10th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2019-068**
18-20 September 2019 - METU, Ankara TURKEY

INVESTIGATION OF UNDERWATER NOISE CHARACTERISTICS OF DTMB4119 PROPELLER UNDER DIFFERENT CONDITIONS

Ahmet Soydan[1]
Istanbul Technical University
Istanbul, Turkey

Baha Zafer[2]
Istanbul University-Cerrahpaşa
Istanbul, Turkey

Şakir Bal[3]
Istanbul Technical University
Istanbul, Turkey

ABSTRACT

The propeller is the most dominant source of noise generated by ships and submarines. Research of underwater noise of the marine propellers has a great interest in recent years. In this study, the hydro-acoustic performance of DTMB 4119 model propeller has been investigated with varies diameters, revolutions, blade number under in open water at non-cavitating conditions. Flow around the propeller has been solved computational fluid dynamics method using unsteady Reynolds Averaged Navier Stokes (uRANS). Hydro-acoustic analysis have been performed using unsteady RANS with Ffowcs-Williams and Hawkings (FW-H) equation. Propellers Sound Pressure Level (SPL) values also have been carried out with semi-empirical Brown Formula and then Overall Sound Pressure Level (OASPL) values have been calculated. Finally, OASPL formulas have been developed and results have been compared.

INTRODUCTION

Traditionally, only engineers and designers of submarines, naval fishing and research vessels have had a significance interest in underwater radiated noise. In recent years, however, underwater noise has become a growing concern throughout the entire maritime industry. Sources of underwater radiated noise on a marine vessel can be divided into three main categories; engine, flow noise and propeller noise [Carlton, 2012]. To reduce the engine noise, isolation equipment can be installed, or the engine foundation may be resiliently mounted instead of rigidly mounted. Ship hull form should also be designed to decrease the hydrodynamic noise. But it is the propeller that is the dominant noise source on marine vessels.

[1] Ph.D. student in Faculty of Naval Architecture and Ocean Engineering, Email: ahmetsoydann@gmail.com
[2] Assoc. Prof. in Faculty of Engineering, Email: baha.zafer@istanbul.edu.tr
[3] Prof. in Faculty of Naval Architecture and Ocean Engineering, Email: sbal@itu.edu.tr

Propeller noise is important for detection of vessel location and velocity, but also impacts the comfort of passengers and the environment. Due to these reasons, hydrodynamic properties and acoustic performance should be taken into consideration when designing propellers. Therefore, an accurate calculation of the noise due to marine propellers is an important subject within the maritime industry. The designer should consider that the propeller must satisfy the desired thrust and torque values, while minimizing the radiated noise in the concept design stage.

One of the most important studies that formed the basis of today's acoustic studies was carried out by [Lighthill,1952]. Based on Lighthill's work, [Curle, 1955] conducted a study about body and fluid interaction. In 1969, a method developed by Ffowcs-Williams and Hawkings (FW-H) for calculation of noise of an arbitrary body moving in a fluid became one of the milestones of acoustic studies [Ffowcs Williams and Hawkings, 1969]. With the development of computer technology and numerical methods, FW-H method became available also hydro-acoustic predictions. [Seol, Suh and Lee, 2002] investigated the non-cavitating underwater propeller noise using time-domain acoustic analogy (FW-H equation) and boundary element method. [Seol, Suh and Lee, 2005] extended their work to calculation of blade sheet cavitation noises of the underwater propeller. The flow field was analyzed with potential-based panel method, and the time-dependent pressure and sheet cavity volume data were used as the input for FWH formulation to predict the far-field acoustics. [Salvatore and Ianniello, 2003] published the preliminary results for cavitating propeller noise predictions. [Ozden, Gürkan, Ozden, Canyurt and Korkut, 2016] investigated numerically the INSEAN E1619 submarine propeller in open water, behind a generic DARPA suboff submarine and within imposed wake cases at non-cavitating condition. [Purwana, Ariana, Wardhana and Handani, 2017] used to numerical simulation to predict hydrodynamic performance and noise around non cavitation propellers. The performance of propeller was predicted by MRF technique (Multiple Reference Frame). The 3D model propeller of B-series propeller was simulated with various advance coefficients. [Tewari, Misra and Vijayakumar, 2019] also investigated the underwater radiated noise levels of DTMB 4119 model propeller by a 3D numerical simulation of the flow around propeller operating in non-cavitating regime for the uniform flow (no wake) condition with different advanced coefficients. The influence of skew and rake angles on noise and hydrodynamic performance of propeller is very crucial. [Gorji, Ghassemi and Mohamadi, 2017] conducted a numerical simulation of the acoustic pressure generated by a marine propeller (DTMB 4119) in different skew and rake angles.

Lin 1996, into quantifying propeller noise inboard a twin-screw passenger vessel took a practical approach [Raestad, 1996]. Full scale experiments were conducted on 15 cruise liners and ferries. According to this study, noise caused by tip vortices can be estimated by tip vortex index (TVI) technique. Later this TVI technique, coupling an empirical formula with a lifting surface method, was applied for the prediction of the inboard noise level of a three bladed DTMB 4119 model propeller [Sezen, Dogrul and Bal, 2017]. Two and three-bladed model propellers were investigated for the hydro-acoustic performance operating under cavitating and non-cavitating conditions.

In this study, underwater propeller noise of DTMB 4119 propeller is investigated under different conditions by a 3D numerical simulation and Brown formula. Also, a very practical and simple method, based on the semi-empirical Brown formula is described for non-cavitating marine propellers.

GOVERNING EQUATIONS

The governing equations are the continuity and the uRANS (Unsteady Reynolds Averaged Navier-Stokes) equations for the time dependent, three-dimensional, incompressible flow [Versteeg and Malalasekera, 2007];

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = 0 \qquad (1)$$

is the continuity,

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}(-\rho\overline{u_i{}'u_j{}'}) \qquad (2)$$

is the momentum equations where x_i and v_i expresses the tensor form of axial coordinates and velocities, respectively, δ_{ij} is Kronecker Delta, ρ is the density , v is the kinematic viscosity of the fluid and $-\rho\overline{u_i{}'u_j{}'}$ are the unknown Reynolds stresses.. The well-known SST k-ω turbulence model is used to simulate the turbulent flows. Further details for the SST k-ω turbulence model can be found in [Wilcox, 2006].

