**THE TRANSACTIONS OF THE ROYAL INSTITUTION OF NAVAL ARCHITECTS**

**Part A – International Journal of Maritime Engineering**

# ASSESMENT OF THE TAKE OFF SPEED AND DYNAMIC BEHAVIOUR OF A SMALL HYDROFOIL VESSEL

(DOI No: )

**H Pruszko,** Gdańsk University of Technology, Department of Ship Manufacturing Technology, Quality Systems and Materials, Poland

## SUMMARY

Following article describes the numerical investigation into the dynamic behaviour of a small hydrofoil vessel during the transition to foil-born mode. The case study boat was designed by the students of Gdańsk University of Technology for solarboat competition.

The proper estimation of speed at which vessel enters the foil-borne mode is of the primary interest. Several simulations were run for broad range of vessel speed to assess the take-off speed and resistance of the foiling boat.

As a result the curve of resistance was obtained, with a shape typical for foiling vessels. Different ways of modelling the propulsion was compared. Overset technique with planar motion carriage mechanism was found to be the most satisfactory. The results were compared with the towing tank experiment. The model was manufactured at scale of 1:5. It was not feasible to measure the resistance of the model in the basin so only the take-off speed was compared. It was observed that position of centre of gravity has significant impact on the transition to foil-borne mode for the model. It influence the initial trim angle of the vessel and required lift force distribution.

According to the experiments the take-off speed for full-scale vessel would be higher than according to the numerical simulations.

## NOMENCLATURE

| [Symbol] | [Definition] [(unit)] |
|---|---|
| $s$ | area ($s^{2}$) |
| $v$ | Velocity ( $m\ s^{-1}$ ) |
| $\rho$ | Density of water ($kg\ m^{-3}$) |
| $\lambda$ | Scale factor (-) |
| $L$ | Lift force (N) |
| AR | Aspect Ratio |
| ITTC | International Toeing Tank Conference |
| U-RANS | Unsteady-Reynolds Averaged Navier-Stokes (Equations) |

## 1. INTRODUCTION

Although the concept of hydrofoil vessel is more than 100 years old its application was not common. Thanks to the development of modern material recently it became widely introduced. It is a well-known fact that application of hydrofoils is very efficient way to significantly reduce drag of a high speed vessels. This solution is applied in the high performance cutting-edge sailboats taking part in the most prestigious regatta such as America's Cup and Vendee Globe. However, application is not only limited to those competitions. In order to promote green technologies in the maritime sector the regatta of solar powered small vessels have been organised for many years. The most popular events are SolarSport1 and Monaco Solar & Energy Boat. Challenge. The races gather members of industry and academia from all over the world that are competing to build the fastest and most energy efficient vessel.

The team of students from Gdańsk University of Technology, Faculty of Ocean Engineering and Ship technology founded scientific group KSTO Korab. Their aim is to design and build the hydrofoil vessel to participate in the international solarboat regatta.

The competition is tough and demanding. Building a solarboat is complex multi-disciplinary project. It requires the involvement of many expert in many fields: hydrodynamics, electric system, control and mechanics, just to name a few.

One of the popular solutions is application of hydrofoils. Thanks to generated lift force, main hull is raised above the water surface and drag is significantly reduced. Boats that managed to achieve it during the competition gained huge advantage over other opponents and proved this solution to be very beneficious. With high aspirations the students from KSTO Korab are striving to re-design their current vessel and build solar-powered hydrofoil vessel that is able to compete with the best teams.

This paper describes part of the research that focuses on the initial design and its verification from the hydrodynamic point of view. It focuses on the verification of the assumed take-off speed value and dynamic behaviour, namely, lateral and longitudinal stability in foiling condition.

The article is organised as follows, in the Section 2 was described the aim and scope of the research, Section 3 gives an insight into the design process. It is followed by Section 4 and Section 5 that describe numerical and experimental investigation respectively. The Section 6 provides with analysis and the discussion of the results, the article is summarised in the Section 7.

## 2. AIM AND SCOPE

Aim of the research is the investigation into dynamic behaviour of small hydrofoil vessel by means of the numerical simulations and towing tank tests to assess the take-off speed, stability in foilborne condition and total resistance of the vessel. Scope of the research included initial design stage when the position, area, angle of attack and shape of the hydrofoil was evaluated having the target take-off speed as a reference point. For designed vessel the full-scale numerical simulations were run for a range of speeds from 3.0 m/s to 6.2 m/s. The running trim and sinkage of the vessel as well as total resistance was investigated. The scope of the research included also the experimental investigation. The towing tank test with model manufactured at a scale of 1:5 were done to verify the correctness of the assumed target take-off speed value for the designed hydrofoil.

