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A Practical Noise Prediction Method for Cavitating Marine Propellers

Original scientific paper

The article presents an analysis procedure that includes noise prediction for marine propellers. As analysis of the propellers is carried out using a lifting surface method, noise prediction due to the blade sheet cavitation is taken into account using a semi-empirical formula for low frequencies. Using this procedure, an application is performed for a conventional propeller model (DTMB 4148), and noise levels of the propeller are compared with the values proposed by ICES (International Council for Exploration of the Sea). In addition, two different propellers (DTMB 4119 and Seiun-maru HSP) are analyzed by lifting surface and CFD methods; the results are compared with those of the Hoshino panel method and experimental ones. It can be concluded that the present approach provides easy, fast and reliable solutions for noise analysis with low cost and time for propeller pre-design.

Keywords: *propeller analysis, lifting surface, noise prediction, sheet cavitation, CFD*

Praktični postupak za predviđanje buke kavitirajućih brodskih vijaka

Izvorni znanstveni rad

Ovaj članak prikazuje analitički postupak koji uključuje predviđanje buke pomorskih vijaka. Analiza vijka provedena je primjenom postupka uzgonskih površina, a predviđanje buke kavitirajućih krila vijaka uzeto je u obzir primjenom poluiskustvene formule za niske frekvencije. Opisana procedura primijenjena je na konvencionalni vijak (DTMB 4148), a razine buke vijka uspoređene su s preporučenim vrijednostima od strane ICES (International Council for Exploration of the Sea). Dodatno, još su se dva različita vijka (DTMB 4119 i Seiun-maru HSP) analizirala postupcima uzgonskih površina i CFD metodom, a rezultati su uspoređeni s Hoshinovom panel metodom i s rezultatima pokusa. Može se zaključiti da prikazani pristup predstavlja jednostavno, brzo i pouzdano rješenje za analizu buke uz mali utrošak sredstava i vremena u fazi pretprojektiranja vijaka.

Ključne riječi: *analiza vijka, uzgonska površina, predviđanje buke, kavitacija krila, CFD*

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Nomenclature

V_S	Design speed (m/s)
n	Propeller rate of rotation per second
D	Propeller diameter (m)
Z	Number of propeller blades
c	Propeller blade section chord length (m)
r/R	Non-dimensional radius
t/c	Blade section thickness distribution
f/c	Blade section camber distribution
P/D	Pitch ratio
P	Pitch (m)
J	Advance coefficient
C_p	Non-dimensional pressure coefficient
K_Q	Torque coefficient
K_T	Thrust coefficient
L_s	Noise level (dB re 1μPa)
A_c	Sheet cavitation-swept area in propeller disc (m^2)
σ_n	Cavitation number
P_0	Far upstream pressure, at the propeller axis (N/m^2)
P_v	Vapour pressure of water (N/m^2)
A_d	Propeller disc area (m^2)
f	Noise frequency (Hz)
η_o	Propeller open water efficiency

1 Introduction

Propeller theories have been considerably improved during the last decades due to developments in computer technology, and today several methods are available for propeller design and analysis. In literature for marine propeller analysis, theoretical methods such as lifting surface, boundary element (BEM) or panel methods have been widely employed. In lifting surface methods, the propeller blades are considered as lifting surfaces over which the singularities (vortex, source or dipole) are distributed to model the effects of blade loading and thickness [1,2,3,4,5].

