# Tip Vortex Index (TVI) Technique for Inboard Propeller Noise Estimation

**Savaş Sezen[1], Ali Dogrul[2], Şakir Bal[3]**

[1]ssezen@yildiz.edu.tr, [2]adogrul@yildiz.edu.tr, [3]sbal@itu.edu.tr

*[1,2] Department of Naval Architecture and Marine Engineering, Naval Architecture and Maritime Faculty, Yildiz Technical University, Istanbul, Turkey*

*[3] Department of Naval Architecture and Marine Engineering, Faculty of Naval Architecture and Ocean Engineering, Istanbul Technical University, Istanbul, Turkey*

**Abstract**

Cavitating marine propeller is one of the most dominant noise sources in marine vessels. The aim of this study is to examine the cavitating propeller noise induced by tip vortices for twin screw passenger vessels. To determine the noise level inboard, tip vortex index (TVI) technique has been used. This technique is an approximate method based on numerical and experimental data. In this study, it is aimed to predict the underwater noise of a marine propeller by applying TVI technique for two bladed and three bladed propellers. The hydrodynamic performance of cavitating propeller has been calculated by a potential flow code based on lifting surface method. The effect of cavitation number and propeller rotation speed on sound pressure level has been discussed.

**Keywords:** Acoustic, Lifting Surface Method, Underwater Noise, Tip Vortex Index

**Nomenclature**

| Symbol | Description |
|---|---|
| $\vec{\upsilon}_\Gamma$ | velocity vector by unit strength vortex element |
| $\vec{\upsilon}_Q$ | velocity vector by unit strength source element |
| $Q_B$ | line source for blade thickness source strength |
| $Q_C$ | line source for cavity source strength |
| $\vec{n}_m$ | unit vector normal |
| $\Gamma$ | circulation |
| $k_{tbl}$ | thrust coefficient per blade |
| $k_{tip}$ | tip loading factor |
| Z | number of blades |
| $\sigma$ | cavitation number |
| $P_{atm}$ | atmospheric pressure |
| h | operating depth of the propeller |

| | |
|---|---|
| ρ | fluid density |
| g | gravitational acceleration |
| $P_v$ | saturation pressure |
| n | propeller rotation speed |
| D | propeller diameter |
| dB | decibel |
| J | advance ratio |

## 1. Introduction

Underwater noise has become a growing concern in view of its significant effect on marine environment although underwater radiated noise is a main interest for submarines, naval vessels, fishing vessels and research vessels traditionally. Underwater radiated noise is mostly caused by shipping activities which masks the natural background noise and communication network between marine animals. International Maritime Organization (IMO) recently has investigated to reduce underwater noise from shipping activities.

Underwater radiated noise sources on marine vessels are mainly divided into three different categories: engine noise, flow noise and propeller noise (Carlton, 1994). To reduce the engine noise, isolation equipment can be applied and also engine foundation has to be resiliently mounted instead of rigidly mounted (Wittekind, 2014). Ship hull design should also be proper to decrease the hydrodynamic noise which is caused by the flow. Marine propellers on the other hand, are one of the most important noise sources on marine vessels. Reducing the propeller noise is especially important for detection of vessel position and velocity. Due to this reason, not only hydrodynamic properties but also acoustic performance should also be taken into consideration for propeller design. Therefore, accurate calculation of the marine propeller noise is considerable subject in maritime industry.

Propeller noise can be mainly divided to two sub-categories: cavitation noise and non-cavitation noise. The cavitation is one of the main sources of underwater radiated noise. Cavitation noise is especially inevitable for high speed vessels. Because of sudden changes of cavitation phenomenon on propeller blades, cavitation noise prediction is a difficult task. Empirical calculations based on full or model-scale measurements and theoretical estimations can be applied. To predict the propeller cavitation noise, acoustic analogy methods are also used. As the first step of the analogy, the strength of noise source can be solved by numerical methods such as CFD (Computational Fluid Dynamics), LSM (Lifting Surface Method) and so on. The sound field is then calculated by the helping of Ffowcs-Williams Hawkings (FW-H) equation (Zhang and Xiong, 2011).