## 3. INITIAL DESIGN STAGE

First step of the initial design was the estimation of the required lift force to raise the hull from water. It is known that it must be equal or greater than the weight of the vessel so that the hull can emerge. The lift force is dependent on the planform surface of the hydrofoil, density of fluid, square of speed and lift coefficient of the foil. The general expression for the lift force is as follows:

$$L = C_L \cdot \frac{1}{2}\rho v^2 S \tag{1}$$

Where: $C_L$ stands for lift force coefficients, $\rho$ is fluid density, v is velocity and S is the planform area of the foil. The lift coefficient is mainly related to the angle of attack, however, the aspect ratio, profile shape, Reynolds number, proximity to free surface and several other aspects has an influence too.

First step of the initial design was the precise elaboration of the vessel mass. To do so, all the components of the existing vessel were checked. It included the motor with controller, pod thruster, batteries and cooling system, bilge pump, steering system, control panel, solar panels and of course bare hull with hydrofoils and the crew. Assumed weight of the skipper was equal to 70 kg. The required total lift force of the boat and the skipper was estimated to be equal to 1570 N.

Another aspect is related to lift distribution between front and rear foils. According to the literature there are three longitudinal configurations: conventional (airplane) when most of the lift is generated by the front foil, canard when mass is mainly supported by the rear foil and tandem when lift is distributed equally (Faltinsen, 2005). The lateral configuration depends on the centre of gravity. Due to stability and operational issues hydrofoils might be split into two (SNAME, 1988). Centre of gravity was calculated based on the mass and position measurements of the equipment, hull and crew. It resulted in the choice of tandem configuration with split T-shaped front foil. For longitudinal flight stability it was decided to move foils away from each other as much as possible. For reduction of the induced drag the aspect ratio of the foil should be as high as possible, on the other hand the structural and operational issues limits the span of the wing. It was decided that the front foils will have an elliptical shape, whereas the rear foil a trapezoidal shape, which allows for the reduction of induced drag. The exact distribution of the lift force was calculated based on the moment equilibrium in flight condition for chosen hydrofoils location.

The target take off speed was estimated based on the analysis of the mean velocity of vessels participating at the solarboat regatta. It was assumed that the flight mode must be achieved for relatively low speed, so that even for cloudy condition vessel would foil all the time, otherwise too much drug would be generated. The fastest boat in the competition was taken as reference.

The lift coefficient was assumed to be equal to 0.4 based on the current state of the art, own experience and results of experimental investigation (Shuster & Shwanceke, 1960).

After assessment of all unknown terms in the equation, the required planform area of each foil was estimated.

The Table 1 presents the main particulars of the vessel and foils. The FF abbreviation corresponds to front foil, whereas RF to the rear foil.

Table 1. Main particulars of the vessel

| Name | Value |
|---|---|
| Length | 6.0 m |
| Breadth | 0.6 m |
| Draft (foil) | 1.0 m |
| Displacement | 1570 N |
| Longitudinal centre of gravity | 2.5 m |
| Moment of inertia $I_{YY}$ | 180 kg/m$^2$ |
| Position of the FF | 5.1 m |
| Position of the RF | 0.4 m |
| Area of the FF | 0.067 m$^2$ |
| Area of the RF | 0.227 m$^2$ |
| AR of the FF | 7.73 |
| AR of the RF | 8.63 |
| Angle of attack FF | 0.5 degrees |
| Angle of attack RF | 0.0 degrees |
| Profile | Round back |
| Take – off speed | 4.5 m/s |

On the Figure 1 was presented the final 3D CAD model of the designed hydrofoil vessel that was used for computations.