In BEMs, for calculation of cavitation field of lifting surfaces, the panels are placed on the cavity boundaries, the shape of which is determined in an iterative manner until both the kinematic and dynamic boundary conditions are satisfied. Cavitating or free-streamline flows were first addressed in nonlinear theory via the hodograph technique introduced by Helmholtz, Kirchoff and Levi-Civita [6]. The hodograph technique was extended numerically to treat arbitrary geometries [7] and later applied to the analysis of supercavitating hydrofoils in the presence of a free surface [8]. The linearized cavity theory was introduced by Tulin in [9] and it quickly became very popular. Unfortunately, the linearized theory tended to grossly over-predict the thickness and extent of cavities for thick hydrofoils. And later on, the short cavity theory was developed by Tulin and Hsu in [10]. A nonlinear numerical method was employed to analyze cavitating hydrofoils by using surface vorticity technique [11,12]. A surface vorticity technique to deal with thick foil sections which employed an open cavity model was developed by Yamaguchi and Kato in [13]. Similar boundary element method techniques were developed by Lemonnier and Rowe in [14] and by Rowe and Blottiaux in [15]. Numerical boundary element methods within non-linear cavity theory were naturally extended to treat supercavitating 3-D hydrofoils by Pellone and Rowe in [16] and 3-D hydrofoils with partial cavities by Kinnas and Fine in [17] or cavities with mixed (partial and supercavities) planforms by Fine and Kinnas in [18]. Finally, non-linear potential-based boundary element methods were applied to cavitating propellers in non-uniform flows by Fine and Kinnas in [19], Kim and Lee in [20], and more recently to predict sheet or developed tip vortex on lifting bodies by Kinnas et al. in [21,22], Lee and Kinnas in [23].

Reynolds Averaged Navier-Stokes (RANS) methods (or CFD methods) have been recently used as a practical tool in place of conventional methods based on the potential theory. RANS methods have been applied not only to predict the pressure distributions on blades and viscous flow around ship hulls, but also propulsion and cavitation characteristics of marine propellers. There are number of studies in this context. Feng et al. in [24] presented a CFD model for calculating tip vortex of open water marine propellers. In their study, a numerical approach based on solving the RANS equations with k-ε turbulence model was presented to model the tip vortex flow. Hsiao and Pauley in [25] solved a 3-D incompressible Navier-Stokes equation for a steady state tip vortex flow over a rectangular foil, and also Hsiao and Pauley in [26] carried out a different technique to solve the uniform flow past a marine propeller. Watanabe et al. in [27] presented RANS simulations of flow around two different conventional propellers. Both propellers were analysed at non-cavitating and cavitating operating conditions using the model proposed by Singhal et al. in [28]. Sanchez-Caja et al. in [29] presented analysis of the flow around a ducted propeller by a solver which was initially developed at the *Helsinki University of Technology* for the analysis in compressible flow and was a multiblock multigrid structured finite volume RANS code. Berntsen et al. in [30] investigated sheet and tip vortex cavitation using a commercial CFD code, Fluent 5. They used 2D NACA 0015 hydrofoil and 3D NACA 66_2-415 as an elliptical planform hydrofoil. Gu and Kinnas in [31] described a general numerical method based on CFD method for the analysis of contra-rotating and ducted propellers. They coupled a vortex-Lattice Method (VLM) and a Finite Volume Method (FVM) based on Euler solver. Abdel-Maksoud in [32] investigated the aptitude of a general purpose cavitation model for calculating cavitation behaviour of ship propellers. In that work, numerical results based on CFD method are given for a cavitating five bladed model propeller operating in steady flow. Kulczyk et al. in [33] aimed to carry out an analysis of a screw propeller 4119 using the RANS method. They used two turbulence models (k-ε and k-ω) in calculations. Salvatore et al. in [34] presented results from the Rome 2008 Workshop on modelling cavitating propellers. In their work, seven computational models by RANS, LES (Large-Eddy Simulation) and BEM were benchmarked against a common test case addressing the INSEAN (The Italian Ship Model Basin) E779A model propeller in uniform and non-uniform flows.

