ABSTRACT

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.

NOTATION

AC  America’s Cup
AC50  America’s Cup 50 class
CFD  Computational fluid dynamics
VOF  Volume of fluid
DVPP  Dynamic velocity prediction program
OTUSA Oracle Team USA
RANSE  Reynolds averaged Navier-Stokes equations
VPP  Velocity prediction program

 AoA  Angle of attack (°)
AWA  Apparent wind angle (°)
AWS  Apparent wind speed (kn)
BS  Boat speed (kn)
Δtstep  Delta time of step (s)
F  Force vector (N)
HDG  Heading (°)
S  State vector
S₀  Initial values state vector
t  Time (s)
TWA  True wind angle (°)
TWS  True wind speed (°)
VMG  Velocity made good (kn)

INTRODUCTION

The America’s Cup (AC) 50 class for the 35th AC in Bermuda in 2017 is the second generation of foiling catamarans used in the AC. In the campaigns leading up to the 34th AC, the foiling concept was developed and utilized for the first time with the AC72 class. When designing a hydrofoil supported sailing vessel, the stability and dynamic behaviour are important characteristics to consider. For being competitive in the 34th AC it was important to foil controllable and stable. For the 35th AC this is of course still important, but it must be done as efficiently as possible to be competitive.

Efficiency and stability tend to oppose each other for these types of sailing craft. The more efficient the foil design and configuration gets, the more unstable it gets as well. In addition to the foil design, the control systems are therefore a very important performance driver. A very responsive and accurate control system allows a less stable and more efficient foil design to be controllable. The AC50 class requirements drive the design to complex foil control systems.

Foil and control system design also impacts the maneuverability of the vessel and drives the maneuvering procedures. Depending on the control system design and set-up, maneuver procedures need to be developed and adjusted. For evaluating the overall performance of a configuration, maneuvering needs to be considered in addition to the straight-line performance.

Sailing and maintaining AC50 yachts is complex and expensive. Sailing time in preparation for an AC is very valuable, limited and needs to be prioritized. A dynamic velocity prediction program (DVPP) model is therefore set up to assist with assessing 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 DVPP requirements for the yacht model and input data are quite different to a steady-state velocity prediction program (VPP). For dynamic simulations a wide range of sailing states needs to be covered by the model and input data. While for a steady-state VPP a much smaller range of sailings states is required, the model accuracy is paramount to enable the software to assist in making the correct design choices. High fidelity input data is important for a steady-state VPP,
while a DVPP requires input data covering a wide range of sailing states.

The DVPP is set up as a second VPP in addition to the OTUSA VPP for steady-state velocity prediction. This enables cross-checking of steady-state results and allows both tools to be optimally developed and utilized for their specific purpose. The DVPP is interfaced with the OTUSA data acquisition, processing and analysis environment based on Bravo Systems\(^1\) technologies. This enables efficient exchange, analysis and comparison of simulation results with measurements. DVPP simulations can be displayed in real-time when sailing and used as performance benchmarks for maneuvers.

**DYNAMIC VELOCITY PREDICTION PROGRAM (DVPP)**

FS-Equilibrium is an advanced workbench for the analysis of steady-states of equilibrium (VPP) and transient states of motion (DVPP). It is an open modular workbench for the analysis of floating rigid body equilibrium conditions and motions. Using a flexible architecture with so called force modules, specific set-ups can be built. The individual force components acting on the rigid body are modelled by force modules, which calculate the component forces and moments with theoretical, semi-empirical or numerical approaches or use data fed from external sources such as experiments or CFD.

The steady-state mode solves equilibrium conditions of external aero- and hydrodynamic forces and moments acting on yachts, ships and floating bodies for up to 6 degrees of freedom. The development started with the work of Hochkirch, 2000. Since then the software has continually been expanded and advanced.

Richardt et al., 2005, describes implementation of the transient mode to integrate the nonlinear differential equation of motion and compute the trajectory of a vessel so that maneuvers such as turns, stops, zig zag tests and real-time sailing scenarios can be simulated. Details of modelling unsteady motion and dynamics of flight are taken from Etkin, 2005. The DVPP is then used by BMW Oracle Racing in the 32\(^{nd}\) AC campaign to build a sailing simulation for starting maneuver training as described by Binns et al., 2008.

