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Performance Analysis and Investigation of the Slipstream Flow of Podded Propellers

Original scientific paper

Especially high speed craft (HSC) and vessels with large propellers have unfavourable effects on the marine environment. These effects are mostly observed on other vessels and on the marine life. The most important sources of these negative effects caused by ships are the propeller slipstream flow and the ship wake. Marine propellers in particular can create a large effect area by accelerating the flow behind the ship, so they can cause erosion on coastal structures and on the sea bed while they traverse narrow channels and straits.

In this study the effects of the propeller slipstream on the marine environment are analyzed for a model propeller and a podded propeller of a RO-RO ship by a computational fluid dynamics method. The validations of the numerical results are made through the comparison with the experimental results. The numerical predictions of the propeller slipstream flows are important for obtaining results which cannot be acquired by experimental measurements. The computations are made separately for the open water and behind the hull conditions for the podded propeller. Additionally, the propeller characteristics for the model and the podded propeller are calculated for various advance coefficients.

Keywords: *CFD, marine propellers, model experiment, t-pod, propeller slipstream*

Analiza učinaka i ispitivanje polja strujanja iza azipodnih propulzora

Izvorni znanstveni rad

Vrlo brza plovila kao i ona s vijcima većih dimenzija imaju neželjene učinke na morski okoliš. Ovi učinci opažaju se na drugim plovilima, te na okolnoj flori i fauni. Najvažniji su izvori ovih negativnih učinaka polje strujanja iza brodskog vijka i polje strujanja iza krme broda. Učinci brodskih vijaka mogu biti primjetni na velikom području na koje utječu ubrzavajući strujanje iza broda, pa mogu izazvati eroziju obalnih struktura i morskog dna dok prolaze npr. uskim kanalima.

U ovoj studiji učinci polja strujanja iza vijka RO-RO broda razmatrani su korištenjem metode računalne dinamike fluida. Validacije numeričkih rezultata provedene su pomoću rezultata eksperimenata. Numeričke prognoze polja strujanja iza vijaka važne su s obzirom da se određeni rezultati ne mogu dobiti pomoću modelskih ispitivanja. Izračuni su provedeni zasebno za uvjete vijka u slobodnoj plovidbi i iza trupa za azipodne propulzore. Dodatno, značajke propulzora za model i za vijak u naravi izračunate su za različite koeficijente napredovanja.

Ključne riječi: *azipod, brodski vijci, modelska ispitivanja, polje strujanja iza vijka, računalna dinamika fluida*

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1 Introduction

The increase of marine transportation causes the widespread use of high speed craft with speeds up to 50 knots [1]. Despite the advantages of HSC in transportation, the wake field and the propeller induced velocities can cause negative effects on the marine environment especially in still and shallow waters, in sea bays, in narrow channels and in transition zones. The main effects are the influences on other vessels and on the shoreline, erosion effects on the seabed and effects on the marine life [2].

With the growing use of podded propellers in large and fast ships their effects on the environment are of interest. In addition to experiments, numerical approaches offer also a good possibility for analyzing propeller characteristics and wake field predictions. The numerical methods are also important for obtaining results that cannot be acquired by experimental measurements [3]. There are various experimental and numerical studies about podded propellers. A detailed content of studies about podded propellers can be found in the Proceedings of the 25th ITTC [4]. Atlar et al. [2] have realized comprehensive experimental studies on the effects of podded propellers of a RO-RO ship on the marine environment. For the analysis of hydrodynamic characteristics of podded propellers, some studies based on potential theory alone or in combination with RANS/Euler equations and studies where only RANS methods are used have been carried out [5-14].

The flow around only the pod body has also been investigated in various studies. In these studies the flow around the pod body has been modelled according to the non-viscous theory with panel methods [15-17] or with Euler Methods [18-21]. The flow around the pod body has also been modelled based on the solution of RANS equations. Sanchez-Caja et al. have investigated the influence between the propeller and the pod body by a RANS method where they have used the sliding mesh for modelling the stationary and rotating parts of the podded propellers. Furthermore Ohashi and Hino [22] have investigated the flow around a contra-rotating propeller with unstructured mesh by a hybrid RANS method. The scale effects on the pod resistance have been investigated with the use of a hybrid method by Lobatchev et al. [23] and with the use of a RANS code by Sanchez-Caja et al. for all the podded propeller system [13-14].

In this study the experimental open water characteristics and propeller induced velocities of a three bladed model propeller and of a four bladed model podded propeller of a RO-RO ship [2] are compared with the results obtained by a computational fluid dynamics method. For the analysis the commercial CFD code FLUENT 6.2.16 which finds increasing application area in the propeller analysis is used. For the validation of the numerical method, a mesh dependence study is made by the comparison of the propeller characteristics of the DTMB 4119 model propeller. Required grid sizes are found according to the mesh dependence study for the analysis of a model propeller with similar dimensions. The propeller characteristics of the podded propeller and of the propeller alone are investigated and compared with the results of the model experiment. The induced velocities downstream of the propeller are analyzed for both cases, and also for the behind hull condition of the podded propeller. Furthermore, the axial induced velocities of the podded propeller are compared with those of the propeller without pod.

