Sigma J Eng & Nat Sci 36 (4), 2018, 1127-1139

Sigma Journal of Engineering and Natural Sciences
Sigma Mühendislik ve Fen Bilimleri Dergisi

Research Article

AN EMPIRICAL APPROACH FOR PROPELLER TIP VORTEX CAVITATION NOISE

Savaş SEZEN*[1], Ali DOĞRUL[2], Şakir BAL[3]

[1]*Yildiz Technical University, Department of Naval Architecture & Marine Engineering, Esenler-ISTANBUL;* ORCID: 0000-0002-7185-1799
[2]*Yildiz Technical University, Department of Naval Architecture & Marine Engineering, Esenler-ISTANBUL;* ORCID: 0000-0003-3236-555X
[3]*Istanbul Technical University, Department of Naval Architecture & Marine Engineering, Maslak-ISTANBUL;* ORCID: 0000-0001-8688-8482

Received: 15.01.2018 Revised: 09.04.2018 Accepted: 12.06.2018

ABSTRACT

In this study, the TVI (Tip Vortex Index) technique has been applied to a marine propeller to predict the noise due to tip vortex cavitation. The benchmark DTMB4119 model propeller has been chosen for the hydro-acoustic performance analysis in open water condition. The flow around the model propeller has been solved both under non-cavitating and cavitating conditions by lifting surface method (LSM) based on potential flow theory and RANS (Reynolds Averaged Navier Stokes) approach based on finite volume method. TVI technique has been coupled with LSM. Uncertainty study based on grid convergence index (GCI) has also been done for RANS approach to determine the optimum grid number. The results of LSM and RANS methods have been validated with the available experimental data under non-cavitating condition. LSM and RANS methods have also been compared in terms of cavity patterns and hydrodynamic performance. The effects of blade number, cavitation number and advance coefficient on propeller tip vortex cavitation noise have been discussed.
Keywords: Cavitation, lifting surface method, propeller noise, RANS, tip vortex index, uncertainty.

1. INTRODUCTION

Propeller cavitation noise is a critical interest for survivability of the vessel and underwater detection especially for military purposes. Although there are several types of cavitation such as sheet cavitation, tip vortex cavitation, bubble cavitation and cloud cavitation; each cavitation type has different effect on propeller hydro-acoustic performance. Tip vortex cavitation noise can often be observed under high loading conditions and appears with intense pressure fluctuation.

In the past, the propeller noise due to tip vortex cavitation has been investigated in different studies. Propeller hydro-acoustic performance has been investigated both numerically and experimentally by Kim et al. [1]. In this study, the propeller tonal noise and broadband noise have been calculated with different methods. The semi-empirical formula for noise was based on aero-acoustic theory of tip vortex formation and experimental results have been developed for tip

* Corresponding Author: e-mail: ssezen@yildiz.edu.tr, tel: (212) 383 28 62

vortex cavitation noise. The propeller cavitation noise has been investigated by Lafeber et al. [2] via both computational and experimental methods. ETV (Empirical cavitating Tip Vortex) noise model based on TVI technique has been used for prediction of cavitating vortex noise for three different marine propellers. Szantyr et al. [3] have focused on tip vortex cavitation in their study. The main aim of the study was to develop a reliable method for numerical prediction of tip vortex cavitation. The inception of tip vortex cavitation has been studied by Lee et al. [4]. A detailed noise spectrum analysis has been applied to determine the tip vortex cavitation noise. Wijngaarden et al. [5] have investigated the broadband inboard noise and vibration on passenger vessels for a frequency range. Hydro-acoustic calculations involving tip vortex cavitation have been examined both by sea trials and model experiments. Raestad [6] has studied on the tip vortex cavitation noise for twin screw passenger vessels. Full scale experiments have been conducted on different ship types. The tip vortex cavitation noise formulation has been developed with the help of a lifting surface method (LSM). The reference distance for the calculations has been considered as three decks above the propeller. The final report of specialist committee on hydrodynamic noise in 27th ITTC conference [7] emphasizes that TVI technique related to the tip vortex cavitation has given a good agreement with measured inboard noise data. Wave effects on cavitation and pressure pulses of a tanker with twin podded propulsor have been investigated by Taskar et al. [8]. In their study, TVI technique has been used in order to calculate the propeller noise induced by tip vortex cavitation. In the calculations, the tip circulation value has been taken from the blade section of r/R=0.997 at 12 O'clock blade position. Sezen et al. [9] have investigated inboard tip vortex cavitation noise of a marine propeller. Tip Vortex Index (TVI) technique coupled with lifting surface method has been applied for the prediction of inboard noise level under cavitating and non-cavitating conditions. Pennings et al. [10] have also studied on the effect of resonance of tip vortex cavity on high amplitude broadband pressure fluctuations for a model propeller experimentally. Experimental method and boundary element method have been used for tip vortex cavity resonance frequency. It has been found that steady tip vortex cavitation in a uniform flow has not produced significant noise. Tip vortex cavitation noise has been analyzed by Park et al. [11] numerically. The most significant parameters on overall tip vortex cavitation noise have been determined. The relationships of the cavitation nuclei size, cavitation inception and sound pressure level have been investigated for different cavitation numbers. Pennings et al. [12] have made a study on the effect of tip vortex dynamics on propeller cavitation noise experimentally. Tip vortex cavitation has been observed with the collapse of the cavity bubble on propeller tip. Wang et al. [13] have studied on the tip vortex cavitation inception in the homogeneous flow field with a panel method. The effect of various parameters on tip vortex cavitation noise has been investigated. Hydrodynamic features and noise levels of a model propeller have also been predicted using LSM (Lifting Surface Method) and empirical formulations by Ekinci et al. [14].