Foiling sailing craft have since also been modelled with the workbench. Boegle et al., 2012, implement foil control systems of an International Moth and describe design considerations looking at the tradeoff between speed and stability. Paulin et al., 2015, discuss the performance assessment and optimization of a C-Class catamaran hydrofoil configuration.

**DVPP YACHT MODEL**

The core of the yacht model constitutes of the force modules set-up to model the forces acting on the yacht. Based on the state variables and the parameter settings, each force module returns the six force and moment components. In steady-state mode the forces/moments of all modules are added, and the residual force/moment of each component is minimized by adjusting the control variable associated with each degree of freedom. In addition, trim parameters can be defined to find the optimum with respect to an objective function, typically boat speed (BS) or velocity made good (VMG). A selection of balancing and optimization algorithms is available to achieve this.

In the DVPP mode the excess forces and moments are used to calculate the rigid body accelerations according to Newtons second law. The damping terms can be modelled by appropriate force modules and are then considered as part of the excitation force. The accelerations are fed into the numerical integration scheme to determine the values of the state variables for the next time step. A fourth order Runge-Kutta scheme, as well as a fifth order Runge-Kutta-Feldberg scheme, a variable time step scheme adapted from Cash-Carp and an explicit Euler scheme are available for time integration as described by DNV GL, 2018. The process flow of the time stepping procedure is schematically shown in Figure 1.

![Figure 1 – Time stepping process flow](image)

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1 Bravo Systems SL, www.bravosystems.es
Force Modules

The force components acting on the AC50 are defined by different types of force modules. Figure 2 shows an expletory list of force module types used to describe the AC50. Mass modules including inertia terms are specified for platform, wing and crew members. The mass of each crew member is defined in a separate force module so that individual crew movements to be modelled during maneuvers.

The wing and jib forces are modelled based on CFD data sets for upwind and downwind sail trims. The coefficients of the six force/moment components are modelled with an UniversalForce module as functions of the wing and jib trim parameters and the apparent wind angle (AWA), resulting in 8 independent variables. The UniversalForce module uses multidimensional regression models with freely definable independent variables to model an arbitrary force. The local velocity used to calculate the apparent wind speed (AWS) and AWA includes the dynamic components from the vessel’s rotation.

During maneuvers such as tacks and gybes, the wing shape relative to the onset flow can be very different than in normal straight-line sailing conditions. A much larger range of operating conditions needs to be covered by the data set compared to the input data for a steady-state VPP. During a tack or gybe the AoA of the wing and the wing camber can become negative depending on the timing of the wing inversion and the wing trim. The wing inversion is crucial when simulating and investigating tacks and gybes, and the aerodynamic data must be included in the DVPP for these unusual operating conditions of the wing. To produce these extensive data sets, potential flow simulations of the wing and jib combination are conducted for a matrix of all relevant trim parameter variations and AWAs. Correction terms obtained from Reynold averaged Navier-Stokes equations (RANSE) volume of fluid (VOF) simulations are utilized to account for viscous effects.

Figure 2 – List of force modules (left) and AC50 model in motion player (right) showing hull sections from BuoyantForce model in green

An aerodynamic damping model is developed from CFD data and implemented as a force module. The windage of the vessel’s components is defined by a combination of high-fidelity CFD data and coefficient-based calculations.

The dagger boards and rudders are also modelled based on CFD data sets with UniversalForce modules. Each foil is modelled independently. The force/moment components are defined in a local foil coordinate system as functions of local flow and immersion parameters. While this approach disregards interaction between the foils, it allows to describe a wide range of operating conditions for each foil. This is required when simulating maneuvers in which each foil moves (changes position and/or orientation) and sees very different local flow and immersion depending on the maneuver characteristics.
The input data is predominantly developed from extended vortex lattice models with correctors from high-fidelity RANSE VOF simulations. The correctors account for viscous effects and apply penalties at the operational boundaries of the foils to emulate the effects of ventilation and cavitation. The BS during maneuvers is typically well below the maximum achievable BS so that significant cavitation or ventilation is not very likely.

