Reconstruction of Hull Form of Traditional Croatian Fishing Vessel and Prediction of Effective Power

Rekonstrukcija forme trupa tradicionalnog hrvatskog ribarskog broda i predviđanje efektivne snage

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Abstract

Recently, an increasing attention is given to preservation and popularization of Croatian traditional boat building, which plays an important role in Croatian cultural and national heritage. Reconstruction and revitalization projects of individual historical vessels are key factors within preservation process, where the lack of technical documentation is one of the main issues. In this paper, a simple and efficient procedure for taking offsets of a traditional fishing vessel *guc* is presented to document and preserve the traditional Croatian vessel form. A 3D model of a *guc* is generated using the points on the hull surface obtained by the manual measurement and a fairing process. Numerical simulations of the resistance test for a fishing vessel are carried out for a wide range of speeds, and the curve of effective power as a function of vessel speed is provided.

KEY WORDS
fishing vessel
reconstruction
hull offsets
3D model
CFD
resistance
effective power

Sažetak

U posljednje vrijeme sve više pozornosti posvećuje se očuvanju i popularizaciji hrvatske tradicijske brodogradnje, što ima važnu ulogu u hrvatskom kulturnom i nacionalnom naslijeđu. Projekti rekonstrukcije i revitalizacije individualnih povijesnih brodova ključni su čimbenici u procesu očuvanja, gdje nedostatak tehničke dokumentacije predstavlja jedan od glavnih problema. U ovome radu predstavljen je jednostavan i učinkovit postupak za snimanje forme tradicijskog ribarskog broda tipa guc u cilju dokumentiranja i očuvanja tradicionalne forme hrvatskog broda. Izrađen je 3D model guca koristeći ručno izmjerene točke na trupu broda koje su potom izglađene. Numeričke simulacije pokusa otpora za ribarski brod provedene su za široki raspon brzina te je dobivena krivulja efektivne snage kao funkcije brzine broda.

KLJUČNE RIJEČI
ribarski brod
rekonstrukcija
očitanja trupa
3D model
RDF
otpor
efektivna snaga

1. INTRODUCTION / *Uvod*

The Republic of Croatia has an outstanding reputation in wooden ship and boat building and is worldwide known for its long tradition and distinguished ship and boat builders. The skill and the art of building wooden vessels are recognized by the Ministry of Culture of the Republic of Croatia and protected as a part of the intangible cultural heritage. Traditional ship and boat building is based on artisanal small-scale production in smaller ship and boatyards, the use of traditional vessel constructions, forms, materials (wood), production technologies and tools, while the ship and boat builders gained their skills through apprenticeship and transmission from one generation to another. Today, traditional ship and boat building most often includes the construction of wooden vessels (wooden ship and boat building) intended for recreation or tourism. In a broader sense, the building of any historical vessel while preserving the authenticity of its shape, dimensions, materials, and manufacturing technology is considered traditional shipbuilding [1]. Croatian traditional ship and boat building, thanks to its longevity and significance is an important part of Croatian cultural heritage and national culture, so recently more and more attention has been paid to its preservation and popularization. This is carried out through reconstruction and revitalization projects of individual historical vessels. One of the Croatian traditional vessels is *guc*. The *guc* is a smaller sea fishing vessel similar to a *gajeta* with smooth lines and a round bottom with two stems, with one pair of oars and a mast with a lateen sail. The vessel is middle sized, usually with a length of three to eight meters. The small *guc* is entirely open and undecked, so that the hull is stiffened by transverse and the longitudinal benches [2]. There is almost no significant

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difference in shape of structure between the bow and the stern. Although it originates from the Tyrrhenian Sea, it spread to all regions receiving the most diverse local features [3].

During the process of the revitalization and reconstruction of a traditional vessel, one of the main issues is the lack of technical documentation, where this primarily refers to the lines plan [4]. The lines plan of a traditional vessel can be obtained by hull form measurements using either traditional or modern measurement methods. Vorobyev et al. [5] performed full scale mechanical tests to identify structural properties on a wooden replica of a hull section of the 17th century warship Vasa for three load configurations. The authors showed that 3D laser scanning is useful in quantifying displacements of a wooden replica for different load configurations. Terrestrial laser scanning was applied to capture ship hull geometry in [6]. The authors discussed the data processing procedure to obtain a 3D surface model from the point cloud for the purpose of hydrodynamic calculations. Burdziakowski and Tysiac [7] proposed a method that combines photogrammetry and laser scanning appropriate for modelling ship hull in unfavourable conditions. For the case of hull modelling, the authors showed that it is possible to obtain an accuracy of 10 mm when laser scanning provides edge information, while photogrammetry provides spatial data between the edges. The measurement methods mentioned in [5, 6, 7] require expensive technology and modern equipment. The advantages of traditional measurement methods by manual measurement of points on the hull without using any special tools are the cost-effectiveness, simplicity of the procedure, as well as the use of simple tools.

Traditionally, the fisheries sector is a very important sector in Croatia. Croatia's coastline is the second largest in the Adriatic Sea, establishing the importance of Croatia's maritime and fisheries policy [8]. The Fishing Fleet Register of Croatia includes 4039 vessels. Over 80% of the fleet consists of vessels with a length overall less than 12 m, which also forms the largest part of the fleet capacity in terms of power with a share of about 50% kW [9]. Very often the fishing vessels have a traditional design and are consequently inefficient in terms of fuel consumption and CO_2 emissions [10]. Therefore, it is of utmost importance to predict the resistance and effective power of these vessels.