In the past, Seol and Lee (Seol and Lee, 2002) have investigated non-cavitation and cavitation noise of propeller numerically. The non-cavitation noise has been predicted using time-domain acoustic analogy and boundary element method. Additionally, they have developed computational methods for the analysis of the propeller surface cavitation noise. The flow field has been analyzed with potential based panel method and then the time-dependent pressure datum has been used as the input for Ffowcs-Williams Hawkings formulation to estimate far field acoustics. Ekinci et al. (2010) have investigated hydrodynamic features of model propeller and noise prediction has been made by empirical formulations which are improved for low frequency. Hydrodynamic characteristics of DTMB 4119 propeller and Seiun-Maru HSP propeller have been compared with both potential based LSM (Lifting Surface Method) and CFD code. Noise based on propeller blade sheet cavitation has been investigated with empirical formulations. In addition, this method has been applied under uniform and non-uniform flow conditions. Lidtke et al. (2016) have investigated propeller noise which belongs to commercial vessel and cavitation has been modeled with Schnerr-Sauer model. For cavitation condition, time-dependent change in URANS model could not have been predicted totally and cavitation at the tip vortex area could not have been observed as well. Therefore, it has been stated that LES method is more suitable for observing cavitation. Salvatore and Ianniello (2003) have studied on theoretical prediction of the acoustic pressure field induced by marine propellers with a coupled hydrodynamics and hydroacoustic analysis based on boundary element method. The hydroacoustic FW-H model has been coupled with an inviscid-flow unsteady cavitation hydrodynamics calculation based on boundary element method. Numerical predictions of the propeller noise by using FW-H equation have been compared by a classical Bernoulli equation. Propeller noise has been predicted for non-uniform inflow conditions under non-cavitating and cavitating flows. Kim et al. (2016) have developed a numerical method to predict propeller tonal noise whereas contributor of the broadband noise has been investigated experimentally. Propeller tonal noise has been calculated by taking into account of cavitation volume variation on propeller blades. Broadband noise calculations have been done in water tunnel and onboard measurements in the real ship. Tonal noise acoustic results have been validated in water tunnel experiments. The semi-empirical formula based on experimental results for tip vortex cavitation noise has been developed. Lafeber et al. (2015) have investigated propeller cavitation noise via both computational and experimental methods. Three different propellers have been used for acoustic calculations. The unsteady flow around the propeller has been calculated by PROCAL method. ETV noise model based on TVI technique has been used for prediction of cavitating vortex noise. Matusiak and Brown's model has been calculated in terms of the sheet cavitation noise. Szantyr et al. (2012) have studied on tip vortex cavitation. The main aim of the study is to develop a reliable method for numerical prediction of tip vortex cavitation. The calculations were based on both experiments and numerical calculations. The experimental study on tip vortex cavitation behind the hydrofoil has been done in a cavitation tunnel and flow around the hydrofoil has been calculated by particle image velocimetry (PIV) method. For numerical calculations, Fluent and CFX commercial CFD codes have been used. It was shown that experimental and numerical results have been in a good agreement with each other. Jeung-Hoon et al. (2013) have studied on detecting the inception of tip vortex cavitation. Short-Time Fourier Transform (STFT) analysis and Envelope Modulation On Noise (DEMON) spectrum analysis have been applied to determine the tip vortex cavitation noise. The scope of the study was to compare the applicability to the detection of cavitation inception. Wijgaarden et al. (2005) have studied the broadband inboard noise and vibration on passenger vessels between 20-70 Hz frequency ranges. Especially, hydroacoustic calculations involving tip vortex cavitation has been investigated both by sea trials and model experiments. Sezen et al. (2016b) have applied TVI technique for prediction of inboard noise level of a three bladed DTMB 4119 model propeller without taking the thickness effect into account.

