Advanced simulations of Underwater Radiated Noise (URN) predictions for naval ships

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Synopsis

Characteristics of underwater Radiated Noise (URN) is an important index to evaluate stealth performance of naval vessels. In general, URN signature is measured after the vessel is built and at that stage any effort to minimize URN becomes a big challenge as consequential structural modification or changes to any critical machinery may lead to substantial cost implications and in some scenarios might not be possible. Hence, it is always beneficial to perform design iterations based on URN predictions at the initial design stage.

In recent years numerical simulations have evolved a lot especially in the field of aerospace and automobile industry. The perfectly matched layer (PML), recently formulated by Berenger, for the absorption of radiated/scattered waves in computational acoustics and its effectiveness as a non-reflecting boundary, is applied to predict the sound radiated/scattered in far field. This paper explains a hybrid approach involving finite element method (FEM) and adaptive PML model for structure borne noise (SBN) due to critical mechanical machinery and Computational Fluid Dynamics (CFD) - Boundary Element Method (BEM) model for hydrodynamic noise due to propeller action. This paper addresses some of the challenges encountered and demonstrates how they can be mitigated using hybrid approach and the use of novel techniques.

Keywords: Hybrid; FEM; BEM; CFD; PML; SBN; SPL.

1. Introduction

In recent years underwater noise radiated from ships has attracted much attention of both researchers and engineers. The reason for this is not only stealth requirements of naval ships, but also prevention of negative consequences to marine life (IMO MEPC.1/Circ.833, 2014). In addition to this, there are significant advances in ship design leading to reduced amount of steel and increased stiffness with different noise and vibration patterns, and consequently making the ship structure more sensitive to noise issues. Ships with low noise characteristics have always been an important asset especially for naval vessels, and also submarines due to their specific mission and operational requirements.

In practice, underwater noise levels are measured at ship delivery, and in case of non-compliance with prescribed Underwater Radiated Noise (URN) levels it becomes a big challenge to meet the requirements. In spite of variety of noise reduction methods, since using them at delivery stage becomes rather expensive and, in some cases not possible, it is desirable to predict noise levels in the preliminary design stage. Structure borne noise (SBN) due to main propulsion machinery (main engine) radiating from the hull surface and hydrodynamic noise from propeller are the two most dominant sources of underwater noise. These noise sources are the only traceable signals for sonars particularly for naval surface ships and submarines since all other noise sources can be eliminated by the use of appropriate insulation/ noise reduction methods on board. Nevertheless, URN determines the detectability, operability and even survivability of the ship. Therefore, noise predictions of SBN radiating from hull surface and hydrodynamic noise from propellers have always been an important issue in naval architecture. Using conventional methods for underwater noise prediction, based on few empirical formulas or CFD methods (Özden et al, 2016), might not provide complete URN. For this purpose, the hybrid approach seems to be reasonable choice, due to its simplicity and accuracy.

In this paper, a methodology for complete URN prediction is established using advanced numerical techniques. The new hybrid approach is explained in detail with its advantage over the conventional/ traditional approaches for underwater noise prediction.

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2. Hybrid approach for URN prediction

There are several numerical models available for noise prediction. Each model has its acceptable accuracy, for example, in the case of FEM it is fair to say that in the high-frequency domain the method becomes rather inaccurate. Likewise, each numerical method has its limitations. For predicting underwater acoustic signature up to 10 KHz, we may have to use multiple numerical models to predict complete URN of a vessel. This paper proposes a hybrid method that allows engineers to build predictive models for the full frequency domain (0-10000Hz).

For URN, the two dominant noise sources are structure borne noise (SBN) from main propulsion machinery radiating into water from the hull surface and hydrodynamic noise from propeller as shown in Figure 1. FEM is more appropriate for low frequency structural analysis for frequencies up to ~200Hz. In this paper, to analyse the SBN radiated/scattered from hull surface, FEM together with adaptive PML model is used. For hydro-acoustic predictions from propeller, CFD method together with BEM is investigated in two steps, first by solving the flow around the propeller using CFD, followed by the acoustic computations using BEM. A sample naval vessel is considered for URN predictions.