The prediction of resistance and effective power is important for the assessment of the technical performances of a vessel, but it also enables the determination of the economic and environmental impacts of a vessel during its operation. The determination of resistance and effective power can be performed using several methods depending on the design stage. These methods vary depending on the accuracy, reliability, and rapidity of predictions of resistance and power of the vessel. One of the rapid methods for the prediction of resistance and effective power which can be used in the early design stage is presented in [11] and it is based on the Holtrop-Mennen method. Another rapid method which can also be used in the early design stage is presented by Yildiz [12]. The method is based on the artificial neural network for the prediction of residual resistance for a trimaran vessel. Later in the vessel design process, more accurate and reliable methods are required for the determination of resistance and effective power. Thus, the combination of towing tank experiments and certain extrapolation procedures is considered to be the most reliable method even though the scaling of the viscous forces represents the main issue [13]. Towing tank tests can be used for various assessments including manoeuvring [14], seakeeping [15], wave wake characteristics [16], roll damping [17], etc. Lately, a huge potential of accurate and reliable methods based on Computational Fluid Dynamics (CFD), as an alternative to towing tank experiments, has been proven for the prediction of ship resistance and effective power [18]. There are numerous studies in the literature based on the application of CFD for various problems in ship hydrodynamics [19, 20, 21].

Within this research, a simple and efficient procedure for measuring the hull form of a traditional fishing vessel *guc* is presented to document and preserve the traditional Croatian vessel hull form. Based on the offsets obtained by the hull form measurement, a 3D model of a *guc* is generated. Numerical simulations of the resistance test for a fishing vessel are carried out and the curve of effective power as a function of vessel speed is obtained.

2. HULL FORM MEASURING AND COMPUTER MODELLING / *Mjerenje forme trupa i računalno modeliranje*

Taking lines and offsets of an existing vessel is required if there is no complete technical documentation on the vessel hull form. This is more often the case with boats, fishing, coastal and similar vessels. Given the later use of offsets, it is important to achieve sufficient accuracy to ensure sufficiently accurate calculations based on these measurements. The first condition for accurate measurement is the availability of the required number of offsets on the outer shell in the actual conditions of the shipyard or other place where the vessel is located. Although sometimes taking of the offsets must be done in adverse conditions, care should be taken to ensure that the following conditions are met as much as possible:

- The vessel should be raised ashore, on a slipway, dock, shore or other operating surfaces. Measuring the vessel in a floating condition is only possible from the inside, and this significantly reduces the accuracy because there are structure elements, equipment and devices that make it difficult to access the hull.
- The vessel should be placed in the design condition as much as possible to reduce the need for subsequent corrections that introduce inaccuracies in the measurements.
- While the vessel is still in the sea, the design waterline or at least the waterline on which the vessel most often floats should be marked or measured.
- The vessel ashore should be placed on a flat surface. A flat concrete base that allows easier access would be ideal. If the vessel is lifted by a travel lift on a flat surface, it is possible to obtain the horizontal waterline by placing suitable blocks. If the vessel is pulled out to a slipway, most often the longitudinal inclination of the design waterline cannot be avoided.
- Particular care should be taken to place the vessel upright without a heel. The heel can be taken into account when fairing lines of the hull, but it is much easier if this has already been addressed during the measurement.
- Sufficient workspace should be provided as well as scaffolding that allows access to the vessel hull. Safe ladders

or platforms for persons performing measurements are needed.

- The number of blocks must be sufficient for the vessel to be securely supported. At the same time, a large number of blocks make it impossible to measure in places where the blocks are placed.
- Good lightning should be ensured by daylight or artificial illumination.

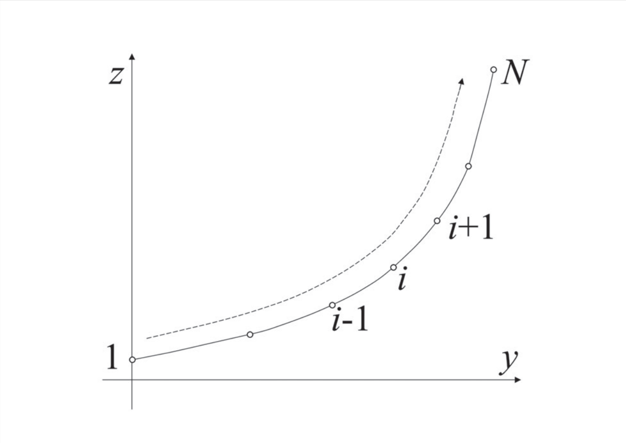


Figure 1 Defining section by offsets
Slika 1. Definiranje rebra pomoću očitanih točaka

There are many difficulties in taking offsets, especially on wooden or older vessels with the uneven outer shell. Taking offsets is based on the same principles as drawing the lines plan. A number of curves of the outer shell should be recorded by taking the coordinates of the offsets of each of these curves. The curves that are usually recorded are the sections, the bow and stern contours and especially the shape of the sheer and keel line. Later, these curves are reconstructed on lines plan or using the software and based on them the hull shape is defined and finally faired.

In this paper, the sections of the selected vessel are measured to reconstruct the entire hull form of the vessel. The sections are defined by offsets in the yz plane, according to Figure 1. The offsets on the section are taken in the direction from the keel line to the sheer line, following the curve of the section, in sufficient numbers to encompass all the characteristics of the section.

Before taking the section offsets, the sections should be in some way marked on the outer shell. Usually, the sections or offsets are marked with chalk, self-adhesive tape or some other means that can be easily removed later. The choice of the number and position of the sections is related to the complexity of the hull form and the possibility of access. It should be ensured that all offsets, which define one section, lie in the same plane perpendicular to the vessel centerline. If the offsets are not in the same plane, it is practically impossible to obtain accurate reconstruction of the section retrospectively.

The plane of the section is determined by sighting perpendicularly to the centerline. The centerline shall be marked on the deck by means of a string taut from bow to stern, Figure 2.

