# An Improved Simulator of AC45 Foiling Catamarans for Crew Training

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Abstract: To-day America's Cup catamarans have many innovative features such as hydrodynamic foils and rigid wings instead of soft sails. They are designed not only to float but also to heave and "fly" over the sea surface. These new features require new skills that the crew must acquire. The work presented in the paper deals with this problem and describes a foiling catamaran simulator designed for training purpose. The simulator is designed primarily to interact with the in-training team and to feedback the crewmen with realistic physical reactions in an immersive scenario; secondly the simulator gives the opportunity to compare different race strategies and to select the most promising one. The main features of the simulator are illustrated, some graphical evaluations are displayed and results are discussed.



## 1 INTRODUCTION

The design and construction of high-speed sailing multihulls is going through a very innovative period. Since the 2007 America's Cup, done with monohulls, a large number of high performance multihulls have been built. These boats have the power to attract media interest and a larger proportion of the general public because of their speed and athletic skill required by the crew.


Figure 1: AC72 Oracle Team USA.

Since 2007, one of the most important teams, BMW Oracle, has developed the 90-foot trimaran that won, in 2010, one of the strangest America's Cup ever raced, due to the presence of one catamaran, with a classic sail plan, and one trimaran, with a large wing sail. Following that, after the change of the America's Cup rules, a number of AC45 and AC72 class boats have been designed and built. The September 2013 event in San Francisco Bay, shows the power of these boats that can be considered as the Formula 1 of the water. They are large, beautiful, fast and built with high-tech materials. They have innovative features such as foils and wings which make them completely new.

The knowledge of how to handle these boats is not only important to win the Cup but also to ensure the safety of the crew. The importance of the latter topic is paramount, as demonstrated by the Artemis AC72 capsize, which led to the loss of life of Olympic sailor Andy Simpson.

These reasons highlight a need for the formulation of sailing simulators, in order to provide the Teams with a key tool. It has to be more realistic as possible and provide a user experience as close as possible to the reality to allow crew members to train and know how to handle the boat adapting their individual, diverse sailing background to the new boats. These considerations led to the formulation of an AC45 simulator by University of Southampton students, (*Breschan L.M., Lidtker A., Giovannetti L.M., Sampson A., Vitti M., 2012/2013.*). The scope of this simulator, however, is limited: only the tack manoeuvre is taken into account, and the boat cannot sail in foiling mode. The simulator described in the present paper was formulated using the Southampton simulator as a starting point, and overcomes some of its limitations.

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# 2 THE SIMULATOR

The simulator consists of three different parts: the graphical interface, the mathematical modelling and the physical interface.

The graphical interface consists of a screen view of the virtual scene seen from the boat to know the instantaneous setting of the catamaran. This aspect was touched only marginally in order to verify the model's reliability which was developed on the work.

The mathematical modelling of the AC45 provides the boat's response to the different environmental conditions encountered during a race (aero and hydrodynamic forces) as well as the crew actions. In this work only these two areas were considered.

The physical model aims to provide sailors with a physical reproduction of the catamaran. Using the results of the mathematical model, it is intended to give to the crew a more immersive, realistic feel of the boat and the race scenarios.

# 3 MATHEMATICAL MODELLING

## 3.1 Geometric Characteristics


Figure 2: AC45 Oracle team USA with foils.

The model simulates the behaviour of the AC45 catamaran equipped with different appendages in order to make it able to fly over the water. The main parameter of the AC45 are available in the official America's Cup website but, in order to exactly reply its behaviour, some parameters - which are not of public domain - were introduced in the model on the basis of previous experience on catamarans. Moreover, in order to implement new characteristics and to make the simulator able to deal with the new frontiers of the technology, the capability to lift over the sea and to "fly" thanks to the foils was introduced.

These new features of the catamaran make it incredibly different from a classical catamaran. When the boat flies, the hull resistance goes to zero and each variation of the rudders position has a big effect on the boat heading. The same sensation could be experienced on fast skiff boats, and this is the reason why many of the team's crewmen came from small dinghy. In this contest, the simulator plays an important role on adapting the helmsman and the crew skills to the new boats.