For the acoustic analysis of the propeller the integral equation FW-H (Equation 3) is solved to find the far-field sound of the propeller [Ffowcs Williams and Hawkings, 1969].

$$\frac{1}{a_0{}^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i \partial x_j}\{T_{ij}H(f)\} - \frac{\partial}{\partial t}\{[P_{ij}n_{ij} + \rho u_i(u_n - v_n)]\delta(f)\} + \frac{\partial}{\partial t} \qquad (3)$$
$$\{[\rho_0 v_n + \rho(u_n - v_n)]\delta(f)\}$$

Where p', is the far field sound pressure ($p' = p - p_0$) , T_{ij} is the Lighthill tensor and a_0 is the sound velocity in the far field. The terms at RHS are defined as quadruple, dipole and monopole source, respectively. Also $\delta(f)$ and $H(f)$ are the Dirac delta function and the Heaviside function, respectively.

NUMERICAL MODELLING

Geometry and Boundary Conditions

DTMB 4119 propeller has 3 blades and no skew and no rake with diameter 0.3048 meters. DTMB 4119 propeller, as given below in Table 1, are designed with NACA 66 modified profile and a=0.8 camber line. 3-D model of the propeller is shown in Figure 1.

Table 1. DTMB 4119 propeller geometry [Brizzolara, Villa and Gaggero, 2008]

r/R	c/D	P/D	tmax/c	fmax/c
0.20	0.3200	1.1050	0.2055	0.0143
0.30	0.3635	1.1022	0.1553	0.0232
0.40	0.4048	1.0983	0.1180	0.0230
0.50	0.4392	1.0932	0.0902	0.0218
0.60	0.4610	1.0879	0.0696	0.0207
0.70	0.4622	1.0839	0.0542	0.0200
0.80	0.4347	1.0811	0.0421	0.0197
0.90	0.3613	1.0785	0.0332	0.0182
0.95	0.2775	1.0770	0.0323	0.0163
0.98	0.2045	1.0761	0.0321	0.0145
1.00	0.0800	1.0750	0.0316	0.0118

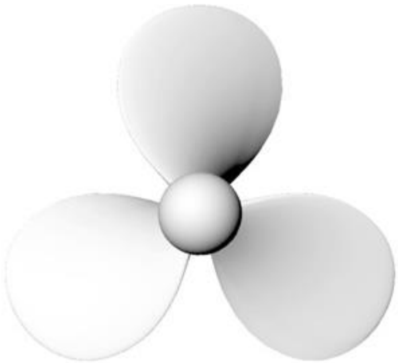

Figure 1: DTMB 4119 propeller geometry

Figure 2 shows the computational domains and boundary conditions with propeller in the rotational domain. The right and left sides of the computational domain have been defined as the velocity inlet and pressure outlet, respectively. The propeller has been defined as no slip wall to impose the kinematic boundary condition. The upper surface has been defined as symmetry plane. The computational domain consists of unstructured tetrahedral elements. Figure 3 shows the unstructured tetrahedral mesh generated around the propeller.

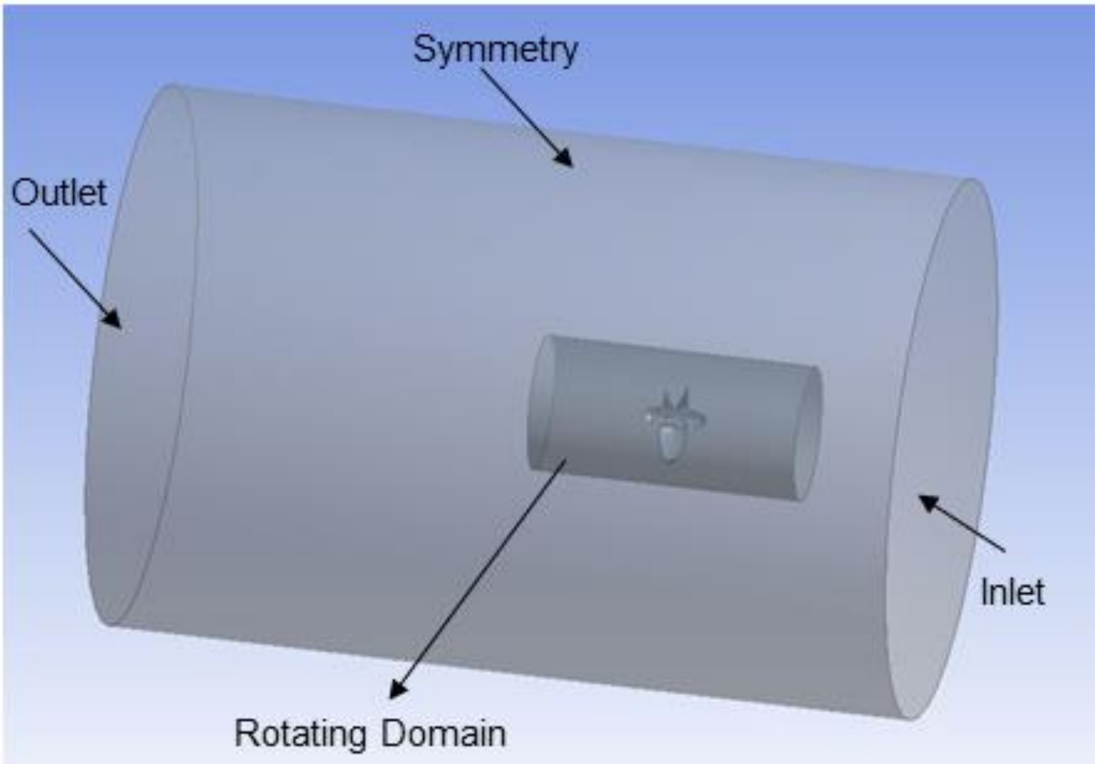

Figure 2: Computational domain and boundary condition for validation and verification case

Verification and Validation

In the first place, verification and validation study has been carried out. Flow around DTMB4119 propeller has been solved with uRANS. SST k-ω turbulence model has been used. Second order-upwind scheme has been selected for the momentum and turbulence terms and the simple algorithm for velocity pressure interaction has been selected. Time step size has been chosen as the time required for a 0.1° of reference frame rotation of the propeller [Ozden, Gürkan, Ozden, Canyurt and Korkut, 2016].

Three different mesh have been generated for verification and validation study. Uncertainty analysis has been applied with Grid Convergence Index (GCI) as recommended by ITTC for CFD verification [ITTC, 2011]. Grid length refinement has been selected greater than 1.3 as recommended in (Celik, Ghia, Roache, 2008] and [Roache, 1998]. The number of elements are given below in Table 2.

Table 2. Number of grids.