2 Numerical method, grid generation and boundary conditions

2.1 Numerical method

For obtaining the propeller characteristics of the model propeller and of the podded propeller, calculations with moving reference frame for steady flow conditions are made for 10^{-5} convergence criterion. The flow is assumed as incompressible and turbulent. The k-ω SST turbulence model is set. The governing equations are discretized using a second-order upwind interpolation scheme. The SIMPLE method is selected as the pressure-velocity coupling scheme.

For the behind hull condition unsteady calculations with moving mesh are made so that the convergence criterion is less than 10^{-5}. Calculations are made for a time step equivalent to a 5 degree rotation of the propeller. The k-ω SST turbulence model is used and the pressure-velocity coupling scheme is selected as the PISO method. In the behind hull condition, the propeller inflow is applied according to the nominal wake distribution at the propeller plane behind the hull obtained from experimental results.

2.2 Grid generation

The pod and the propeller geometries are created in a CAD program; and the grid generation is made in Fluent pre-processor GAMBIT. For keeping the number of cells small, two domains are created for the analysis of the model propeller DTMB 4119. The rotating inner domain contains the propeller with triangular elements, while the outer domain is filled with hexahedral mesh elements. In the analysis of the podded propeller, six domains are used for the case without the pod, whereas ten domains are used for the case with pod (Figures 1, 2 and 3).

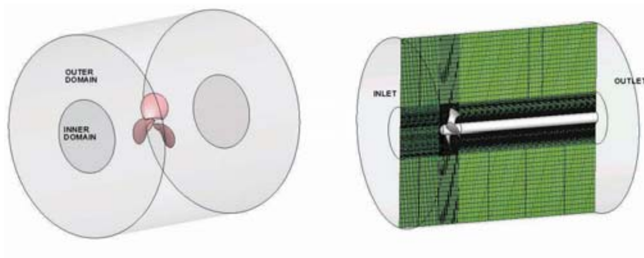

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Figure 1 **Computational domain; a) Computational domain for DTMB 4119 model propeller, b) Computational domain for propeller (without pod),**
Slika 1 **Proračunska domena; a) Proračunska domena za DTMB 4119 model vijka, b) proračunska domena za vijak (bez tijela)**

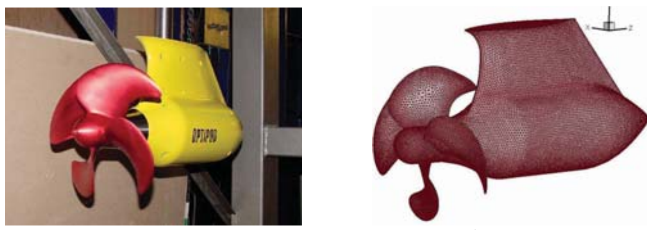
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Figure 2 **a) Model of the podded propeller used for experiment, b) Computational grids on the podded propeller surface**
Slika 2 **a) Model azipodnog propulzora korištenog za modelsko ispitivanje, b) Proračunska mreža površine azipodnog propulzora**

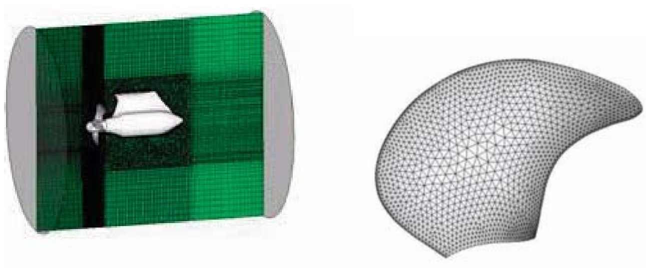
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Figure 3 **a) Computational domain for podded propeller, b) Computational grids on the blade surface of the podded propeller**
Slika 3 **a) Proračunska domena za azipodni propulzor. b) Proračunska mreža površine krila azipodnog propulzora**

The physical boundary conditions for all cases are set as the velocity-inlet on the inlet boundary for the free stream velocity; the pressure outlet condition is set to zero gauge pressure on the outlet boundary. The propeller, hub and pod surfaces are defined as non-slip wall condition and the outer boundary is set as specified shear where all the components are set to zero.