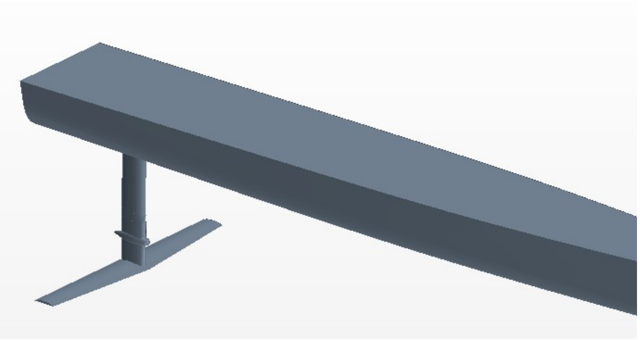

Figure 1 CAD model of hydrofoil vessel

## 4. NUMERICAL SIMULATIONS

### 4.1 SIMULATIONS SETUP

### 4.1 (a) Selected Models

The commercial software STAR-CCM+ was used to perform computations by means of U-RANS simulations. The selected model of the flow was as following: three dimensional, turbulent with realizable k-ε model, unsteady, multiphase as model is moving in two phases - air and water. Frequently used for marine applications is the Volume of Fluid (VOF) model, which can resolve the interface between phases of the mixture (Siemens PLM Software, 2017). Due to significant translations of the model inside domain overset mesh was chosen.

Motion and rotation of body was simulated using the Dynamic Fluid Body Interaction model, that compute reaction of rigid bodies on external shear and pressure forces. Centre of mass and moments of inertia computed before are now essential as all the motions and rotations was modelled in reference to those values. Body a allowed to pitch, heave and surge, whereas remaining 3 degrees of freedom were restrained. Assessment of the motions was possible thanks to 6-Degree of Freedom Solver which computes fluid and gravitational forces on a body. Those forces and resulting moments are used to calculate angular and translational motion of the model.

### 4.1 (b) Modelling Propulsion

For great majority of cases the simulations are based on the reversed flow principle, which allows to greatly reduce the computational domain. At first, such approach was used as well, however, modelling of the vessel propulsion turned out to be a challenge. The propelling force was first simplified to the user-defined body coupling. This method allows to define particular force profile with the coupling element attached at two different points in the domain. This approach is the simplest and does not require any additional mesh refinement. However, after the comparison with behaviour of the model during towing tank testing it was concluded that this type of modelling propulsion to some extend restrained the motions of the vessel.

Second approach for modelling the propulsion was by the virtual actuator disk. Theoretically it is the technique that resembles the reality best. The additional mesh refinement was required only in the propeller plane. However, a very important aspect of the simulations was the final sinkage of the vessel. For the actuator disk completely unphysical behaviour was observed. In the case of approaching the free surface and even emerging from water no reduction of the thrust force was observed. For this reason the planar motion carriage approach was chosen. At that stage of the research, the towing tank experiment was the only accessible benchmark, thus it was decided to model the experimental conditions as much as possible. On the contrary to the towing tank experiments, the full sale CFD simulations were performed

The planar motion mechanism in STAR-CCM+ simulates a captive motion in the X-Y-plane of the laboratory coordinate system (Siemens PLM Software, 2017). In principal, this approach is used for manoeuvring tests, however, it allows for restraining the motions in Y-plane. Application allowed the model to move along X-axis with a constant speed as it does in the towing tank. For this reason the size of the numerical domain had to be extended by far and overset motion needed to be applied. The attachment point of the carriage was at the same point as for the experiment.

Such approach allowed for running the simulations that model the experimental conditions to great extent, however, the obvious drawback is the size of the mesh and computation time.

### 4.1 (c) Mesh and domain

Due to significant translations of model inside domain the overset mesh was chosen. This model of mesh consists of two meshes: background and overset that overlap each other. Background region is in other words virtual towing tank and overset mesh is defined directly around the body. In principle, the former can move freely inside the latter. Thanks to that, resolution of mesh around the body remains the same. Following ITTC guidelines in overlap must be sufficient number of grid points and cell size must be identical (ITTC, 2011c) What is more, according to CD Adapco guidelines there must be at least 4 cells between wall and overset boundary region (Siemens PLM Software, 2017). If motions are computed as it is in described case, that must be hold for all time steps.

Special attention was payed to following regions, where mesh refinement is necessary: free surface, wake, surface of the body and overlap area between background and overset mesh. Applied size of element allowed to generate geometrically high-quality model, special attention was payed to high resolution around leading and trailing edges. Challenging task is proper refinement of free surface. Expected motion of model is equal to about 50 cm, which means that it need to be extended to relatively broad area. If significant difference in cell size in transition from background mesh to overset occurs two unwanted effects might take place. Either will appear artificial wave or simulation might even crash.

Another issue is resolving boundary layer. ITTC suggest that hexahedral or prismatic cells should be used, as it will result in higher accuracy. Stretch ratio within prism layer should be 1.2 or less, maximum acceptable value is 1.5 (ITTC, 2011). The value used in simulations was equal to 1.4. To reduce time of primary viscous sublayer was not solved directly, but using wall functions that require values of y+ in range: $30<y+<100$.