Grid Type	Number of Elements
Course	650,981
Medium	946,006
Fine	1,389,509

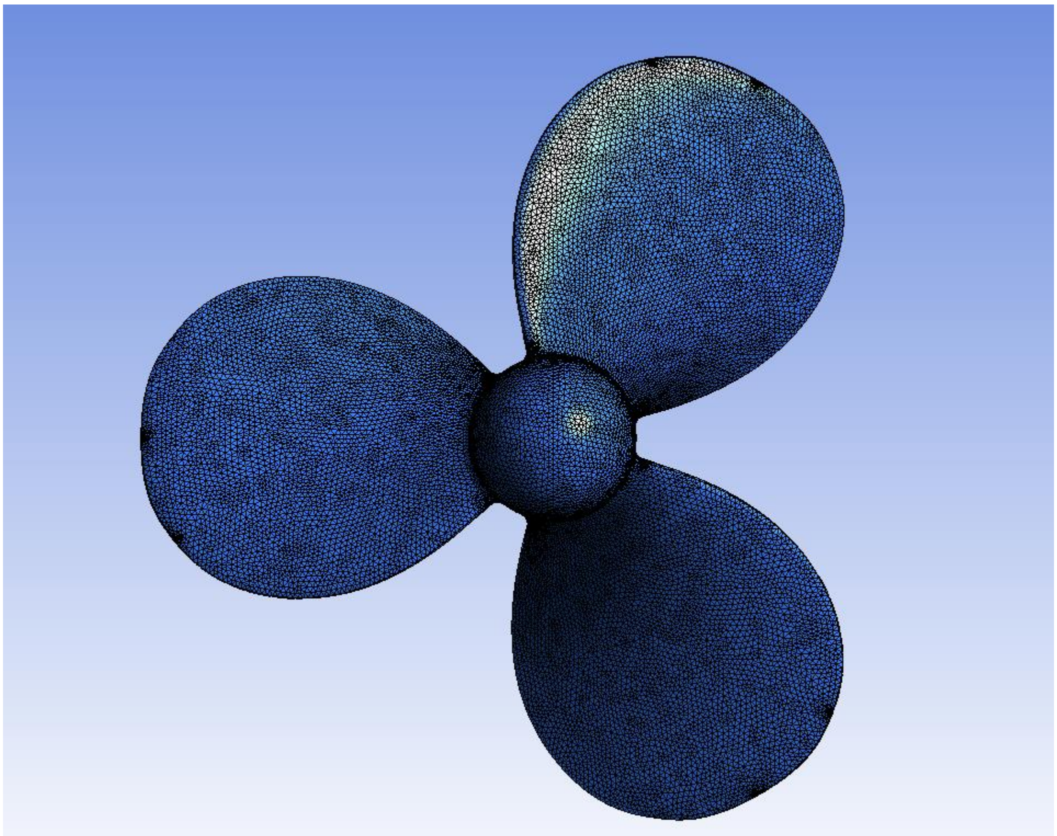

Figure 3*:* Unstructured mesh around propeller

Advanced coefficient (J) is taken as 0.833 (design point) for uncertainty analysis and convergence condition (R) has been calculated as 0.667 that means solution is converging monotonically. The uncertainty value has been calculated as %3.05 and is given below in Table 3. Fine grid has been selected and all analysis have been carried out with fine grid.

Table 3. Uncertainty value for open water analysis.

Analysis Set	%GCI_{FINE}
1 2 3	3.05

After verification study, the Thrust Coefficient (K_T) of the propeller has been validated with the experimental result for J=0.833. Experimental data have been taken from [Brizzolara, Villa and Gaggero, 2008]. The comparison of the CFD results with experimental data is given in Table 4. Relative difference between numerical and experimental results have been found as 1.370%.

Table 4. Comparison of the numerical and experimental results

	CFD	Experiment	Relative Difference (%)
K_T	0.148	0.146	1.370

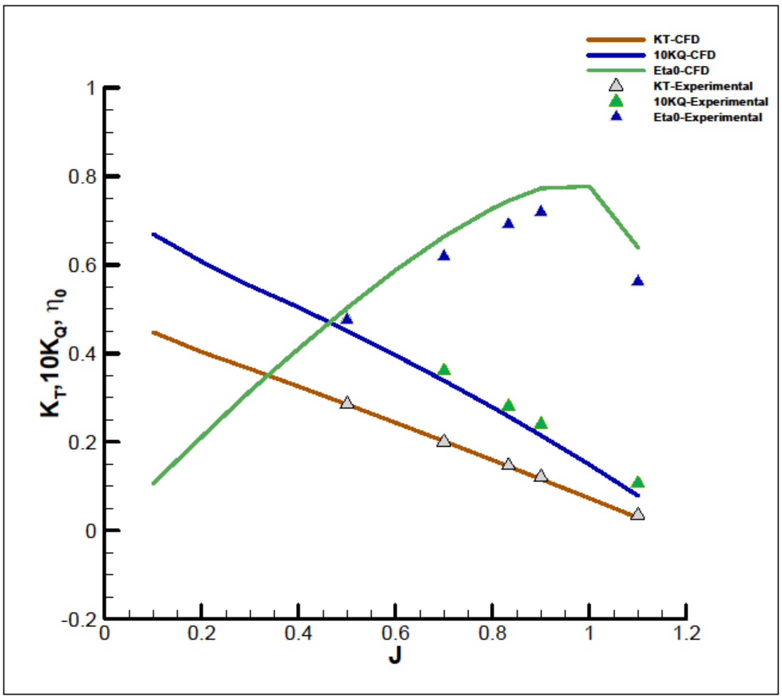

Figure 4: Comparison of K_T ,$10K_Q$ and η_0 values for DTMB 4119 propeller with experimental data taken by [Brizzolara, Villa and Gaggero, 2008]

For Validation of acoustic prediction, DTMB 4119 propeller is operated at 2 rps with a 1.6 m/s forward speed as in [Seol, Suh and Lee, 2005]. Results are compared in Figure 5 to those obtained by [Seol, Suh and Lee, 2005]. Density and velocity of sound in the undisturbed medium, standard water, are 1026 kg/m3 and 1500 m/s, respectively. The reference pressure for Sound Pressure Level calculations is 1 μPa.