In this study, the benchmark DTMB 4119 model propeller with different blade numbers (Z=2, 3, 4) has been selected for analyzing of tip vortex cavitation noise. The main aim of this study is to investigate the propeller noise due to the tip vortex cavitation. As a first step, PLL (propeller lifting line) solution [15] has been used to obtain the optimum radial distribution of circulation over the radius of the blade. Verification of the results has been done with lifting surface method (LSM). Verification study has also been done using grid converge index (GCI) method to determine the optimum grid number for RANS (Reynolds Averaged Navier Stokes) method. Later, the flow around the model propellers has been solved using LSM and RANS methods under both cavitating and non-cavitating conditions. RANS and LSM results have been validated with the available experimental data under non-cavitating condition. For tip vortex cavitation noise, tip vortex index (TVI) technique has been used coupled with lifting surface method (LSM). The results have been discussed for different cavitation numbers, advance coefficients and number of blades.

2. NUMERICAL METHODS

2.1. PLL and LSM

PLL (Propeller Lifting Line) theory and a LSM (Lifting Surface Method) have been coupled to design the propeller with optimum circulation distribution. PLL has first been applied to represent the propeller as a set of a number of blades and straight and radial lifting lines. The blades have angular spacing and equal loading. The continuous distribution of vortices along the lifting line is discretized by vortex lattice elements with constant strengths. The velocity induced at the lifting line by this system of vortices can be computed using the very efficient formulas given by Kerwin [15]. They are not repeated here. The PLL uses the Betz-Lerbs condition to obtain the optimum circulation distribution over blades. Detail information for PLL theory can be found in [15] and [16].

LSM has also been applied to calculate the propulsive performance and to check the optimum circulation distribution obtained by PLL, similar to the one given [16], [17]. The lifting surface method models the three-dimensional unsteady cavitating flow around a propeller by representing the blade and wake as a discrete set of vortices and sources, which are conveniently located on the blade mean camber surface and wake surface. In this method, a discretized version of the kinematic boundary condition can be employed as:

$$\sum_{\Gamma} \Gamma \vec{\upsilon}_{\Gamma} . \vec{n}_m = -\vec{\upsilon}_{in} . \vec{n}_m - \sum_{Q_B} Q_B \vec{\upsilon}_Q . \vec{n}_m - \sum_{Q_C} Q_C \vec{\upsilon}_Q . \vec{n}_m \tag{1}$$

where $\vec{\upsilon}_{\Gamma}$ the velocity vector is induced by each unit strength vortex element, $\vec{\upsilon}_Q$ is the velocity vector induced by each unit strength source element, and $\vec{n}_m$ is the unit vector normal to the mean camber line or trailing wake surface. Q_B and Q_C represent the magnitude of the line sources that model the blade thickness and cavity source strengths, respectively. Details about LSM and coupling with PLL are given in [16].

2.2. Unsteady RANS Method

The governing equations are the continuity equation and the RANS equations for the unsteady, three-dimensional, incompressible flow. The continuity can be given as;

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{2}$$

Velocity U_i can be decomposed into mean velocity part and fluctuating velocity part, respectively;

$$U_i = \overline{U_i} + u_i^{'} \tag{3}$$

The momentum equations are expressed as;

$$\frac{\partial U_i}{\partial t} + \frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] - \frac{\partial \overline{u_i^{'} u_j^{'}}}{\partial x_j} \tag{4}$$

In this study, the analyses have been conducted in steady state manner under non-cavitating conditions while transient analyses have been carried out in order to simulate the cavitation on propeller blades. In momentum equations, U_i (m/s) states the mean velocity while $u_i^{'}$ states the fluctuation velocity components in the direction of the Cartesian coordinate x_i (m). P expresses the mean pressure (Pa), ρ (kg/m^3) the density and ν (m^2/s) the kinematic viscosity of the fluid. The k-ε turbulence model is applied to simulate the turbulent flow around the model propellers under both non-cavitating and cavitating conditions. Detailed explanations for the k-ε turbulence model can be found in the literature [18].