Considerable part of noise generated by ship system is underwater noise. Underwater noise is related to machinery, propeller and flow noise [35]. Amongst these sources, the propeller noise is the most important one. Above all, it is important to reduce propeller noise on the basis of sheet cavitation. There are numerous studies in this context presented in literature. Okamura and Asano in [36] applied a semi-empirical formula for the prediction of propeller broadband noise. They applied principle of acoustic-mechanical reciprocity for the propeller tonal noise in model experiment. In that work, propeller cavitation noise is predicted using theoretical calculations and is compared to data model experiments obtained from full-scale measurements performed on two ships, a cargo liner and a training ship. Salvatore and Ianniello in [37] presented a numerical prediction method of the acoustic pressure field induced by cavitating marine propellers. In this work, a hydrodynamic model for transient sheet cavitation on propellers in a non-uniform inviscid flow field is coupled with a hydroacoustic model based on the Ffowcs-Williams-Hawkings equation. Both hydrodynamic and hydroacoustic model equations are solved via boundary integral formulations. Yılmaz et al. in [38] carried out a numerical study based on a semi-empirical approach that is able to predict the cavitation inception point and calculate the broad-band 1/3-octave noise spectrum for a marine propeller operating in a non-uniform inflow field. Yoshimura and Koyanagi in [39] used a design method for a small fisheries research vessel to reduce the underwater-radiated noise level. They used measured full-scale noise data and empirical formulas and also concluded that Brown's semi-empirical formula is very useful for the prediction of the cavitation noise level. Seol et al. in [40] presented a numerical study on the non-cavitating and blade sheet cavitation noises of the underwater propeller. The noise is predicted using time-domain acoustic analogy while the flow field is analyzed with potential-based panel method and, then the time-dependent pressure and sheet cavity volume data are used as the input for Ffowcs-Williams-Hawkings formulation to predict the far-field acoustics. Park et al. in [41] numerically analyzed the tip vortex cavitation behaviour and sound generation. In their work, they used hybrid method which integrates RANS solver and Dissipation Vortex model for flow field. Also, they investigated relationship between cavitation inception, sound pressure levels and cavitation nuclei sizes at several conditions.

In this study, an analysis method including noise prediction for marine propellers is presented. The blade sheet cavitation noise of the propeller is estimated using a semi-empirical formula which is adapted to lifting surface method for low frequencies. The blade sheet cavitation regions, pressure distributions and performance coefficients of the propeller are calculated based on finite volume (CFD) and Szantyr's lifting surface methods (Szantyr, 1994). As the blade sheet cavitation noise of a propeller (DTMB 4148) operating underwater is estimated using the present propeller noise prediction procedure, the results are compared with those proposed by ICES and Fraser formula in [42]. Also propeller performance characteristics and pressure distributions over the blades for different two propellers (full scale Seiun-maru HSP at non-uniform velocity field, model DTMB 4119 at uniform inflow) are determined from lifting surface and CFD methods, and the results are shown in comparison with those of the experimental and Hoshino panel method.

2 The hydrodynamic analysis and noise prediction methods of propellers

2.1 Lifting surface method

In this study, a lifting surface model based on Szantyr's work is developed to predict the performance of propellers operating in non-uniform velocity fields. In this method, the hydrodynamic loading on the propeller blades is represented by appropriate distribution of vorticity and the thickness of the propeller blades, modelled by the appropriate distribution of sources and sinks. These singularities distributed on the surfaces are built up by the mean lines of the propeller blade sections. It is shown that the method is capable to predict unsteady pressure distributions and hydrodynamic forces on propeller blades. The kinematics boundary condition is the basis for the lifting surface formulation equation. This condition requires that the resultant relative velocity of flow at the lifting surface has to be tangent to the surface. In another words, there should be no flow through the lifting surface. Detailed descriptions of this method can be found in [5].

2.2 Sheet cavitation noise from propeller blades

Noise emitted from ships into water has become a serious problem, on account of its harmful interference with the functioning of sonars and other acoustic appliances used by research vessels, warships, fishing boats and other craft for sound source probing, underwater communication, detection of objects under water and for other purposes. Propellers and, in particular, propeller cavitation have been acknowledged to be the most important noise sources in ship acoustics. In this context, in order to determine reliable source of underwater noise level, it is important to predict the level of noise generated due to cavitation. Moreover, it is known that the highest noise among other noise sources, machinery and flow, is generated by unsteady sheet cavitation [35].

In general, acoustic calculations are made in the 1/3 octave band. Here, frequency upper band limit is $2^{1/3}$ times greater than the lower band limit In general, 10-100 kHz frequency range is used in calculations.