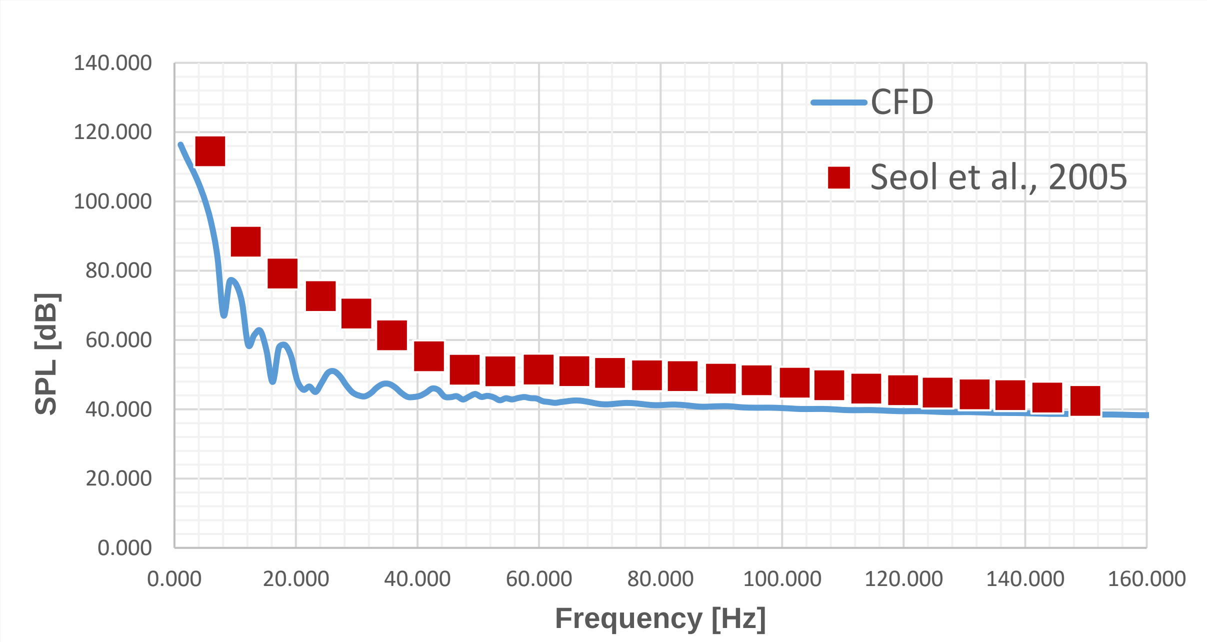

Figure 5: Comparison SPL values with those of Seol et al., 2005

Semi-Empirical Brown Formula

Later, the semi-empirical Brown formula, which is based in broadband noise estimation, was applied for the noise spectrum [Brown, 1976]]Brown, 1999]. This approach is used to calculate the total sound pressure level (SPL) as a reference distance (1 meter) in Z direction.

$$SPL(f) = 105 + 10log\left(\frac{Z*n^3*D^4}{f^2}\right) \quad (4)$$

In equation above (Equation 4) Z, D, n and f are the blade number, the propeller diameter (meters), the propeller rotation speed (rps) and the noise frequency (Hz . SPL represents the noise level in dB. The coefficient on the right-hand side of above equations (Equation 4) Is found as 105 dB after the validation study of selected DTBM 4119 propeller with those of another study [Seol, Suh and Lee, 2005]. SPL can also be given as (by definition),

$$SPL = 10\log\left(\frac{p}{p_{ref}}\right)^2 \quad (5)$$

Where p is acoustic pressure (P_a) and p_{ref} is reference acoustic pressure (for water p_{ref} =10e-6 Pa). Overall sound pressure level (OASPL) can then be computed by,

$$OASPL = 10\log\left(\frac{p_{rms}}{p_{ref}}\right)^2 \quad (6)$$

Here, p_{rms}, is the root sum square of pressure (NASA, 1996). Computed OASPL values including thrust and torque values under different working conditions are shown in Table 6. Advance coefficient, J=V/(nD) is taken as constant and equal to 0.833 for all cases here.

Now let us assume that OASPL can be given as,

$$OASPL = 20\log(n^a V^b D^c Z^d T^e Q^f) \qquad (7)$$

a, b, c, d, e and f powers can be calculated by using the values given in table 6 (Based on the semi-empirical Brown formula) .

RESULTS AND DISCUSSION

Receivers have been located 1 m away from the propeller centre, as shown in Figure 6.

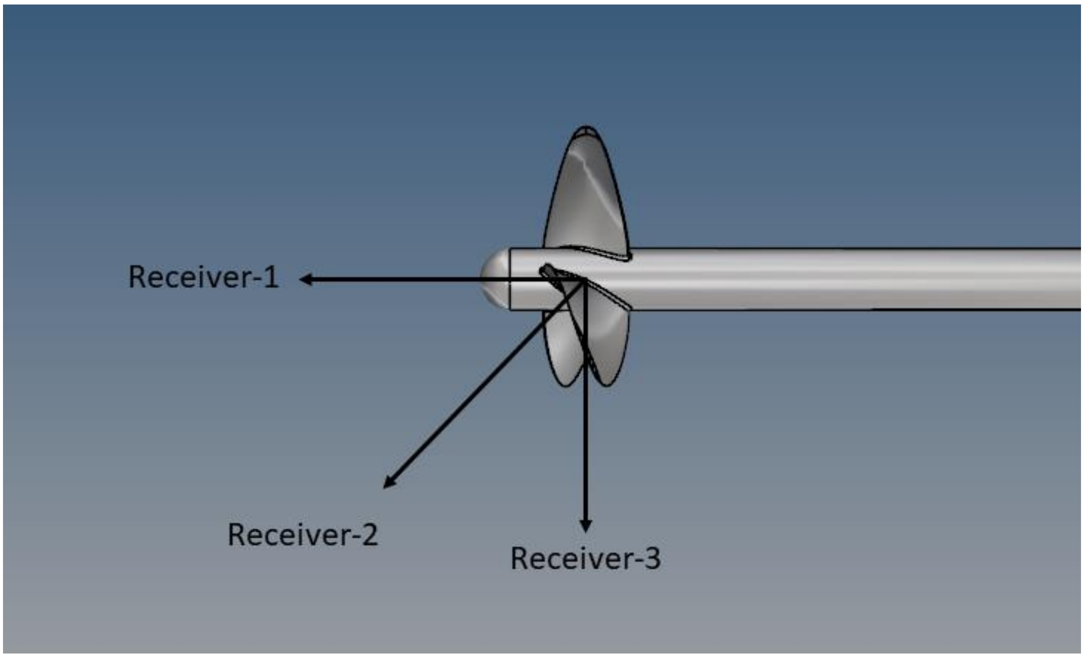

Figure 6: Receiver locations for CFD calculations

The acoustic analysis of the DTMB 4119 propeller has been performed under the conditions given in the table below, Table 5.