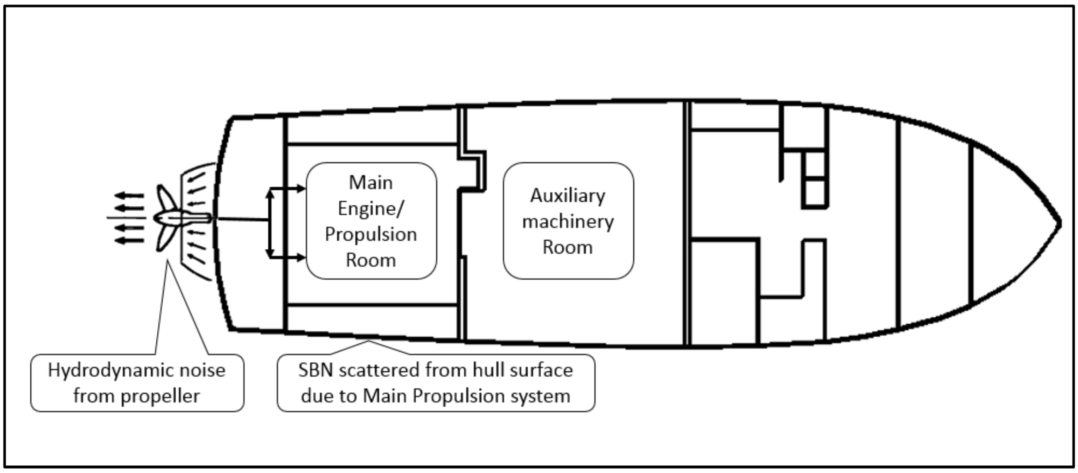

Figure 1: Major Noise sources for URN prediction

2.1. URN from SBN source

2.1.1. PML model and Engine foundation impedance calculation

In this work, adaptive "Perfectly Matched Layer (PML)" model is used. The PML concept has been initially introduced by Berenger (Berenger, 1994) with the objective of developing an absorbing boundary condition for the finite difference time domain (FDTD) method. This was initially developed for absorption of radiated/scattered waves in computational electromagnetics and later adapted to computational acoustics. Considering its effectiveness as a non-reflecting boundary, it is used in various domains (Quan and Geers, 1998). In this paper, PML with an absorbing boundary condition for Finite Element Frequency Domain (FEFD - deterministic) is used for applying fluid load/damping on hull surface and this methodology is compared with the FE-BEM and FE-Wavelet-based fluid structure interaction methods (Blanchet, 2012).

PML model

Section of hull with Main Engine (ME) room is modelled up to the weather deck. This section is surrounded by acoustic elements referred as "acoustic layer" (Red colour in Figure 2(a)). Extent of acoustic layer covers the near field (vicinity of the engine room structure). Sea water property is given to acoustic layer. Inner part of the acoustic layer, i.e. the interface of the structure and the acoustic layer is called as the 'acoustic surface' (Yellow colour in Figure 2(a)). Radiation of the noise is through acoustic surface into the acoustic layer. Outer part of the acoustic layer is the PML surface (Blue colour in Figure 2(a)), this is the non-reflecting boundary acting as absorbing surface. Perfectly matched layer (Light Green colour in Figure 2(a)) is created by extruding PML surface. PML contains a volume meshed with special PML elements that can absorb the sound.

The optimal thickness and mesh density in this PML varies with frequency as adaptive PML model is used (Figure 2(b)) and the type of elements in PML layer matches with the element type of the acoustic layer.

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FEA-PML model analysis is performed using the commercial software Wave6 (Dassault Systèmes).