In this paper, it is aimed to carry out some calculations using an empirical method considering that the propeller noise is caused by the tip vortices of the propeller blades. An acoustic study has been performed for a twin screw passenger vessel. The propeller has been considered as the noise source and acoustic results have been carried out at three decks above propeller and aft perpendicular. DTMB 4119 propeller has been investigated by means of hydrodynamic performance via lifting surface method under cavitating condition considering that the blade number is 2 and 3, respectively. The results have been discussed depending on advance ratio and cavitation number using tip vortex index (TVI) technique. This paper is the extended version of the study (Sezen et al., 2016b) presented in the symposium organized by Turkish Chamber of Naval Architects.

## 2. Mathematical model

### 2.1. Lifting surface method

A lifting surface method was applied to calculate the propulsive performance and induced velocities due to the propeller, similar to the one given (Bal, 2011b) & (Bal, 2011a) & (Kerwin, 2001) & (Bal and Güner, 2009). The lifting surface method (propeller analysis code) models the 3-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 particular, the 3 components of the discretization are as follows:

i) A vortex lattice on the blade mean camber surface and wake surface to represent the blade loading and trailing vorticity in the wake.

ii) A source lattice on the blade mean camber surface to represent blade thickness.

iii) A source lattice throughout the cavity extent to represent cavity thickness.

The sources representing blade thickness are line sources along the spanwise direction. The strengths of the line sources are given in terms of derivatives of the thickness in the chordwise direction and are independent of time. The unknown bound vortices on the blade and the unknown cavity sources are determined by applying the kinematic boundary condition and the dynamic boundary condition.

In this method, a discretized version of the kinematic boundary condition can be employed as:

$$\sum_{\Gamma} \Gamma \vec{\upsilon}_{\Gamma}.\vec{n}_{m} = -\vec{\upsilon}_{in}.\vec{n}_{m} - \sum_{Q_B} Q_B \vec{\upsilon}_{Q}.\vec{n}_{m} - \sum_{Q_C} Q_C \vec{\upsilon}_{Q}.\vec{n}_{m} \qquad (1)$$

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. The kinematic boundary condition must be satisfied at certain control points located on the blade mean camber surface. The kinematic boundary condition requires that the sum of the influences for all of the vortices' sources and the inflow normal to a particular control point on the blade is equal to zero. Another way to explain this is that the kinematic boundary condition requires the flow to be tangential to the surface. Other assumptions employed throughout the method include:

i) The cavity thickness varies linearly across panels in the chordwise direction and is piecewise constant across panels in the spanwise direction.

ii) There are no spanwise flow effects in the cavity closure condition.

iii) Viscous force is calculated by applying a uniform frictional drag coefficient, $C_f$ , on the wetted regions of the blade.

The details of the method can be found in (Bal, 2011b) & (Bal, 2011a) & (Bal and Güner, 2009).

## 2.2. TVI technique

Tip vortex index (TVI) technique has been developed by Det Norske Veritas (DNV GL) in order to estimate inboard noise caused by marine propeller. The technique consists of several empirical formulations based on experimental studies. Experimental studies have been conducted for 15 ships including cruise liners and ferries. In this method, the propeller itself is considered as the source of transmitting the noise to the ship hull while the hull is the receiver of the pressure fluctuations (Raestad, 1996).
TVI has been used to predict the inboard noise level in a location at three decks above the propeller and aft perpendicular. It is the non-dimensional factor expressing the pressure field from the tip vortices.

