for a case. Throughout the discussions presented below, the reader should keep in mind that this was not a "blind" comparison as it was for the original Wide Light Project participants who published their numerical results.

Effect of Sweep and Variations in Free-Surface Cross Section Geometry on the Lift and Drag of Transom-Hung Sailboat Rudders

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Conventional transom-hung rudders are often used on small sailboats because of their simplicity compared to rudders mounted under the hull; however, they present substantial performance penalties, including (1) the rudder is more likely to ventilate by drawing air down from the free surface, (2) the effective aspect ratio, and therefore the lift-to-drag ratio, is not increased by the mirror-plane of the hull bottom and (3) there is additional spray and wavemaking resistance that arises as a result of the rudder passing through the free surface. This study focuses on a means to mitigate the last of these penalties, the increased spray and wavemaking resistance. While many transom-hung rudders are essentially parallel, or tapered with the maximum chord at the top where it meets the tiller handle, the reader will recognize that having the largest cross section of rudder at the free surface will generate maximum spray and wavemaking resistance, especially when the rudder is turned. This study investigated the use of minimizing the rudder chord length where it passes through the free surface, demonstrating the findings by full-scale towing tests of a series of rudders designed for a *Fireball*-class dinghy. Additionally, full-scale tests, matching Reynolds number and Froude number, eliminate questions on scaling. Experimentation on the effects of sweep angle, section shape and chord length at varying angles of attack and velocities showed a noticeable increase in lift-to-drag ratio of foils with reduced chord length at the free surface. To complete the case study, a velocity prediction program was used to estimate the change in speed around a notional race course.

Sailing Catamarans: Design for Cruising

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Statistics is provided for number of sailing catamarans and approaches to craft dimensioning are reviewed. Styling trends and typical catamaran arrangements are featured. Weight components are studied for number of catamarans of different size and level of comfort on board. Effect of catamaran architecture on performance is studied by combining VPP predictions with CFD modeling of various deck/cabin configurations. Summary of safety requirements specific to catamarans is given. Case studies are presented number of cruising catamarans designed by AMD; new perspective concept of 44' catamaran featured.

Recent Advances in Experimental Downwind Sail Aerodynamics

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Over the past two decades, the numerical and experimental progresses made in the field of downwind sail aerodynamics have contributed to a new understanding of their behaviour and improved design. Contemporary advances include the numerical and experimental evidence of the leading-edge vortex, as well as greater correlation between model and full-scale testing. Nevertheless, much remains to be understood on the aerodynamics of downwind sails and inherent flow structures. A detailed review of the different flow features, including the effect of separation bubbles and leading-edge vortices will be tackled, to provide a comprehensive presentation of the aerodynamics of downwind sails. New experimental measurements of the flow field around a highly cambered thin circular arc geometry with a sharp leading edge will also be presented. These results allow for the first time to interpret some apparently inconsistent data from past experiments and simulations, and to provide guidance for future model testing and sail design.

Scoring Methods for Handicap Racing.

Jim Teeters

Two boats sailing in close proximity may inevitably compare their boat speeds, perhaps even “race” each other. Over the last few centuries there have been numerous handicap systems designed to equalize the competitive chances of racing sailboats. Corollary to handicapping is another arcane art; that of scoring races. Scoring methods have both technical options, in part determined by handicap rules, as well as “human engineering” options in the sense that different solutions can work best for different constituencies, be they race organizers or sailors. Options may include single vs. multiple ratings, time on distance vs. time on time, pre/during/post race handicapping, attempts to predict the environmental conditions on the race course, constructed courses, pursuit vs. staggered vs. fleet start racing, performance line and performance curve scoring. The underlying assumptions and motivations for these choices are presented along with the consequences of adopting them. The expectations of the competitors, and indeed their ability to intuitively grasp the fundamentals of how elapsed times are transformed into race rankings, are discussed with a view towards finding solutions that achieve a successful balance of fairness, transparency and acceptance.

Impact of Composite Layup on Hydrodynamic Performances of a Surface Piercing Hydrofoil

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Composite materials are good candidates for hydrofoils manufacturing, ensuring a good balance between strength and weight. In the high performances sailing yacht domain, hydrofoils are thin structures, highly loaded that experience significant displacements. This study investigates experimentally and numerically the influence of the laminate layup on the hydrodynamic performances of a surface piercing hydrofoil. Four hydrofoils with a constant chord, geometrically identical with different composite layups are mechanically characterized and tested in a hydrodynamic flume. The foils are designed to have a significant tip

displacement of 5 to 10% of the span. Experimental results highlight a bending-twisting effect that leads to significant change in the hydrodynamic performances of the structures. Two different FSI numerical approaches: from a potential code coupled with beam theory to the full coupling of a shell structural code and a VOF hydro model with free surface are compared to the experiments with great results. The two approaches are two complementary bricks in the design process to compute the effect of passive deformation on hydrodynamic performances of the foils and therefore the yacht stability.

Science of 470 Sailing Performance

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In order to sail 470 faster, authors consider the sailing performance of 470 from the various measured data and the simulated results of VPP (Velocity Prediction Program). This is a summary of TOBE-470 presented by the author.

An Energy Aware Autopilot for Sailboats

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In this paper, we propose a new control method for the next generation of autopilots. These new systems will need to manage more actuators to control the hydrofoils, which is going to significantly increase the energy requirements. So, this method is aware of the autopilot power consumption. It uses a model predictive controller to manage the actuators (position control - appendage angle control). This controller uses a dynamic model of the actuator, running in real time, to anticipate the future behavior of the system. Once the predictions are made, it determines the future control sequence to apply in order to follow the reference trajectory. To do so, it minimizes a cost function which includes the quadratic error according to the behavior prediction and the associated energy consumption. So, it takes into account two criterions: the precision/rapidity of the system and the energy. With the proposed control method, skippers can weight each criterion in order to focus on one or the other depending on their goals and the boat's energy balance. We apply this method to one of the autopilot's subsystems, namely the rudder control. The electric actuator intervening in this control loop and the load representing the force opposed to its motion are modelled to design the control law. The first results of that method are compared with a standard autopilot. We increase by 40% the precision level and we are able to reduce the consumption by at least 20%. This work provides the first necessary components of a future autopilot that will control the whole appendages to a three-dimensional piloting. Moreover, this type of management is a first step towards possible fossil fuel free sailboats.