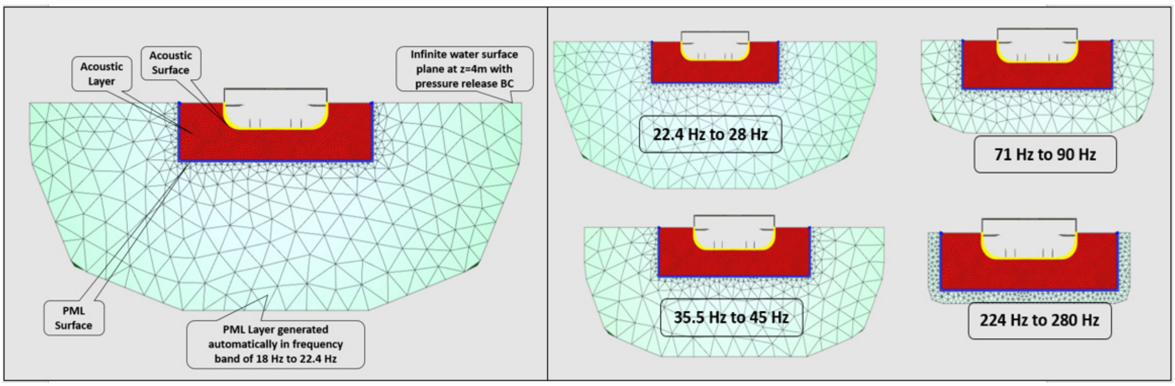

Figure 2(a) Left: PML model for Main Engine Room; Figure 2(b) Right: Adaptive PML generated for various frequency bands

Fluid loading plays a significant role in the vibration of the hull, especially at low frequency. The fluid loading changes natural frequencies and mode shapes in a significant way. Using FEA-PML model the effect of fluid loading is analysed at lower frequency for the ME room as shown in Figure 3(a).

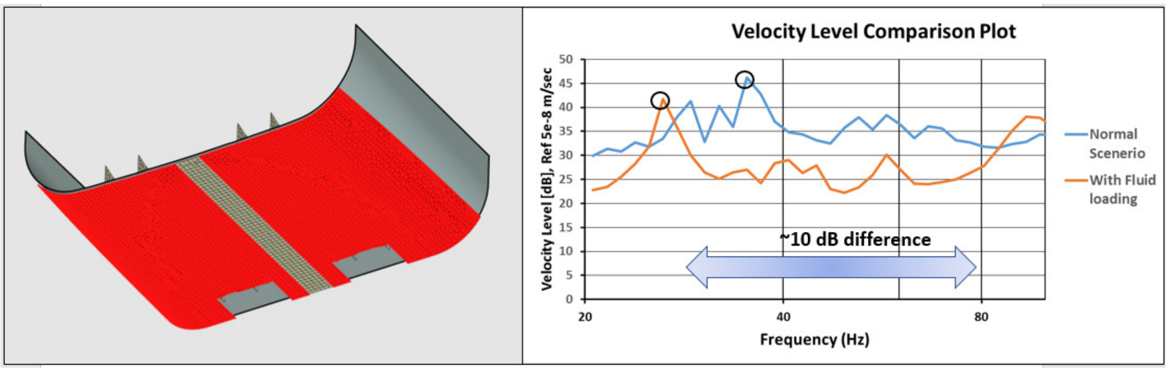

Figure 3(a) Left: Section of ME room for which Velocity levels recorded; Figure 3(b) Right: Velocity Level Comparison Plot (Blue arrow shows range of frequencies for which approximately 10dB difference in the velocity levels is observed)

Velocity level is plotted for a section of hull (Red colour in Figure 3(a)) for both the cases i.e., with and without fluid loading for a frequency range of 20 Hz to 100 Hz. By applying fluid loading (FEA-PML model) on hull surface a velocity level difference of ~10 dB is observed in lower frequency and also shift in peak value of velocity level from 35 Hz to 26 Hz is observed (Figure 3(b)). These results are in line with the BEM and Wavelet-based models for a case of 70 m yacht referred in (Blanchet, 2012). Computation time for URN prediction for ME room is 9.5 sec/freq up to 500 Hz. For SBN radiation into water this model proves to be efficient up to 500 Hz, it can also solve for higher frequencies provided model size is compact and good computational resources are available. One of the main advantages of using FEA-PML model over other models is that we need not couple FE model with other models (such as BEM, Wavelet, etc.) to analyse the effect of SBN propagation with fluid loading. Adaptive PML model automatically creates PML layer mesh for various frequency bands using existing FE mesh, hence there is no need to create any additional mesh for FEA-PML model unlike FE-BEM and FE-Wavelet models. Sound reflection and scattering from nearby surfaces and free surface can be modelled efficiently for full frequency range (20 Hz to 10 kHz). FEA-PML model is well adapted and used across various industries for acoustic analysis.