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

This technique considers that the noise is caused by the tip vortices of the propeller blades in a cavitating condition. $k_{tip}$ is for the relative tip loading factor. This factor is nearly constant for a wide range of speed in fixed pitch propellers while it is dependent on the pitch settings for controllable pitch propeller.
Here, Z is the blade number and σ is the cavitation number.

$$\sigma=\frac{P_{atm}+\rho gh-P_v}{0.5\rho\left(nD\right)^2} \quad (3)$$

Cavitation number is calculated by considering the operating depth of the propeller (h) is 5 meters while the saturation pressure ($P_v$) is taken as 2000.7 Pa. The propeller rotating speed (n) is derived from the non-dimensional cavitation number.

$$k_{tip}=\left(\Gamma_{tip}/k_{tbl}\right)/\left(\Gamma_{tip}/k_{tbl}\right)_{ref} \quad (4)$$

The circulation distribution on the propeller blades is significant in calculating the tip vortex index. Thrust force per blade is represented by $k_{tbl}$ while $\Gamma_{tip}$ is the circulation at the propeller blade. The optimum circulation distribution can be observed by taking $k_{tip}$ as 1.

$$dB_{ref}=20\log\left(\mathrm{TVI}.n^2D^2\right)+80 \quad (5)$$

It is assumed that the noise level is directly related to the sound pressure level at any selected position. Detailed information about TVI technique can be found in (Raestad, 1996).

## 3. Results and discussions

DTMB 4119 model propeller has been chosen for the investigation of flow and prediction of acoustical performance. Geometrical properties of the model propellers have been presented in Table 1. 3-D view of the DTMB 4119 model propellers have been shown Fig. 1.

**Table 1.** DTMB 4119 main particulars

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

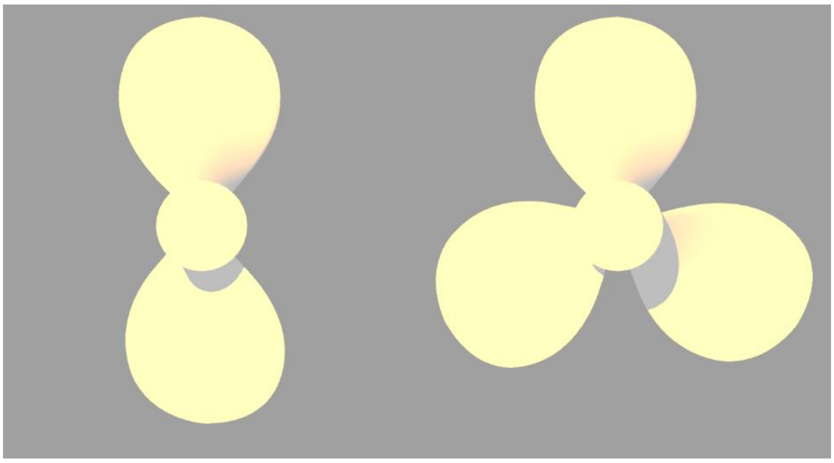

**Figure 1.** 3-D models of DTMB 4119

The flow around the model propeller has been solved by lifting surface method. The code has been applied in order to predict the hydrodynamic performance of the propeller by means of circulation distribution per blade. Hydrodynamic results have been derived for different cavitation numbers and advance ratios. In Fig. 2, the elements used are shown with wakes.