The size of numerical domain was depending on the vessel speed between 115 and 200 m along the X-axis, 6 m along Y-axis and 9 m in Z direction. Size of overset was 8 m x 2 m x 2.7 m in X, Y and Z direction respectively. Total cell count was between 2.2 M and 4.9 M in background region and 1.8 M in the overset region.

Only half of the hull was used to reduce the computational costs, so symmetry boundary condition was used in the symmetry plane of the vessel. The same type was prescribed to side boundary to reduce the undesired reflection from the wall. For the front, top and bottom boundary the velocity inlet condition was applied. Behind the model the pressure outlet boundary was placed.

4.1 (d) Simulation cases

The simulations were run for the speed 3.0 m/s, 4.0 m/s, 4.5 m/s, 5.0 m/s, 5.5 m/s and 6.2 m/s. The values that were measured were resistance as well as motions of the vessel – pitch and heave. Crucial aspect of the simulations was observation of the longitudinal stability – it means if the flight is stable and vessel continue foiling once the hull emerges from the water. Another element is assessment of the velocity for which the transition to foiling mode occurs.

## 4.2 RESULSTS

In the Figure 2 the hydrofoil vessel in the foiling condition was presented.

Figure 2 Foiling v = 4.5 m/s

The iso-surface that was included in the figure represents the position of the free surface. It allows to visualise the relative position – sinkage and trim of the vessel.

In the Figure 3 the curve of total resistance and effective power was presented. The dashed line stands for the former and the solid line stands for the latter. The right axis corresponds to the total resistance.

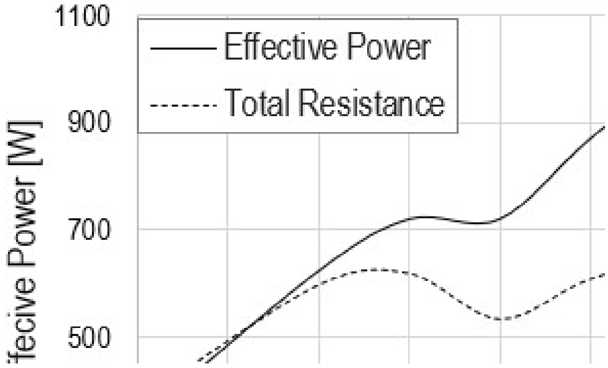

Figure 3 Curve of the Effective Power and Total Resistance

In the Figure 4 were presented the plots of sinkage and trim versus the speed of the vessel.

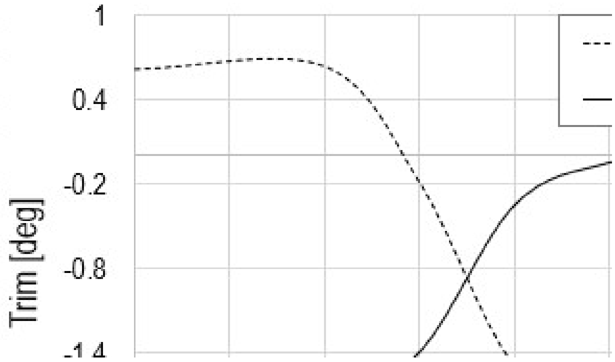

Figure 4 Trim and Sinkage

The dashed line and left axis corresponds to the trim angle, whereas the solid line and axis on the right to the sinkage. The positive trim angle corresponds to the bow up. For the speed between 4.0 m/s and 5.0 m/s the trim and sinkage changes significantly. The maximum trim angle appears for 4.0 m/s and then it decreases.

## 5. TOWING TANK EXPERIMENTS

## 5.1 EXPERIMENTAL FACILITY

The experiments were done in the towing tank of Gdańsk University of Technology. The dimensions of the model basin are 40 meters long, 4 meters wide and 3 meters deep. The maximum speed of the carriage is 2.5 m/s. For standard towing tank tests of displacement vessel the single post is attached to the model. However, in this case it was not possible to use it, because of very little weight of the model. Possible data to be measured during the test are model resistance, pitch, heave and acceleration at given point and sampling frequency of measured data is 500 Hz. On everyday basis the models that are tested are considerably greater and dynamometers were customized to such measurements. As a result, the accuracy of measured data would not be sufficient and the resistance was not recorded. Therefore, the main objective of the experiment was to verify the take – off speed for the model. In other words experiments was run to check if the transition to foilborne mode would occur for particular weight, speed and position of centre of gravity for the model.