Noise radiated from propeller cavitation can be considered in two parts. One is called "tonal noise", which stands for periodic variation of the total bubble volume of unsteady cavitation due to rotating propeller in the ship's wake. The other one is called "broadband noise", which is caused by random growth and collapse of cavitation. In the present study, only the source level of the broadband noise is estimated using Brown's semi-emprical formula given by (1).

$$L_s = 163 + 10\log\left[\frac{Z D^4 n^3}{f^2}\right] + 10\log\left[\frac{A_c}{A_d}\right] \qquad (1)$$

$$A_c = \int_0^{2\pi} \int_{r_{E1}}^{r_{E2}} r\,dr\,d\theta \qquad (2)$$

$$A_d = \pi D^2 / 4 \qquad (3)$$

where, A_c is sheet cavitation swept area bounded by counters of radii r_{E1} and r_{E2} varying with θ, expressed by (2) and Figure 1.

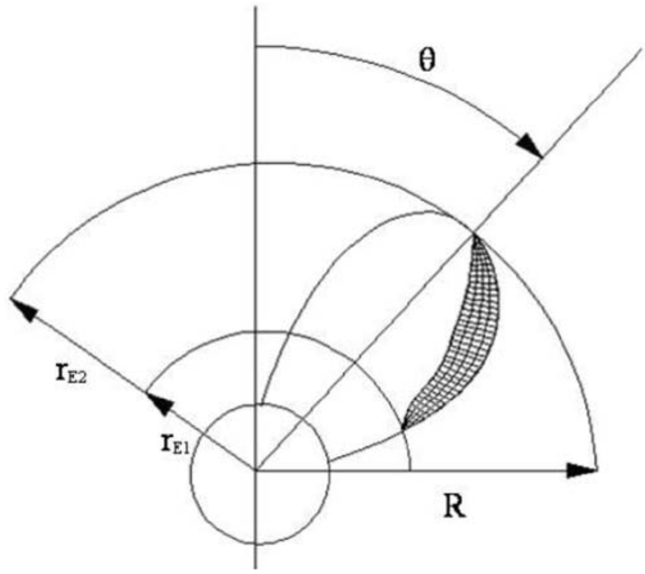


Figure 1 **Description of sheet cavitation swept area**
Slika 1 **Prikaz prebrisane površine slojastom kavitacijom**

According to Brown's method, in order to estimate the noise level on a cavitating propeller, the most important point is finding out the cavitation swept area. This area is defined by the angular integration of sheet cavitation area limited by non-dimensional radius of r_{E1} and r_{E2} during a complete revolution of the propeller. The integration is made in an iterative manner by means of lifting surface method for each blade position within the scope of hydrodynamic analysis procedure.

It is not easy to precisely estimate cavitation characteristics (length, area, volume etc.) using cavitation tunnel tests. Cavitation area which is an important parameter especially in prediction of the noise caused by unsteady sheet cavitation is hard to be estimated. In this case, importance and availability of the presented numerical method is of great value.

3 Procedure of hydrodynamic analysis with noise prediction

In this study, a method for propeller analysis and noise prediction is presented. For a given propeller geometry and operating conditions (rate of rotation, wake distribution, advance speed, shaft immersion), the pressure distributions and sheet cavitation regions over the propeller blades is calculated in non-uniform flow field. Then sheet cavitation swept area during a rotation is determined by using sheet cavitation regions calculated from the lifting surface method for different blade positions. The narrow band propeller noise levels are calculated using the swept area in Brown's semi-empirical formula. Also hydrodynamic performance characteristics of the propeller can be obtained by the present propeller analysis procedure. In Figure 2, flow chart for the propeller analysis and noise prediction procedure is shown.