2.3. Uncertainty Assessment

In this study, uncertainty assessment has been carried out by Grid Convergence Index (GCI) as recommended in the ITTC procedure for CFD verification [19]. This method firstly was proposed by Roache [20] and then improved with other studies. The procedure implemented in this study has briefly been explained below [21]:

Let h_1, h_2 and h_3 are grid lengths and $h_1 < h_2 < h_3$. The refinement factors are as follows:

$$r_{21} = \frac{h_2}{h_1} \qquad r_{32} = \frac{h_3}{h_2} \tag{5}$$

Refinement factors should be greater than 1.3 in accordance with the experiments [21]. Grid lengths' refinement has been selected as $\sqrt{2}$ as in the studies of Tezdogan et al. [22] Luca et al. [23] and Ozdemir et al. [24].

$$r_{21} = \left(\frac{N_1}{N_2}\right)^{1/3} \qquad r_{32} = \left(\frac{N_2}{N_3}\right)^{1/3} \tag{6}$$

Differences between generated grid numbers can be calculated as below:

$$\varepsilon_{21} = X_2 - X_1 \qquad \varepsilon_{32} = X_3 - X_2 \tag{7}$$

At this point, the convergence condition R can be examined as,

$$R = \frac{\varepsilon_{21}}{\varepsilon_{32}} \tag{8}$$

The solution has an oscillating convergence when $-1<R<0$ while the solution is monotonically convergent if $0<R<1$ [25].

2.4. TVI Technique

TVI (Tip Vortex Index) technique has been implemented to predict the tip vortex cavitation noise of marine propellers. This technique has been developed in accordance with the experimental studies for different type of vessels such as cruise liners, passenger vessels [6]. In this method, the propeller has been considered as the acoustic source of transmitting the noise. In the report of the 27th ITTC conference [7], it has also been mentioned that TVI technique gives satisfactorily good results with experimental measurements.

TVI technique has been widely used for prediction of tip vortex cavitation noise at a reference distance (three decks above the propeller and aft perpendicular). The non-dimensional TVI factor is given as;

$$\text{TVI}=\left(k_{tbl}.k_{tip}\right)^2 Z^{0.5}/\sigma \tag{9}$$

Here, k_{tip} is the relative tip loading factor. k_{tbl} is the non-dimensional thrust coefficient per blade. Z is the blade number and σ is the cavitation number. Cavitation number is given as;

$$\sigma=\frac{P_{atm}+\rho gh-P_v}{\rho n^2 D^2} \tag{10}$$

Cavitation number is calculated by considering that the operation depth of the propeller (h) is 5 meters while the saturation pressure (P_v) is taken as 2000.7 Pa (for water at T=17.5 ^oC). P_{atm} is the atmospheric pressure level (Pa), D is the propeller diameter (m) and ρ is the fluid density (kg/m^3). The propeller number of revolution (n, rps) is calculated from the non-dimensional cavitation number.

$$k_{tip}=\left(\Gamma_{tip}/k_{tbl}\right)/\left(\Gamma_{tip}/k_{tbl}\right)_{ref} \tag{11}$$

After calculation of TVI, the sound pressure level due to the tip vortex cavitation is calculated as follow,

$$SPL_{ref}=20\log\left(TVI\times n^2\times D^2\right)+80 \tag{12}$$

Detailed information about TVI technique can be found in [6], [8].

3. NUMERICAL RESULTS

The numerical calculations have been made for propeller hydrodynamics and hydroacoustic. The flow chart in Figure 1 shows the procedure for predicting propeller noise due to the tip vortex cavitation.

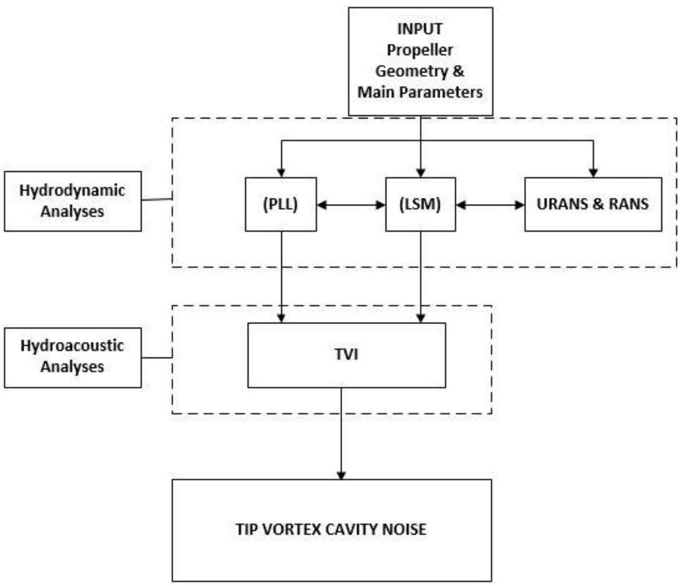

Figure 1. Flow chart for propeller hydrodynamic and hydroacoustic analyses

3.1. Optimum Blade Design

In this study, DTMB 4119 model propeller has been chosen for the investigation of the tip vortex cavitation noise. The original DTMB 4119 propeller has three blades. The number of blades of the original DTMB 4119 propeller has later been changed to 2 and 4, respectively. All other geometrical properties (such as blade sections, pitch ratios, chord lengths etc.) are same as in the original three-bladed propeller. The geometrical properties of the model propellers have been given in Table 1. Detailed information about the propeller geometry can be found in [26]. 3-D views of the DTMB 4119 model propellers have also been presented Figure 2.