There is a large piece of information in literature about normal catamarans or multihull boats. In fact, they are used to complete the round around the world and to break every year different records because of their velocity. But the presence of foils is a new phenomenon appeared during the last America's Cup. Before that date, no team had any experience about it and a massive research effort was carried on to acquire new experience and knowledge. Unfortunately all the knowledge acquired is proprietary of the teams and held confidential

Table 1: Main boat parameters.

| | | |
|---|---|---|
| **LOA** | 13,45 | m |
| **Bmax** | 6,77 | m |
| **Mast height** | 21,50 | m |
| **Wing width (max)** | 5,50 | m |
| **Upwind sail plane (wing+headsail)** | 133 | $m^2$ |
| **Downwind sail plane (wing+gennaker)** | 210 | $m^2$ |

### 3.1.1 Appendages

Surfing on internet, it is possible to see some videos and pictures that show Oracle team USA and Artemis team using the L-shape daggerboards and T-shape rudders. It is easy to see that the shapes among the two teams are different. Each team tries to reach the more stable and less resistant configuration. Another problem influencing daggerboards shape is that they carry the weight of the entire boat and the crew and the stresses are high because of their small cross section. The appendage shape could suffers also some limitation due the difficulty to obtain sharp angles with composite materials. To solve these problems, the designers have utilized aerospace technology in composite elements manufacturing.

The simulator model implements a normal daggerboard and - in order to give the sideforce necessary to balance the heeling force - a NACA 0012 shape foil was added at its tip allowing the boat lift. All the characteristics of this shape were found on the literature and 3-D effects were added later (*Abbott I.H., von Doenhoff A.E., 1959.*). As a result the two parts of the daggerboard are considered separately and all the parameters vary independently from each other .

The other innovation of the 34°th America's Cup was the wing sail. It was showed to the big public during the America's Cup of 2010, when the Alinghi catamaran lost the Cup versus the big trimaran of Oracle which had a huge wing. The AC45 is characterized by a symmetric wing sail formed by a main wing rotating about the mast and three rear flaps distributed spanwise rotating at 90% of the chord of the forward wing. Due to the symmetry and the possibility to rotate the four parts, the wing is able to produce lift in both port and starboard tack. The structure of the wing is made of a carbon fibre frame covered with a light soft membrane. The crew is able to change during the race the sheeting angle of the main wing, the camber of the whole wing and the twist of the flaps. The advantage of the wing respect to a classic soft sail is the possibility to produce a larger lift due to a absence of turbulence behind the must yielding a more uniform and continuous pressure on the sail surface (*Haack N., 2010/11.*). Another important feature is the possibility to have high lift even with low apparent wind angle . That is very important on high speed catamaran. In fact, they can reach speed two times larger than true wind velocity

## 3.2 Equations

In order to have the possibility to insert the foils and make the AC45 able to fly, the equations of pitch and heave were added to the model:

$$(m + m_z) * \ddot{z} = Z_H + Z_{Wi} + Z_A + Z_{HS} + Z_{WS} + Z_{\dot{z}} * \dot{z}$$

$$\left(I_{yy} + J_{yy}\right) * \ddot{\omega} = M_H + M_{Wi} + M_A + M_{HS} + M_{WS} + M_{\dot{\omega}} * \dot{\omega}$$

Where "z" reperesants the vertical lift, ω the pitch rotation and the subscripts "H", "Wi", "A", "HS", "WS", refer, respectively, to hull, windage, appendages, headsail and wing sail.

The equations contain all the forces in the vertical direction and the moments around the pitch axis acting on the boat. The model has the possibility to change the setting of the boat taking into account the actions of the crew trimming, the position of the headsail, wing and rudder or modifying the twist of the wing or the flatting of the headsail. Also the daggerboards position can be modified as they assume a basic role on the ability of the crew to complete the manoeuvres. The America's Cup showed the importance of fast sailing with the hull lifted from the sea in order to maintain constant high speed. The simulator allows the crew to test all this manoeuvres in an immersive environment, finding the best solution and acquiring the skills to beat the other team.