2.3 Validation of the numerical method

For the validation of the numerical results with experimental measurements of the DTMB 4119 model propeller a grid dependence study is made. DTMB 4119 which has been developed in the *David Taylor Model Basin* is a widely used model propeller for the validation of numerical methods. The propeller is three bladed and has a diameter of 0.3048 m. The open water experiment results have been performed with the operating conditions of 600 rpm and the advance coefficient as J = 0.833. Five different cases for the same domain are considered by increasing the volume element number of the whole domain (Table 1).

Table 1. **Grid specifications**
Tablica 1 **Specifikacija mreže**

Case	Element Number	Smallest element size (m³)	Largest element size (m³)
1	85 674	1×10^{-6}	9.40×10^{-5}
2	103 495	6×10^{-7}	5.16×10^{-5}
3	632 495	1×10^{-7}	9.30×10^{-6}
4	1 149 286	6×10^{-8}	5.16×10^{-6}
5	2 181 481	3×10^{-8}	2.55×10^{-6}

The results depending on the element number for the thrust and torque coefficients (K_T and K_Q), and the axial velocity values (at three points downstream the propeller) are shown for J = 0.833 design advance coefficient (Figure 4 and 5).

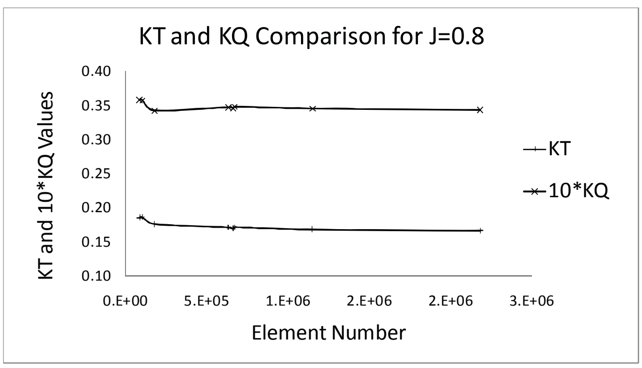
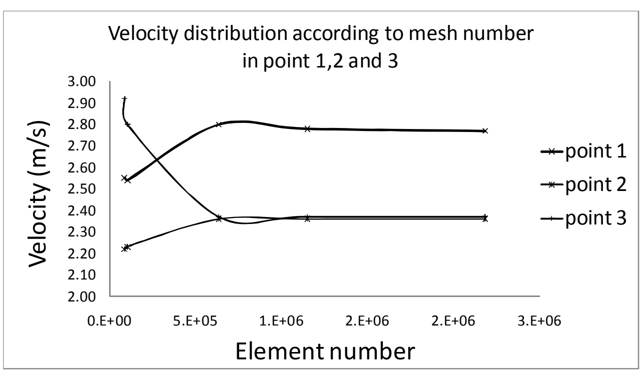


Figure 4 **Thrust and torque coefficient variation**
Slika 4 **Varijacije koeficijenata poriva i momenta**

Figure 5 **Velocity variation**
Slika 5 **Varijacije brzine**



While the grid dependence study demonstrates that the K_T and K_Q values are not sensitive to grid refinement it is observed that the velocity values are effected strongly. It is shown in Figure 5 that the velocity values remain approximately constant for the element number of Case 4. Therefore, the element sizes of Case 4 are considered sufficient for all other cases of the podded propeller.

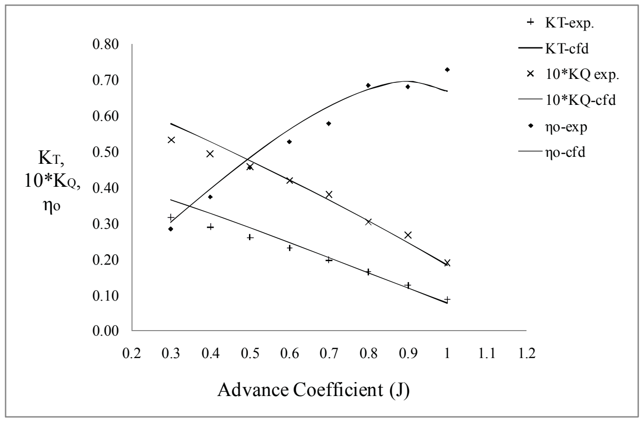


Figure 6 **Comparison of experimental and numerical propeller open water characteristics**
Slika 6 **Usporedba rezultata modelskih ispitivanja i numeričke analiza za uvjete slobodne vožnje**

As seen in Figure 6 the propeller performance characteristics obtained from the experimental and numerical methods are in accordance with the numerical method.

3 Results

The specifications of the analyzed podded propeller are given in Table 2. The propeller performance characteristics and the induced velocities behind the propeller are calculated for the model propeller with the pod housing and without the pod housing. The numerical results are compared with the results from the model experiment.

