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Design of a Marine Autonomous Surface Vehicle for Geological and Geophysical Surveys

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Abstract. Geological and geophysical surveys, which are the basis for engineering studies on marine structures, pipelines, harbours and marinas, both in offshore and in coastal areas, are customarily carried out using fully equipped research vessels or small craft with appropriate equipment related to this work, and with intensive human labour. This traditional method is very costly, requires extra manpower and equipment and increases the risk to life and property, as well as being dependent on ephemeral weather conditions.

A prototype unmanned surface vehicle named JEO-IDA (Marine Autonomous Surface Vehicle) was produced by our team within the scope of a project, which will enable real-time monitoring of the data that are obtained by a side scanning sonar and a single beam echo-sounder installed on the vehicle for geological and geophysical surveys, from a land-based station. The result of this study is the prototype platform of whose mission is to investigate three-dimensional geological and morphological structures of the seabed with high-resolution and to prepare their maps as well as carrying out coastal and offshore surveys in construction and operation phases.

In the scope of this research, studies and hull form selection in the design of the unmanned autonomous surface vehicle are discussed in detail.

1. Introduction

Within the frame of a research project, a prototype Marine Autonomous Surface Vehicle (JEO-İDA) that will enable real-time monitoring of data obtained by side scanning sonar and single beam echo-sounder installed on its platform, was produced for marine geological and geophysical surveys. The mission of this prototype can be listed below:

- Marine geological and geophysical as well as seismic surveys, underwater-surface constructions, engineering and excavation projects are traditionally carried out by research vessels or small craft. It is aimed to reduce operating and research costs, increase measurement accuracy, shorten working times and reduce risk of life and property by performing such researches through the high energy efficient vehicle.
- JEO-İDA can also be equipped with sensor technologies that can acquire physical, chemical and biological data. Thus, high-cost research that is usually performed with traditional research ships, can be carried out with these and similar prototypes efficiently.
- This vehicle will be portable with its compact dimensions and can be used in coastal surveys at various locations as well as in inner waters such as rivers, dam reservoirs and lakes.

- Operations will be performed with a single operator from the land by means of this unmanned surface vessel, providing the advantage of low maintenance and repair costs without the necessity of crew.
- The prototype can be equipped with alternate systems that can be used in other research areas, such as research on commercial fish stocks and fisheries management.
- It can be used for underwater archaeology surveys and for searching ship wrecks as well as sunken objects.

The main objective of this study is to develop a proper underwater surveying vehicle to conduct research on the areas above-mentioned with the maximum and service speed in operation 10 *knots* and 2-3 *knots*, respectively.

2. General Design and Materials Selection

When the above mentioned tasks to be carried out by the autonomous surface vehicle (ASV) named JEO-İDA, namely bathymetric measurements, obtaining data with side scanning sonar and single-beam echo sounder, data acquisition with seismic measurements, operation areas (mainly İzmir Bay and surroundings) and equipment, are taken into account, the initial literature survey and experiences from similar studies suggest that the length of the vehicle should be around L_{OA}=1500-2400 *mm* and its maximum speed should vary between V_S = 7-11 *knots*.

The beam, draught, height and block coefficient (C_B) of the vehicle with the above-mentioned length will change with the hull types selected; the alternatives being monohull displacement boat, catamaran or SWATH (Small Waterplane Area Twin Hull) boat. Generally, the type and form of a boat is decided after the analysis of all boat types by considering the function of the vessel in the preliminary design phase. However, the first design consideration to be taken into account in this phase is the stability and power need of the vehicle when considering the mission and measurement systems to be equipped, and these two demands have conflicting characteristics. In order to obtain a stable boat, it is necessary to increase the beam of the vehicle during the design phase; but its beam requires greater engine power at the same service speeds, due to raising of the resistance nonlinearly. In this case, larger, and hence costly, batteries will be needed during the operation which in turn shall result in difficulties in the maintenance and the recharge of the batteries.

For this reason, the first optimal design decision was a twin hull catamaran or a SWATH boat which has a high transverse stability and which requires a lower engine power at the same service speeds due to its slender hull forms, but at the same time providing a large deck area for positioning measurement systems and equipment. Of course, the construction and workmanship of these types of vehicles cost higher than those of the displacement boats. When considering the form types and the vehicle size mentioned above, the basic criteria in materials selection can be listed as follows according to importance:

i. Low magnetic and acoustic characteristic, because of the requirements of data acquisition devices such as side scanning sonar and single beam eco-sounder,
ii. Low density (weight) and sufficient structural strength,
iii. Ease of formability and manufacturability,
iv. Good resistance to corrosion and marine organisms
v. Cost-effective components including manufacturing, operation and maintenance-repair,
vi. Good seakeeping character
vii. Good resistance to environmental aging conditions (temperature, corrosive and chemical substances, etc.)

The materials that can be used meeting these criteria are aluminum, wood, composite and thermoplastic materials. The use of high quality aluminum and/or high-density polyethylene (HDPE) in the construction of the vehicle that will be designed in a very finely slender and light hull form so as to have low resistance, will make it relatively costly. In addition, as aluminium material will have magnetic properties, albeit low, due to eddy currents formed within the hull material and aluminum welding as well as protection against corrosion will always be a problem.

The use of wood in the construction of the vehicle makes the craft light, cheap and antimagnetic. However, it requires extremely careful manufacturing and extensive protection measures against severe environmental effects of the sea during its use.

Due to basic criteria and the advantages mentioned above and the fact that the cost factor is one of the basic design parameters, glass fibre reinforced polyester (GFRP) material with the hand lay-up method in which sufficient strength can be achieved with a uniform thickness distribution of the material, was selected, also taking into account the dimensions of the vehicle to be produced and operated in the sea conditions of İzmir Bay [1-3].

3. Hydrodynamic Design and Hull Form Selection

Autonomous surface vehicles (ASV) provide an important opportunity for the collection of detailed oceanographic and seismic data from the depths of the seas. The most important design factors for these ASVs are to reduce their body resistance force and to increase the related thrust force, namely increasing the propulsive efficiency. Accurate prediction of the body resistance of an ASV is the most fundamental factor for determining a specific range of power requirements and hence the operation route of the vehicle. Another design objective is that the hull is to be constructed with a low cost and be mechanically resistant.

In general, moving objects submerged in a fluid are exposed to viscous drag that can be resolved to two components, namely the viscous pressure and frictional resistance depending both upon the Reynolds number. If they are floating at the free fluid surface, these objects additionally experience wave resistance depending on the Froude number. Since the SWATH boat model is floating at free sea surface, all of the three components of the resistance, namely the frictional and viscous pressure as well as the wave resistance arise synchronously. Thus this type of analysis is more complicated than the simulation of the objects submerged in fluid. In this regard the SWATH boat form consisting of two torpedo shaped boundary elements and four struts was selected for validation of the CFD analyses carried out in this research (Figure 1 and 2).

For estimating the body resistance of the ASV to be designed, first the study of Begovic et al. [4] was examined. In this study, the different hydrodynamic aspects of the SWATH (Small Waterplane Area Twin Hull) concept were treated; their advantages and critical issues arising from this design were discussed. Furthermore, detailed numerical towing tank analyses were performed and the results obtained were validated by the physical towing tank tests carried out.

Volker [5] and Poehls [6] have described experimental and numerical methods for the prediction of ship resistance and propulsion, manoeuvring, seakeeping ability, hydrodynamic aspects of ship vibrations, hydrodynamic characteristics and options for fuel efficiency as well as new developments in computational methods and model testing techniques. Data regarding resistance and seakeeping characteristics of the boats were obtained from these sources.

Li and Bachmayer have described a robust autonomous marine vehicle capable of operating in severe oceanic conditions near to the coastal waters of Newfoundland and Labrador in detail [7]. The reliable Controller Area Network (CAN) protocol is implemented to build the on-board communication and control system.

Dunbabin et al. have examined a new autonomous marine surface vehicle that has the characteristics of surveying in inner waters such as rivers, dams and lakes and can measure various water quality properties and greenhouse gas emissions [8]. The 4.88 m long solar-powered catamaran is capable of collecting the data to be measured along the water column while in motion on its track. The study also provided an overview of the vehicle design and operation including vision-based inspection capabilities and control of laser-based obstacle avoidance.

Brizzolara et al. have presented conceptual designs of two autonomous sea surface vehicles of a new series from non-traditional SWATH vessels, optimized to achieve low resistance values at high speeds [9]. The research focuses on the determination of the hydrodynamic characteristics and optimization methods used to design body forms to reduce power for the propulsion of the vehicle at service speed. For both vessels, a modern automatic parametric optimization procedure was developed, and RANSE calculations were performed to validate the final design.