The possibility to jibe without touching the water was already known. The new challenge is now to complete also the tack without wetting the hulls. The team that will obtain this result will probably win the Cup. The simulator can offer an interesting tool to improve the catamaran features and the crew skills (*Masuyama Y., Fukasawa, T, 2011*).

With the foil the problem of the pitch pole is damped but still central on the catamarans. When the boat bears away, the bow is pushed into the water and the ability of the crew to set off, first all the sails and then the headsail, is of fundamental importance. The helmsman as well has to move smoothly the rudder not to throw out of the boats the crew members as happened to Dean Barker in the final race of the Louis Vuitton Cup versus Luna Rossa.

## 3.3 Forces on the Model

In the sailing boats, there are different forces, which are due both to aerodynamics and hydrodynamics components that make the model complex (*Keuning J.A., Sonnenberg U.B, 1998*). These two fluids are very well know and there are many references in literature; however, the interaction between them make all the problem more complex and needs to be simplified. Moreover, the model has to change depending on the position of the boat. In fact, if the boat is floating, the hull has a large resistance force arising from the friction resistance, wave resistance, induced resistance and heeling resistance. These components can be evaluated with classical formulae as presented on the ORC VPP Documentation (*ORC VPP 2012*). The innovation of the new catamarans is the lift forces of the foils. These are found using the lift coefficients and the wetted area of the foils.

$$F_{z,daggerboar} = \frac{1}{2} * \rho * V^2 * C_l * A_{dag}$$

The area changes with the heave position of the boat, with a linear reduction when the boat is over 0.5 m whilst the lift coefficient is fixed and changes with the pitch angle. It is obvious that the ability of the crew consist of launching the boat as faster as possible in order to have the maximum lift force and lift the whole boat over the sea. The ability to have a smooth variation of heading appears of crucial importance to keep the boat always fast and lifted from the water.

### 3.4 Cues to the User

In order to ensure efficacity and effectivness of the simulator the cues from the simulator to the users are extremely important. The crew must be able to communicate with the simulator and receive the right feedback from it. The torque on the rudder, wing or headsail are very important and allow the sailors to feel the minimum variation of the wind speed, of its angle of attack of the boat speed.



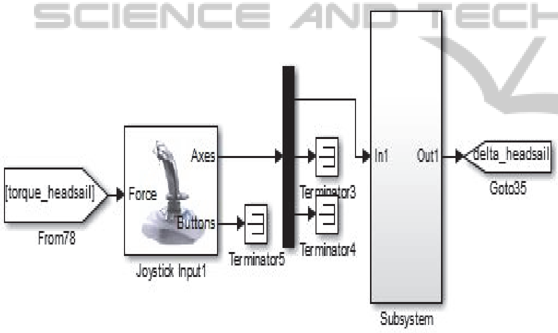


Figure 3: Headsail input and feedback system.

The simulator has three input signals and three feedback signals, this means that it is intend for three members crew. They must work together and interact simultaneously with the simulator. They must synchronously cooperate to keep the boat stable. Even if the simulator does not still have a position sensor, it can be obtained with the supervision of a coach who can see any error.

The possibility to easily teach the user is the main advantage of the simulators but a second capability is represented by the possibility to compare different race strategies and to select the most promising one on the basis of weather forecasting (*Scarponi et a. -2006*).

The crew can also move and change the appendages position. As explained above, the daggerboards position is very important on the manoeuvres and the possibility to set in or off when they want, allow them to find the best setting and the best actions sequences. To see the behaviour of the catamaran the crew can see through some scope and have the feedback of their actions.

This solution appear very realistic because in the last America's Cup the wear technologies were massively used all the crew components could see instantly the parameters of their interest.