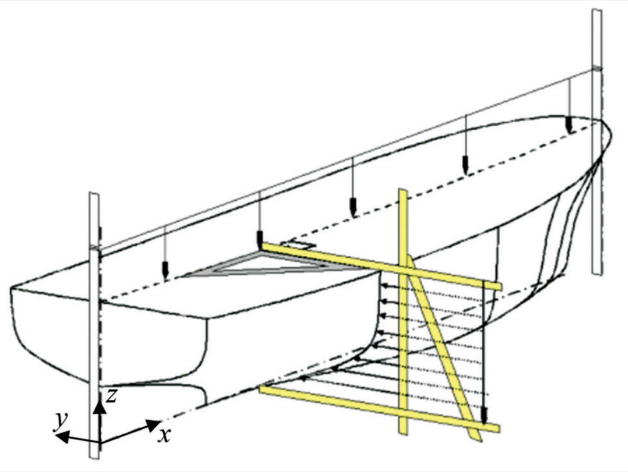


Figure 2 The principle of obtaining section offsets [22]
Slika 2. Način očitavanja točaka rebra [22]

The section plane is formed by a construction made of wooden laths. By measuring the distance between the vertical lath and the outer shell and subtracting this distance from the distance between the vertical lath and the centerline, the section offsets are obtained. The procedure is repeated for all sections, Figure 2.

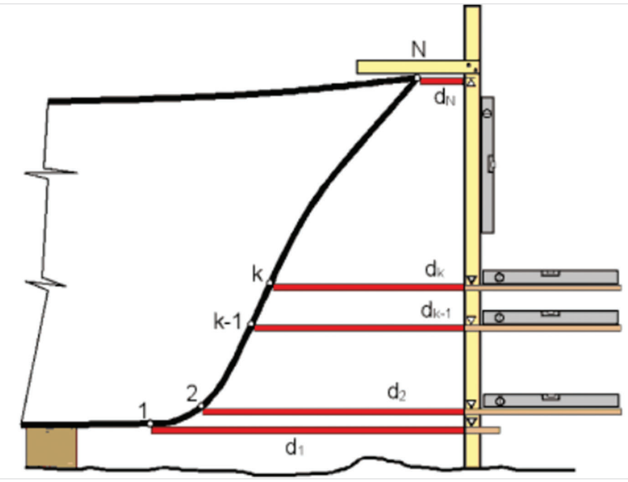


Figure 3 The principle of taking the offsets of the bow contour [22]
Slika 3. Način očitavanja točaka pramčane statve [22]

Taking the offsets of the vessel ends is performed analogously to taking the section offsets. The vessel must be placed in the longitudinal position closest to the actual trim while floating i.e., on the design waterline. The installation of a vertical lath makes it possible to record the shape of the contours (bow or stern), but the problem is to connect these offsets with other taken offsets. The relation is established by offsets on the keel and sheer line, Figure 3. In Figure 3, variable $k = 1,\ldots,N$ represents the points on the hull surface whose distance $d = d_1,\ldots,d_N$ is being measured from the vertical lath placed next to the hull at the predefined position.

As the results of the measurements, for example of the bow contour, the horizontal distances between the vertical lath and the offsets on the contour are obtained.

The described procedure was chosen to take the offsets of the fishing vessel, Figure 4. The hull form to some extent follows the shape of the Croatian traditional vessel *guc*. The main particulars of the vessel are given in Table 1.

Table 1 Main particulars of the fishing vessel

Tablica 1. Glavne značajke ribarskog broda

Particular	Symbol	Value, m
Length overall	L_{OA}	5.85
Length of waterline	L_{WL}	5.53
Breadth	B	2.3
Depth	D	1.35
Draft	T	0.623

Before taking the offsets of the sections, the sections should be in some way marked on the outer shell. For this purpose, an auxiliary structure was made, Figure 5, which consists of a vertical lath with guides and two beams placed horizontally at a predefined distance from the centerline. It is important that the beams are parallel and placed horizontally, which is achieved with a water level. Furthermore, it is necessary to define in advance the positions of the sections i.e., the x coordinate of each section to be measured. The origin of the coordinate system is placed in a symmetry plane at the position of the keel end at the stern. Considering the size of the vessel, the measured sections were 0.3 m apart, which makes 18 measured sections. Along the sections, the bow and stern contours were taken according to Figure 3. After the x coordinates of all sections have been determined, the positions of the sections are marked on the pre-set beams. Furthermore, by knowing the position of each section, the auxiliary structure (vertical lath) is brought to the position of each section using guides, by translation in the direction of the x -axis. Also, the vertical lath is divided in height into intervals of 0.10 m, which indicate the heights at which the offsets of the sections will be read off. If the offsets are taken at the same heights along the hull, it is possible to define waterlines, which assures additional control of the taken geometry. The following is the marking of the sections on the