The study "Unmanned surface vehicles - A survey" by Bertram covers both unmanned marine researches and USVs which were manufactured or are intended to be manufactured [10]. Such studies have so far been made on small and medium sized vehicles with limited autonomy. Most of the developments concentrated on the USVs are originated from the USA.

Othman's research has discussed the operating capability of unmanned surface vehicles in various sea conditions and advanced technologies that enable the acceptance of those systems [11]. The author has compared the USVs from their previous concept until their current design and their function and suitability.

Molland et al. have presented tests results of a comprehensive catamaran model series in calm water conditions [12]. This experimental program is a continuation of the previous work in which a series of models generated from three catamarans was tested. The present study has extended the previous parametric research to include a wide breadth-draught ratio within a long range of length-displacement ratios. In the tests, 40 different configurations were examined.

Insel et al. have dealt with the Kelvin source's far field wave system and far field wave coefficients including the effects of channel depth and width using linear theory [13]. Comparing the method with the experimental results, catamarans with separation ratios of 0.2-0.5 were used. The trim and sinkage effects of the hulls have been included by supplying dynamic hull surfaces in the calculation scheme.

Broglia et al. have developed a high-speed catamaran form and carried out CFD analyses with it [14].

DELFIM is an autonomous marine surface vehicle developed by Alves et al.to collect oceanographic data and perform an acoustic relay between a submarine vehicle and a support vessel [15]. In the study, the practical results obtained during the sea tests near the Azores Islands were discussed. The paper describes the navigation, guidance and control systems of the vehicle, together with the mission control system that allows end-users to program scientific missions at sea.

As the first step, in order to confirm the CFD method to be applied to all of the simulations in this study, a SWATH boat model equivalent to this published in [4] was modelled and analysed (Figures 1-5). The results obtained from the simulations were validated with those of the experiments of this boat model executed by Begovic et al. [4] (Figures 1,2,6). Figure 3 indicates the model of the SWATH boat while Figure 4 and 5 show the domain of the system analysed and the meshed model, respectively. As can be seen in Figure 6, a good agreement between the results of the CFD analyses carried out in this study and the experiments performed by Begovic et al. [4], was achieved.

After the successful confirmation of the CFD method applied using the SWATH boat concept of Begovich et al. [4], all of the five models treated in the section below were analysed numerically in which the turbulence modelling of ANSYS/FLUENT "Shear Stress Transport k–ω model (SSTKW-Menter) was applied. The reason for the selection of this algorithm is that it generally gives accurate prediction of the onset and the size of the flow separation under adverse pressure gradient since SSTKW-Menter model contains a modified turbulent viscosity formulation to calculate for the transport effects of the principal turbulent shear stress [16,17]. Separation at the sterns of these models was expected (Equation 1 and 2).

$$\rho\frac{Dk}{Dt}=\tau_{ij}\frac{\partial\bar{u}_i}{\partial x_j}-\rho\beta^{*}k\omega+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]$$ (Equation 1)

$$\rho\frac{D\omega}{Dt}=\frac{\gamma}{\nu_t}\tau_{ij}\frac{\partial\bar{u}_i}{\partial x_j}-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\partial\omega}{\partial x_j}\right]+2\rho(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j}$$ (Equation 2)

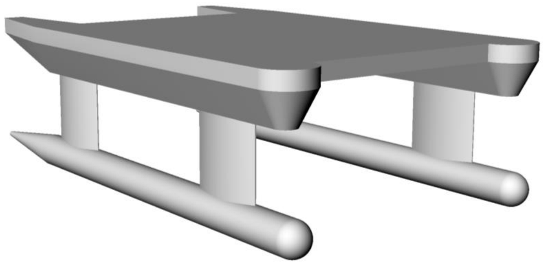


Figure 1. SWATH boat model designed in [4]

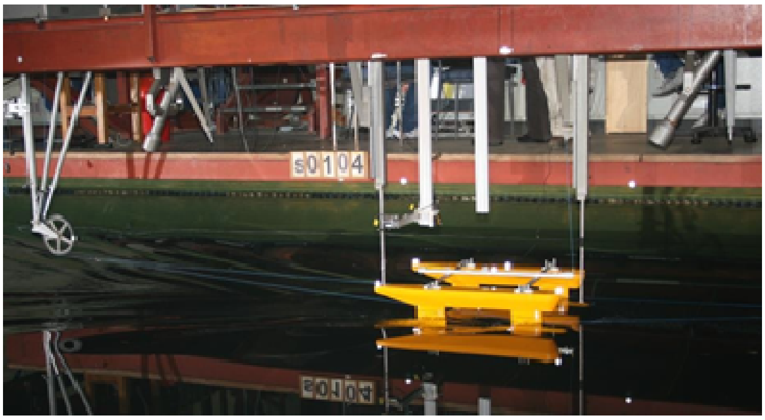


Figure 2. Resistance test of the physical model [4]