The added mass of the principal hydrodynamic and aerodynamic components is calculated based on formulas for flat plates taken from Saunders, 1957.

While the primary focus is on modelling foiling states, a hydrodynamic model of the hulls is included to be able to simulate scenarios where the hulls briefly touch the water. The intention is not to model displacement sailing or take-off maneuvers. The BuoyantForce module generates and utilizes the hull sections shown in Figure 2. It calculates displacement, wetted surface area, frictional resistance and the resulting force/moment components at each time step. A viscous damping approximation is also computed. The added mass can be calculated from the Lewis transformation. An ExpressionForce module is created to account for additional forces and moments from hydrodynamic effects during takeoff. The mathematical expression is formulated based on CFD simulations.

**Controllers**

Controllers are defined in the DVPP to model the crew actions involved when sailing the yacht. With controllers, maneuvers can be repeated consistently and systematic studies can be carried out. The DVPP can also run in “simulator” mode where an operator controls the vessel through input commands.

Controllers are further utilized to model the control system of the boat. The control system design and implementation have great impact on the stability and controllability of the AC50 class yachts. The control system constitutes of hydraulic and mechanical actuators, and feedback control is limited by the class rules. The control system speed, responsiveness, accuracy and repeatability are all important parameters to consider and optimize. Key characteristics of the actuators installed on the boat are obtained from measurement data acquired when sailing. These characteristics are described by controllers in the DVPP to set up a simplified control system model. By changing the values of the controller parameters, modifications to the control system can be modelled and the effect on the controllability in straight-line sailing and in maneuvers can be investigated.

Besides typical linear time-invariant (LTI) relations, the controllers can use arbitrary mathematical expressions of time or state to define the rate of change and/or value of the respective actuator. Conventional proportional–integral–derivative (PID) dependencies as well as step changes and time delays can model the behaviour of the crew and the hydraulic and mechanical actuators of the control system.

Figure 3 shows, as an example, the ride height control implemented in the DVPP. One controller is defined for the human behaviour. The controller input is the ride height error. In an effort to minimize the error the controller determines the target rake. In this example the rake is adjusted by button pushes, which trigger step changes in the target rake. The target rake is the output of the human behaviour controller and becomes the input for the controller describing the rake actuator. This controller models the response time and speed of the rake actuator. The output of the rake actuator controller is the actual rake of the dagger board, which influences the boat response and affects the ride height.

![Figure 3 - Ride height controllers for human behaviour and system response](image-url)
Crew

Controllers are implemented and employed to model the three main crew functions to control the vessel:

- **Rudder angle**: A controller simulates the helmsman changing the rudder angle to steer the vessel to a target TWA. The controller minimizes the error between target and actual TWA. For a maneuver the target TWA is prescribed by a sequence of target angles or a continuous function. The turning rate is utilized by the controller as the change rate of the error. The output of the controller is the rudder angle.

- **Target wing rotation/twist**: A controller simulates the wing trimmer changing the mast rotation or the wing twist to sail the vessel at a target heel angle. The controller minimizes the error between target and actual heel angle. The controller is disabled during certain parts of some maneuvers when controlling the heeling moment with the wing trim is not possible. This is for example the case in the middle of a tack or gybe while the wing is inverting. The heeling rate is used by the controller as the change rate of the error. The controller output is the target wing rotation/twist, which is the input for the wing rotation/twist actuator.

- **Target dagger board rake**: A controller simulates the pilot/flight controller changing the dagger board rake and thereby the AoA to sail at a target ride height. The controller minimizes the error between target and actual ride height. The vertical speed is utilized as the change rate of the error. The controller output is the target dagger board rake, which is the input for the rake actuator. During a maneuver when both dagger boards are in the water, the controller of both boards can be active at the same time or the active dagger board control is switched from one dagger board to the other at a certain point during the maneuver. This depends on the maneuver playbook. DVPP is for example also used to investigate approaches of controlling the dagger boards during maneuvers.

A reaction time of the crew and a sensitivity threshold to disturbances is not included because the sailors anticipate required actions and sense disturbances. The sailors comment is “if we only reacted once the boat starts heeling we would not be able to sail the boat. We anticipate the required actions based on the environment and the sailing condition.” The parameter values are selected so that the controller response resembles the observed and measured crew response.