Figure 4 The fishing vessel

Slika 4. Ribarski brod

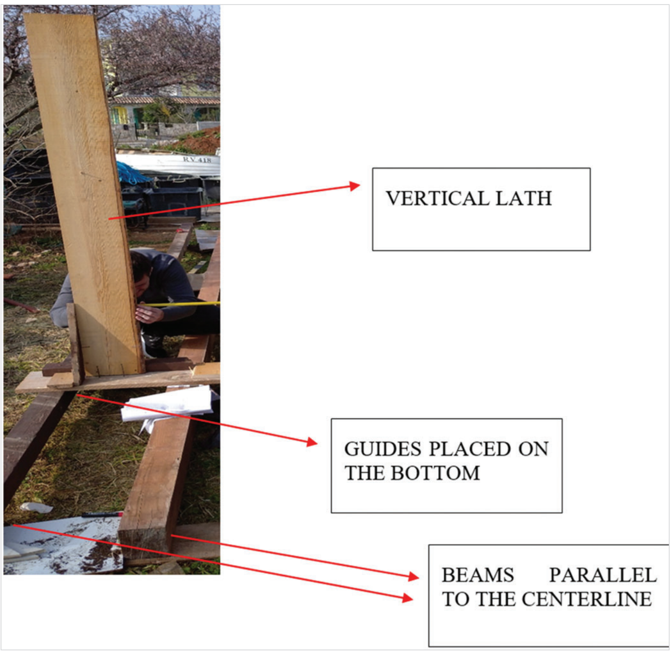


Figure 5 An auxiliary structure for taking the offsets of the sections

Slika 5. Pomoćna konstrukcija za očitavanje točaka rebara

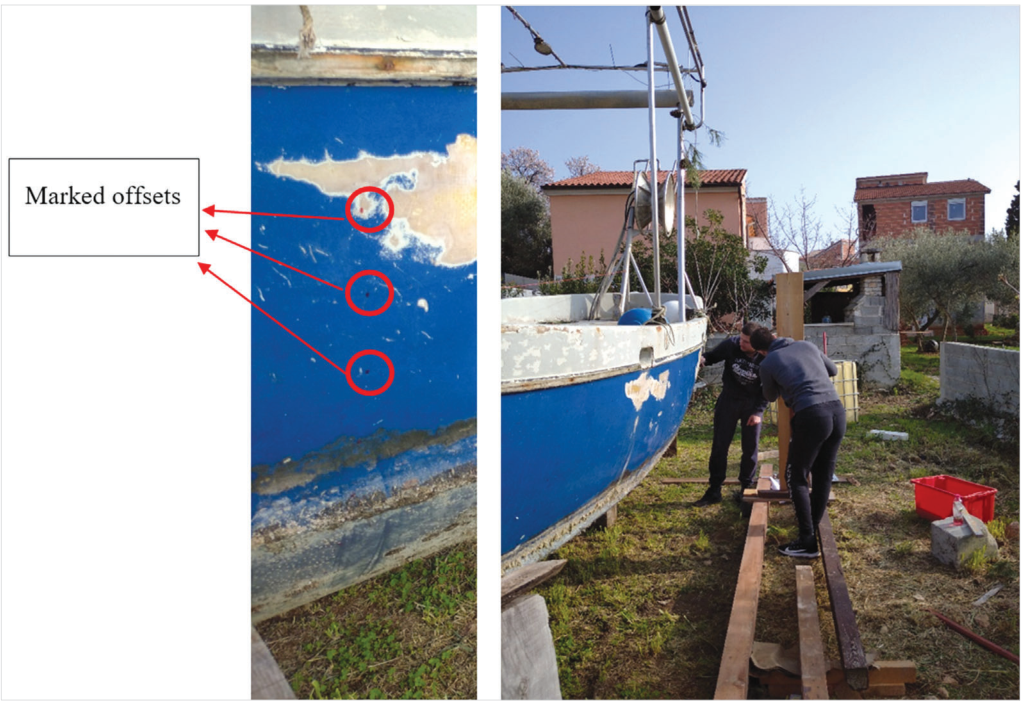


Figure 6 Procedure for marking section offsets
Slika 6. Postupak označavanja točaka na rebru

outer shell by “sliding” the vertical lath along the horizontally placed beams to the marked positions of the sections. Offsets are marked on the height of each section, Figure 6. After all the sections are marked, the distance of the marked offsets from the vertical lath is measured, Figure 7. By subtracting the measured distance from the known distance between the vertical lath and the centerline, the y coordinate of each offset is obtained.

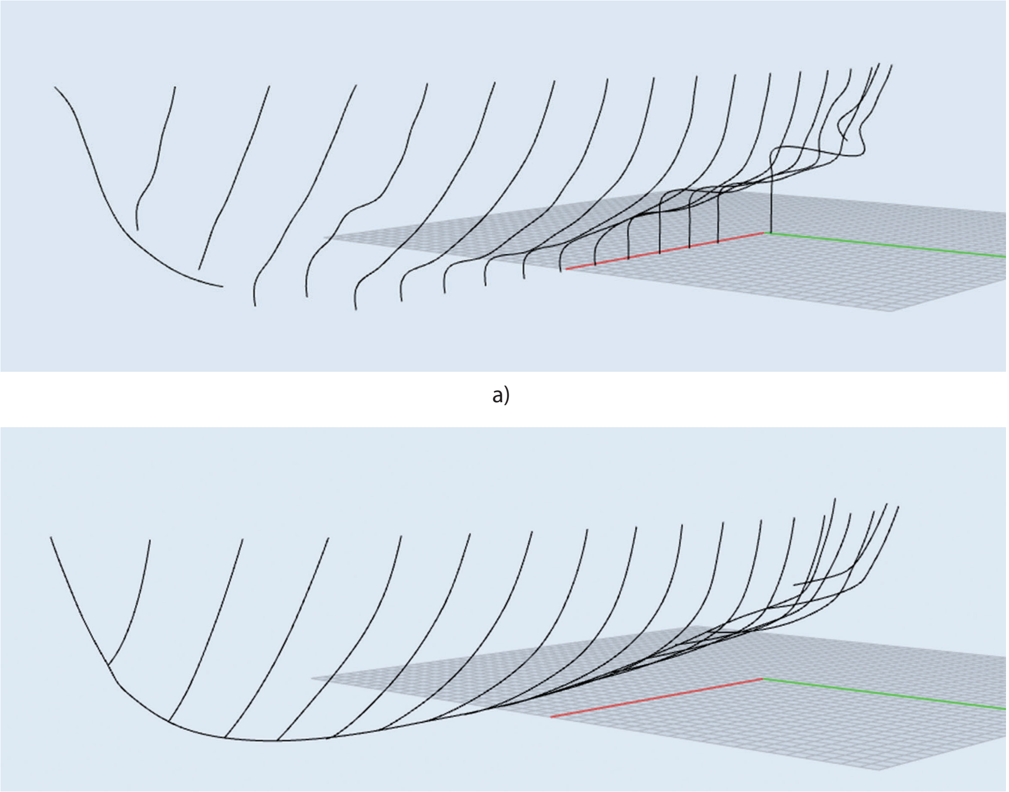
Figure 7 Procedure for measuring the distance of the marked offsets from the vertical lath
Slika 7. Postupak mjerenja udaljenosti označenih točaka od vertikalne letvice

An example of the table of offsets of Section 11 is shown in Table 2. It should be noted that all readings include the thickness of the outer shell.