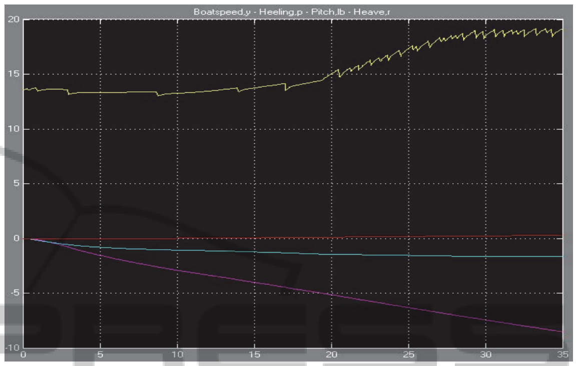


Figure 4: Time histories of boat main parameters: Boat Speed, Yellow – Heave, Red – Pitch, Blue – Heel, Purple.

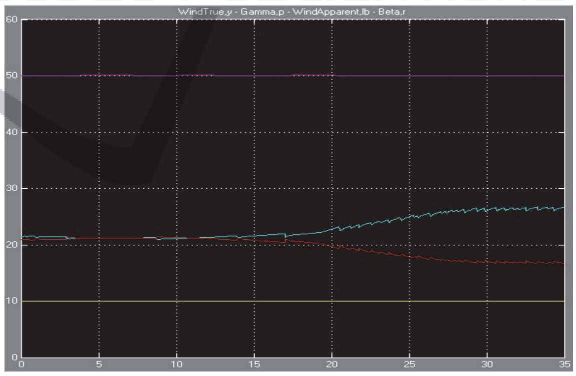


Figure 5: Time histories of true and apparent wind: True Wind Angle, Purple – True Wind Speed, Yellow – Apparent Wind Angle, Red – Apparent Wind Speed, Blue.

## 4 RESULTS

The validation of the simulation was demonstrated by a critical evaluation of its results and some tests. In should be borne in mind that a comparison with results from other simulators is not possible because no other foiling AC45 simulators are available to date. This shows the difficulty in working to this project but also the importance of the challanging task. The results given below show that the simulator's behaviour is in agreement with that of the actual boat. All the main parameters, such as pitch and heave, are consistent with those observed on real boats.

### 4.1 Total Resistance

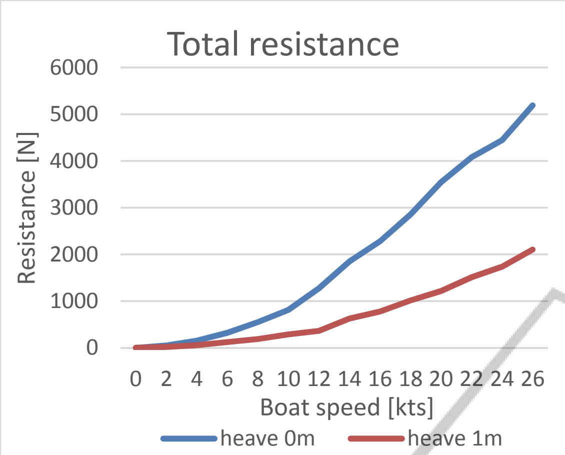


Figure 6: Resistance graph.

The graph above compares the total resistance when the boat sails in the water and when it is flying. It has to be read considering that until the boat speed is below 10 kts, the catamaran has all the hull resistance (blue line). Above that velocity, the catamaran starts foiling: the hull resistance drops to zero and the appendages' resistance and windage resistance (orange line) are the only resistance components left.

### 4.2 Bear Away

The behaviour of the simulator to the changing of direction is important in order to capture the catamaran's motion.

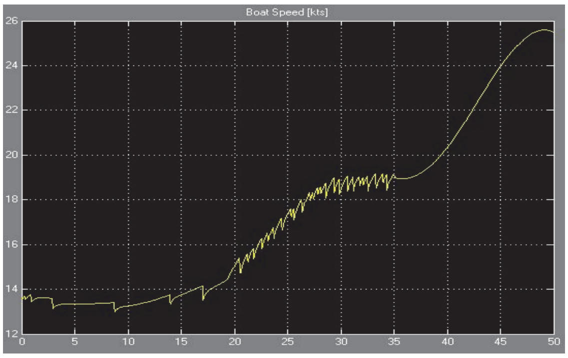


Figure 7: Time history of boat speed [kts] when bearing away at the upwind mark.