Table 2 **Podded propeller specifications**
Tablica 2 **Značajke azipodnih propulzora**

	Full Scale	Model
Diameter (m)	5.299	0.23
Hub Diameter (m)	1.333	0.0533
Pitch Ratio at 0.7 R	1.389	1.389
Blade Area Ratio	0.756	0.756
Number of Blades	4	4
Scale Factor	23	1
Pod Diameter (m)	2.875	0.125
Pod Length (m)	9.43	0.41

3.1 Propeller set alone (without pod)

In the case of the propeller without pod, the flow around the propeller and its shaft is analyzed. The computational domain surrounding the propeller consists of 1,130,000 volume elements. The inner volume where the propeller is located consists of 860,000 volume elements and the outer volume consists of 270,000 volume elements. The largest element size used is 7.36×10^{-6} (m^3) and the smallest element size is 8×10^{-8} (m^3).

The open water characteristics (for 3 m/s inflow velocity) obtained from numerical and experimental methods for the case of the propeller without the pod body are shown in comparison in Figure 7.

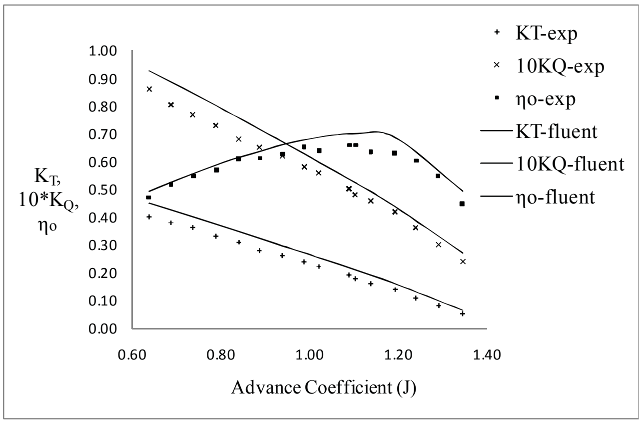


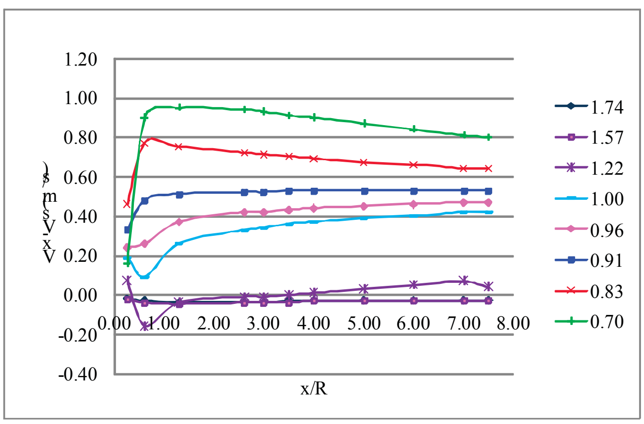
Figure 7 **Open water characteristics of the propeller (without pod)**
Slika 7 **Karakteristike vijka u slobonoj vožnji (bez tijela)**

The propeller slipstream calculations for the case without the pod body are carried out for 4 m/s incoming velocity. The induced velocities are calculated according to Eq. (1).

$$V_{induced} = V_X - V_S \tag{1}$$

Here V_X is the flow velocity behind the propeller and V_S is the ship speed. The results are demonstrated for axial, radial and tangential directions. The induced velocities downstream for the propeller without pod are compared in eight different radii (r/R = 0.70, 0.83, 0.91, 0.96, 1.00, 1.22, 1.57, 1.74) and for 11 locations (x/R = 0.26, 0.61, 1.3, 2.61, 3, 3.5, 4, 5, 6, 7, 7.5), (Figures 8, 9 and 10).

Figure 8 **Induced velocities in axial direction**
Slika 8 **Inducirane brzine u aksijalnom smjeru**