Table 1. Main particulars of DTMB 4119 propellers

DTMB 4119 Model Propeller	
D (m)	0.3048
Z	2-3-4
Skew (^{0})	0
Rake (^{0})	0
Blade section	NACA66 a=0.8
Rotation direction	Right

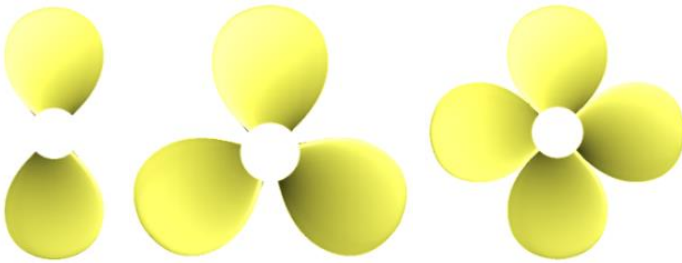

Figure 2. 3-D views of DTMB 4119 model propellers

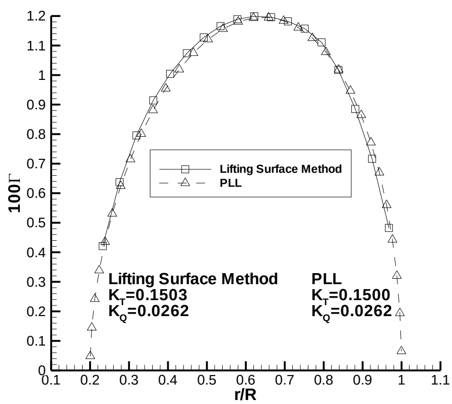

Figure 3. Comparison of circulation distribution with PLL and LSM for non cavitating DTMB 4119 propeller (Z=3) (Bal, 2011a)

The PLL (propeller lifting line) method and LSM (lifting surface method) have been implemented as seen in Figure 3 for design J=0.833, respectively. Here the radial optimum circulation distribution which is non-dimensionalized by $2\pi RV_R$ (here V_R is the resulting velocity at 0.7 R, $V_R = \sqrt{\left(V_S^{\,2} + (0.7\pi nD)^2\right)}$). The obtained radial circulation distributions of PLL and LSM have been compared in Figure 3. The differences of radial circulation distribution of the two methods are quite small. By this way, it can be specified that the blade geometry of the DTMB 4119 model propeller (Z=3) has optimum radial circulation distribution under the design conditions. The non-dimensional thrust and torque values are also given in Figure 3 [16]. For tip vortex cavitation noise calculation, the reference circulation value has been taken at the r/R=0.997 12 O'clock blade position [8]. Besides, the optimum circulation is obtained at J=0.833.

3.2. Verification and Validation for Propeller Hydrodynamic

The grid convergence index (GCI) method has been applied for uncertainty assessment using RANS method. It is implemented for original DTMB 4119 model propeller (Z=3) for thrust value. The optimum grid number has also been used for other blade numbers (Z=2 and Z=4).

As seen in Table 2, three different grid sizes have been used for open water propeller analyses to model the computational domain. The significant part of the uncertainty of the numerical results is the selection of grid [27]. The uncertainty study has been done at design J=0.833.

Table 2. Grid numbers for uncertainty analysis

		Open water condition (OWC)
#	Grid type	Grid number
1	Fine	2352457
2	Medium	1398003
3	Coarse	985612

As a result of the uncertainty study at J=0.833, the convergence condition (R) is calculated as 0.26 which means that the solution is converged monotonically. As a result of the GCI method, the uncertainty value has been found as 0.032 %. Fine mesh algorithm has then been selected for open water propeller analyses.

Validation study of RANS method has also been done with specifying the optimum grid number using GCI method. The numerical results have been compared with the experiments under non-cavitating conditions (Z=3). The relative absolute difference has been found as 0.68 % at J=0.833 with the experiments. After verification and validation study, the rest of the analyses have been done using optimum grid number.

3.3. Non-cavitating Open Water Propeller Analyses

The flow around the DTMB 4119 model propellers have been solved using RANS method and LSM, respectively. The reference axis has been chosen as moving reference frame (MRF). As seen in Figure 4, the computational domain is divided into two parts; static region and rotating region. The right and left side of the computational domain has been defined as velocity inlet and pressure outlet respectively. The rest of the surfaces have been considered as symmetry planes in order to capture the normal component of the velocity as zero. The propeller blades and shaft surfaces have been also defined as non-slip wall for no-slip condition [28].

Discretization of the computational domain has been done with the finite volume method. Unstructured mesh algorithm has been used to solve the velocity and pressure fields precisely; mesh refinements have been done on the propeller blade surfaces (Figure 5).