The boat speed on this manoeuvre increases when the helmsman starts to bear away (35th sec.). It means that the mathematical model predicts correctly the acceleration of the boat when it bears away at the upwind mark. The Pitch angle starts to increase and finds a new equilibrium position with the bow closer to the water.

### 4.3 Luff up

Also on the luff up the results given by the mathematical model are consistent with sailing experience and the expected behaviour of a foiling multihull. At first the speed increases marginally and then, when the apparent wind angle drops, the catamaran slows down because of the reduction of the sail forces.

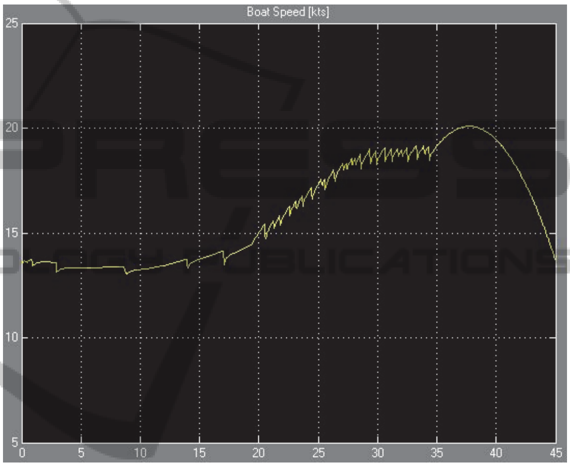


Figure 8: Time history of boat speed [kts] when luffing up.

### 4.4 Graphical Interface

The simulator has a graphical interface to display to the crew the boat position and the movements of the boat. The present implementation is a preliminary version developed at Southampton University (*Breschan et a., 2012/2013*). In order to take full advantage of the simulator the graphical interface must be upgraded and more details must be introduce to yield a full immersive environment. Up to now, the existing version is linked with the simulator and give an essential visual feedback.

## 5 CONCLUSIONS AND FURTHER WORK

The introduction on the simulator of the two more degrees of freedom (pitch and lift) gave the possibility to add the foils at the catamaran. In that way, it was possible to verify the reliability of the mathematical model and to provide the in-training

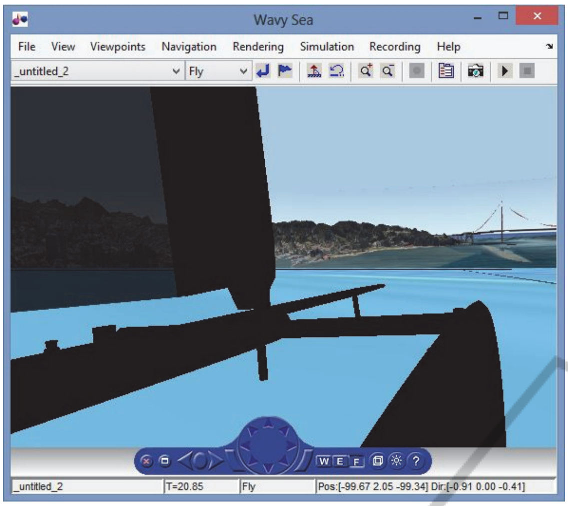


Figure 9: Example of graphical view.

crewmen with realistic physical feedbacks. The reproduction of the effective behaviour of the real catamaran suggests to complete the project with a physical simulator able to interact with the real users and help the crew to adapt its knowledge to the new boat.

Future modelling work will concern the introduction weather conditions (waves and wind) in order to make the simulator able to reproduce all the phenomena. The improvement of the graphical interface appears fundamental to give at the crew the right feeling. In fact, the graphical interface is the first element of judgment from the users. It can be implement using waves, splash on the screen and more realistic boat details. Finally, a physical model - consisting in a movable platform controlled by the simulator - must be introduced to give a realistic feedback to the crew. The degrees of freedom can be inserted on the physical interface. It will need of a movable platform where the movements and the rotations can be implemented. The rudders and the sail sheets could be placed in order to give more reality possible. They has to be able to give to the user the same forces feeling from the crew when the boat is on the water and this can be done using some simple actuators. The improvement of the physical interface can follow what is already done with the Formula 1 simulator and pushes the boat simulator toward a new era.

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