Input Impedance of Main Engine foundation

In diesel engines the engine foundation is one of the critical parameters for sound propagation. In order to analyse main engine foundation design, its input impedance calculation has to be performed. In this paper, impedance calculations are performed using FEA-PML model as explained above. For this analysis, section of ME room is extracted between the watertight bulkheads (WTB). ME room section is modelled up to the weather deck.

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A unit load is applied at one of the engine mount seating, as shown in Figure 4(a). Various load cases are formed by applying unit load at each of the engine mount location one by one. The velocity levels are recorded at the same location/point where unit force is applied for each of the load case. Impedance for each load case is calculated independently, if the results are significantly different, then the average value for velocity level is considered for impedance calculation.

Impedance *Zi(f)* is then given by equation 1:

$$Zi(f) = \frac{F(f)}{V(f)}, \tag{1}$$

where *F,* is unit Force (1N), *V* is Z-direction velocity (m/sec) at location of applied force, and *f* is the frequency. Impedance is converted to decibel using reference impedance of 1Ns/m.

To understand the behaviour of fluid loading, impedance of engine room foundation is calculated with PML and without PML up to 500 Hz. Results are shown in Figure 4(b).

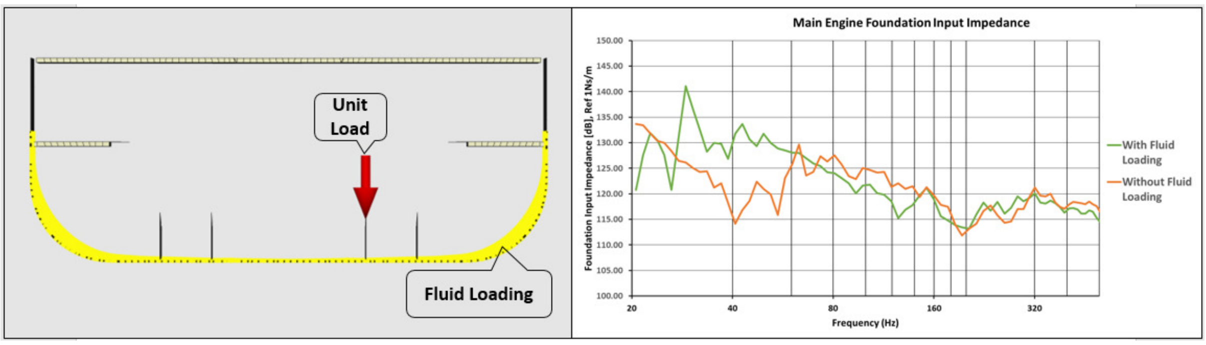

Figure 4(a) Left: ME room section; Figure 4(b) Right: ME foundation input impedance

With fluid loading on hull surface, we can observe a higher impedance level at lower frequencies. Thereafter no significant differences are observed for higher frequency values. Therefore, it’s always virtuous to analyse engine foundation impedance with fluid loading to understand its actual behaviour. Hence FEA-PML model proves to be an accurate approach for analysing engine foundation design.

Sound Pressure Level (SPL) of underwater radiated noise from ME at far field receiver location can be predicted using the FEA-PML methodology, by knowing few more details such as ME source level noise (SBN above mounts) and mounting properties.

2.2. URN for Hydrodynamic noise source

Hydro-acoustic predictions of a propeller, based on computational fluid dynamics (CFD) methods is investigated in two steps. First solving the flow around the propeller, followed by the acoustic computations. Calculation of the acoustic field radiated by propeller is critical in the prediction of hydro-acoustic noise for a vessel. The conventional techniques for noise prediction are based on acoustic analogy Curle equation and Ffowcs Williams-Hawkings (FW-H) equation (Williams, 1696 & Farassat, 1988). These methods provide quick results but they have some limitations. The scattering effect from the hull surface and free surface on the propagation of the sound wave is difficult to model using FW-H. Therefore, the acoustic boundary element method (BEM) is a preferred option to predict the underwater radiated sound in the exterior domain (Huang, 2015) for propeller noise.