In addition to the three principle crew functions modelled by controllers, other crew functions are modelled without controllers (open-loop) including crew movement, dagger board dropping and raising, dagger board cant, dagger board rake drop pre-set, elevator rake and wing camber.

Actuators

Controllers are utilized to model the movement of actuators in the control system. The dagger board rake for example is modelled with a delay time for the hydraulic value to open and a rake speed.

The following actuator movements are modelled with controllers: dagger board rake, cant and extension, rudder elevator rake, wing rotation with different maximum speed for easing and bringing in, wing twist, wing camber and crew motion speed.

The rudder angle is modelled without an actuator since the input from the helmsman is directly transferred mechanically to the rudder blade. The actual rudder angle is therefore always equal to the target rudder angle.

Maneuvers

Parametric maneuvers with a series of actions are defined to model the maneuvers. The actions are triggered by conditions. A typical condition is a time delta to a reference time. Any other parameter than time can also be used to describe a condition, such as for example TWA, AWA and ride height.

Actions triggered by a condition include crew movement, dagger board dropping and raising, dagger board cant, dagger board rake drop pre-set, elevator rake, wing camber, changes in target TWA, target heel and target ride height, and activating and deactivating of controllers.
TACKING PROCEDURES

Together with the sailing team the DVPP is used to investigate tacking procedures to understand the influence of parameters on stability, controllability and performance. As a measure of performance, the distance lost during the tack is calculated. It is defined as the distance lost to windward relative to sailing continuously with the VMG at the beginning of the tack. The target TWA at the end of the maneuver is the inverse of the starting TWA. The boat set-up is symmetric so that the VMG will eventually be the same again after the tack. Provided the simulation time is sufficiently long, the distance lost is not affected by the time interval.

Assessing the distance lost in maneuvers from real-life measured data is often strongly dependent on the time interval due to fluctuations in TWS, TWA and BS. It is therefore very difficult to systematically evaluate different tacking procedures from measured data. Another reason is of course that it is impossible to achieve the required repeatability in the maneuver execution to allow a detailed assessment of variations in the maneuver procedures with respect to distance lost. The DVPP is therefore employed to investigate tacking procedures and suggest improvements, which can be tried on the water.

To investigate maneuver procedures, a baseline maneuver representing the current benchmark is typically set up in the DVPP. It is based on the analysis of measured data, videos, observations, the maneuver playbook and discussions with the sailors. The baseline maneuver is then used to systematically vary parameters to investigate their influence on the distance lost.

Crew Righting Moment

The effect of crew righting moment during a tack is one of the parameters investigated. Depending on the control system layout and the maneuver procedures, crew members are required to windward and leeward at different times during the maneuver. For making control system layout decisions and develop maneuver procedures it is therefore of interest to place a penalty on crew being to leeward during a maneuver.

Figure 4 shows the righting moment of the crew and BS against time for the baseline tack and for variations of crew movement during the maneuver. The baseline tack (black) is hidden first behind the green (circles) and then behind the blue (squares) crew righting moment curve. Each step in the righting moment indicates one or more crew members moving from one side to the other. It can be seen how sending crew to leeward earlier reduces the entry BS into the tack, which results in a reduced minimum (bottom) BS. The black vertical line indicates head to wind. Furthermore, it is evident that reduced righting moment from crew being to leeward when coming out of the tack slows down the speed build.

Figure 4 – Crew righting moment and BS against time during tack for different crew movement patterns

For each of the crew movement patterns the distance lost during the tack is computed and plotted in Figure 5 as the delta distance lost relative to the baseline tack. The x-axis shows the time that crew members are to leeward longer compared to the baseline tack. One scenario for example has the crew in positions 1 and 2 (sailors furthest forward) staying to leeward for 9.5s longer to raise the dagger board, which is a total of 18s crew is longer to leeward. Another scenario models the crew movement of a competitor, which is obtained from the analysis of video footage. From these and the other scenarios the relationship can be seen that one crew member being to leeward one second longer costs about 0.45m distance to windward. This number is used by the sailors to evaluate crew being the leeward against other parameters, such as having the windward dagger board in the water longer while the crew moves to the windward hull before raising the board.
Dagger Board Dropping and Raising