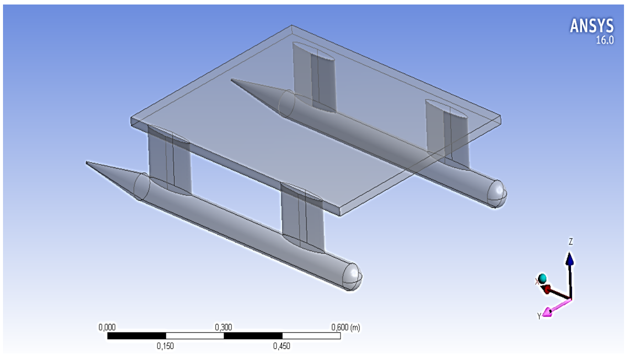


Figure 3. SWATH boat modelled in this study

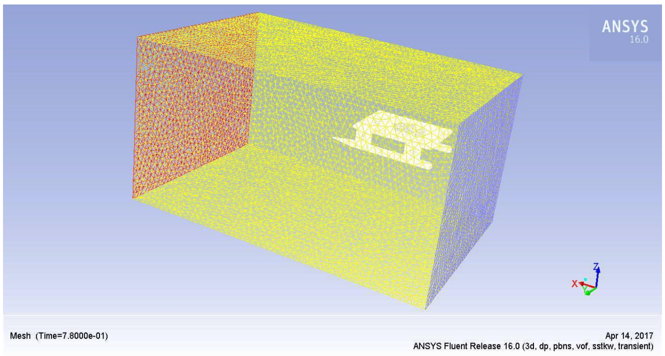


Figure 4. Domain of the model

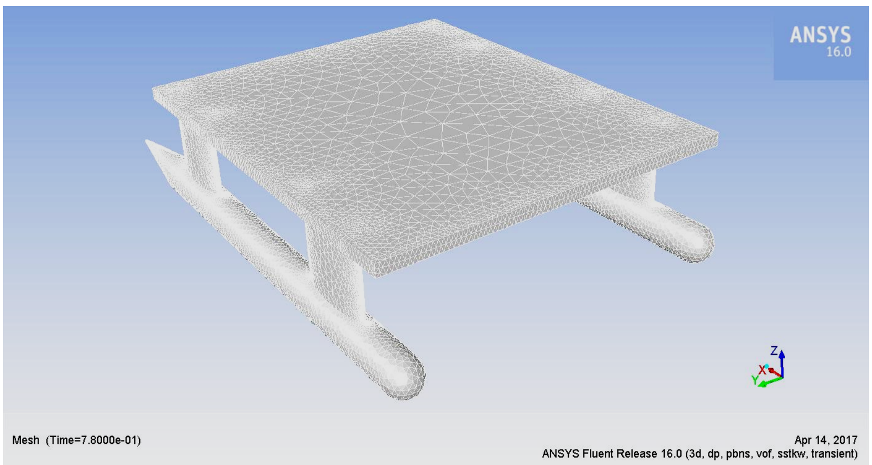


Figure 5. Meshed model of the SWATH boat

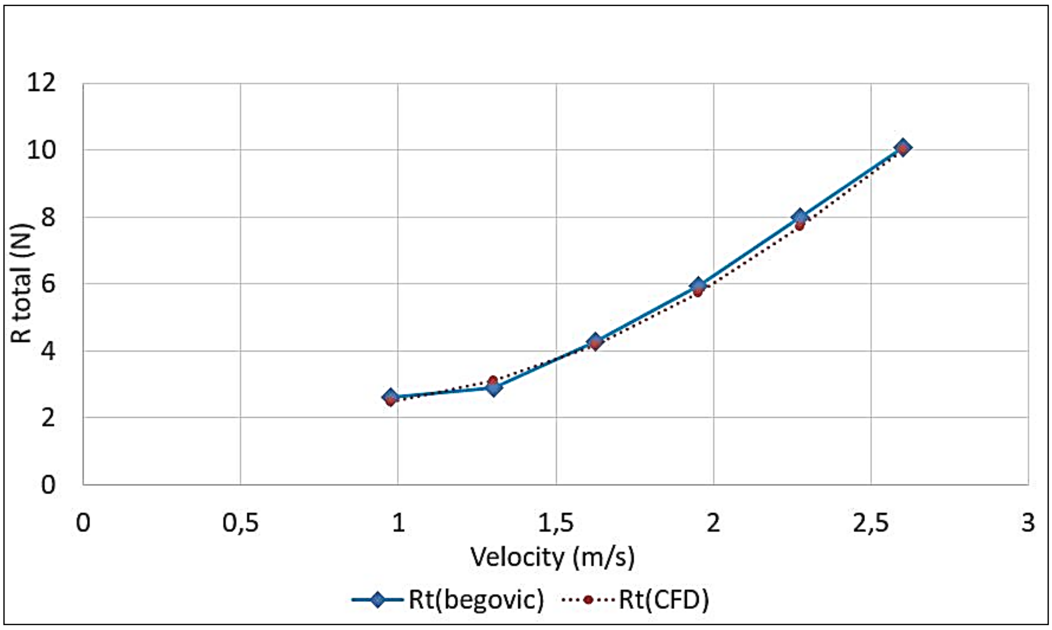


Figure 6. Total resistance values of the SWATH boat determined by experiment [4] and CFD analysis in this study

Moreover, it had been observed that the longitudinal instability at the model having freedom degree of pitching and sinking, occurred at v_1 = 1.952 m/s and v_2 = 2.603 m/s during the simulations of the model which led it to trim by the stern. (Figures 7 a, b) [4].

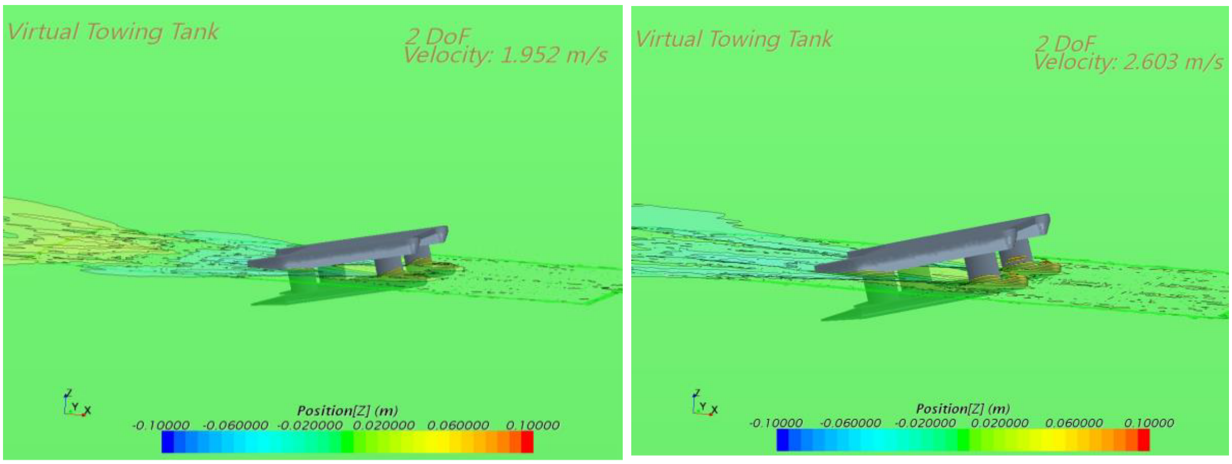


Figure 7a, b. Longitudinal instability of the SWATH model at speeds v_1 = 1,95 and 2,6 m/s [4]

On the bow of all floating marine vessels in forward motion, a positive pressure field arises due to the basic principles of fluid mechanics, and a negative pressure field in front of the propeller which usually results in trimming by the stern. However, SWATH boats do not have a buoyancy to compensate this type of instability in this region. Because of this, as the vehicle speed increases, a trimming moment which results in trimming by stern arises. The SWATH form, which is particularly suitable for wave resistance reduction and therefore for higher speeds, is extremely sensitive to weight change since their struts have small waterline areas. Thus, relatively small changes in weight and trimming moment can result in excessive changes in trim and draught. This characteristic is a very negative feature for a marine vessel where the payload needs to be changed during the operation. Due to the above mentioned significant drawbacks of the SWATH form, it has been decided to choose the catamaran boat form which generally does not have these disadvantages [5-15].

4. Form Development of a Catamaran and Final Hull Form

The literature survey for boats of catamaran type shows that the boat forms vary significantly, and it was initially thought that the most favourable forms could be obtained from sources [12-13] in the literature list. After reviewing and analysing the catamaran boat forms developed by Molland et al. with systematic model experiments, it has been found that they are suitable for very slender sport and recreation yachts (Figure 8) [12]. Moreover, in the analyses carried out in the study, it was found that the resistance values in the range of 1-20 m/s obtained under equal displacement conditions were above the expected values (Figures 9-12).

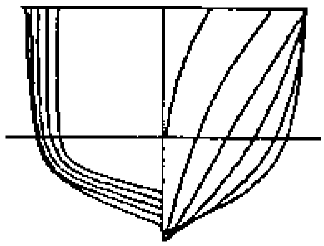


Figure 8. Catamaran forms developed by Molland et al. [12]

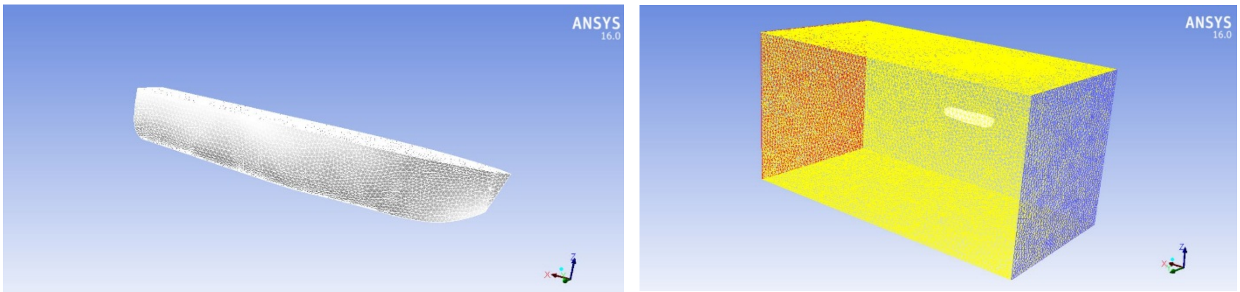
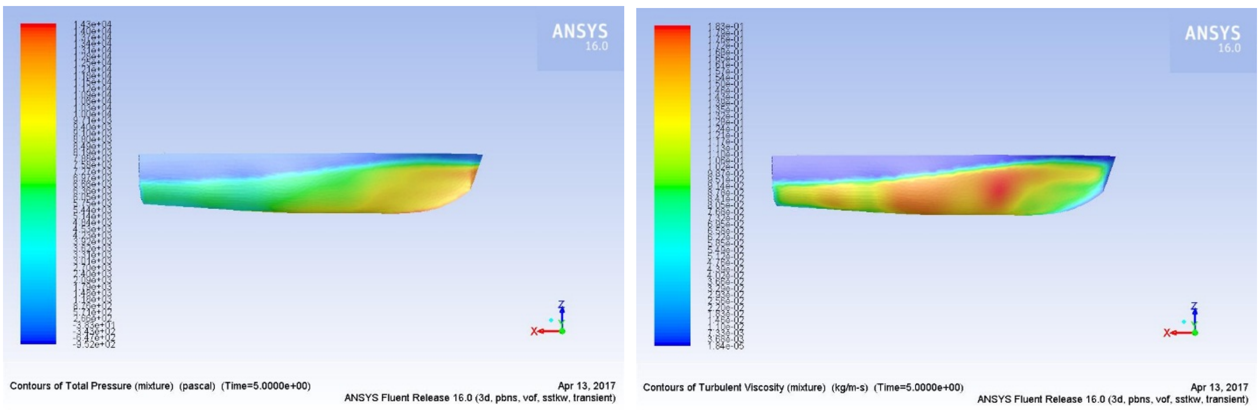


Figure 9 a,b. Meshed model developed by Molland et al. and the domain of the model



10 a, b. Total pressure contours and turbulence viscosity contours detected at the speed of 5 m/s on the surface of the model developed by Molland et al.