2.2.1. CFD flow Simulation

In this work, CFD simulations are performed using the CFD tool StarCCM+. Simulations were run on a HPC server with 82 cores. An URANS approach was applied, using a transient approach and a reliable two-layer k-ε turbulence model is applied. Multiphase fluids have been included in the simulation using the Volume of Fluid (VoF) approach.

The computational domain is modelled in accordance with ITTC guidelines (ITTC, 2014) as below, where L is the ship length:

- 1L in front of the vessel and 3L behind, giving an overall longitudinal distance of 5L
- 2.5L on either side of the vessel giving an overall transverse distance of 5L
- 0.3L above the still water plane and 1.7L below giving an overall height of 2L

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The built-in meshing capabilities of the StarCCM+ software have been utilized. The hull and rudder surfaces were meshed using the "Surface Remesher" to triangulate the surface. The volume domain is meshed using the "Trimmer" mesh to create a structured predominantly hexahedral grid.

An unsteady RANSE based CFD analysis is performed for non-cavitating condition using standard B- series propeller, to obtain fluctuating surface pressures on rotating propeller surface and on stationary source (hull surface). Time domain fluctuating surface pressure data from the CFD analysis is utilized for acoustic analysis (Figure 5). The vessel considered for this study is same as used in Chaturvedi et al, 2018. Basic studies such as resistance computations and the propeller characteristics can be found in Chaturvedi et al, 2018.

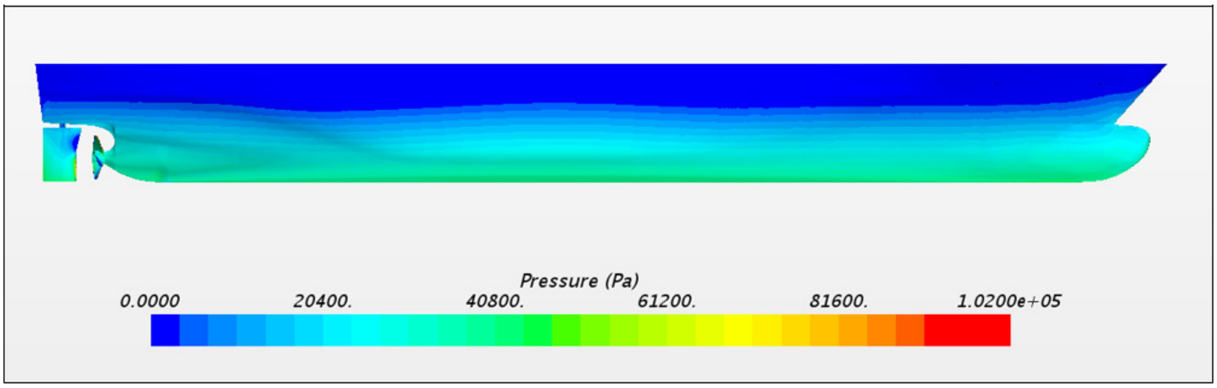

Figure 5: CFD Computed Pressure Field on the hull, propeller and rudder at an instance