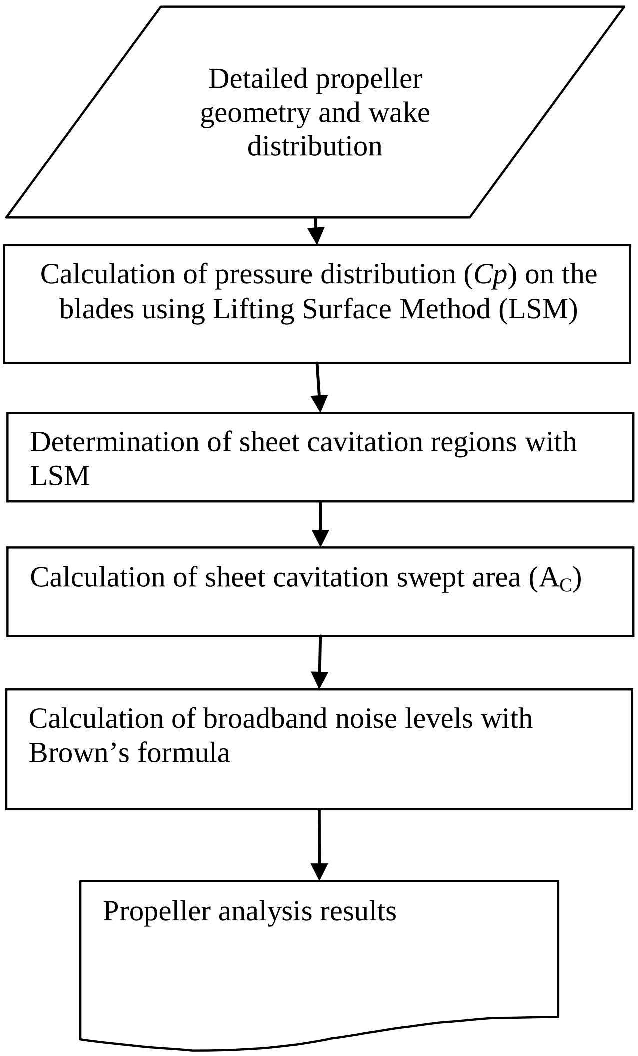


Figure 2 **Propeller analysis and noise prediction procedure**
Slika 2 **Postupak analize vijka i prognoze buke**

4 Examples of analysis procedure

In this section the analysis procedure of the propeller mentioned above is applied for a model propeller (DTMB 4148) for noise prediction and obtained results are compared with the values proposed by ICES and Fraser formula (Example 1). Besides, for a model propeller (DTMB 4119) and a high skewed propeller (Seiun-maru HSP) at full scale, propeller performance characteristics are calculated and the results obtained are compared with the experimental and CFD results. Pressure distributions for both propellers at various conditions are given in comparison with experimental, CFD and Hoshino panel method results [43] (Example 2).

Example 1: Noise prediction for DTMB 4148

The data and geometry of the propeller is given in Table 1 and Table 2, respectively.

Table 1 **Propeller data of DTMB 4148**
Tablica 1 **Značajke vijka za DTMB 4148**

Blade number	3
Propeller diameter (m)	0.3048 m
Propeller rate of rotation per second	17.17 (1/s)
Advance coefficient ($J_S = V_S/ND$)	0.954
Cavitation number ($\sigma_n = \dfrac{P_0 - P_V}{1/2\rho(nD)^2}$)	2.576
Skew (degree)	0
Rake (degree)	0
Blade section	NACA66 a= 0.8 mean line for all radius

Table 2 **Propeller blade geometry for DTMB 4148**
Tablica 2 **Geometrijske značajke vijčanog krila za DTMB 4148**

r/R	Chord distribution (c/D)	Pitch Distribution (P/D)	Thickness distribution (t/D)	Camber distribution (f/D)
0.2	0.16	0.9921	0.0329	0.0174
0.3	0.1818	0.9967	0.0282	0.0195
0.4	0.2024	0.9987	0.0239	0.0192
0.5	0.2196	0.9975	0.0198	0.0175
0.6	0.2305	0.9944	0.0160	0.0158
0.7	0.2311	0.9907	0.0125	0.0143
0.8	0.2173	0.9850	0.0091	0.0133
0.9	0.1806	0.9788	0.0060	0.0125
0.95	0.1387	0.9740	0.0045	0.0115
1	0.0010	0.9680	0	0