The effect of having two dagger boards in the water during a tack is also investigated. From a stability and controllability point of view, it makes sense to drop the windward board and let the boat settle for a moment before starting the turn. The dagger board behaviour during the immersion phase is very hard to predict and control consistently so that the board drop often unsettles the boat. On the other hand, the second board in the water adds additional drag. DVPP simulations are conducted with different delay times between board immersion and initiation of the turn into the tack. The turn is delayed by 1, 2, 3 and 4s compared to the baseline tack as can be seen by the heading (HDG) plot in Figure 6. The BS plot in Figure 6 shows that the tack entry BS reduces significantly the longer the turn is delayed. If the turn is delayed by 4s, the entry BS drops from around 23kn to 21kn. This results in a reduction of the minimum (bottom) BS by almost 1kn.

Figure 6 also includes the rake angle and the heave load of the dropped dagger board. The rake angle plot shows that the dagger board is stored at a rake of 2.87° and set to -4° before the drop. In this tacking procedure the ride height controller for the dagger board is activated when the turn is initiated. The controller increases the rake to the maximum angle. As the boat turns through the wind, the wing is inverted, and the boat weight is transferred to the dropped dagger board as shown in the heave load plot in Figure 6. As the boat reaches the bottom BS, the maximum rake angle is required to produce the required lift to stay on the foils.
In this tacking procedure the windward dagger board is set up to produce little heave force before and after the load transfer from and to the leeward dagger board. The heave load plot in Figure 6 shows that little force is produced by the windward dagger board after the drop until the rake angle increase.

The DVPP is also utilized to highlight that upwards heave force on the windward dagger board is unfavorable as it reduces the righting moment. Downward heave force increases the righting moment. DVPP simulations show that the drag of the dagger board outweighs the benefits of the additional righting moment. The distance lost increases. On the exit of the tack, the BS is at its minimum. Additional upwards force on the leeward dagger board to compensate downwards force on the windward board increases the required minimum BS to keep foiling. Consequently, the required tack entry BS is higher. A larger speed build before the tack is necessary, which further increases the distance lost.

The effect of delaying the turn by 1, 2, 3 and 4s shown in Figure 6 is expressed as the delta distance lost relative to the baseline tack in Figure 7. The relationship between delay and distance lost is close to linear. Delaying the turn after dagger board immersion increases the distance lost by around 3m per second delay.

![Figure 7 – Effect of delaying turn after dagger board drop on distance lost in tack](image_url)

The effect of raising the dagger board slower is investigated analogously with the same baseline tack as reference. The time it takes to raise the dagger board is varied by adjusting the actuator speed with which the dagger board moves. The starting time of raising the dagger board is not changed. The motion starts as soon as the wing inversion is completed. At this point heeling moment to the new leeward side is generated and the heave load is transferred to the new leeward dagger board. The windward dagger board can be raised.

Figure 8 shows the effect of raising the dagger board slower. The distance lost is plotted against the delta time the dagger board is in the water relative to the baseline tack, which results from the slower dagger board retraction speed. The relationship is close to linear again. The distance lost increase by around 1.6m per second the dagger board is longer in the water.

These studies highlight that having the second dagger board longer in the water at the beginning of the tack (3m loss per second) has a larger negative effect than having the dagger board in the water longer when exiting the tack (1.6m loss per second). In the beginning of the tack the BS is much higher and the absolute reduction in BS and VMG is greater. The integral of the VMG change is the distance lost. In addition, a reduction in BS at the beginning of the tack is carried through the whole tack. Losses (or mistakes) in the beginning of a maneuver are therefore often costlier than mistakes later in the maneuver.

The influence of having the dagger board longer in the water when exiting the tack (1.6m loss per second) can also be evaluated against having crew to leeward longer (0.45m loss per second). If the crew crosses first to the new windward hull before raising the dagger board, it might be in the water 3s longer. This is approximately equivalent to having two crew members to leeward 5s longer to raise the board immediately.