Table 5: Operating Conditions

Case	Z	J	n (rps)	D (m)	V (m/s)	Re. Number
1	3	0.833	10	0.3048	2.539	1837428
2	3	0.833	15	0.3048	3.808	2756143
3	3	0.833	20	0.3048	5.078	3674857
4	3	0.833	40	0.3048	10.156	7349714
5	3	0.833	5	0.6096	2.539	3674860
6	5	0.833	10	0.3048	2.539	1837428

Here Z, J, n, D and V are the blade number, advanced coefficient, propeller rotation speed, diameter and free stream velocity, respectively.

Sound pressure level (SPL) of case 1,2,3 and 4 at receiver 1 and receiver 3 are shown in figure 7a and figure 7b, respectively. As shown in these figures, SPL increases as rotation speed is increased. Also, as shown figure 8a and 8b, the noise increases as the propeller blade number is increased, although the effect of blade number on noise is very low.

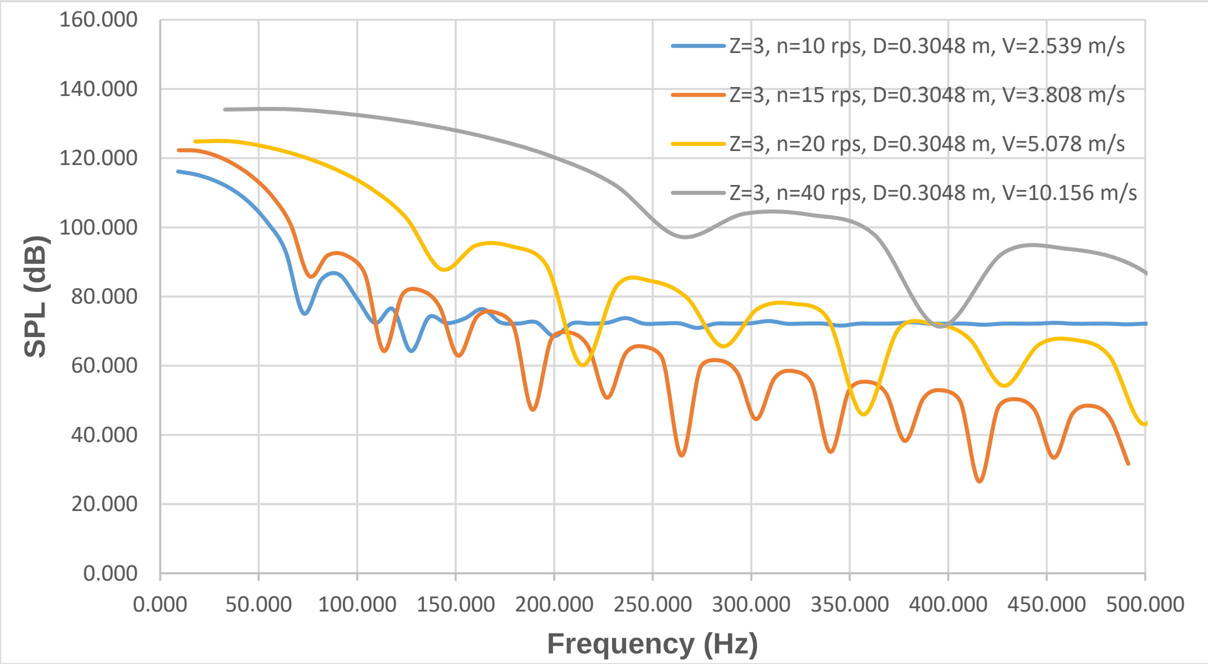