## 5.2 EXPERIMENTAL SETUP

The model was constructed at 1:5 scale. The hull was made from Carbon Fibre Reinforced laminate, infusion technology was used for manufacturing. The foils and struts were made from aluminium. The choice of this material was based on the previous experience. Two sets of experiments with 3D printed foils had been done before and the material was not stiff enough. Aluminium is very popular choice for foils and it assures good compromise between weight, strength and stiffness. To simplify the manufacturing process the selected profile had a classic round back shape.

The dimensions of the foils were estimated based of Froude law scaling method and assumed lift coefficient.

According to scaling rules the weight of the model is smaller than the full scale object by the $\lambda^3$, where $\lambda$ is the scale factor.

The model was ballasted using the pendulum method and with a scale. The model was attached to the towing carriage by the system of ropes. At the centre of gravity was fixed the perpendicular bar. At its ends were attached the lines of equal length. Two ropes were attached to the carriage in front of the model and two of them behind it. Such set up allowed to ensure the complete freedom of movement at 5 degrees of freedom and towing it straight without any yaw angle at the same time. Another advantage of such set up was possibility to verify the hydrofoil vessel stability during the take – off and flight. The attachment system was schematically presented in the Figure 5.

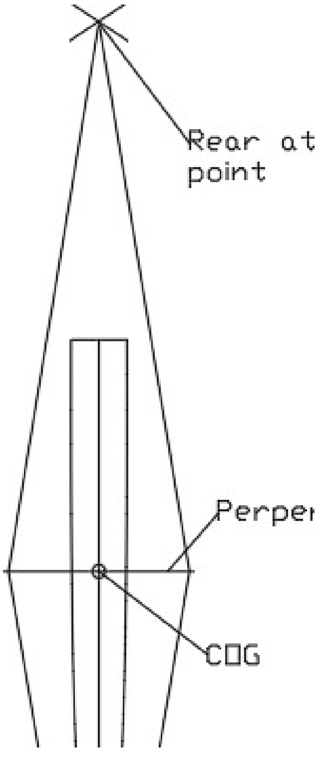

Figure 5 Experimental Setup

A special system was developed to allow for very precise regulation of angle of attack. The roman screws were attached to the end of the strut and the side of the model. The regulation system is presented in the Figure 6.

Figure 6 Regulation system of the front foil angle of attack

Before each run the angle of attack was measured with the use of two-direction inclinometer. The model was put on the deck, that was specially prepared for this purpose and inclinometer was attached to the flat lower side of the foil. For final check of the centre of gravity longitudinal position the model was raised with the ropes and weights inside it was moved to reach an equilibrium state.

## 5.3 RESULTS

The first run was realised for the ballasting condition and speed corresponding to the assumed take off speed. In the Figure 7 was presented the model before the take off.

Figure 7 Model before transition to foilborne mode

For the initial conditions the transition to foilborne mode did not occur. The bow of the model emerged from the water, however, the stern remained in the water. Next step was systematic increase of angle of attack of the both foils. Maximum values of were equal to 3 degrees and 1 degree for the front and aft foil respectively. The only difference was greater submergence of the bow from water. Next step of the experiment was systematic reduction of the weight and for each mass of the model position of the centre of gravity was modified as well.

For all the runs depending on the variation of the centre of the gravity position the bow was emerging from the water or remaining submerged.

Finally for the mass of the model that corresponded to the displacement of the vessel equal to 1250N the vessel transition the foilborne mode occurred. The COG was at the initial position. In the Figure 8 is presented the model in foiling condition. The photo was taken by the camera placed on the towing carriage.

Figure 8 Model after transition to foilborne mode

For the entire duration of the run the model was foiling in a stable position. Both front foils and rear foil were running in the close proximity to the free surface.

## 6. ANALYSIS OF THE RESULTS

According to the Figure 3 the resistance hump typical for hydrofoil vessel occurred for the speed equal to 4.5 m/s. The analysis of the simulation for lower speed revealed that at a speed of 3.5 m/s the hull was still immersed whereas for 4.0 m/s it was just about to start foiling, as just very small part of it was submerged. It was presented in the Figure 4. The sinkage raised significantly, whereas the trim changes to the bow down. The submergence of the rear foil was bigger. For high speed significant amount of lift was generated and it caused high emergence of the stern. The effect of lift reduction occurred when the aft foil was running close to free surface, The rear strut was longer, so it occurred for the condition of trim with bow down. Equal length of the struts would probably result in trim angle around 0 degrees. For all the simulations except for 4.5 m/s the vessel achieved stable condition. Most probably the reason for it was the fact that for this speed the natural mechanism of hydrofoil vessel stabilisation due to loose of lift while approaching the free surface has not occurred yet, so the movement of the vessel was not stable. For simulations with speed above 5.5 m/s the sinkage of the vessel was significant. In real condition such sinkage could not be achieved because the propeller would emerge from water, thus the value of resistance will be higher and should not be taken without any corrections as an input data for engine power selection.