For the DTMB 4148, as shown in Figure 3, the noise levels obtained from Brown's semi-empirical formula are given in comparison with (4) proposed by ICES and (5) given by Fraser.

$$L_s = \begin{cases} 135 - 1.66\log f & 1 \le f(\mathrm{Hz}) \le 1000 \\ 130 - 22\log(f/1000) & 1000 \le f(\mathrm{Hz}) \le 100000 \end{cases} \qquad (4)$$

$$L_s = \begin{cases} 10\log\left[\dfrac{D^6(60n)^6 Z}{4}\right] - 6 & f \le 100\mathrm{Hz} \\ 10\log\left[\dfrac{D^6(60n)^6 Z}{4}\right] + 34 - 20\log f & f \ge 100\mathrm{Hz} \end{cases} \qquad (5)$$

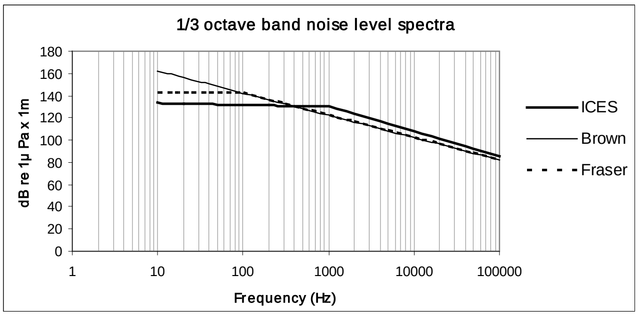


Figure 3 **Noise levels generated by blade sheet cavitations for DTMB 4148**
Slika 3 **Razine buke razvijene sa slojastom kavitacijom za DTMB 4148**

Example 2: Propeller analyses for DTMB 4119 and Seiun-maru HSP

The operating conditions of the propellers are given in Table 3.

Table 3 **Propeller data**
Tablica 3 **Podaci o brodskom vijku**

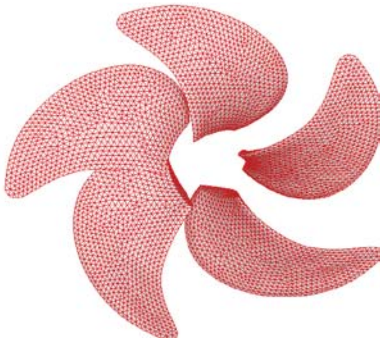
	DTMB 4119	**Seiun-maru HSP**
P_D (kW)	0.474	360
V_S (knot)	4.938	9
N (rpm)	600	90.7
D (m)	0.3048	3.6
Z	3	5
Blade section	NACA66 a=0.8	Mod. SRI-B

4.1 CFD analysis

In CFD analysis, the flow is assumed to be incompressible and turbulent. The k-ε (standard) model is chosen as the turbulence model [44]. In Fluent, the governing equations are discretized using a second-order upwind interpolation scheme, and the discretized equations are solved using SIMPLE algorithm.

Propeller geometries shown in Figures 4-5 are modelled in Rhino, CAD program, and meshed using FLUENT pre-processor GAMBIT. For both propellers, the computational domains are split into two separate cylindrical parts; inner rotational domain (including propeller) and outer stationary domain. The blade surfaces are meshed with smaller triangles and the remaining surfaces that belong to moving domain, are meshed with larger triangles and filled using tetrahedral cells. Finally, a simple cylindrical mesh is generated for outer stationary block. The number of cells in this mesh is about 1,000,000.