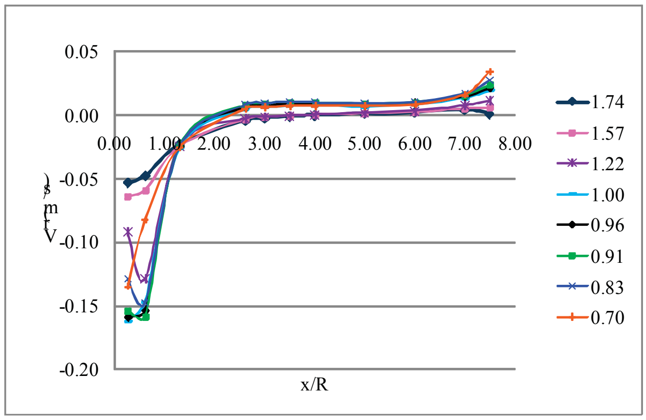


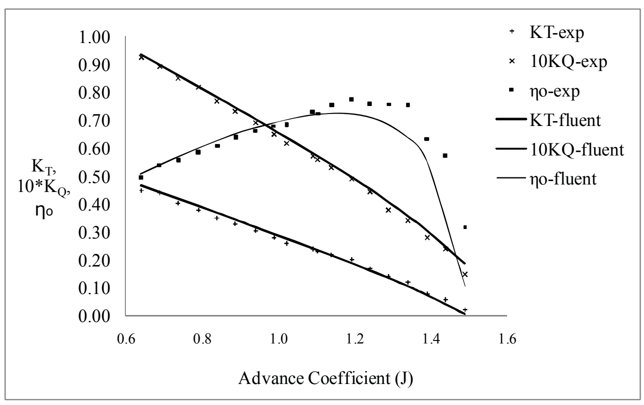
Figure 9 **Induced velocities in radial direction**
Slika 9 **Inducirane brzine u radijalnom smjeru**

3.2 Podded propeller

In the podded propeller analysis the volumes containing the propeller and the pod body are separated with the aim to reduce the element number in the control volume. The volumes of the propeller and the pod are meshed with triangular elements and other volumes are created with hexahedral elements. The propeller and the pod body are surrounded with an unstructured mesh while the other parts are formed with a structured mesh. The total element number is 2,006,871. The smallest element size is 2.52×10^{-10} (m^3) and the largest element size is 2.77×10^{-6} (m^3). The rotation motion for the inner volume containing the propeller is provided by the moving reference frame option. The validation of the calculated propeller characteristics against the experimental results for 3 m/s inflow velocity and nine different advance coefficients are given in Figure 10.

The propeller slipstream calculations for the case with the pod body are made for 4 m/s inflow velocity. The induced velocities downstream the propeller with the pod are compared in eight different radii (r/R = 0.70, 0.83, 0.91, 0.96, 1.00, 1.22, 1.57, 1.74) and for four locations (x/R = 0.26, 0.61, 1.3, 2.61). The induced velocities in axial, radial and tangential directions in comparison with the experimental results are shown in Figures 11, 12 and 13.

Figure 10 **Open water characteristics of propeller (with pod)**
Slika 10 **Karakteristike azipodnog propulzora u uvjetima slobodne vožnje (sa tijelom)**



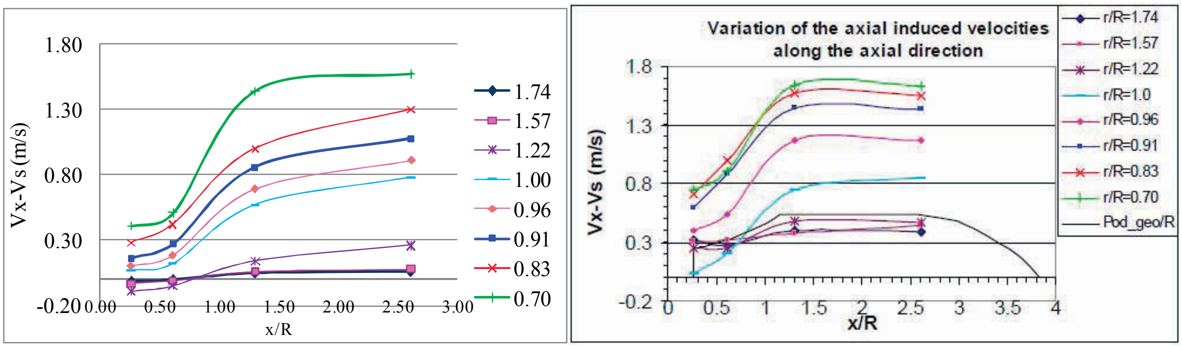


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Figure 11 **Axial induced velocity distributions; a) CFD results, b) Experiment results [24]**
Slika 11 **Raspodjela aksijalne inducirane brzine; a) numerički rezultati, b) rezultati modelskih ispitivanja [24]**

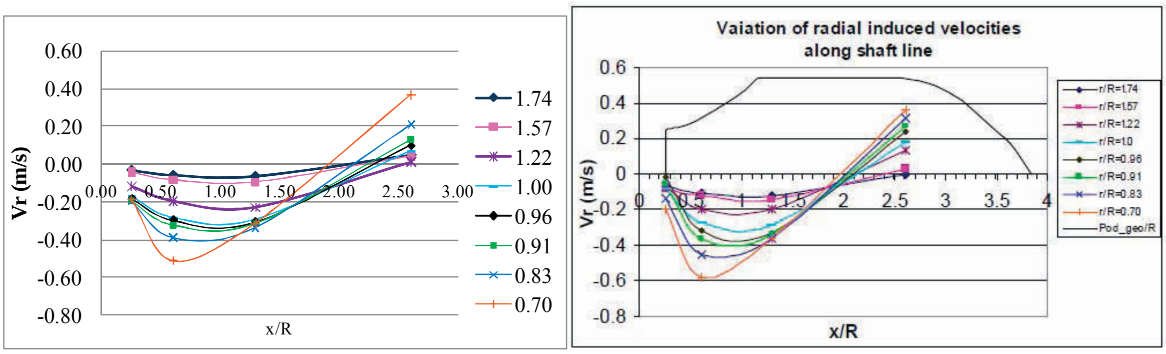

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Figure 12 **Radial induced velocity distributions; a) CFD results, b) Experiment results [24]**
Slika 12 **Raspodjela radijalne inducirane brzine; a) numerički rezultati, b) rezultati modelskih ispitivanja [24]**