2.2.2. BEM Acoustic Simulation

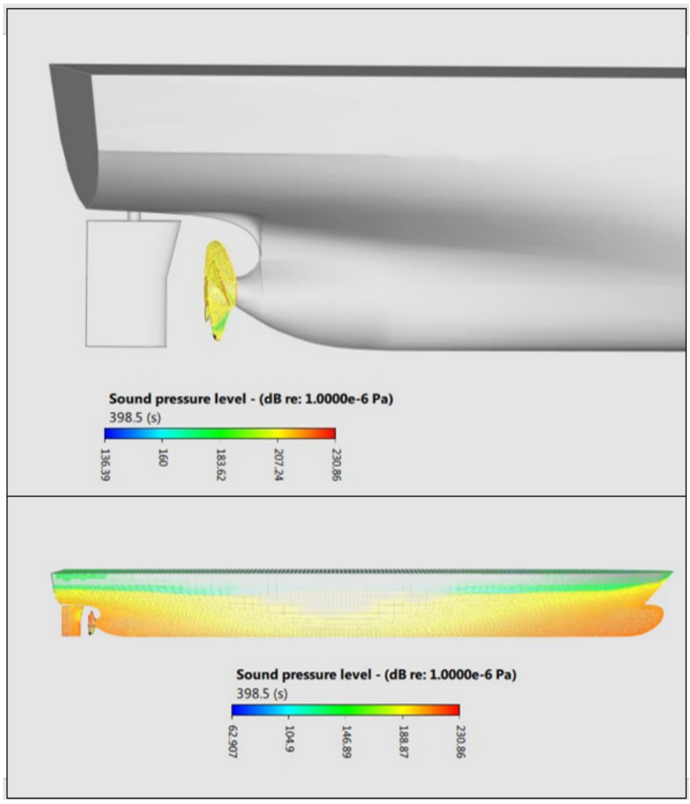

Figure 6(a)Top: Hydrodynamic pressure computed from CFD mapped on propeller; Figure 6(b) Bottom: Hydrodynamic pressure computed from CFD mapped on hull, propeller and rudder surface

Acoustic computations are performed using the vibro-acoustic tool Wave6. An acoustic BEM model is created which includes fluctuating fan source (FFS), which is used to describe rotating propeller surface. Additionally BEM model allows to describe the scattering that occurs from nearby surfaces e.g. hull, rudder and free surface.

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Thus the fluctuating pressure on hull and rudder computed using CFD can be considered (Figure 5). These pressures are mapped on the BEM surfaces for acoustic calculations (Figure 6(a) & Figure 6(b))

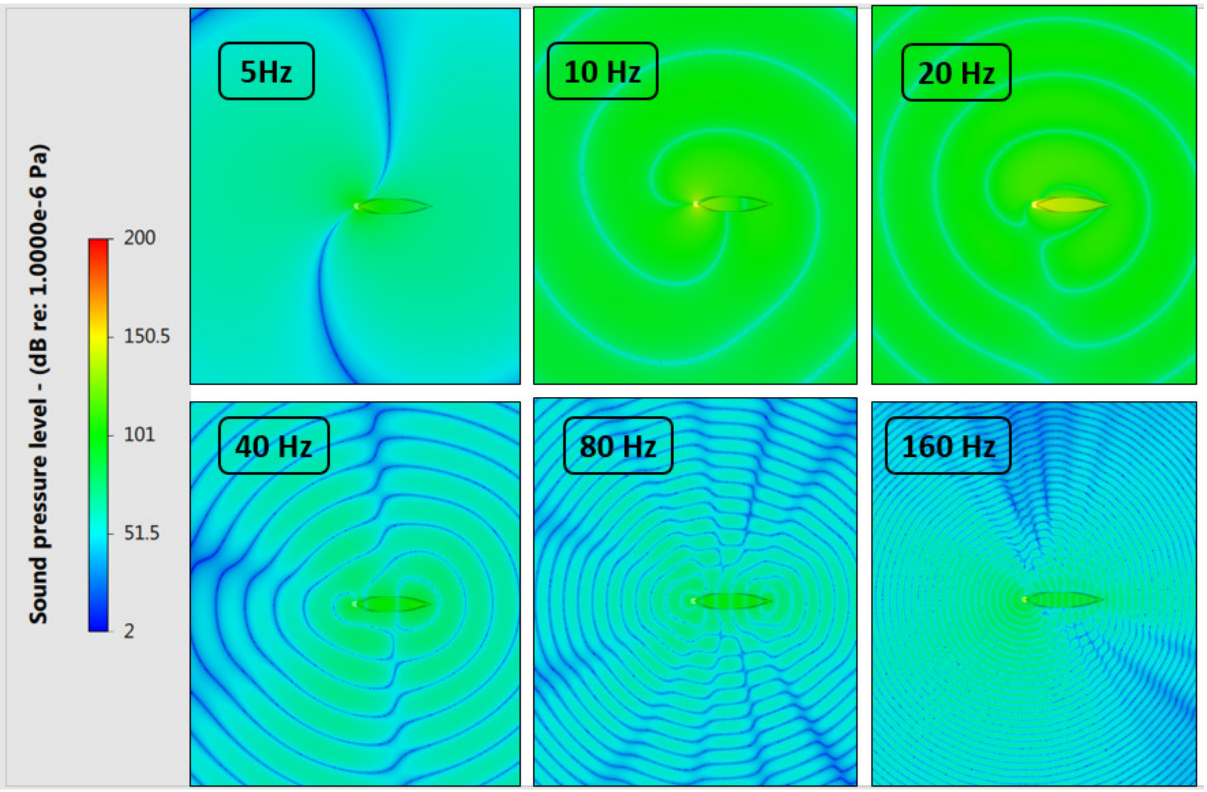

Figure 7. Sound propagation pattern at various frequencies using BEM for propeller noise including scattering effect