Figure 4 **Geometry of Sein-maru HSP**
Slika 4 **Geometrija od Seinu-maru HSP**



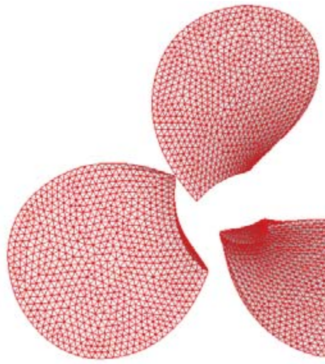


Figure 5 **Geometry of DTMB 4119**
Slika 5 **Geometrija od DTMB 4119**

Boundary conditions set to simulate the flow around a rotating propeller in open water are as follows: on the inlet boundary, velocity components of uniform stream with the given inflow velocity are imposed for the DTMB 4119, and the flow simulation is performed for steady case using moving reference frame technique. Unsteady flow simulation in non-uniform ship wake is carried out for the Seiun-maru HSP propeller using the sliding mesh technique implemented in Fluent, and the non-uniform inflow condition at the velocity inlet boundary is imposed through the Boundary Profile feature of the code. The nominal wake distribution is included to a Boundary Profile file at 120 points. For both propellers, on the exit boundary, the static pressure is to be zero and on the outer boundary, the slip boundary condition is imposed, and on the blade surfaces the no slip condition is imposed.

First, solution is carried out in the case of steady flow for both propellers. Then unsteady simulation is performed only for the Seiun-maru HSP, time step size is set to 0.00183756 s, which corresponds to rotational angle of 1° and solution data is saved for every 15°. The solution is considered converged when continuity residual is less than 10^{-4} and velocity residuals are less than 10^{-5}, which are obtained for both cases at almost 600 iterations for steady simulations (approx. 50 iterations for each time step of unsteady simulation for the Seiun-maru). All numerical computations are performed on an IBM computer with 2 GB RAM, Pentium 4 2.7 GHz CPU and 40 GB HDD.

In Figure 6, variation of the DTMB 4119 propeller characteristics depending on advance coefficient (J) is given. In Figures 7-8, chordwise distribution of pressure coefficient depending on non-dimensional chord length for $r/R = 0.3$ and $r/R = 0.7$ sections obtained from the lifting surface method, CFD, Hoshino panel method and model tests for DTMB 4119 is shown.

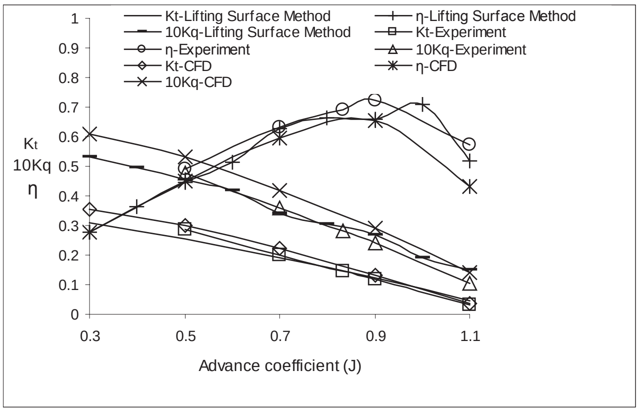


Figure 6 **Open water diagram for DTMB 4119**
Slika 6 **Dijagram otvorene vožnje za DTMB 4119**

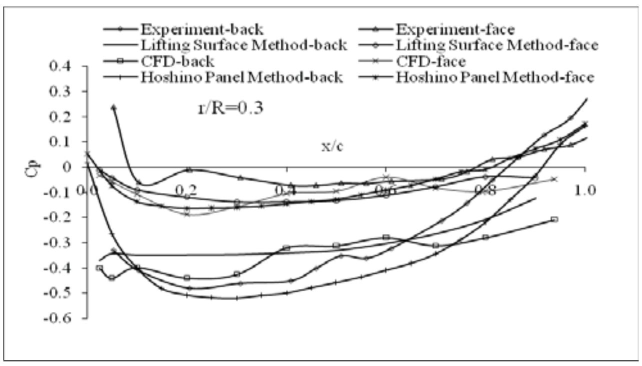


Figure 7 **Chordwise pressure distribution (C_p) on 0.3R for DTMB 4119**
Slika 7 **Raspodjela tlaka (C_p) duž raspona presjeka vijčanog krila na 0,3 R za DTMB 4119**