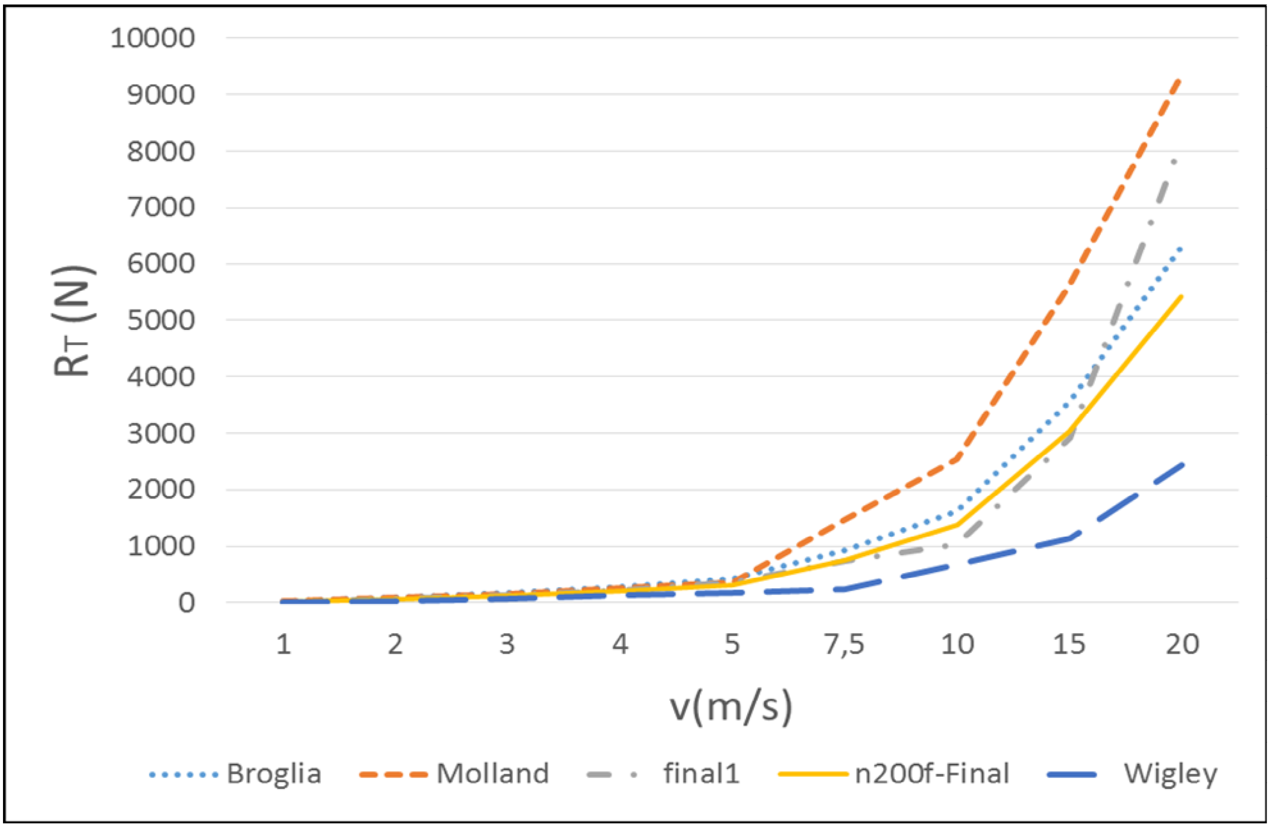


Figure 11. Total resistance values of all examined models determined at speed range of 1-20 m/s

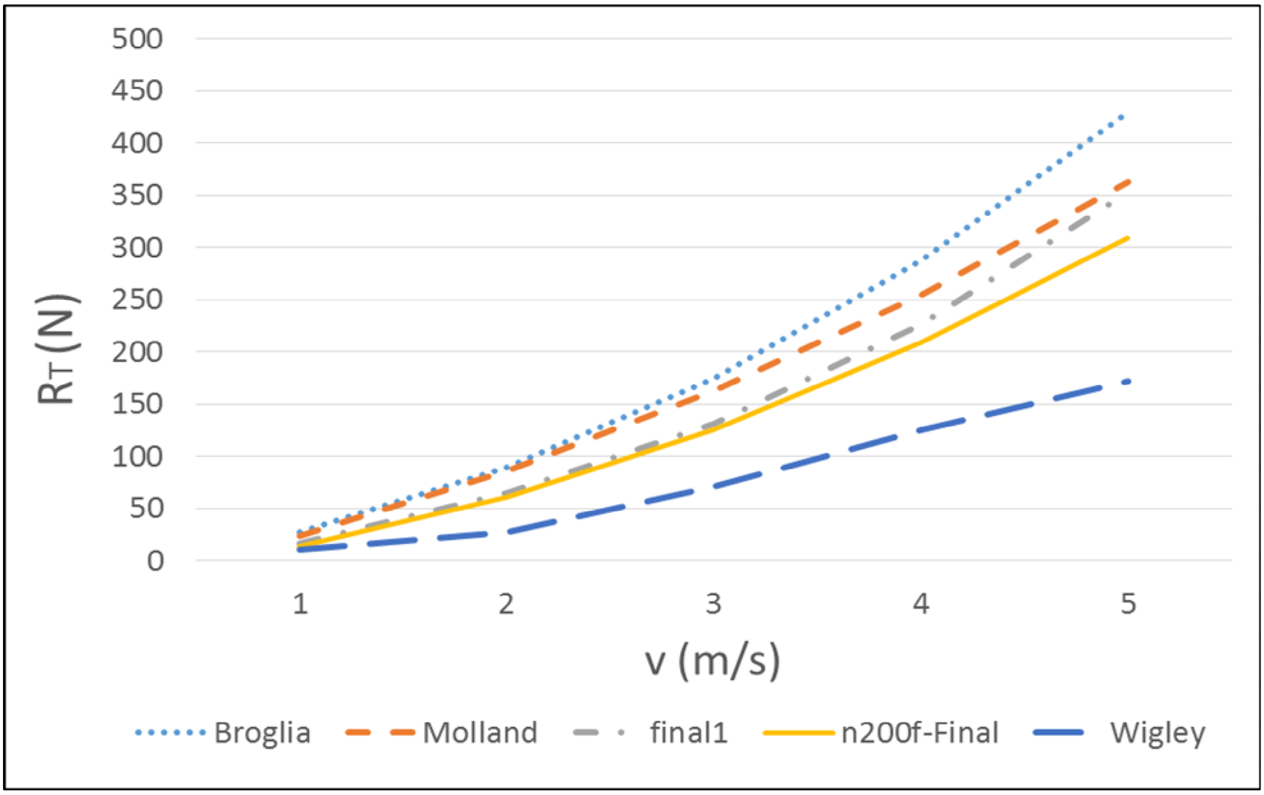


Figure 12. Total resistance values of all examined models determined in speed range of 1-5 m/s

Further, the hydrodynamic analyses were performed following the modelling of the catamaran form developed by Broglia et al. [14] (Figures 13-15), and the resistance values obtained were given in Figures 11-12. The resistance values determined were above the expected values, and due to the raised form of the stern, the vehicle will be free to trim at the high speed range as a result of its poor longitudinal stability characteristics (Figures 13-15).

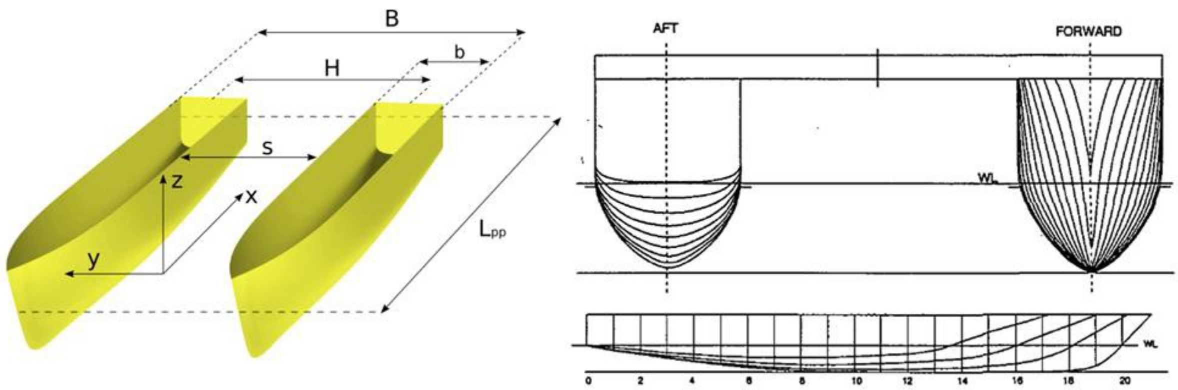


Figure 13. Catamaran form developed by Broglia et al. [14]