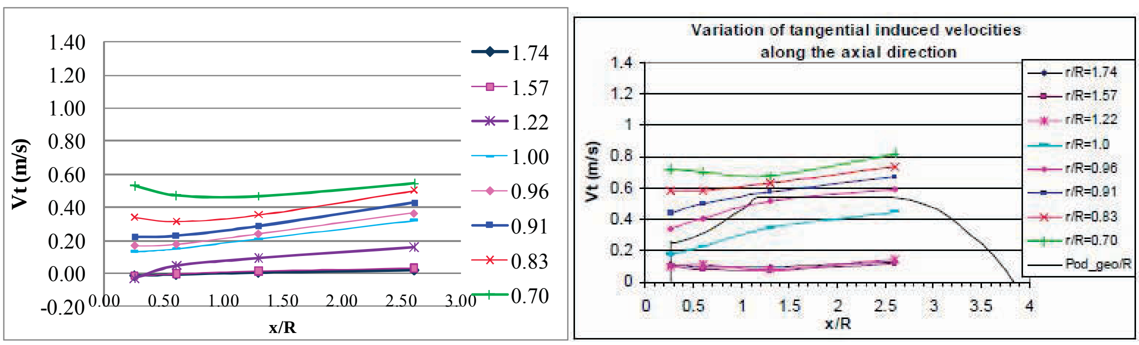

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Figure 13 **Tangential induced velocity distributions; a) CFD results, b) Experiment results [24]**
Slika 13 **Raspodjela tangencijalne inducirane brzine; a) numerički rezultati, b) rezultati modelskih ispitivanja [24]**

4 Comparison of the axial induced velocities of the propeller with and without pod

The axial induced velocities downstream the propeller with the pod and without the pod are compared in eight different radii (r/R = 0.70, 0.83, 0.91, 0.96, 1.00, 1.22, 1.57, 1.74) for the locations x/R = 4 and x/R = 7.5 (Figure 14). The plane x/R = 4 is about the trailing of the pod housing. In Figure 14 for the plane next to the pod housing and for the regions outside the ratio r/R = 1, in both locations (x/R = 4, x/R = 7.5) the increase of the axial induced velocities due to the pod housing are shown. Contrary to the regions outside the ratio r/R = 1, for the regions r/R<1 a decrease of the axial induced velocities is seen.

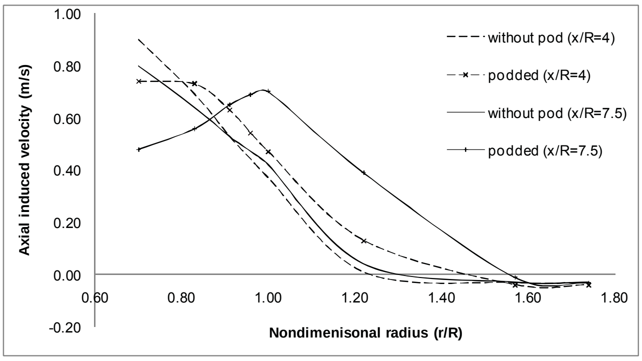


Figure 14 **Axial induced velocities for the podded propeller and the propeller without pod**
Slika 14 **Aksijalne inducirane brzine za azipodni propulzor i vijak bez tijela propulzora**

5 Behind the hull condition (podded propeller)

In this section the propeller induced velocities for the behind hull condition are investigated. The non uniform inflow velocity distribution (Figure 15) of the propeller is obtained from the experimental wake values. At the velocity inlet boundary, the non-uniform inflow condition is imposed through the Boundary Profile (BP) feature of the CFD code FLUENT. The axial velocity distribution is included into a BP file at 380 points. The flow simulation for the propeller is carried out using the moving mesh technique implemented in the code. The calculations are made in the same conditions as the model experiment in 706.5 RPM, with the torque coefficient equivalent to 0.0559 in 3 m/s flow velocity. The axial velocities at the propeller plane are calculated according to Equation (2).

$$V = (1\text{-}w) \times V_{inflow} \tag{2}$$

In this formula V_{inflow} defines the inflow velocity and w the wake values at any point of the propeller plane.