The outcome of studies like these is used by the sailing team to analyse, evaluate and improve maneuvering procedures.
Figure 8 – Effect of raising dagger board slower on distance lost in tack

TACK TRAJECTORY OPTIMIZATION

Another aspect investigated to improve tacks is the trajectory. A formal optimization approach is utilized with the objective of minimizing the distance lost. The course through the tack is described by the change in heading as a function of time. From the change in heading the target TWA for the rudder controller simulating the helmsman is obtained. The target TWA at the end of the tack is the inverse of the TWA at the beginning of the tack.

The change in heading is defined as a function of time by spline elements with 7 free variables as shown in Figure 9. The build angle and build ratio define how quickly the turn is initiated. The turn rate specifies the maximum turn rate during the tack. The fade angle and fade ratio describe how abruptly the turn fades out. The overshoot angle defines how wide the boat comes out of the tack and the overshoot time expresses how long it takes to come back up to the target TWA. Tangentiality constraints are applied between the spline elements and the spline elements describing the overshoot shape are defined with fixed build and fade parameters.

Figure 9 – Target heading definition as spline elements with 7 free variables
In the parametric maneuver, the dagger board drop is the main reference action. All other actions are defined relative to the board drop. The first crew members move to leeward before the board drop and the turn is initiated 1s after the board drop. Subsequent actions do not take place at fixed times but are triggered by conditions that account for different timing depending on the trajectory. The wing inversion is triggered by a threshold AWA, which is a function of turn rate. Further crew movement and dagger board raising are relative to completion of the wing inversion. The rudder elevator movement is controlled by rake changes on the dagger board.

For the baseline tack, the free variables of the target heading function are chosen to resemble a reference benchmark tack at the time. Figure 10 shows TWA, turn (yaw) rate and rudder angle against time of the measured reference benchmark tack (back dotted lines) and the baseline tack (red lines) from the DVPP. The baseline tack captures the characteristics of the reference tack well, including the overshoot angle. The baseline tack is defined to be symmetric, i.e. the TWA after the tack is the inverse of the TWA before the tack. The measured reference tack is not symmetric and therefore the TWAs do not match after exiting the tack.

For the trajectory optimization the DVPP is driven through the optimization tool FS-Optimizer. Sobol (quasi-random low-discrepancy sequence) and NSGA-II (Non-Dominated Sorting Genetic Algorithm) optimization algorithms with 7 free variables and the objective function to minimize the distance lost are employed. For each optimization at a TWS approximately 2000 trajectory variations are assessed.

Figure 11 shows optimization results for 14kn TWS. The distance lost objective is plotted against turn rate. The green circles denote fully foiling tacks while the orange circles are “touch and go” tacks where at least one hull touches the water. The baseline tack and the optimum tack with the minimal distance lost are highlighted with blue circles. The best tacks are all fully foiling tacks and the optimum turn rate is around 29°/s. The turn rate of the baseline tack and the optimum tack are similar.

It is conceivable that a higher turn rate is generally better since it reduces the time where wing and jib do not produce forward thrust. The distance lost increases as the turn rate decreases. With turn rates below 20°/s, fully foiling tacks are almost impossible. The distance lost also increases for turn rates above 30°/s. The time required to invert the wing and the dagger board rake actuator speed make tacks with higher turn rates difficult to control and less effective.

Figure 12 shows the same set of results for 14kn TWS. This time the distance lost objective is plotted against the overshoot angle. The best tacks have almost no overshoot angle (<1°). The distance lost increases with overshoot angle. Sailing at a wider TWA reduces the VMG out of the tack. Unlike heavy displacement sailing yachts, these lightweight and responsive catamarans have very little inertia so that bearing away to build speed out of a tack has no benefit.
Figure 11 – Distance lost as function of turn rate for foiling (green, dark), “touch and go” (orange, light) and baseline and best (blue, filled) tacks

Figure 12 – Distance lost as function of overshoot angle for foiling (green, dark), “touch and go” (orange, light) and baseline and best (blue, filled) tacks

Figure 13 shows the distance lost objective plotted against the build angle when starting the turn. A small build angle means that the turn is initiated quicker, i.e. the turn rate increases more rapidly. Many of the best tacks have small build angles. Good tacks are also possible with larger build angles. But for these tacks the build ratio is high, which also results in a rapid increase in turn rate. These catamarans have very little inertia and lose momentum quickly as soon as wing and jib produce less forward thrust. It is therefore crucial to turn through the wind as quickly as possible. A rapid initiation of the turn reduces the turning time.