Figure 7 shows the sound propagation pattern for various frequencies (BEM approach). Scattering effect is clearly visible. URN computations are performed using CFD-BEM methodology and the predicted URN at a fixed far field receiver location (100 m away perpendicular to ME room and at 30 m depth) starboard side, for propeller noise source including sound radiation and scattering effect up to 2000 Hz (Figure 8). Computation time for CFD-BEM model for underwater radiation is ~225 sec/freq up to 2000 Hz. These simulations can be performed up to 10 KHz.

The BEM model results are compared with the FW-H model results (Chaturvedi et al, 2018). It can be observed that with BEM model, the SPL at Blade Passing Frequency (BPF) is captured accurately. In FW-H model, the SPL does not decay beyond 700 Hz, whereas in BEM model the SPL results appear to be more realistic following the physics of underwater sound propagation. In BEM model the sound reflection and scattering from the hull, rudder surface and free surface are considered which are ignored in FW-H model.

From BEM results (Figure 8), an average of ~3dB increase in SPL is observed for a BEM model with hydrodynamic pressure computed from CFD mapped on hull, propeller and rudder surface, when compared with a BEM model of hydrodynamic pressure computed from CFD mapped on propeller surface only.

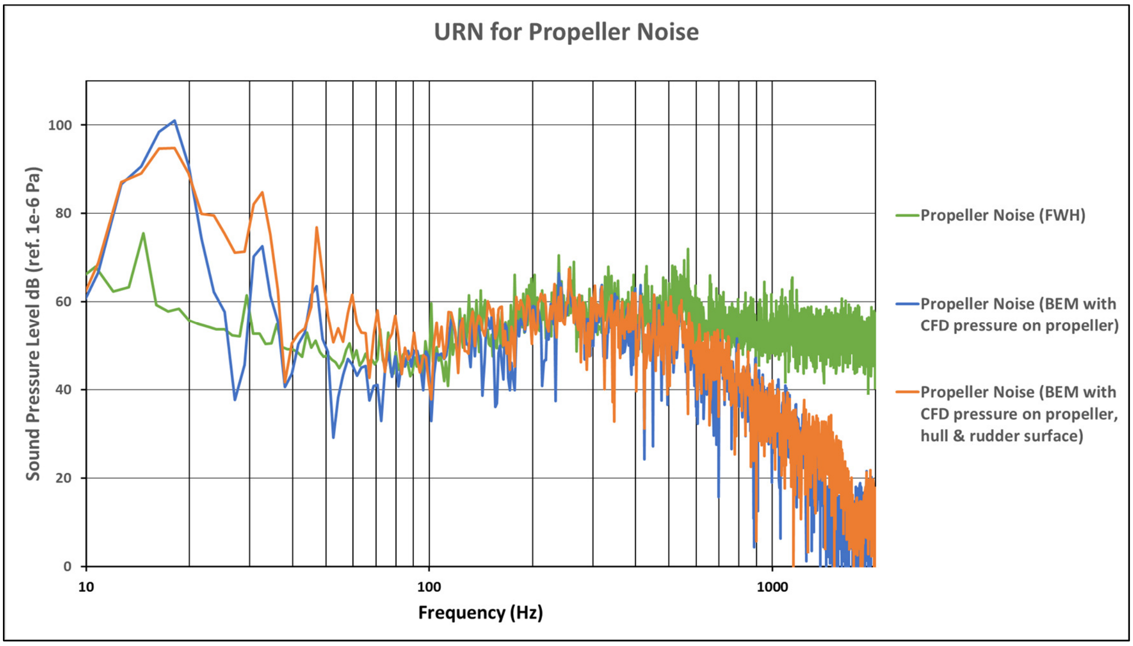

Figure 8 URN from propeller as a noise source for various numerical models

3. Total URN

For the complete URN of vessel. SPL of ME and SPL of Propeller are added logarithmically, as these two separate noise sources are not coherent, they can be added using the equation (2).

$$L_\varepsilon = 10 * \log_{10}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + \cdots \ldots + 10^{\frac{L_n}{10}}\right) dB \qquad (2)$$

L_ε= Total level and L_1, L_2, …. L_n= sound pressure level of separate sources in dB SPL.