Figure 7a: Noise prediction of case 1, 2, 3 and 4 at receiver 1

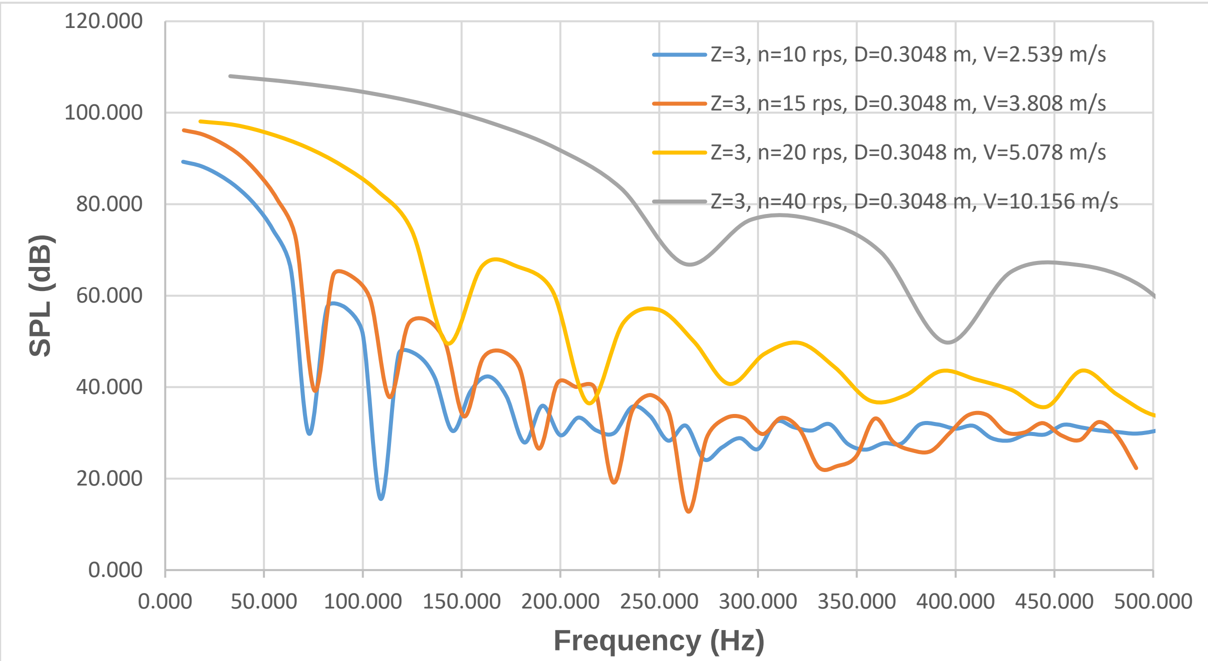

Figure 7b: Noise prediction of case 1, 2, 3 and 4 at receiver 3

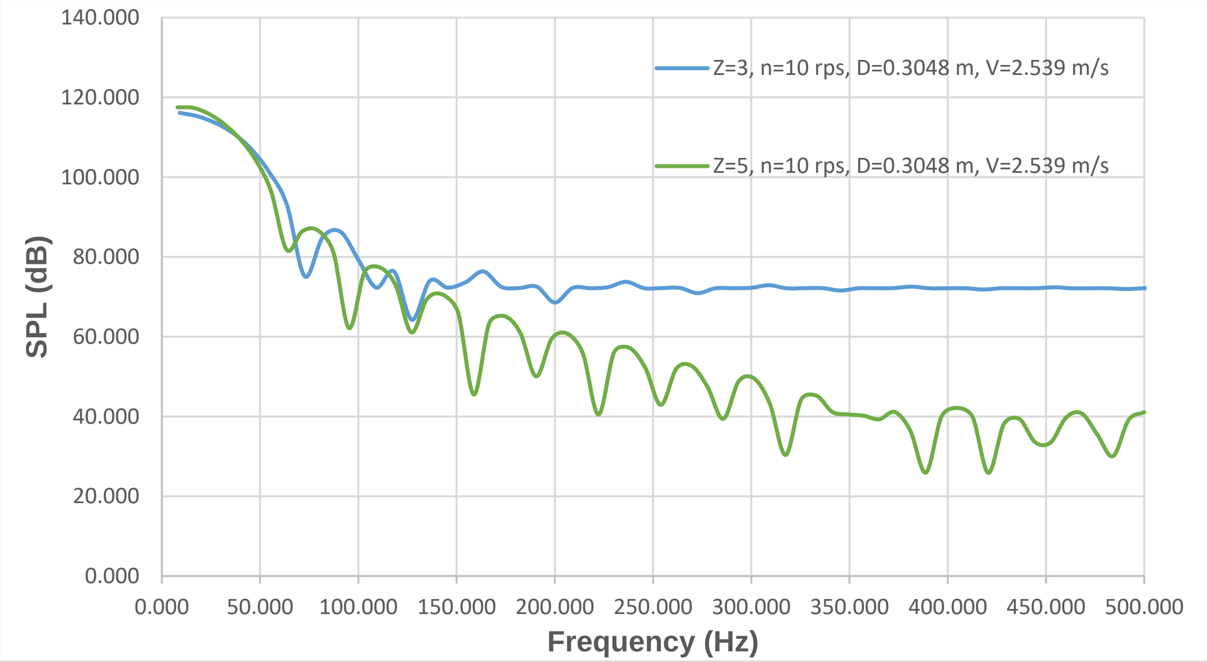

Figure 8a: Noise prediction of case 1 and case 6 at receiver 1

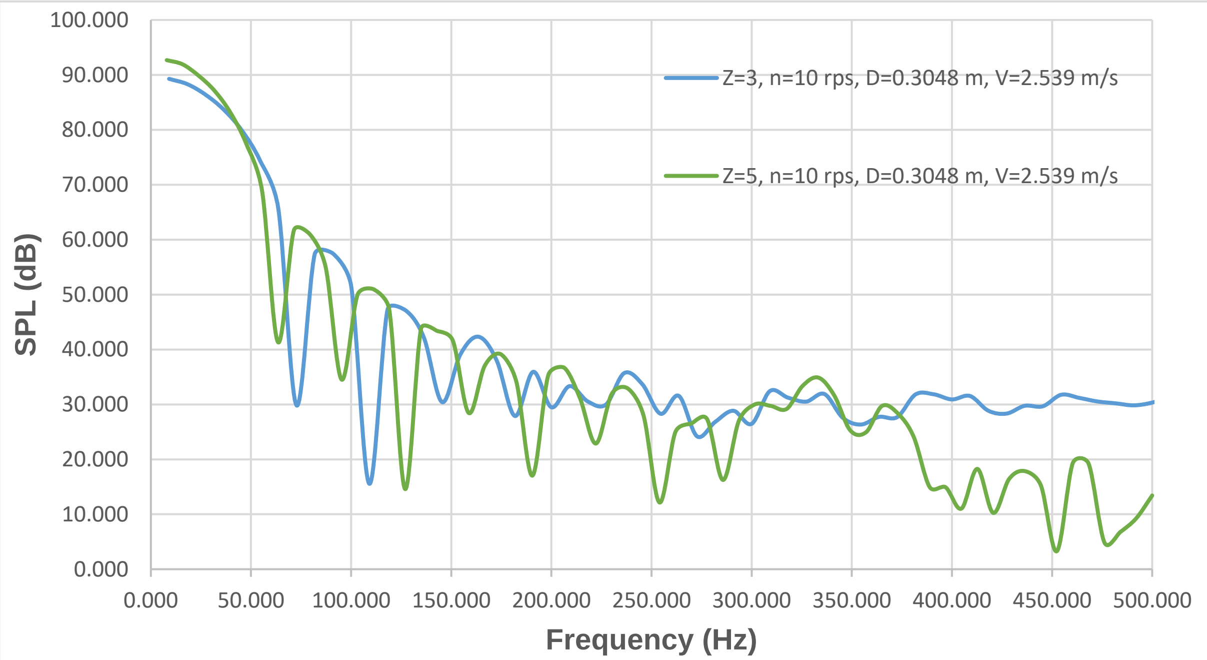

Figure 8b: Noise prediction of case 1 and case 6 at receiver 3

SPL of case 1 and 5 at receiver 1 and receiver 3 are shown in figure 9a and figure 9b, respectively. In order to investigate the effect of propeller diameter on noise and compare with the effect of propeller rotation speed on noise, the propeller diameter has been scaled doubled. It has been observed that SPL increases as the propeller diameter is increased and the effect of propeller diameter on propeller noise is more dominant than the effect of propeller rotation speed.