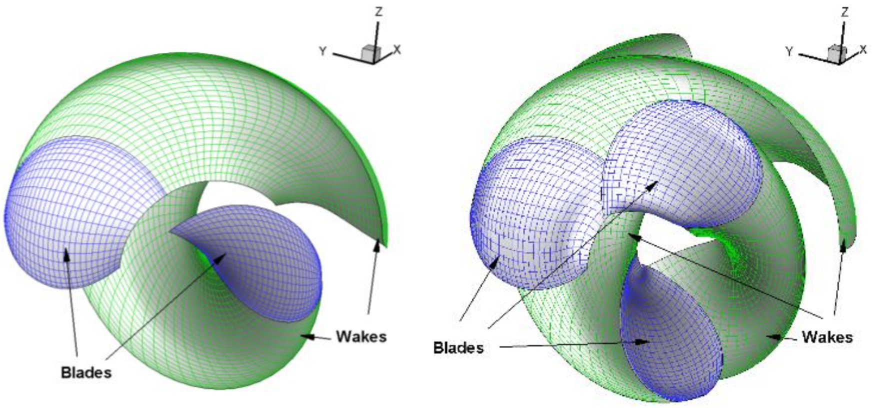


**Figure 2.** Perspective view of DTMB 4119 propeller blades and wakes

In Fig. 3, the cavity pattern on the blades is shown at critical cavitation numbers for both two and three bladed propellers. One can see from fig. 3 that the cavity patterns are quite similar for both model propellers.

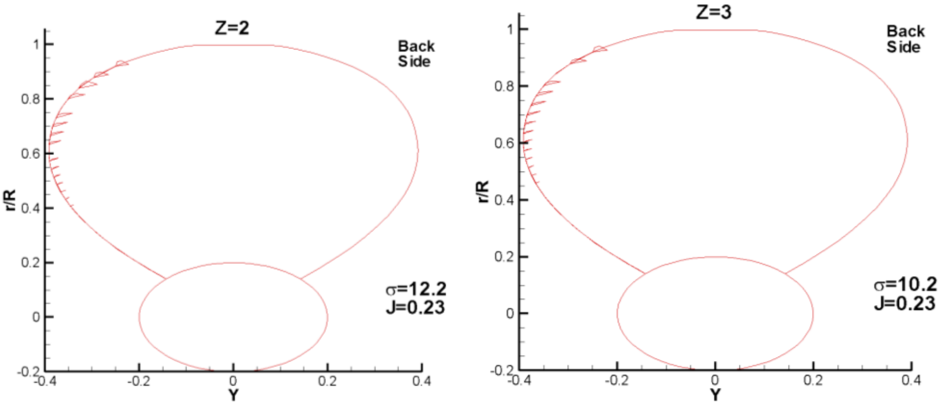


**Figure 3.** Comparison of cavity pattern of DTMB 4119 propeller

The circulation distribution on the propeller blades have been given in Fig. 4 for different advance ratios by means of blade numbers. As expected, the blade loading is decreasing with the increasing advance ratio. In addition, it has been observed that the blade loading is decreasing while the blade number is increasing.

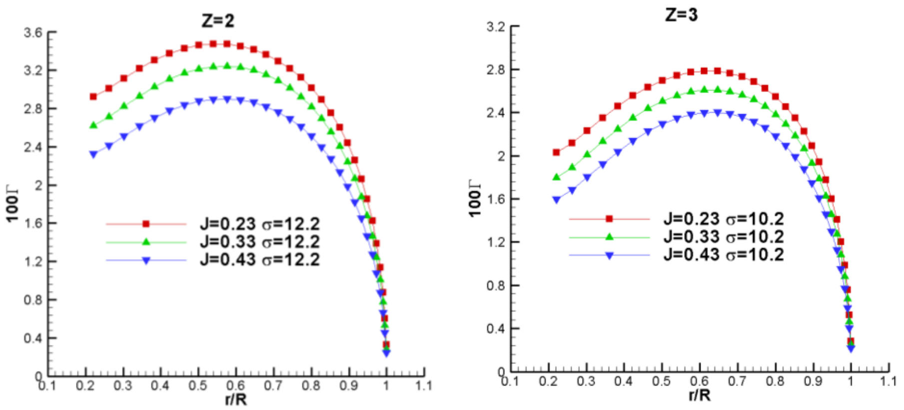


**Figure 4.** Circulation distribution on the blades for different blade numbers

Fig. 5 gives the performance characteristics of the model propeller DTMB 4119 at critical cavitation numbers of two and three bladed model propellers. The propeller performance has been observed in an operating range with high propulsive efficiency both in hydrodynamic and hydroacoustic manner. As can be seen from the figs. 4-5, higher circulation distribution has been obtained from two-bladed propeller which provides higher efficiency.