URN is to be corrected with 20log(R), where R is the distance from vessel to receiver location to obtain URN of vessel @ 1m.

4. Conclusion

Methodology for a realistic assessment of URN from vessel based on hybrid approach using novel advanced numerical techniques is discussed in this paper. The FEM-PML model is used to describe the dynamic behaviour of the structure with acoustic loading and the CFD-BEM model is used to analyse hydrodynamic noise due to propeller action. Advantages of using PML over BEM and Wavelet based methods are highlighted. BEM for URN is discussed and its advantages over conventional methods such as FW-H are deliberated.

In the initial stage of design of ships, FE-PML approach can be effectively used to estimate the foundation impedance of the critical machinery. This would help in assessing the foundation and taking decisions on structural changes to meet URN requirements.

Propeller noise assessment using FWH and BEM techniques can help in assessing blade tonal and its overall effect on URN at very early design stage. These studies can be performed independently (without hull interaction) to arrive at the contribution to URN.

Further detailed studies for transmission loss (Lloyd's mirror effect) can be investigated with FE-PML and BEM techniques. ABN contribution to the vessel URN can also be dealt with FE-PML methodology to predict complete URN due to machinery. Such detailed studies, its validation and computational resource requirement needs attention in near future.

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6. References

Blanchet, Denis & Caillet, A. (2012). "Predicting underwater sound radiation and directivity pattern of vibrating structures in deep and shallow water." Proceedings of ISMA 2012.

Chaturvedi A, Joga Ramkumar, Doshi K, Dhavalikar S, Kar A. R. (2018). "Prediction of On-board and Underwater Sound Level Using Computational Methods, International Maritime Conference & Exhibition," Mumbai, (INMARCO)

F. Farassat and K. S. Brentner, "Supersonic quadrupole noise theory for high-speed helicopter rotors," Journal of Sound and Vibration, vol. 218, no. 3, pp. 481–500, 1998.

F. Farassat and K. S. Brentner, "Uses and abuses of the acoustic analogy in helicopter rotor noise prediction," Journal of the American Helicopter Society, vol. 33, no. 1, pp. 29–36, 1988.

Huang, J., Zhang, C., Xiang, S., Yang, L., Yi, M. (2015). "Computation of Aerodynamic Noise Radiated From Open Propeller Using Boundary Element Method." CMES-Computer Modeling in Engineering & Sciences, 108(5), 315–330.

IMO MEPC.1/Circ.833. "Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life", April 2014.

ITTC, 2011, Recommended Procedures and Guidelines, Practical Guidelines for Ship CFD Applications, 7.5-03-02-03

J. E. F. Williams and D. L. Hawkings, "Sound generation by turbulence and surfaces in arbitrary motion," Philosophical Transactions of the Royal Society, vol. 264, no. 1151, pp. 321–342, 1969.

J. P. Berenger, "A perfectly matched layer for the absorption of electromagnetic waves", J. Comp. Phys, vol. 114, no. 2, pp. 185-200, Oct. 1994.

Quan Qi, Thomas L.Geers, "Evaluation of the Perfectly Matched Layer for Computational Acoustics", Volume 139, Issue 1, 1 January 1998, Pages 166-183

Özden, M., Gurkan, Ahmet Yusuf, Arıkan Özden, Yasemin, Canyurt, Talat Gökçer, Korkut, Emin. (2016). "Underwater radiated noise prediction for a submarine propeller in different flow conditions." Ocean Engineering. 126. 10.1016/j.oceaneng.2016.06.012.

Wu, Hua-Tung & Chen, pei-tai. (2017). "Application of coupled FEM/BEM on the analysis of underwater radiated noise of a surface ship induced by hull vibrations." Journal of Marine Science and Technology (Taiwan). 25. 196-204. 10.6119/JMST-016-1118-2.