Due to the limited speed of the towing carriage the only possibility to investigate the stability in foil borne mode was to reduce the mass of the model. According to the experiment to reach the foil borne condition at the target take-off speed the model weight have to be reduced by about 25% of model weight. For the full scale vessel it means that its mass would have to be reduced by about 35 kg. Alternatively the surface of the foil or foils angle of attack could be increased. According to the obtained experimental results the take-off speed for the vessel in the initial conditions was estimated to be equal to 5.04 m/s. An important observation was the influence of the centre of gravity. Moving the mass to the back caused positive initial trim angle and increased angle of attack in the consequence. The bow was prone to emerge from water, however not enough of the lift was generated by the rear foil to start fully foiling. The centre of gravity moved to the front caused smaller initial trim and bigger difficulties with bow emerging. Nevertheless, it was observed that for particular foil arrangement optimum position of COG exists.

There are several ideas that are trying to explain big differences between the take–off speed obtained numerically and experimentally. The first is the precision of the model manufacturing. All parts were handmade or with use of rather simple tools, what always introduce a loss of accuracy. Next aspect is the flow regime during the tests in the towing tank. It was not possible to estimate weather the turbulent flow occurred. Another probable reason for big differences between simulations and experiments was suction of the stern to the free surface during the experiment. It is a complicated phenomenon that most probably would not be captured by the numerical simulations. More lift at the rear foil have to be generated as the consequence to overcome this suction force. According to the Figure 8 the foils are running in a very close proximity to the free surface what can be interpreted as a significant amount of the lift generated by the foil. It was also shown for CFD analysis, that excess of the lift cause very high sinkage. Possibly for different shape of the stern for the same set up foilborne mode would occur for lower speed. Last aspect is the verification of the numerical solution by performing grid and time step sensitivity analysis, that was not performed in this study. It is not excluded that a finer mesh would provide with different results.

## 7. CONCLUSIONS

This paper presented the numerical and experimental assessment of the take-off speed value of small hydrofoil vessel. Full scale CFD simulations for speed range from 3.0 m/s to 6.2 m/s were performed and towing tank tests at scale of 1:5 were made. It allowed to formulate conclusions and define the recommendations for further work.

The effect of loss of lift that provides natural roll and pitch stability was observed in the towing tank experiment and numerical simulations (only pitch). According to the results of the computations the obtained take-off speed was close to the assumed one. According to the towing tank experiments the estimated take-off speed was equal to 5 m/s.

Both the towing tank and the experiments indicate that such foil configuration is able to provide a stable flight.

Based on the observations from the towing tank and numerical simulations two main improvements should be introduced. In the final design the boat need to be equipped with passively controlled hydrofoils for easier take-off, control the height of the flight to avoid emergence of the propeller and for flight stability for big range of speed. The stern of the vessel should be redesigned to minimise the effect of the aft part suction.

Without any doubts this investigation allowed to improve the final design by far and hopefully make it possible to compete with leading solar boat teams successfully.

## 8. ACKNOWLEDGEMENTS

The author would like to express her gratitude to the staff of the towing tank without whom the experiments would not be possible. Experiments would not be made without great involvement of the students from the KSTO Korab scientific group who constructed the model and helped with the towing tank investigation. The research was supported by the Academic Computer Centre in Gdansk (CI TASK).

## 9. REFERENCES

1. Faltinsen, O. M., 2005. *Hydrodynamisc of High-Speed Marine Vehicles.* New York: Cambridge University Press.

2. ITTC (2011) – Recommended Procedures and Guidelines *Practical Guidelines for Ship CFD Application* 7.5 – 03 – 02 – 03

3. Lewis, E. V., SNAME, 1988. vol II *Resistance, Propulsion and Vibration.* Jersey City: Society of Naval Architects & Marine Engineers. pp. 120-126. ISBN: 0939773015

4. Shuster, S. & H., Shwanceke, 1960. *On hydrofoils running near a free surface.* Sheveningen, In Third Symposium on Naval Hydrodynamics

5. Siemens PLM Software, 2017. User Guide Star CCM+ v12.04.