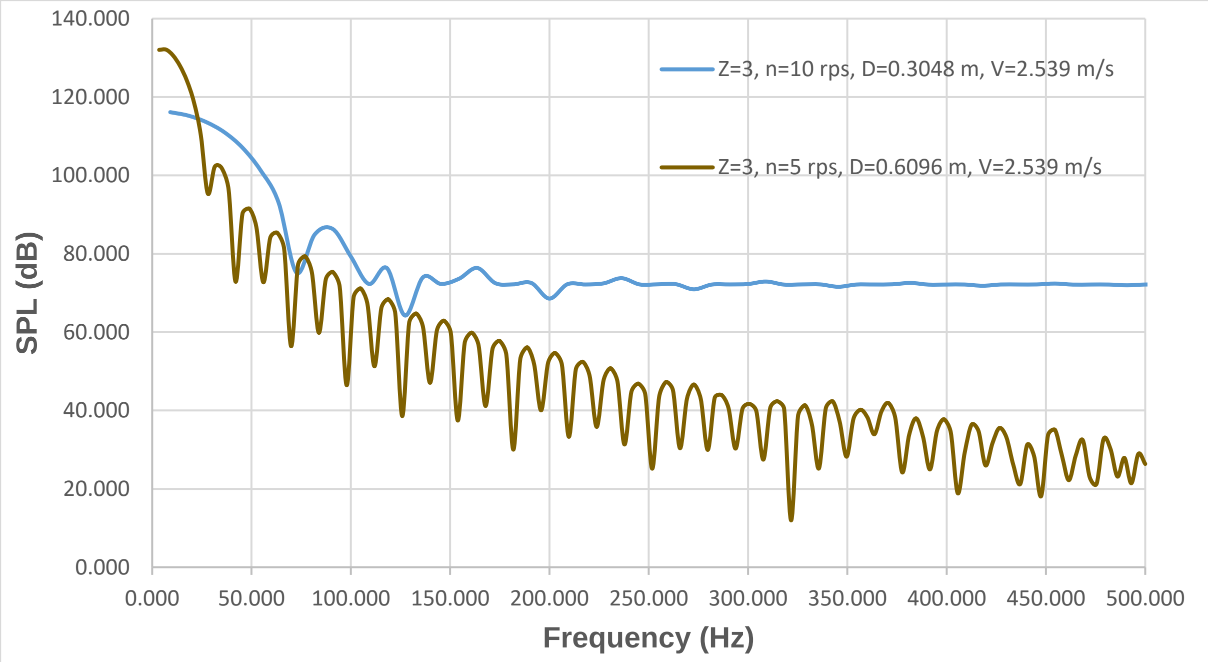

Figure 9a: Noise prediction of case 1 and case 5 at receiver 1

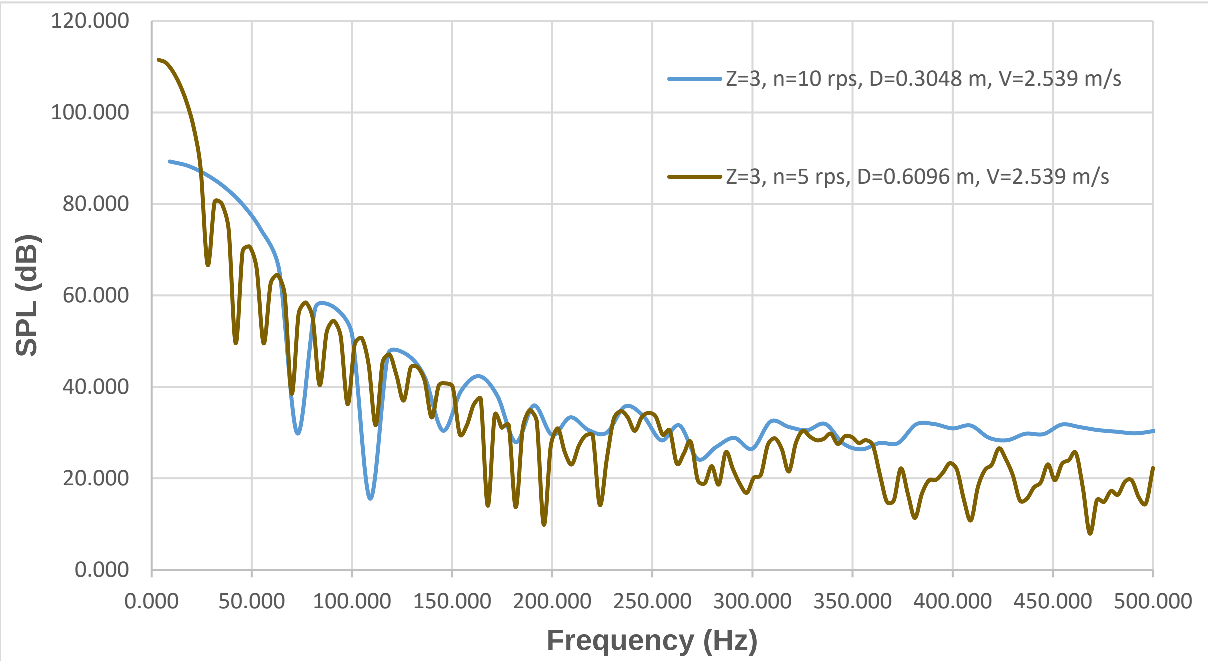

Figure 9b: Noise prediction of case 1 and case 5 at receiver 3

By using Equation 4-6, OASPL values have been calculated at six different working conditions as shown in Table 6. With the help of these OASPL values, a, b, c, d, e and f powers in Equations 7 have been found for DTMB 4119 propeller. These powers can be seen in Equation 8. As shown in the last column of Table 6, this simple and practical approach gives satisfactorily good results.