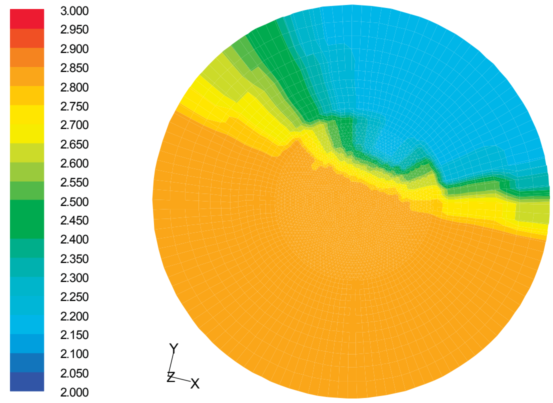
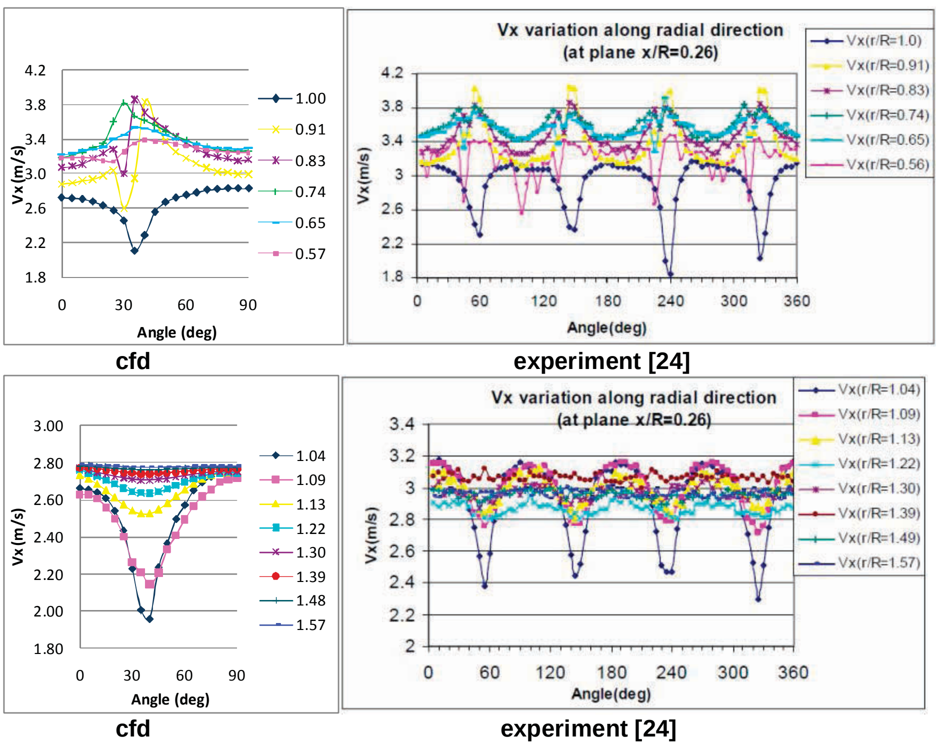
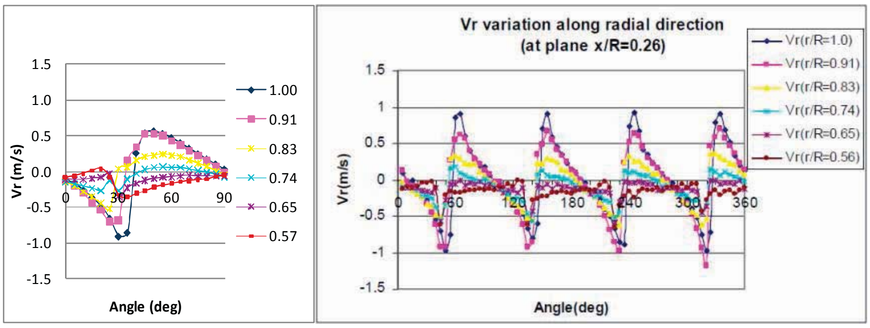


Figure 15 **The inflow velocity distribution at the propeller plane**
Slika 15 **Raspodjela brzine nastrujavanja u ravnini vijka**