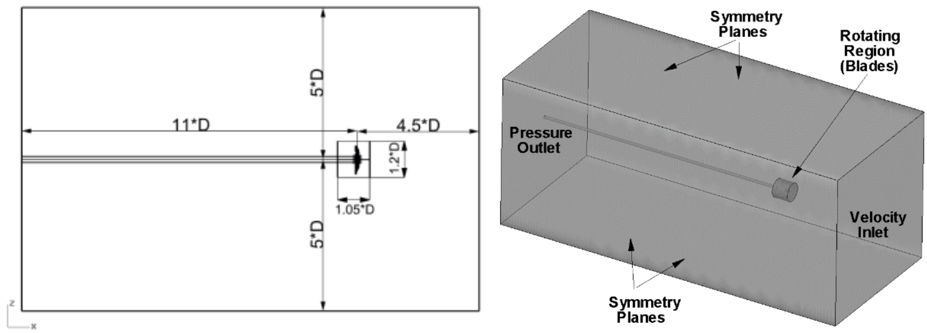

Figure 4. Computational domain and boundary conditions for DTMB 4119 propellers

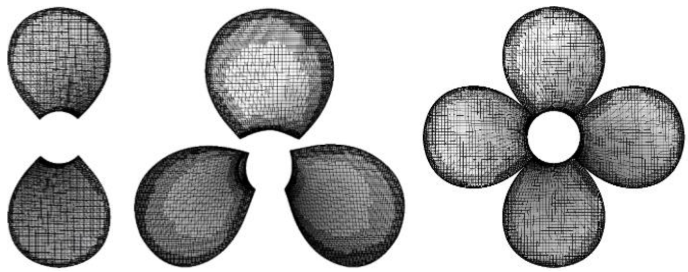

Figure 5. Unstructured mesh on propeller blade surfaces for propellers with different number of blades

Later, the flow around the model propellers has also been solved by the lifting surface method under non-cavitating condition. The panel distributions on the propeller blades and wakes have been given in Figure 6.

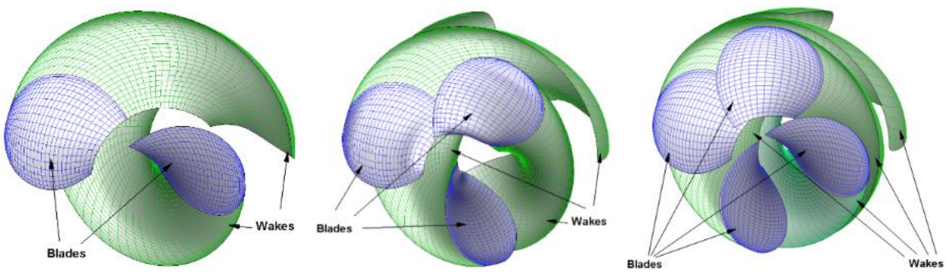

Figure 6. Panel arrangement of DTMB 4119 propellers and their wakes

As can be seen in Figure 7, the results of LSM and RANS method have been validated with the experimental data of three-bladed model propeller under non-cavitating condition. RANS method gives better results for open water propeller efficiency when compared with LSM. Figure 7 also shows the numerical results of two and four-bladed model propellers.

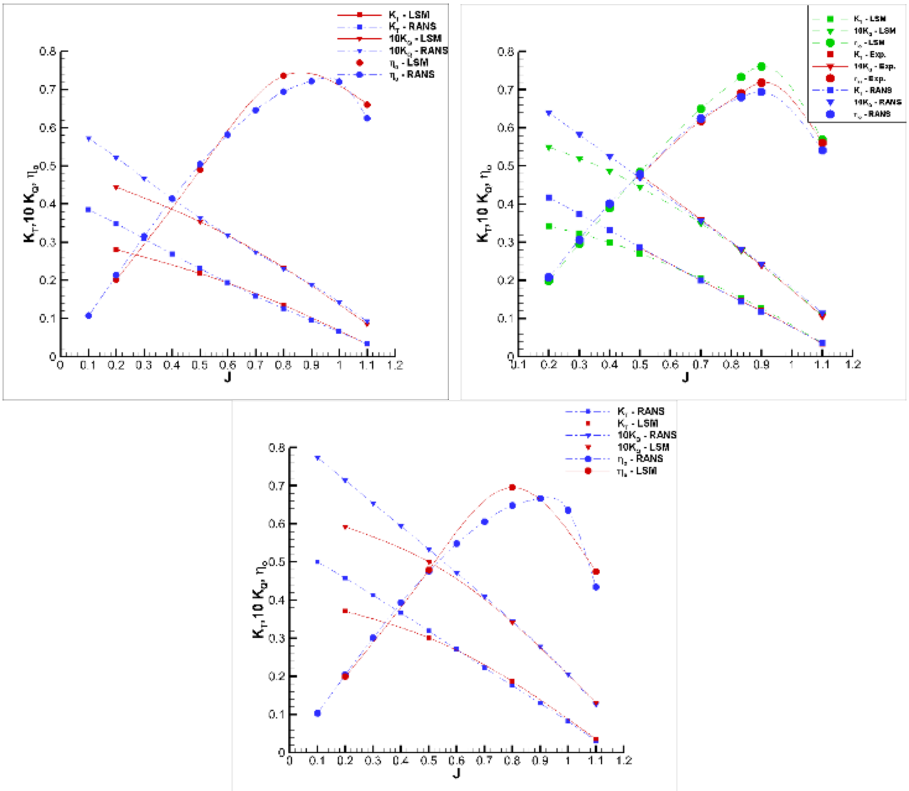

Figure 7. Comparison of thrust, torque and efficiency of DTMB 4119 propeller for Z=2, 3, 4, respectively.