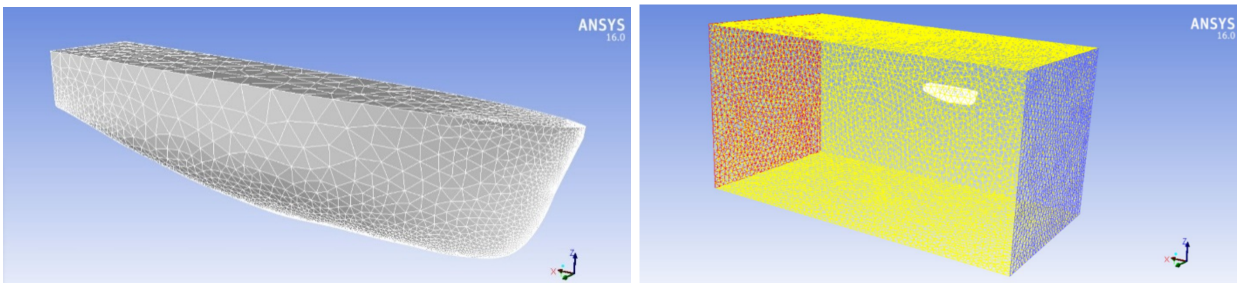


Figure 14 a,b. Meshed model developed by Broglia et al. and the domain of the model

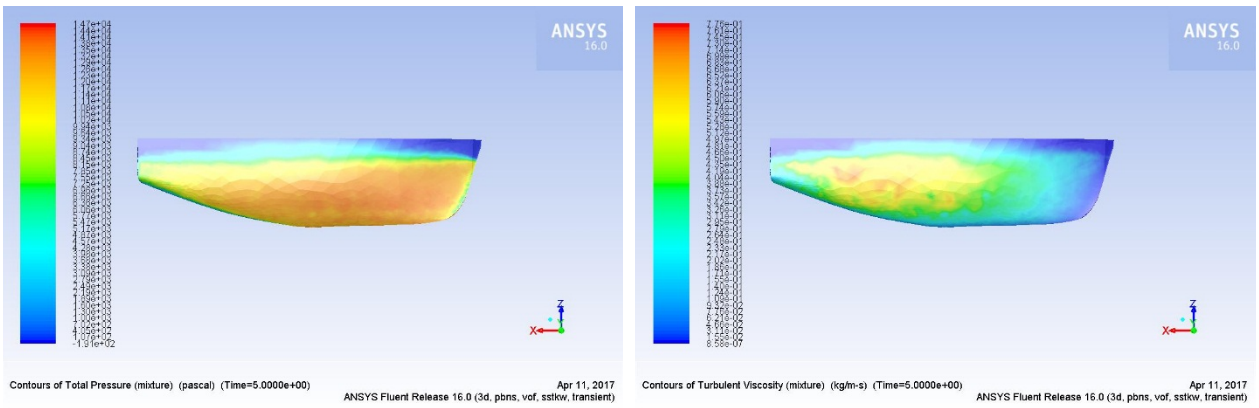


Figure 15 a,b. Total pressure contours and turbulence viscosity contours detected at the speed of 5 m/s on the surface of the model developed by Broglia et al.

In addition to being a mathematically defined hull form, Wigley hulls have been widely used as test cases for computational fluid dynamics codes, particularly for calculations of wave resistance and boundary layer flows. This is due to the fact that those hulls can be modelled exactly in commercial software, and extensive experimental data describing the flow around the models are available. Equation 3 describes the underwater hull shape of the model.

$$y(x,z)=\frac{B}{2}\left\{1-\left(\frac{2x}{L}\right)^2\right\}\left\{1-\left(\frac{z}{T}\right)^2\right\} \quad \text{(Equation 3)}$$

where

x : Distance from mid-ship (positive fwd)
y : Half-breadth in point (x, z)
z : Distance measured from the base line (positive in the direction of keel)
L : Length of the hull
B : Breadth of the hull
T : Draught of the hull.

In this study, a Wigley hull form also was created and its total resistance of the model were determined using the SSTKW Menter-algorithm. The model possesses extremely slender hull form at the same displacement and height compared to the others, thus its length was elongated to L_{OA}=300 *cm* as shown in Figure 16 and 17 [18,19]. The resistance values determined below are in the expected range due to extremely slender hull form, particularly, the slender bow and stern. (Figure 11 and 12).

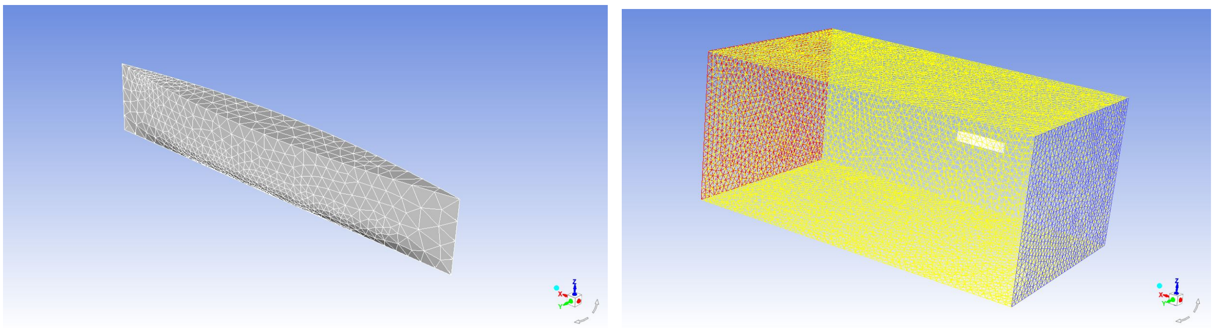


Figure 16 a,b. Meshed model of Wigley hull developed in the study and the domain of the model

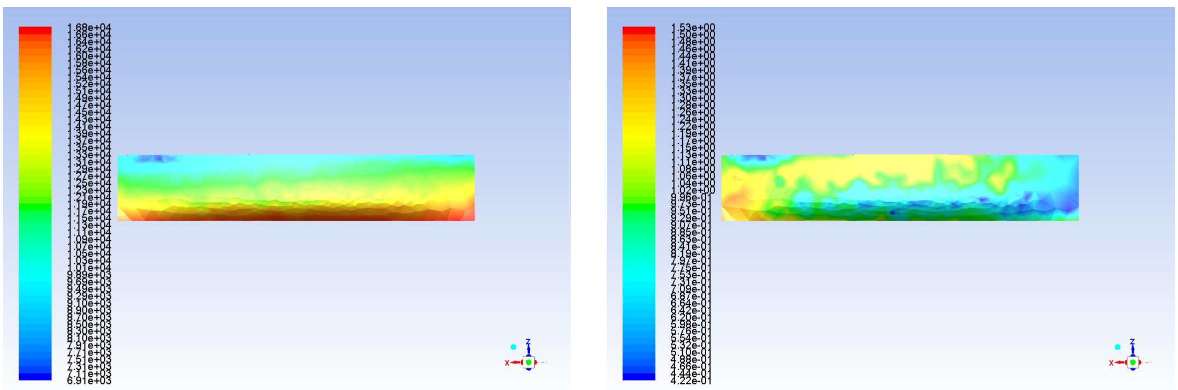


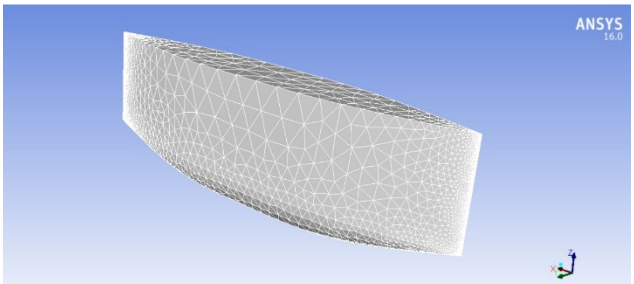
Figure 17 a,b. Total pressure and turbulence viscosity contours detected at the speed of 5 m/s on the surface of the model of Wigley hull

Apart from those models, a catamaran boat form (*final-1*) with length of 200 cm was prepared by means of NACA forms as shown in Figure 18 and 19 [15] und its model was analysed using the same algorithm under equal displacement conditions. The most important feature of this form was the simplicity of the production of the form.