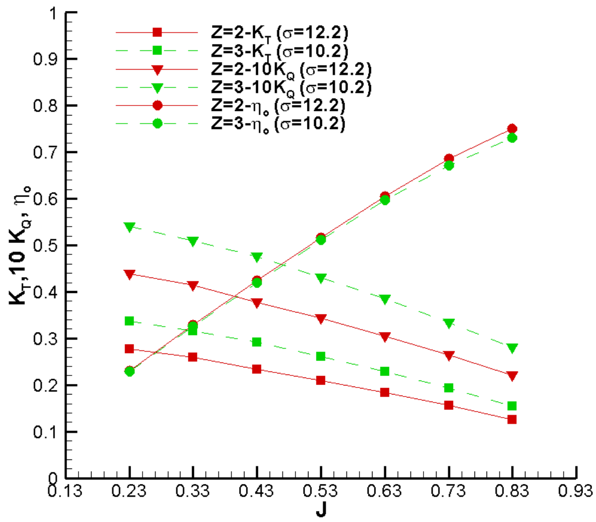


**Figure 5.** Hydrodynamic performance characteristics of DTMB 4119 at a constant cavitation number for different blade numbers

Tip vortex has a significant effect on underwater propeller noise. The vorticity on the propeller blade tips trigger the noise level even inboard the ship (Sezen, 2016), (Sezen et al., 2016a). The tip loading factor is crucial in the calculation of TVI. This factor has been calculated by using the circulation on the tip and the maximum circulation of the blade as reference value. TVI has been used for the estimation of sound pressure level at the reference location inboard the ship.

For observing the effect of cavitation phenomenon on the propeller noise, TVI method has been used for different cavitation numbers at a constant advance ratio. The results have been presented in Fig. 6. It is obvious that the sound pressure level decreases while the cavitation number increases for both blade numbers. This is because the cavitation risk also decreases with an increase in the cavitation number. It is observed that sound pressure level for two bladed propeller is more than that of for three bladed propeller. In accordance with the cavity patterns given in fig. 6, it is obvious that the cavitation phenomenon is more dominant than the blade number by means of sound pressure level.

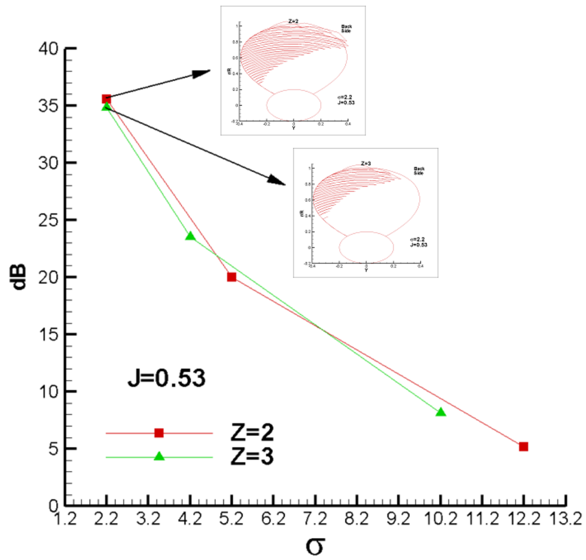


**Figure 6.** Sound pressure level distribution for different cavitation numbers at a constant advance ratio for different blade numbers

Fig. 7 shows the relation between the propeller rotation speed and the sound pressure level for both blade numbers. The noise level has an increasing trend with the propeller rotation speed. This can be explained that the higher propeller rotation speed increases the cavitation risk so the noise level. The main highlight of Fig. 7 is that the sound pressure level increases with the decreasing cavitation number. Note that the critical cavitation numbers are σ=12.2 and σ=10.2 for two and three bladed propellers, respectively. One can observe that the sound pressure level decreases with the decreasing blade number.