3.4. Cavitating Open Water Propeller Analyses

The cavitating flow around the model propellers have been solved using unsteady RANS method with same boundary conditions as in Chapter 3.2. To capture the cavitation pattern on the propeller blades, volume of fluid method (VOF) has been used in the analyses. The thrust and torque values and the cavitation patterns by LSM and RANS methods have been compared at J=0.53 and σ=2.2. As can be seen in Table 3, the non-dimensional thrust and torque values computed by LSM and unsteady RANS solver are in good agreement with each other. The absolute relative differences between URANS and LSM are also given in Table 3.

Table 3. Comparison of hydrodynamic results of URANS method and LSM under cavitating conditions

Z	Method	J	σ	K_T	ε (%)	$10K_Q$	ε (%)	η_0	ε (%)
2	URANS	0.53	2.2	0.229	-	0.370	-	0.523	-
2	LSM	0.53	2.2	0.218	4.80	0.355	4.05	0.518	0.95
3	URANS	0.53	2.2	0.277	-	0.445	-	0.526	-
3	LSM	0.53	2.2	0.262	5.41	0.430	3.48	0.514	2.28
4	URANS	0.53	2.2	0.313	-	0.521	-	0.506	-
4	LSM	0.53	2.2	0.290	7.34	0.483	7.29	0.507	0.19

The cavity patterns by LSM and unsteady RANS method have also been compared at J=0.53 and σ=2.2 in Figure 8. The cavity patterns by both methods have been found to be in good agreement.

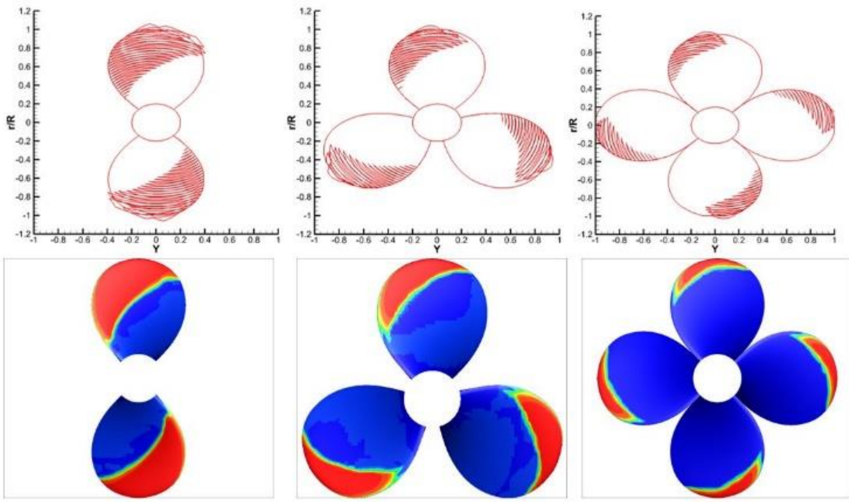

Figure 8. Comparison of cavity patterns of LSM and URANS method at J=0.53 and σ=2.2

3.5. TVI Technique for Tip Vortex Cavity Noise

Tip vortex cavitation has a major effect on propeller radiated noise. The higher blade loading on the tip triggers the noise level inevitably. TVI technique has been coupled with lifting surface method based on the potential theory [6]. In this technique, tip loading factor has been calculated by using the circulation (loading) value on the blade section r/R=0.997 at 12 O'clock blade position which is calculated by LSM [8]. The reference circulation value has been obtained from the optimum distribution of circulation for J=0.833 and three-bladed propeller under non-cavitation condition. The reference circulation for three-bladed propeller value has then been assumed to be same as for two and four-bladed propellers. The noise related to tip vortex cavitation has been calculated at a fixed distance for all three propellers. Table 4 shows the parameters used in TVI calculation at a constant advance ratio (J=0.53) and cavitation number (σ=2.2) for all blade numbers.

Table 4. Numerical values for TVI calculation at a constant advance ratio and cavitation number

Z	J	σ	k_{tbl}	$(k_{tbl})_{ref}$	k_{tip}	Γ_{tip}	$(\Gamma_{tip})_{ref}$	SPL (dB)
2	0.53	2.2	0.11	0.05	2.34	0.37	0.07	89.24
3	0.53	2.2	0.08	0.05	2.53	0.32	0.07	88.39
4	0.53	2.2	0.07	0.05	2.41	0.25	0.07	85.55

The noise level due to the tip vortex cavitation has been calculated for different cavitation numbers at a constant advance ratio (J=0.53).The results have been given in Figure 9 for different blade numbers. As expected, the sound pressure level is decreasing with an increase in blade number. Cavitation volume and lengths increase with a decrease in the cavitation number. Therefore, the sound pressure level due to the tip vortex cavitation is increasing while the cavitation number decreases for all three propellers.