In the form developed by Molland et al., the effects of turbulence appear strongly at the fore shoulder of the model starting from a velocity of 1 m/s and are increased to extreme levels with increasing speeds. In the model developed by Broglia et al., the corresponding turbulence contours arise at the middle of the model and grow with increasing speed partially. For this reason, it can be said that the high total resistance values of these models are entailed by the flow separation from amidships to the stern shoulder at early stages due to the increase of turbulences. In the model *final-1* and Wigley, flow separations depending on the turbulence occur at higher speeds and at lower levels near to the stern shoulder and stern. It was found that high pressure fields on the model surfaces were concentrated on the bows and fore shoulders, as expected.

After the evaluation of all the results obtained, the form of the type "*final-1"* was chosen since it has the optimal hydrodynamic properties within the speed range of 1-5 m/s, has large inner volume and a simple form, therefore offering the advantage of easy production (Figure 11 and 12). The Wigley form was omitted due to its perfectly slender hull form that was hard to manufacture and that had an unacceptably small inner volume. Furthermore, it should be noted that the results of these analyses can be assessed in two zones of speed in terms of the resistance values: 1-5 m/s and 10-20 m/s zones. Due to the maximum speed limitation of the prototype, the lower speed region of 1-5 m/s is essential for the ASV, which in turn shall be determinant for the selection of its engine and propeller.

In the following steps, it was decided to make further improvements in the hull form "*final-1"* of the vehicle with regard to resistance and propulsion characteristics. Flow separations and vortices (increase in turbulence) by the increase of the local pressure, can be avoided by increasing the fluid velocity, by making certain changes in the bow and fore shoulder and especially at the stern shoulder and stern as well as the bottom of the model (Figure 18 and 19).



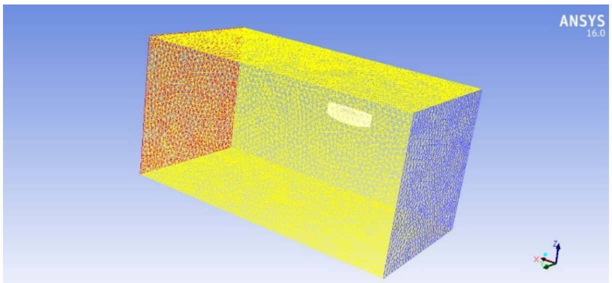


Figure 18 a,b. Meshed model of the type "*final-1*" developed in the study and the domain of the model

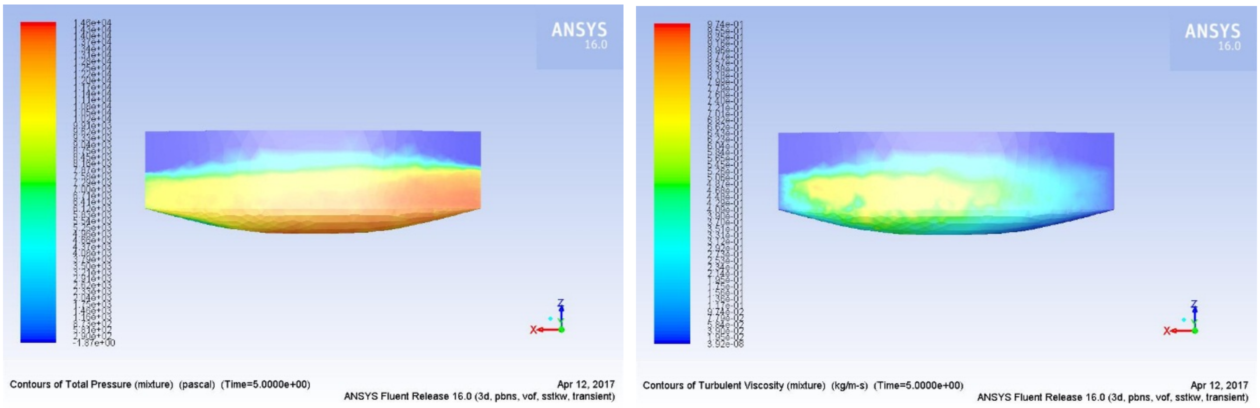


Figure 19 a,b. Total pressure and turbulence viscosity contours detected at the speed of 5 m/s on the surface of the model type *final-1*

Accordingly for increasing the displacement and hence reducing the draught of the model, its bottom was flattened, and further, the stern of the model has been widened to 140 *mm*, in order to provide a support for a stern-mounted outboard motor as shown in Figure 20. The new model created was named “n200f-Final”, and the total resistance values estimated by CFD analyses were given in Figure 11-12, 21a and b compared with those of the other models.

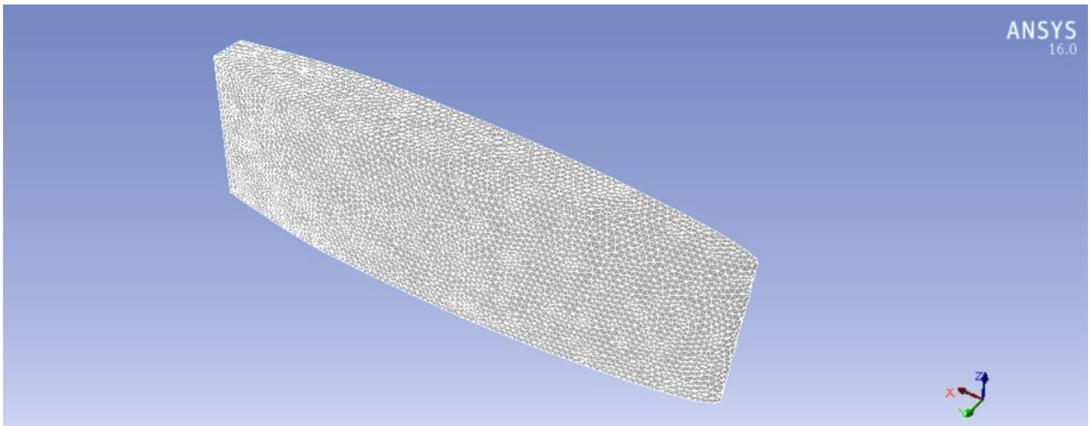


Figure 20. Final hull form “n200f-Final” obtained by changing the model type *final-1*

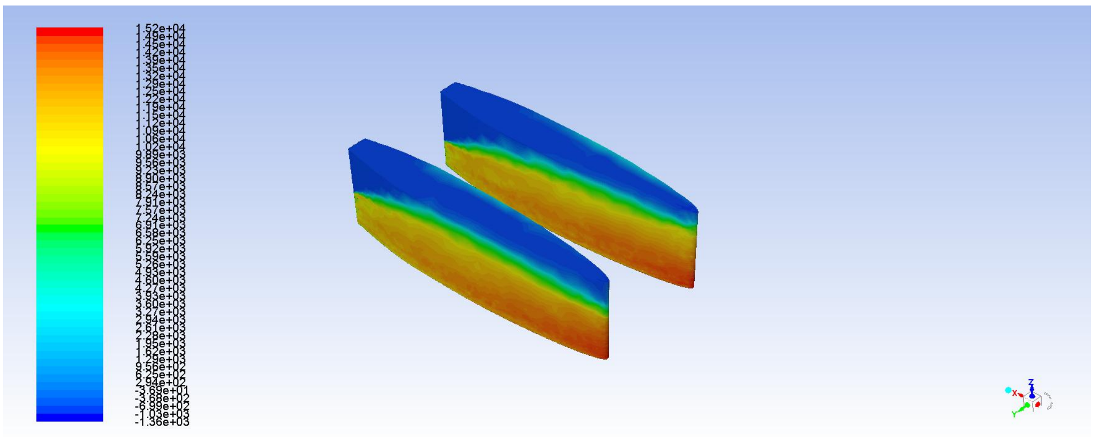


Figure 21 a. Total pressure contours detected at the speed of 5 m/s on the surface of the model type *n200f-Final*

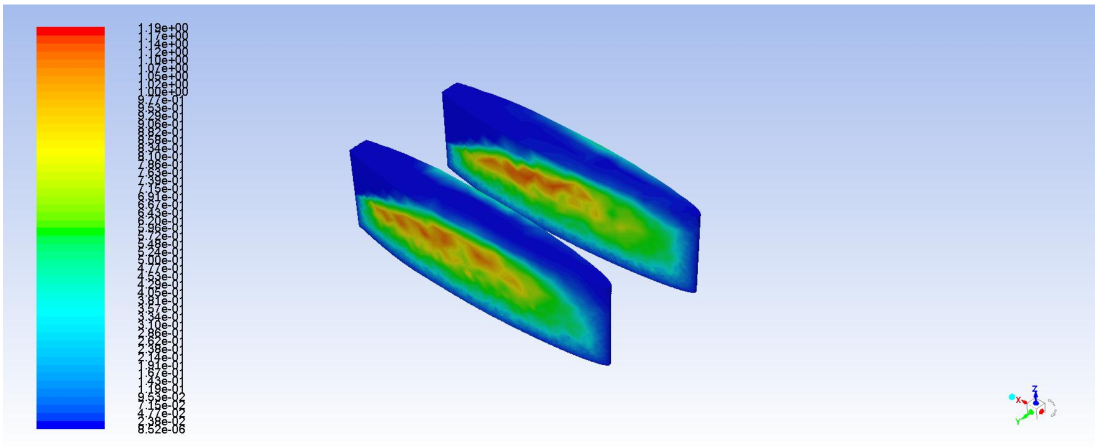


Figure 21b. Turbulence viscosity contours detected at the speed of 5 m/s on the surface of the model type *n200f-Final*