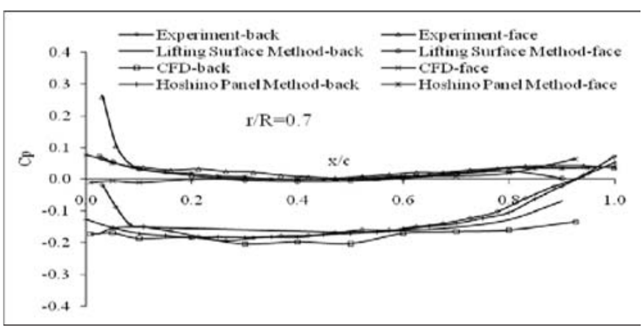


Figure 8 **Chordwise pressure distribution (C_p) on 0.7R for DTMB 4119**
Slika 8 **Raspodjela tlaka (C_p) duž raspona presjeka vijčanog krila na 0,7 R za DTMB 4119**

In Table 4, comparison of the Seiun-maru HSP propeller characteristics corresponding to J=0.851 (design condition) for the lifting surface method, CFD and experiment are given. The agreement between the methods is generally acceptable.

Table 4 **Comparison of propeller characteristics of Seiun-maru HSP**
Tablica 4 **Usporedba značajki vijka za Seiun-maru HSP**

J=0.851	Lifting surface	CFD	Experiment
K_T	0.17266	0.18257	0.172
K_Q	0.02799	0.03231	0.0268
η_O	0.65548	0.60055	0.682

Figure 9 shows chordwise distribution of the pressure coefficient at angular blade position of 0 degree at r/R = 0.7 section obtained from the lifting surface method, Hoshino panel method and model tests for the Seiun-maru HSP. The calculated pressure at 0.7 radius of the Seiun-maru HSP agrees well with the experiment.

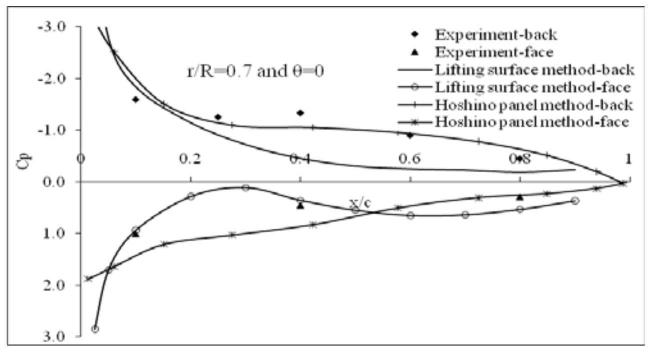


Figure 9 **Chordwise pressure distribution (C_p) at 0.7R blade section at 0 degree blade position for Seiun-maru HSP**
Slika 9 **Raspodjela tlaka (C_p) duž raspona presjeka vijčanog krila na presjeku 0,7 R za položaj krila 0° za Seiun-maru HSP**

5 Conclusions

For the reliable determination of the source of underwater noise, it is important to predict the level of noise generated due to unsteady blade sheet cavitation which generates significant noise under water. Thus, a propeller analysis procedure including noise prediction is presented in this study. It is aimed to be a fast, reliable and useful tool performed at the beginning of the initial design stage prior to cavitation tests.

Using this procedure, an example analysis is performed for a conventional propeller model (DTMB 4148), and the noise levels of the propeller are compared with the values proposed by ICES. Comparison of the predicted noise levels has shown sufficiently good agreement to prove that the presented method is valid for practical evaluation of propeller cavitation noise. In addition, two different propellers are analyzed by the lifting surface and CFD methods; the results are compared with those of the Hoshino panel method and experimental ones.

Further studies are aimed at the prediction of vibration and noise effects on ships regarding comfort, performance and detection, and development of new methods considering vibration and noise level analysis, led by additional rules established by classification societies, such as the lifting surface method, covering tip vortex cavitation. Also, for the calculation program, adding of brand new graphics tools, changing it into a more visual and user friendlier state, is aimed at.

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