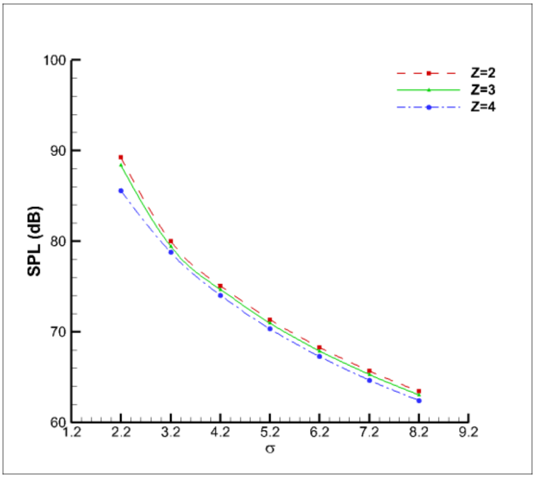

Figure 9. Sound pressure level of tip vortex cavitation for different cavitation numbers at a fixed advance ratio (J= 0.53) for different blade numbers.

On the other hand, the effect of advance ratios on tip vortex cavitation noise at constant cavitation number (σ=2.2) has been investigated as shown in Figure 10. As can be seen in Figure 10, the noise level due to the tip vortex cavitation is decreasing with an increase in advance ratio. It is also decreasing slightly with an increase in blade number since the loading on the blades are decreasing with an increase in blade numbers.

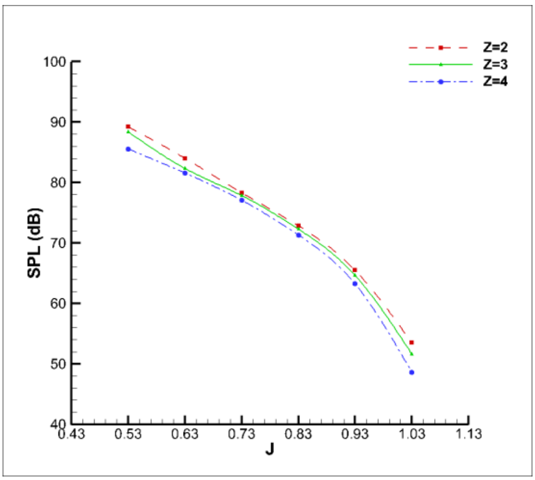

Figure 10. Sound pressure level related to the tip vortex cavitation versus advance ratio for different blade numbers at σ=2.2

4. CONCLUSION

In this paper, noise due to tip vortex cavitation of marine propellers has been computed using tip vortex index (TVI) technique based on a lifting surface method. As a first step, the optimum circulation distribution has been calculated with the propeller lifting line (PLL) solution and the results have been verified using the lifting surface method (LSM). The flow around the selected model propellers have then been solved by LSM and RANS methods under non-cavitating and cavitating conditions. Verification study of the RANS method has been done via Grid convergence index (GCI) method. Validation study has also been done for LSM and RANS methods under non-cavitating conditions with the experimental results in terms of thrust, torque coefficients and efficiency values. The results (cavity patterns, thrust and torque coefficients, efficiency) of LSM and RANS methods have been compared with each other. It has been found that the results of potential based lifting surface method (LSM) are satisfactorily close to those of experiments and RANS methods. This means that TVI technique which couples with LSM is a reliable and robust method in propeller radiated noise due to the tip vortex cavitation. In addition to this, the final report of 27th ITTC has also mentioned that TVI technique gives good agreement with the measurements [7].

This paper highlights the relationship between blade number and propeller radiated noise induced by tip vortex cavitation. The effects of cavitation number, advance ratio and blade number on propeller tip vortex cavitation noise have been discussed by TVI (coupled with LSM) technique. The cavitation on the propeller blades caused an increase in the propeller radiated noise due to tip vortex cavitation. In addition, the higher propeller rotation speed triggers the cavitation risk and so the noise level. On the other hand, the blade number inversely affects the propeller radiated noise due to the tip vortex cavitation. It means that an increase in the number of blades can cause a decrease in cavity area and volume thus a decrease in noise level. Moreover, the tip vortex cavitation noise is also decreasing with an increase in advance ratio. In near future, the approach here will be applied to other types of propellers.

REFERENCES

[1] T. Kim, J. Jeon, S. Chu, S. Kim, and W. Joo, "Numerical and Experimental Prediction Methods of Cavitation Noise Radiated by Underwater Propellers," presented at the International Congress on Acoustics, Buenos Aires, 2016.

[2] F. H. Lafeber, J. Bosschers, and E. van Wijngaarden, "Computational and Experimental Prediction of Propeller Cavitation Noise," presented at the OCEANS2015, Genova, 2015.

[3] J. Szantyr, P. Flaszyński, K. Tesch, W. Suchecki, and S. Alabrudziński, "An Experimental and Numerical Study of Tip Vortex Cavitation," *Pol. Marit. Res.*, vol. 18, no. 4, pp. 14–22, 2012.

[4] J.-H. Lee, J.-M. Han, H.-G. Park, and J.-S. Seo, "Application of signal processing techniques to the detection of tip vortex cavitation noise in marine propeller," *J. Hydrodyn. Ser B*, vol. 25, no. 3, pp. 440–449, Jul. 2013.

[5] E. van Wijngaarden, J. Bosschers, and G. Kuiper, "Aspects of the Cavitating Propeller Tip Vortex as a Source of Inboard Noise and Vibration," presented at the ASME 2005 Fluids Engineering Division Summer Meeting, 2005.