The main dimensions and the basic properties determined for the developed design are summarized below (Figure 20 and 21):

- The tasks of the unmanned, autonomous surface vehicle (JEO-IDA): Bathymetric measurements, deep scanning through side scanning sonar and single beam eco-sounder, seismic measurements and sample acquisitions.
- Operation areas are primarily in the Gulf of İzmir and its surroundings

L_{OA} = *2000 mm*
D = *550 mm*
B = *300 mm (of each individual hull)*
T = *275 mm*
C_B = *0.79155*
V_{max} = *10 kn =5.14 m/s*
$V_{Service}$ = *8.5 kn*
$V_{Operation}$ = *2-4 kn*

5. Optimisation of the Separation Ratio at Catamaran Hulls

In general, catamaran resistance and propeller efficiency depend on separation ratio of the hulls (transverse clearance), hull asymmetry, principal dimension ratios and hull form. Viscous resistance interference between the two hulls is found to be relatively independent of speed and hull separation and rather is dependent on length-to-beam, beam-to-draft and length-to-displacement ratio of each demihull [20]. It is evident that a significant reduction in wave and viscous resistances could be achieved by finding an optimum position of stagger. The wave interference between the two demihulls creates the typical wave system of catamarans and the disturbed waves generate wave pattern resistance downstream after the demihulls' body.

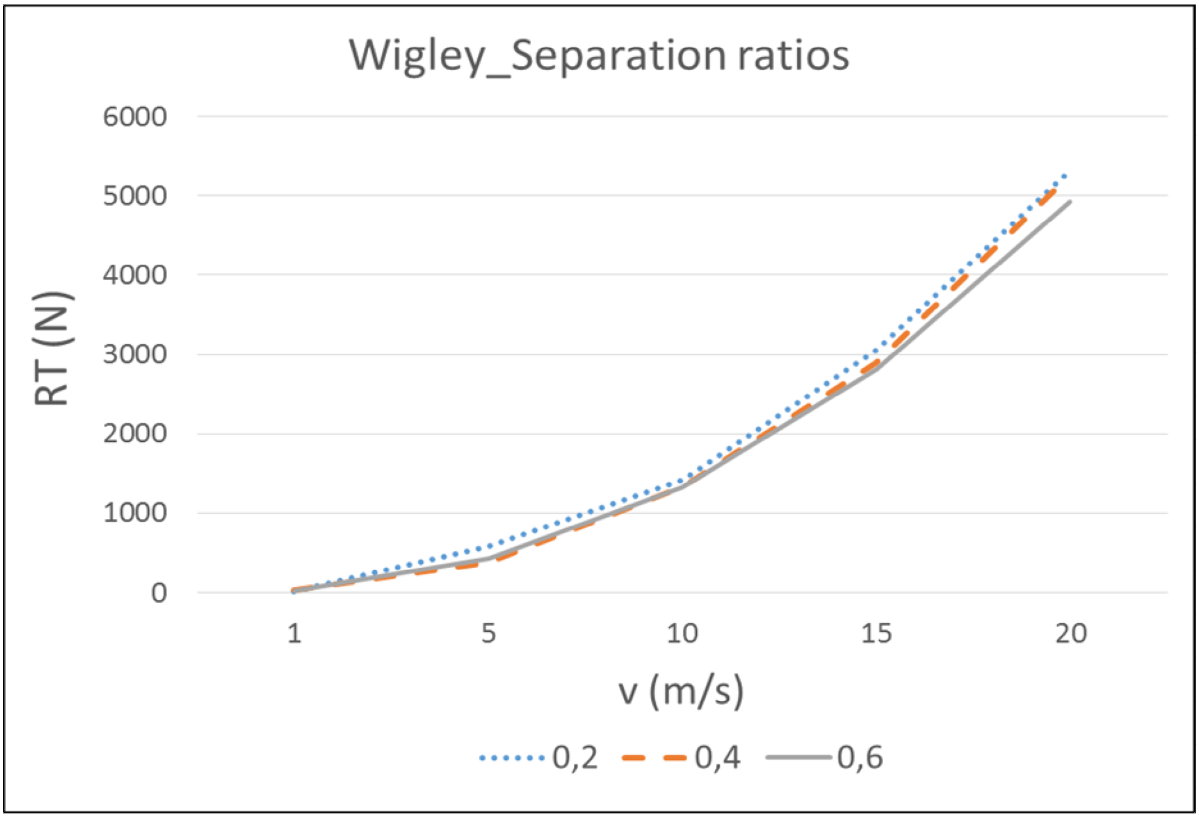


Figure 22. Total resistance values of the model type Wigley at various separation ratios

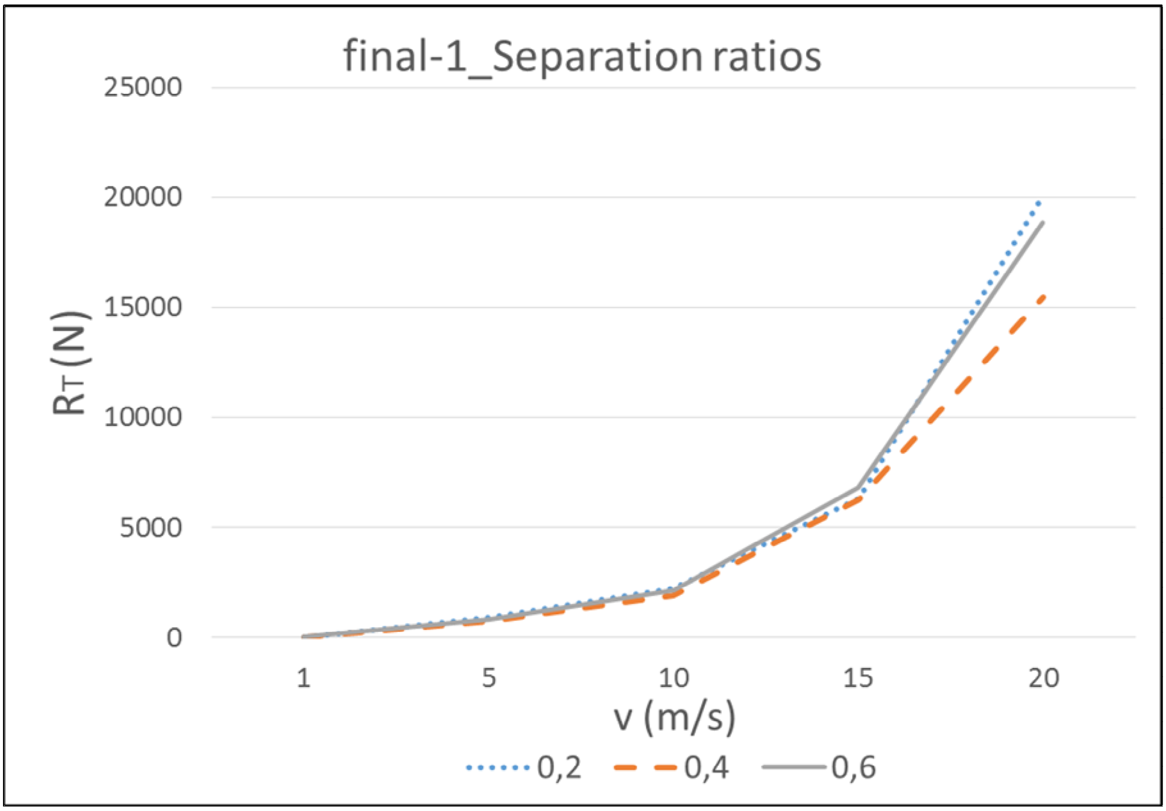


Figure 23. Total resistance values of the model type *final*-1 at various separation ratios