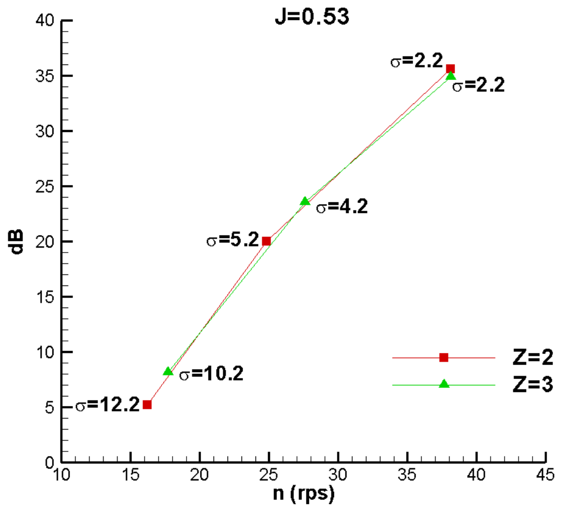


**Figure 7.** Sound pressure level distribution for different propeller rotation speeds and blade numbers

Fig. 8 is given for the observation of effect of advance ratio on sound pressure level at the critical cavitation number. As can be seen in Fig. 8, sound pressure level shows a decreasing behavior with the increase in advance ratio, as expected. This is because that the cavitation occurs only at J=0.23 for the critical cavitation number while there is no cavitation behavior in the other advance ratios for three bladed propeller.

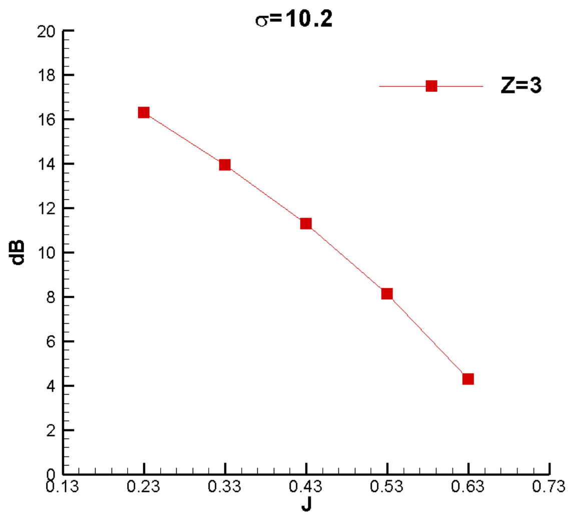


**Figure 8.** Sound pressure level distribution for different advance ratios at a constant cavitation number for three bladed propeller

Tip loading factor has been chosen as another parameter affecting the hydroacoustic performance empirically. As seen Table 2, three different cavitation numbers have been investigated via two different tip loading factors for three-bladed propeller at a constant advance ratio. $k_{tip}$=1 is the case which the propeller has the optimum circulation distribution. Table 2 also shows the cavitation effect on propeller noise clearly.

**Table 2.** Sound pressure level results at different tip loading factors for three bladed propeller

| σ | J | $k_{tip}$ | dB |
|---|---|---|---|
| 10.2 | 0.53 | 0.082 | 8.13 |
| 10.2 | 0.53 | 1.000 | 51.46 |
| 4.2 | 0.53 | 0.082 | 23.54 |
| 4.2 | 0.53 | 1.000 | 66.87 |
| 2.2 | 0.53 | 0.082 | 34.84 |
| 2.2 | 0.53 | 1.000 | 78.17 |

## 4. Conclusions

Two main arguments have been obtained in this study:

- Effect of tip loading factor has shown that hydrodynamically optimum propeller design does not have the optimum hydroacoustic performance.
- Under critical cavitation number, the cavitation phenomenon triggers the underwater noise. This means that the cavitation affects not only the hydrodynamic performance but also hydroacoustic performance.

Some future works have been planned:

- Tip vortex index (TVI) method will be applied to a four bladed DTMB 4119 model propeller in order to predict the noise level.

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