Table 2 Offset coordinates of section 11
Tablica 2. Koordinate očitanih točaka rebra 11

Section 11, x = 3300 mm			
Offset no.	y measured, mm	y, mm	z, mm
1	1665	50	0
2	1665	50	100
3	1493	222	200
4	1320	395	300
5	1185	530	400
6	1067	648	500
7	972	743	600
8	887	828	700
9	817	898	800
10	765	950	900
11	722	993	1000
12	685	1030	1100

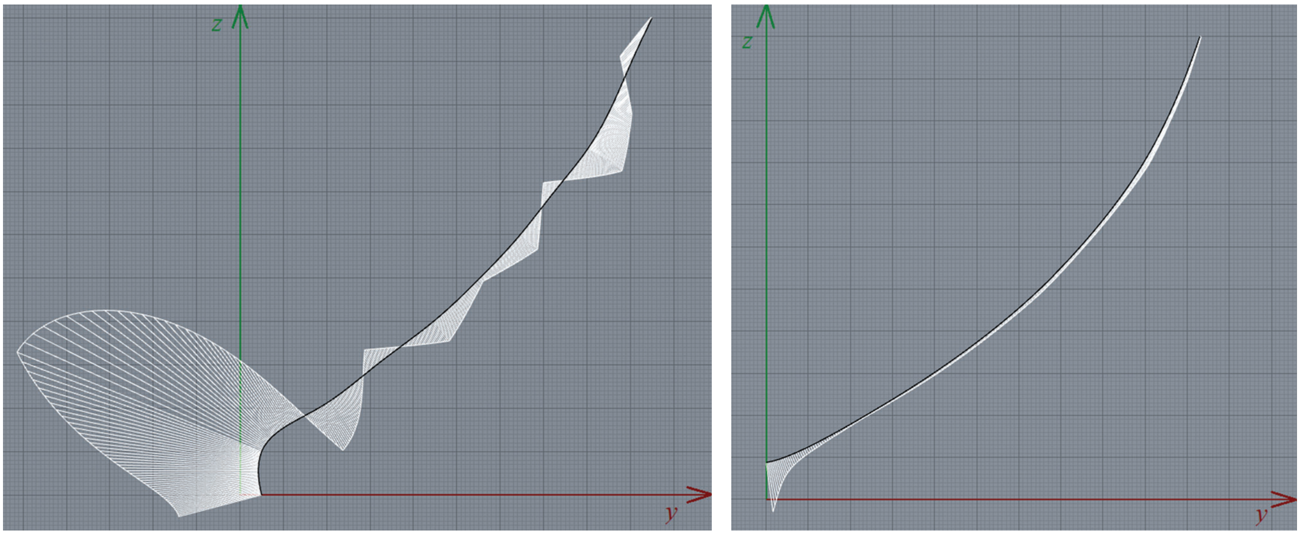
Offsets obtained by hull form measurement are imported into 3D modeller Rhinoceros [23] and hull sections as well as bow and stern contours are obtained by interpolating curves based on the defined offsets. Due to measurement errors, it is necessary to fair the obtained curves before generating the hull surface. Cross sections before and after the fairing process can be seen in Figure 8. The curves are faired by moving the points while taking into account the curvature of the curve. The curvature of one cross section curve before and after the fairing process is presented in Figure 9. It should be noted that the keel is not included in the hull form measurement, because of its simple trapezoidal form. Due to this, the 3D model of the vessel consists of two parts. Hull surface is generated based on the obtained smooth curves and the keel is then attached to it, Figure 10.



a)

b)

Figure 8 Sections before (a) and after (b) the fairing process
Slika 8. Rebra prije (a) i nakon (b) glađenja



a)

b)

Figure 9 Curvature of a section before (a) and after (b) the fairing process
Slika 9. Zakrivljenost rebra prije (a) i nakon (b) glađenja

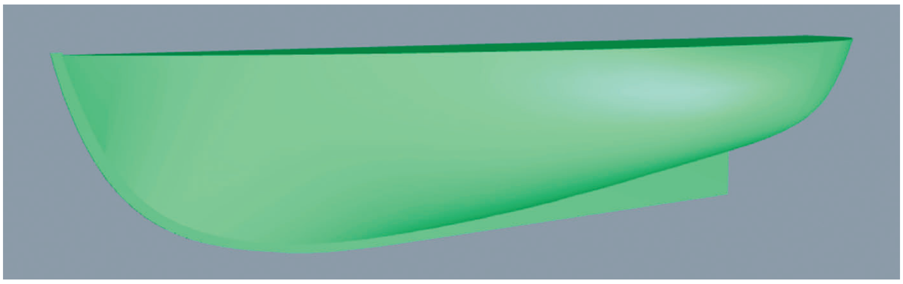


Figure 10 3D model of the measured and faired hull form of a fishing vessel
Slika 10. 3D model izmjerene i izglađene forme trupa ribarskog broda

3. METHOD FOR THE PREDICTION OF RESISTANCE AND EFFECTIVE POWER / *Metoda predviđanja otpora i efektivne snage*

Numerical simulations of resistance test for measured and modelled hull form of a fishing vessel at five speeds are performed using commercial software package STAR-CCM+ [24]. For the description of the incompressible viscous flow, Reynolds Averaged Navier-Stokes (RANS) equations and averaged continuity equation are used:

$$\frac{\partial\left(\rho\bar{u}_i\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\bar{u}_i\bar{u}_j+\rho\overline{u_i'u_j'}\right)=-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial\bar{\tau}_{ij}}{\partial x_j} \qquad (1)$$

$$\frac{\partial\left(\rho\bar{u}_i\right)}{\partial x_i}=0 \qquad (2)$$

where ρ is the fluid density, $\bar{u}_i$ are the averaged Cartesian components of the velocity vector, $\overline{u_i'u_j'}$ is the Reynolds stress tensor and $\bar{p}$ is the mean pressure. The mean viscous stress tensor $\bar{\tau}_{ij}$ is defined as:

$$\bar{\tau}_{ij}=\mu\left(\frac{\partial\bar{u}_i}{\partial x_j}+\frac{\partial\bar{u}_j}{\partial x_i}\right) \qquad (3)$$

where μ is the dynamic viscosity.