[6] A. E. Raestad, "Tip Vortex Index - An Engineering Approach to Propeller Noise Prediction," *Nav. Archit.*, Aug. 1996.

[7] ITTC, "27th ITTC Specialist Committee on Hydrodynamic Noise Final Report," ITTC, 2012.

[8] B. Taskar, S. Steen, and J. Eriksson, "Effect of waves on cavitation and pressure pulses of a tanker with twin podded propulsion," *Appl. Ocean Res.*, vol. 65, no. Supplement C, pp. 206–218, Apr. 2017.

[9] S. Sezen, A. Dogrul, and Ş. Bal, "Tip Vortex Index (TVI) Technique for Inboard Propeller Noise Estimation," *GMO J. Ship Mar. Technol.*, no. 207, pp. 27–37, 2017.

[10] P. Pennings, J. Westerweel, and T. van Terwisga, "Cavitation tunnel analysis of radiated sound from the resonance of a propeller tip vortex cavity," *Int. J. Multiph. Flow*, vol. 83, no. Supplement C, pp. 1–11, Jul. 2016.

[11] K. Park, H. Seol, W. Choi, and S. Lee, "Numerical prediction of tip vortex cavitation behavior and noise considering nuclei size and distribution," *Appl. Acoust.*, vol. 70, no. 5, pp. 674–680, May 2009.

[12] P. Pennings, J. Westerweel, and T. van Terwisga, "Sound signature of propeller tip vortex cavitation," *J. Phys. Conf. Ser.*, vol. 656, no. 1, p. 012186, 2015.

[13] Y. Wang, M. Abdel-Maksoud, K. Wang, and B. Song, "Prediction of tip vortex cavitation inception with low-order panel method," *Ocean Eng.*, vol. 125, no. Supplement C, pp. 124–133, Oct. 2016.

[14] S. Ekinci, F. Celik, and M. Guner, "A Practical Noise Prediction Method for Cavitating Marine Propellers," *Brodogr. Teor. Praksa Brodogr. Pomor. Teh.*, vol. 61, no. 4, pp. 359–366, Dec. 2010.

[15] J. E. Kerwin, "'Hydrofoils and Propellers', Lecture Notes." Department of Ocean Engineering, Massachusetts Institute of Technology, USA, Jan-2001.

[16] S. Bal, "A method for optimum cavitating ship propellers," *Turk. J. Eng. Environ. Sci.*, vol. 35, no. 3, pp. 319–338, Sep. 2011.

[17] S. Bal, "A practical technique for improvement of open water propeller performance," *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.*, vol. 225, no. 4, pp. 375–386, Nov. 2011.

[18] D. C. Wilcox, *Turbulence Modeling for CFD*, 3rd edition. La Cãnada, Calif.: D C W Industries, 2006.

[19] ITTC, "7.5-03-01-04 CFD, General CFD Verification," in *ITTC - Recommended Procedures and Guidelines*, 2011.

[20] P. J. Roache, "Verification of Codes and Calculations," *AIAA J.*, vol. 36, no. 5, pp. 696–702, 1998.

[21] I. B. Celik, U. Ghia, and P. J. Roache, "Procedure for estimation and reporting of uncertainty due to discretization in CFD applications," *J. Fluids Eng.-Trans. ASME*, vol. 130, no. 7, Jul. 2008.

[22] T. Tezdogan, Y. K. Demirel, P. Kellett, M. Khorasanchi, A. Incecik, and O. Turan, "Full-scale unsteady RANS CFD simulations of ship behaviour and performance in head seas due to slow steaming," *Ocean Eng.*, vol. 97, pp. 186–206, Mar. 2015.

[23] F. De Luca, S. Mancini, S. Miranda, and C. Pensa, "An Extended Verification and Validation Study of CFD Simulations for Planing Hulls," *J. Ship Res.*, vol. 60, no. 2, pp. 101–118, Jun. 2016.

[24] Y. H. Ozdemir, T. Cosgun, A. Dogrul, and B. Barlas, "A numerical application to predict the resistance and wave pattern of KRISO container ship," *Brodogradnja*, vol. 67, no. 2, pp. 47–65, Jun. 2016.

[25] F. Stern, R. Wilson, and J. Shao, "Quantitative V&V of CFD simulations and certification of CFD codes," *Int. J. Numer. Methods Fluids*, vol. 50, no. 11, pp. 1335–1355, Apr. 2006.

[26] S. Brizzolara, D. Villa, and S. Gaggero, "A Systematic Comparison between RANS and Panel Methods for Propeller Analysis," in *Proceedings of 8th International Conference on Hydrodynamics*, Nantes, France, 2008.

[27] R. V. Wilson, F. Stern, H. W. Coleman, and E. G. Paterson, "Comprehensive Approach to Verification and Validation of CFD Simulations—Part 2: Application for Rans Simulation of a Cargo/Container Ship," *J. Fluids Eng.*, vol. 123, no. 4, pp. 803–810, Jul. 2001.

[28] S. Sezen, "Numerical Investigation of Ship-Propeller Hydro-Acoustics Performance," MSc Thesis, Istanbul Technical University, Istanbul, 2016.