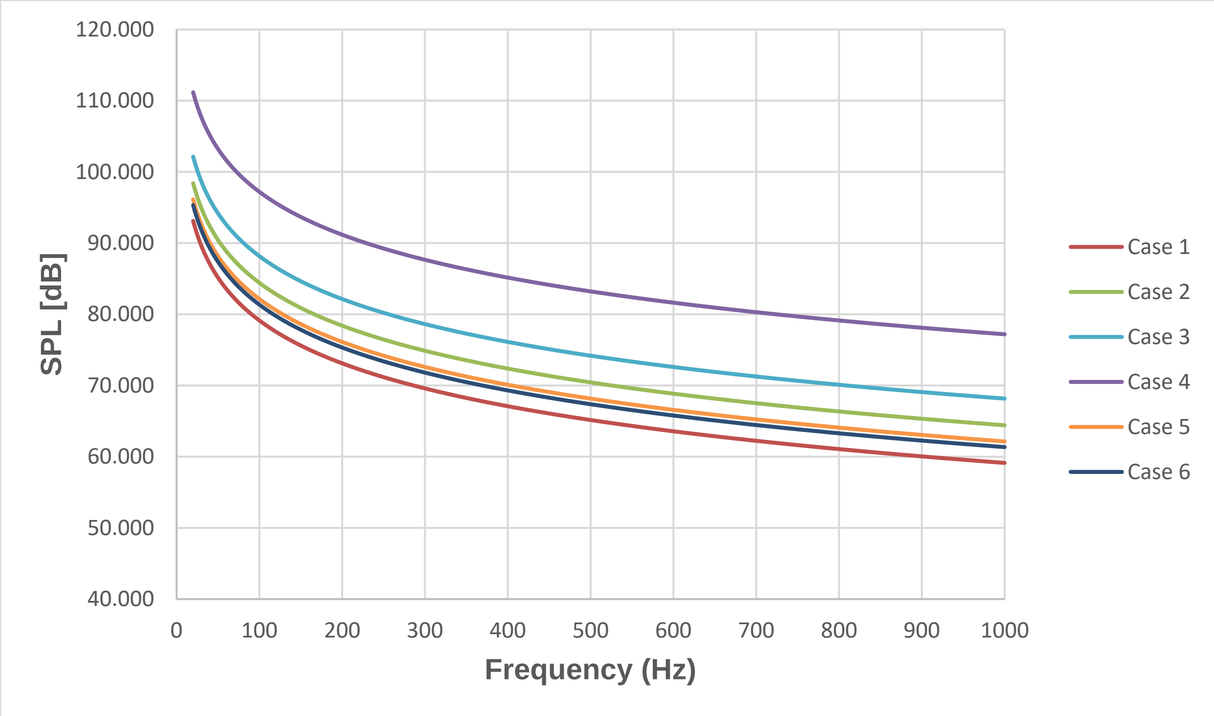

Figure 10: Comparison of SPL by Brown's formula

$$OASPL_{4119} = 20\log(n^{-9.0286}V^{4.1401}D^{-15.2608}Z^{-0.4904}T^{2.8419}Q^{0.3280}) \tag{8}$$

Table 6: Comparison of OASPL values

Case	Thrust (N)	Torque (N.m)	Kt	10*Kq	OASPL (CFD) (dB)	OASPL (Brown) (dB)	OASPL (Eqn. 8) (dB)
1	127.679	6.951	0.148	0.265	146.575	130.980	130.973
2	287.673	15.678	0.148	0.265	153.345	136.263	136.125
3	516.290	28.000	0.150	0.267	158.542	140.011	139.998
4	2079.300	112.620	0.151	0.268	175.981	149.042	148.920
5	518.060	56.168	0.150	0.267	154.581	133.990	133.977
6	149.240	8.404	0.173	0.320	147.072	133.198	133.190

CONCLUSION

This paper is presented the effect of the blade number, propeller diameter and propeller rotation speed on sound pressure level. The results of DTMB 4119 propeller are obtained by 3D numerical simulation and Brown formula. According the numerical and semi-empirical results, the following conclusion can be drawn;

- RANS method has given satisfactory results for propeller noise prediction.

- Propeller sound pressure level increase when the blade number, diameter and propeller rotation speed are increased.

- While the most dominant effect on propeller noise is diameter, the least dominant effect is blade number.

- A very practical and simple method based on the semi-empirical Brown formula is developed. Although there is a difference 15-20 dB compared to the RANS method, it provides accurate information about the order of propeller noise. The method can also be extended to include the cavitation effects and other parameters such as pitch ratio, skew, rake, etc. into Equation 7.

References

Brizzolara, S., Villa, D. and Gaggero, S., (2008). A Systematic Comparison Between RANS and Panel Methods for Propeller Analysis, Proceedings of 8th International Conference on Hydrodynamics, Nantes, France.

BROWN, N. A., Cavitation noise problems and solutions, Proceedings of The International Symposium on Shipboad Acoustics, 1976.

BROWN, N. A., Thruster Noise, Dynamic Positioning Conference, 1999.

NASA. Acoustic Noise Requirement. No PD-ED-1259, 1996

CARLTON, J.S., Marine Propeller and Propulsion, 3rd ed. Butterworth Heinemanni London, 2012.

Celik, I. B., Ghia, U., and Roache, P. J. (2008). Procedure for estimation and reporting of uncertainty due to discretization in CFD applications, J. Fluids Eng.-Trans. ASME, doi: 10.1115/1.2960953. doi: 10.1115/1.2960953

Curle, N. (1955). The Influence of Solid Boundaries upon Aerodynamic Sound. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 231 (1187): 505–14.doi:10.1098/rspa.1955.0191.

Ffowcs Williams JE, Hawkings DL (1969) Sound generation by turbulence and surfaces in arbitrary motion. Philosophical Transactions of the Royal Society A264: 321– 342.

Gorji, M., Ghassemi, H., Mohamadi, J., Effect of Rake and Skew on the Hydrodynamic Characteristics and Noise Level of the Marine Propeller, Iranian Journal of Science and Technology, Transactions of Mechanical Engineering March 2019, Volume 43, Issue 1, pp 75–85

ITTC (2011). 75-03-01-04 CFD, General CFD Verification,ITTC-Recomm. Proced. Guidel.

Lighthill, M. J. (1952). On Sound Generated Aerodynamically. I. General Theory. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences 211 (1107): 564–87.

Ozden, M. C., Gürkan, A. Y., Ozden, Y. A., Canyurt, T. G., Korkut, E., Underwater radiated noise prediction for a submarine propeller in different flow conditions, Ocean Engineering Volume 126, Pages 488-500, 2016.

Purwana, A., Ariana, M., Wardhana, W., Handani, D., W., Performance and Noise Prediction of Marine Propeller Using Numerical Simulation, The 3rd International Seminar on Science and Technology, Surabaya, Indonesia.

RAESTAD, A.E. Tip Vortex Index-an engineering approach to propeller noise prediction, The Naval Architect, July/August 1996.

Roache, P. J. (1998). Verification of Codes and Calculations, AIAA J., 36, 696–702. doi:10.2514/2.457

Seol, H., Suh, JC, Lee, S. Prediction of non-cavitating underwater propeller noise. J. Sound and Vibration. 2002, 257(1), 131-156.

Seol, H., Suh, JC, Lee, S. Development of hybrid method for the prediction of underwater propeller noise. J. Sound and Vibration. 2005, 288(1), 345-360.

Sezen, S., Dogrul, A. and Bal, S. Tip Vortex Index (TVI) technique for inboard propeller noise estimation, GMO Journal of Ship and Marine Technology, 207, pp , 24-35, March 2017

Salvatore, F., Ianniello, S., Preliminary results on acoustic modelling of cavitating propellers. Comput. Mech. 32, 291–300, 2003.

Tewari, A., K., Misra, V., Vijayakumar, R., Numerical Estimation of Underwater Radiated Noise of a Marine Propeller in Non-cavitating Regime, Proceedings of the Fourth International Conference in Ocean Engineering (ICOE2018) pp 149-167