To close the set of equations (1) and (2), the $k-\omega$ SST turbulence model is used, which solves two transport equations, one for the kinetic energy k and one for the specific dissipation rate ω as done in [25].

For the discretization of governing equations, which are solved in a segregated manner, the Finite Volume Method is utilized [26]. For the discretization of convection terms in RANS equations, a second-order upwind scheme is used, and for the temporal discretization first-order temporal scheme is applied as done in [27]. To obtain ship resistance, unsteady free surface simulations are carried out using the implicit unsteady solver.

For the sake of reduction of the computational time, only half of the computational domain is discretized by the unstructured hexahedral mesh using a trimmed cell mesher [28]. The prism layer is generated at the hull surface based on its thickness, the number of cell layers and the size distribution of the layers. Within this research, wall functions are used, and the thickness of the prism layer is defined based on the vessel speed in such a way that the value of $y+$ is larger than 30 [29]. The special care is given to transition from prism layer to core mesh, as done in [30], which reduces potential numerical diffusion. The computational domain is refined in the bow and stern regions, near the hull and free surface, Figure 11, and in the area where Kelvin wake is expected as done in [31]. The mesh used for numerical simulations of the resistance test has approximately 0.7 M cells depending on the vessel speed.

Within the numerical simulations the vessel is fixed and fluid velocity equal to vessel speed is imposed at the inlet boundary. The size of the computational domain is set according to the ITTC recommendations [32] i.e., the outlet boundary is placed at 3 ship lengths away from the ship, while side, front and bottom boundaries are placed 1.5 ship lengths away from the ship. To prevent the wave reflection from boundaries, wave damping according to the damping layer approach is applied within one ship length away from the boundary at the outlet, inlet and side boundaries [33]. Applied boundary conditions are as follows: velocity inlet at bottom, top, side, and inlet boundaries, pressure outlet at the outlet boundary, and symmetry boundary condition at the symmetry plane [34], Figure 12.

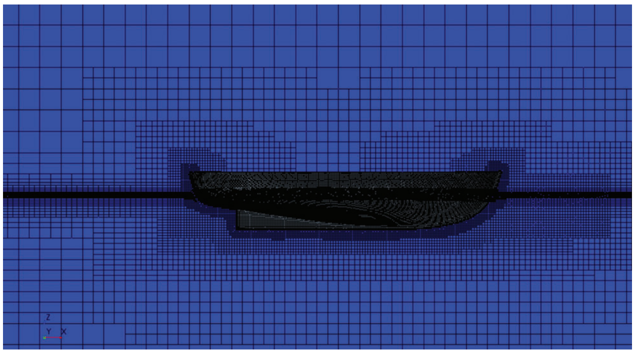


Figure 11 Mesh refinements
Slika 11. Profinjenja mreže

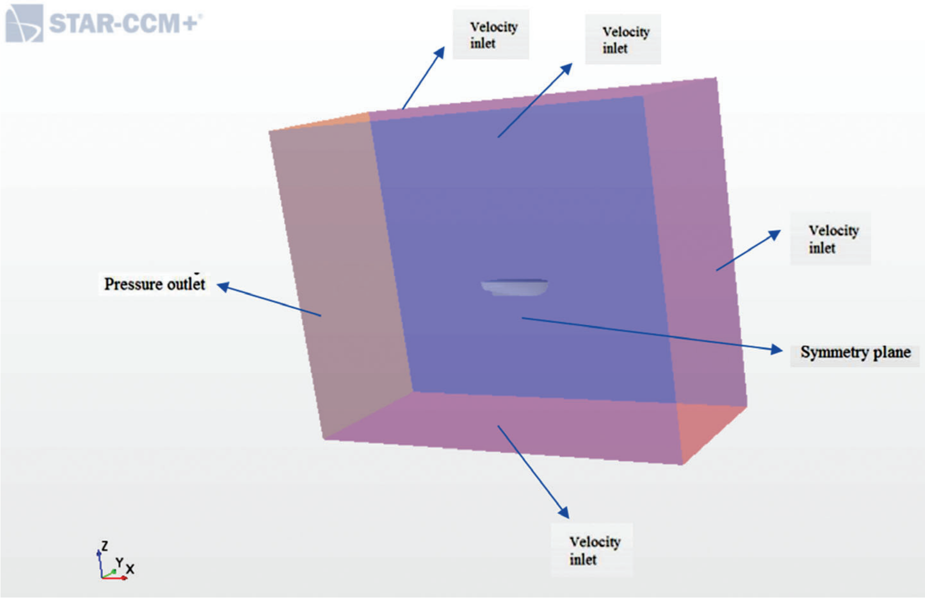


Figure 12 Computational domain and applied boundary conditions
Slika 12. Proračunska domena i primijenjeni rubni uvjeti

4. RESULTS / *Rezultati*

In this paper, the curve of effective power as a function of vessel speed for the fishing vessel is obtained. For this purpose, the numerical simulations of the resistance test are carried out at five speeds i.e., 2, 3, 4, 5 and 6 knots. The physical time for the numerical simulations is defined based on the vessel speed. However, numerical simulations are stopped when the value of the total resistance converged. The effective power of the fishing vessel is calculated based on the total resistance and vessel speed, and the obtained results are presented in Table 3 and Figure 13. It should be noted that the Froude numbers shown in Table 3 are calculated based on the length of waterline.