Figure 13 highlights that the optimum tack has a much smaller build angle than the baseline tack. The key differences between optimum and baseline tack are the more rapid initiation of the turn and the finer exit without overshoot. The optimum tack loses around 3.6m less than the baseline tack.

Figure 14 illustrates the trajectory of the optimum tack (green) compared to the baseline tack (red). The rapid initiation of the turn, the similar turn rate and the finer exit with virtually no overshoot can be seen. The catamaran symbols in Figure 14 mark the time when the boat in the baseline tack is head to wind. It is evident that the boat in the optimum tack has already gone through the wind at this time. The wind arrows in the upper left-hand corner of Figure 14 show that the boat on the optimized tack trajectory leads the boat on the baseline trajectory after exiting the tack.
Figure 13 – Distance lost as function of build angle for foiling (green, dark), “touch and go” (orange, light) and baseline and best (blue, filled) tacks.

Figure 14 – Baseline (red) and optimized (green) tack trajectory.
Figure 15 shows TWA, BS and VMG against time for the optimum tack (green) compared to the baseline tack (red). The TWA plot illustrates again the rapid initiation of the turn and the reduced overshoot angle when exiting the tack. The BS reduces quicker in the optimum tack when initiating the turn more rapidly. The reduced time taken to go through the wind means that the minimum (bottom) BS is reached earlier and is around 0.5kn higher than in the baseline tack. The speed build out of the tack is slower for the optimum tack because of the missing overshoot angle, resulting in a finer exit at a smaller TWA. The VMG plot shows that the finer exit leads to a higher VMG when exiting the tack. The minimum VMG is more than 1.5kn higher in the optimum tack.

The tack trajectory optimization provides valuable insight into factors minimizing the distance lost in a tack. The characteristics of the optimum tack are used by the sailing team as targets. In the training leading up to the Louis Vuitton AC Qualifiers and the 35th AC more and more rapid initiation of turning into tacks could be observed. A fine exit without much overshoot is also an important target and the sailors work on overcoming some additional challenges on the water, which are not present in the DVPP. The challenge for the helmsman is to steer the boat to the desired TWA without overshoot when coming out of a fast turn. True wind direction and TWS vary constantly, and waves disturb the boat. The wing trimmer and grinder need to trim the wing so that the flow reattaches after inversion. At a smaller TWA, the adjustment range in wing trim to achieve this is smaller, the available time frame is shorter due to the smaller rotation angle, and less heeling moment can be generated to counteract the righting moment of the foiling boat. It is harder to “catch” the boat with less overshoot. The margin for error reduces. This is a tradeoff the sailing team must make depending on the specific situation. From the DVPP the sailors know their target and the cost in distance lost when increasing the overshoot angle. This enables them to evaluate the tradeoff between performance and risk better.

CONCLUSIONS

The DVPP is set up and utilized successfully during the OTUSA campaign leading up to the 35th AC in Bermuda. It is employed for investigating the stability and controllability of dagger board configurations and boat set-ups. With the sailing team, maneuver procedures are developed and tested. A few examples are introduced in the paper.

For maneuver simulations, it is important to describe the extended range of operating conditions, such as inverted wing shapes. Modelling the human behaviour with controllers realistically is also critical. The close interaction with the sailing team allows direct feedback from on the water experiences into the DVPP set-up. Interfacing with the OTUSA data acquisition, processing and analysis environment enables efficient use within the team.

For the successful employment of such a tool, a good integration within the team is important. Constantly discussing results within the design, performance and sail team is important to build understanding of the tool and awareness of its capabilities and limitations.

The DVPP set-up is flexible and can be adapted to other types of foiling and non-foiling boats. In the future dynamic simulations including maneuvering can become more widely used. Modelling human behaviour with controllers produces repeatable results so that systematic parameter variations can be conducted. The DVPP model can also be utilized as the backbone of a simulator, where operator inputs drive the simulation. A simulator with a virtual reality environment for the sailors can then be used for training and development off the water.
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