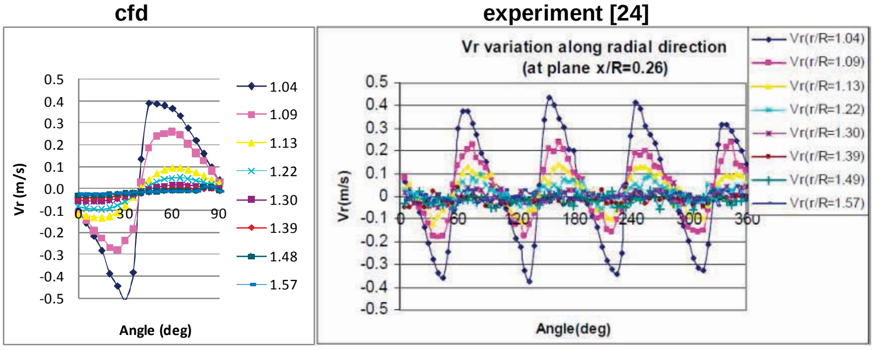
In the plane x/R = 0.26 for 14 different radii (r/R = 0.56, 0.63, 0.74, 0.83, 0.91, 1, 1.04, 1.09, 1.13, 1.22, 1.30, 1.39, 1.49, 1.57), the induced velocity variations in comparison to experimental results are given in Figures 16, 17 and 18.

Figure 16 **V_x variation along radial direction (At plane x/R = 0.26)**
Slika 16 **V_x varijacija uzduž radijalnog smjera (u ravnjini x/R = 0,26)**



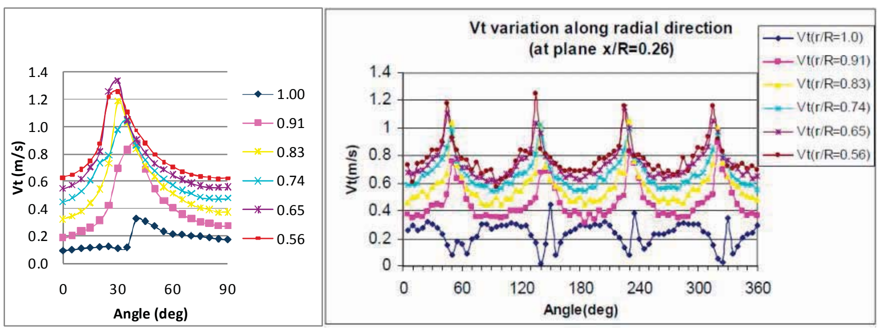


cfd experiment [24]

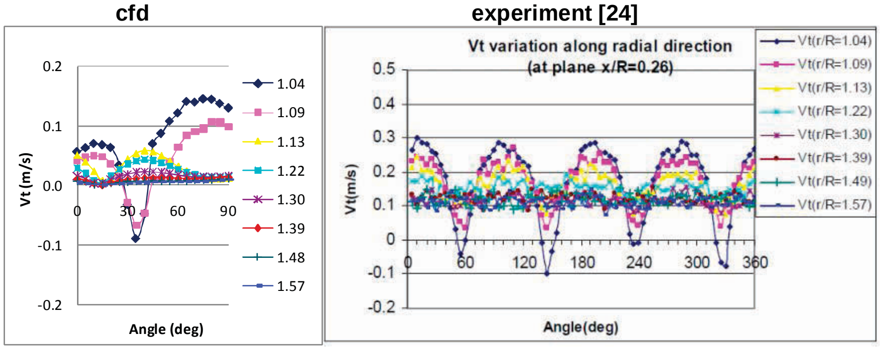


cfd experiment [24]

Figure 17 V_r **variation along radial direction (At plane x/R = 0.26)**
Slika 17 V_x **varijacija uzduž radijalnog smjera (u ravnjini x/R = 0,26)**



cfd experiment [24]



cfd experiment [24]

Figure 18 V_t **variation along radial direction (At plane x/R = 0.26)**
Slika 18 V_x **varijacija uzduž radijalnog smjera (u ravnjini x/R = 0,26)**

6 Conclusions

In this study the impact of a podded propeller of a Ro-Ro ship on the marine environment is investigated by a computational fluid dynamics code FLUENT and the results are compared with experimental results. The propeller induced velocity components are obtained downstream the propeller for three cases; propeller with/without pod and behind the hull condition. Additionally, the propeller performance characteristics for the propeller with and without the pod housing are also calculated. The numerical results are compared with the experimental results. The calculations are made using a commercial CFD code FLUENT. In conclusion, the results obtained from this study are expressed in the following items:

- For design condition (J = 1.104) the error values obtained by the comparison of the CFD results with the experimental results for the case without the pod housing are for K_T 16%, for K_Q 9% and for efficiency 6%. For smaller advance coefficients the error values decrease.
- For design condition (J = 1.104) the error values obtained by the comparison of the CFD results with the experimental results for the case with the pod housing are for K_T 2%, for K_Q 2% and for efficiency 0.1%. For smaller advance coefficients the error values decrease.
- For the propeller induced velocities the agreement between the numerical results and the experimental values is shown.
- The comparison of the axial induced velocities of the propeller alone and the podded propeller demonstrate that there is an increase of the axial induced velocities with the use of podded propellers.

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