Table 3 The total resistance and effective power for different speeds of fishing vessel
Tablica 3. Ukupni otpor i efektivna snaga za različite brzine ribarskog broda

V, kn	Fn	R_T, N	P_E, W
2	0.140	25.4	26.1
3	0.210	58.9	90.9
4	0.279	136.9	281.7
5	0.349	279.3	718.4
6	0.419	721.4	2226.5

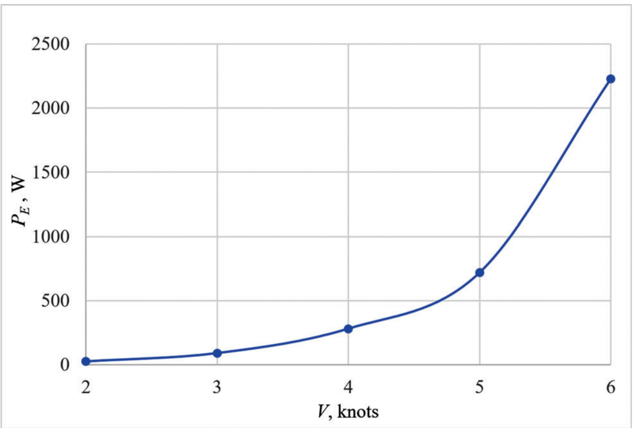


Figure 13 Effective power of the fishing vessel as a function of speed
Slika 13. Efektivna snaga ribarskog broda kao funkcija brzine

In the rest of the paper, the results of the performed numerical simulations are presented for a vessel speed of 6 knots. The obtained $y+$ distribution is shown in Figure 14 and it can be noticed that the value of $y+$ parameter is above 30 on the entire wetted surface. In Figure 15 wave pattern around the fishing vessel is shown, and the Kelvin wave can be observed. In the same figure the z coordinate represents the position of the instantaneous free surface with respect to the still water level ($z = 0$). The highest wave elevations are obtained in the bow area and behind the vessel, while the lowest around the midship. The formation of a bow wave with notable wave height is also visible from the side view of the vessel, Figure 16.

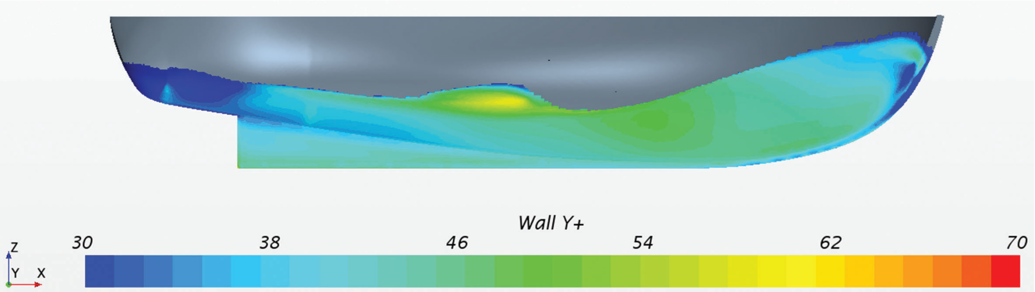


Figure 14 Wall y+ distribution at $V = 6$ kn
Slika 14. Raspodjela parametra y+ pri V = 6 čv

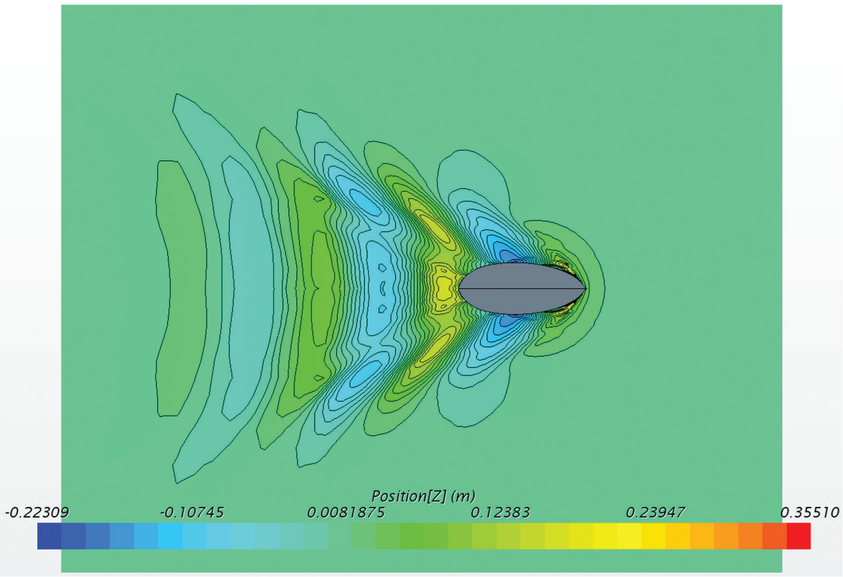


Figure 15 Wave pattern around the fishing vessel at $V = 6$ kn
Slika 15. Slika valova oko ribarskog broda pri V = 6 čv