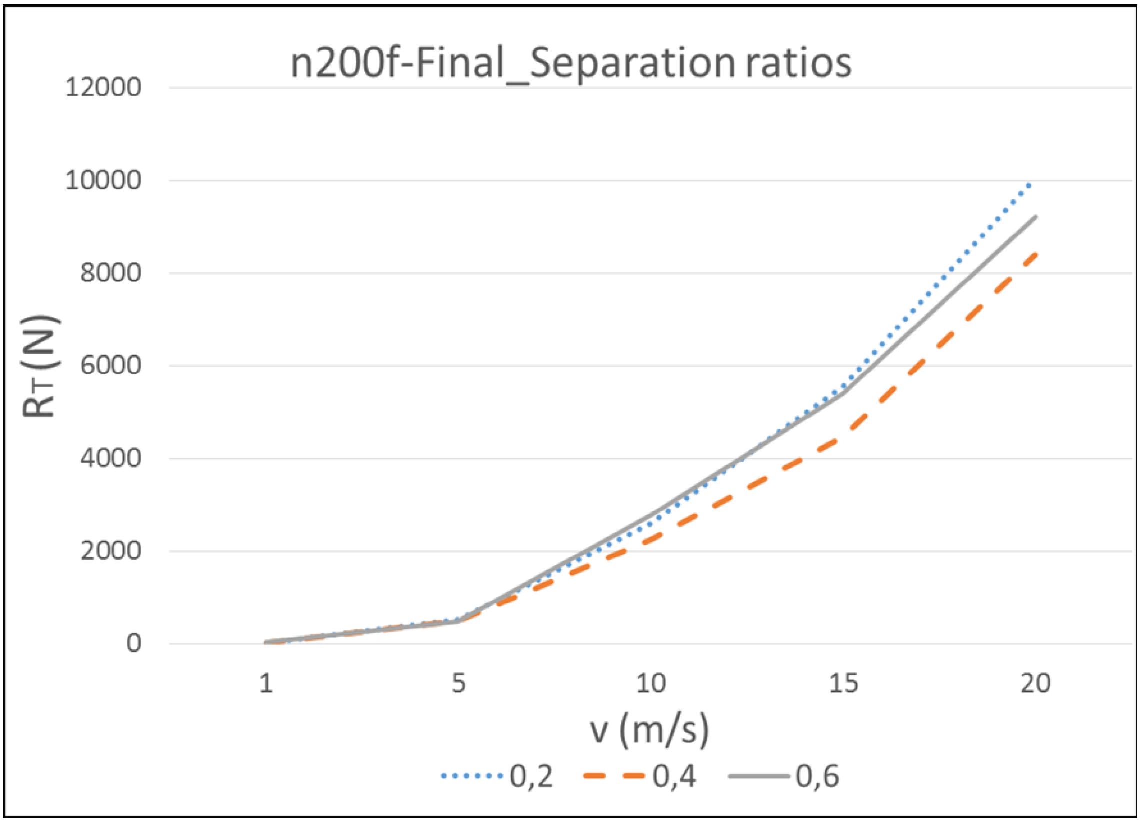


Figure 24. Total resistance values of the model type *n200f-Final* at various separation ratios

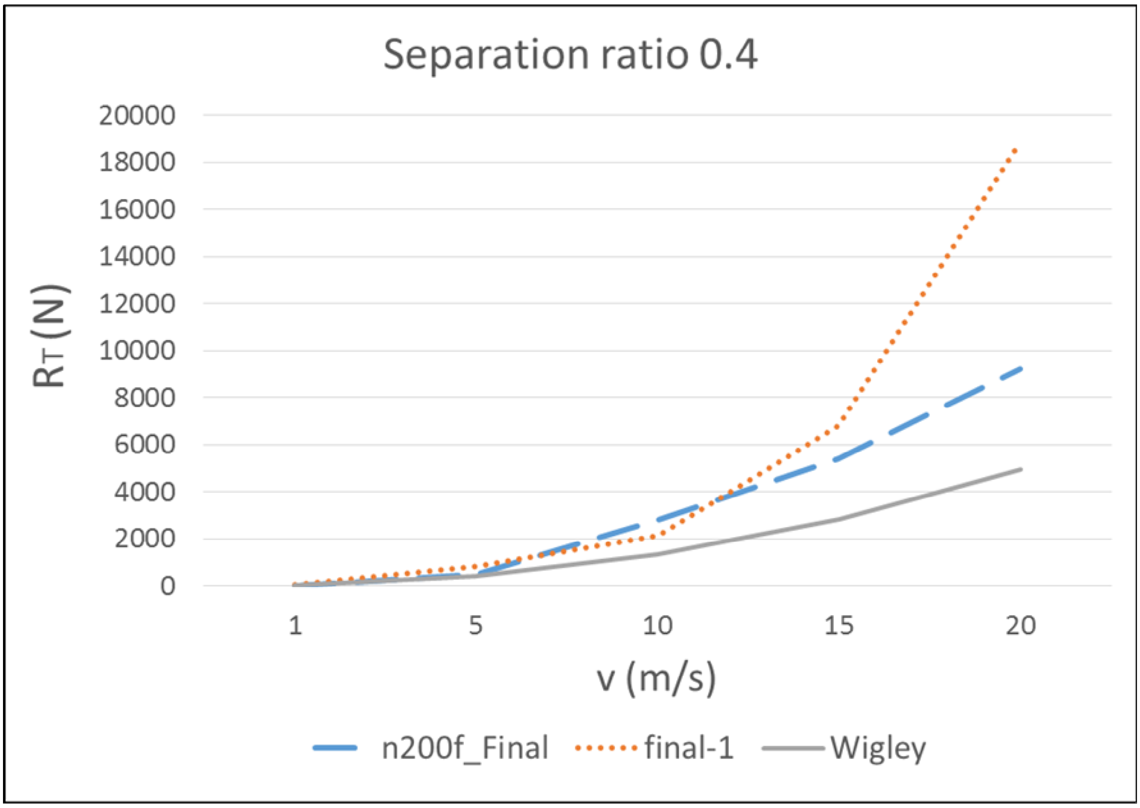


Figure 25. Total resistance values of all the models at optimum separation ratio

It is possible that this wave interference effect due to the interaction of the wave systems generated by each demihull should be minimized by the optimization of the hull separation. The presence of the twin hull has a strong influence on the wave pattern in the inner region (between the hulls), whereas this influence in the outer region is rather small. Resistance of a catamaran can be lower, equal or greater than the sum of its two demihulls depending upon certain ranges of Froude number (Fn) and separation ratio, since this ratio depends on speed levels of catamarans due to interference effect of individual wave systems of demihulls. If the speed increases towards the high speed range (e.g. from Fn=0.40 to 0.45), hull separation becomes narrower to achieve a minimum wave-making resistance, and vice versa e.g. towards the middle speed range from Fn=0.35 to 0.25, large separation ratio [20].

Feasible Froude number range can arise between Fn=0.25 and Fn =0.50 depending upon separation ratio from the point of view of the wave-making resistance by interference of the wave system of catamarans. In order to investigate the effect of the separation ratio on the total resistance of catamarans, the hull forms *final-1*, *n200f-Final* and Wigley hulls, were selected, and they were analysed with separation ratios of 0.2, 0.4, and 0.6 in a speed range of 1-20 m /s as shown in Figures 22-25.

While the analysis results of transverse clearance of the hulls with Wigley forms are in close agreement in the whole speed range between 1-17 m/s, the results indicate that the separation ratio 0.4 is distinguished at the other both forms particularly at *n200f-Final* and *final-1* from from 5 m/s and 15 m/s, respectively (Figures 22-24). Further it was determined that an optimum separation ratio exists about 0.4 and the results of Wigley and *n200f-Final* hulls with this separation ratio agree closely within the speed range of 1-5 m/s in which the ASV was laid out with driving motor and propeller as shown in Figure 25.

6. Results

This study is aimed to develop a design of an unmanned surface vehicle, which will autonomously enable real-time monitoring of the data that shall be obtained by a side scanning sonar and a single beam echo-sounder installed on the vehicle for geological and geophysical surveys that are monitored from a land-based station. The result of the work is the prototype, of whose mission is to investigate three-dimensional geological and morphological structures of the seabed with a high-resolution and to prepare their maps as well as carrying out coastal and offshore surveys in construction and operation phases.

The prototypes, namely, ASVs can be easily manufactured with E-glass fibre reinforced polyester. It has been realised that the hull form developed on the basis of the results of the CFD analyses can be produced in series since it has suitable properties in terms of hydrodynamic design and is suitable for serial production at reasonable costs and is convenient to operate in medium speed category, especially in range of 1-5 m/s and at separation ratio of 0.4, regarding resistance forces arisen compared to those of Wigley hull. In the future stages, SWATH boat forms need to be investigated in detail for very high speed range.

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