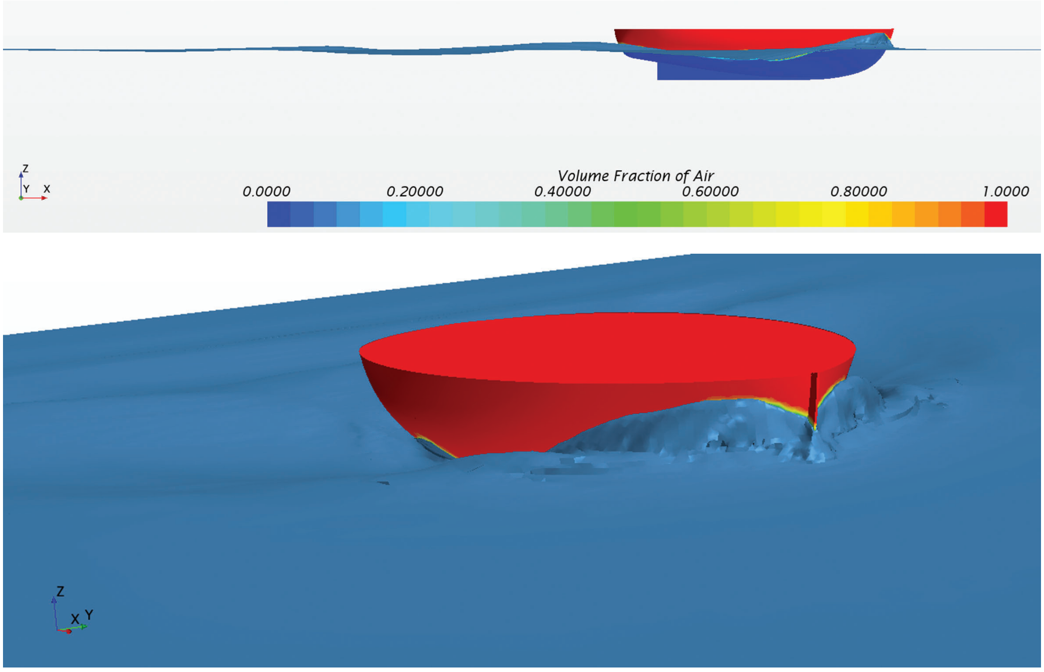


Figure 16 Free surface (upper) and bow wave (lower) for fishing vessel at $V = 6$ kn
Slika 16. Slobodna površina (gornja) i pramčani val (donja) za ribarski brod pri V = 6 čv

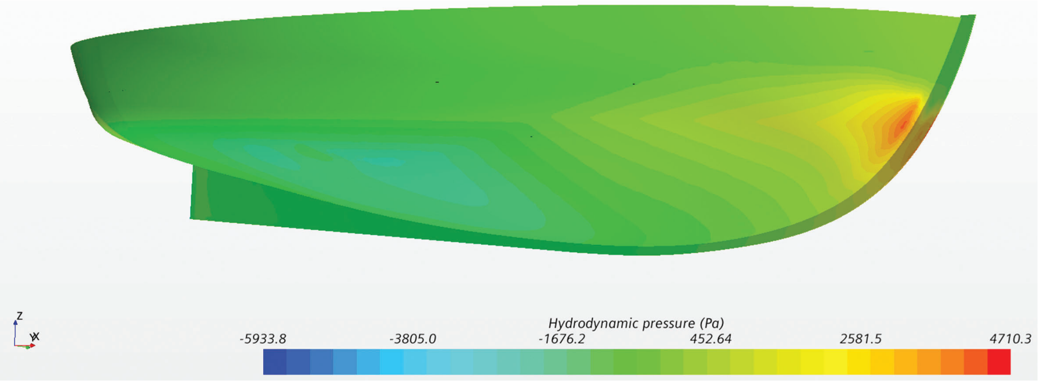


Figure 17 Distribution of the hydrodynamic pressure on the hull of the fishing vessel at $V = 6$ kn
Slika 17. Raspodjela hidrodinamičkog tlaka po trupu ribarskog broda pri V = 6 čv

The distribution of the hydrodynamic pressure is shown in Figure 17 and a region of overpressure in bow area, and underpressure in the midship area can be noticed. Due to the extended keel of the fishing vessel, in the bow region, especially around the free surface, the hydrodynamic pressure increases significantly causing the increase in the bow wave height. It is evident that the hull is not optimized from the resistance point of view, especially for high speeds. But this was expected considering that the vessel had to meet other requirements such as sufficient stability and interior volume.

5. CONCLUSIONS / *Zaključci*

Within this research, the procedure for manual measurement of the hull form is demonstrated using the example of a Croatian traditional guc fishing vessel. Based on the measured hull form a 3D model of the fishing vessel is generated to perform numerical simulations of the resistance test. It is demonstrated that the measuring process could result in some errors regarding the exact offset coordinates, and it is necessary to fair the obtained sections and bow and stern contours. It can be concluded that the hull form measuring process is a complex and demanding task, and it is necessary to ensure a sufficient accuracy of the obtained offsets to properly reproduce the measured hull form for calculations or possible modifications.

Being a part of national heritage, an aspiration is to preserve the traditional vessels that are often in a very bad condition. During the process of the revitalization and reconstruction of a traditional vessel, one of the main issues is the lack of technical documentation, where this primarily refers to the lines plan. Within this research, it is demonstrated that the hull geometry can be properly captured even in unfavourable conditions. Additionally, the measured and modelled hull form is sufficiently accurate to carry out the numerical simulations and thus predict the ship resistance and effective power, which is important for the assessment of its technical performance, but it also enables the determination of the economic and environmental impacts of a vessel during its operation. Very often the fishing vessels are inefficient in terms of fuel consumption and CO_2 emissions. Therefore, it is very important to predict the resistance and effective power of these vessels as accurately as possible. To obtain the resistance curve of the fishing vessel, numerical simulations have been performed at five speeds ranging from 2 to 6 knots. A commercial software package for computational fluid dynamics STAR-CCM+ has been utilized to gain an insight into the flow around the fishing vessel i.e., wave pattern around the vessel as well as the distribution of the hydrodynamic pressure.

The importance of the performed research is twofold: firstly, specification of a simple and efficient measurement procedure is given that can be employed to preserve the hull form of traditional vessels, and secondly use of CFD to assess the technical performance of vessels in service.

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