Numerical Simulations for Investigating Noise Transmission in Naval Vessels

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Abstract

Underwater radiated noise (URN) signature is one of the most important stealth aspects of naval vessels. The limiting criteria of URN may vary from vessel to vessel depending upon the intended operations and operational regimes of the naval vessel.

On-board noise plays important role in day to day activities and the comfort level of crew on-board the vessel. On-board noise criteria are generally in-line with IMO regulations irrespective of the ship type and operations.

The critical noise sources as well as noise propagation for URN and On-board noise vary considerably. However, noise transmission is mainly categorized into the air-borne and structure-borne path. Prediction of noise and limiting excessive noise can be dealt at the design phase of the vessel with numerical aids. The prediction methods deal with air borne noise (ABN) and structure borne noise (SBN) separately. ABN radiated by sources is transmitted not only though open spaces but also through the bulkheads, decks, etc. and is received at various compartments, deck levels as on-board noise. On the other hand, SBN is the one due to acoustic vibrations of the structure. Both ABN and SBN transfer through the water as well at a distance far away from the vessel revealing specific URN signature of the vessel. This paper deals with various numerical techniques to predict noise transmission and to arrive at the design solutions in the initial design phase.

Key words: ABN, SBN, URN, FE-PML, BEM, SEA

1. Introduction

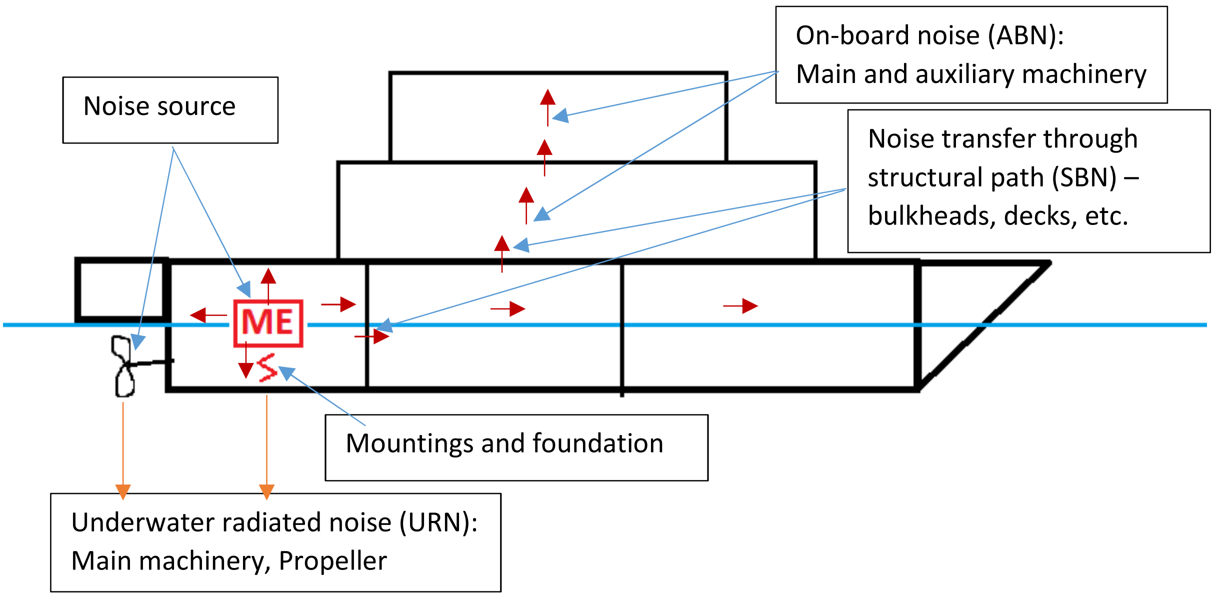

Fig. 1 – Schematic of noise sources and transmission of noise

Fig. 1 shows the schematic of noise transmission in the vessel. The noise transfer path as structure borne and air borne are shown in the figure. Only the main engine (ME) and propeller are shown as

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the noise sources in this figure. Other critical machinery such as diesel generators, AC plants, HVAC plants play important role in overall noise characteristics. Auxiliary machinery such as pumps, Ventilation fans, HVAC system etc. play important role in on-board noise. Following are the major items to be studied for investigating noise transmission and achieving the noise targets –

1. Source noise:
   In order to comply with the specific noise level targets, critical machinery (such as ME) should comply with industry accepted standards e.g. MIL standards. Fig. 2 shows the SBN level requirements in terms of accelerations above mount of the machinery for various 'Type' of machinery as per MIL-740-2 [1]. Similar criteria for ABN also exist. The term "Type" is used to categorize equipment into groups for the purpose of specifying structure borne noise criteria
   - Type I: Reciprocating compressors, internal combustion engines, turbines, reduction gears, Azipod units, propulsion motors, water jets/propeller, and hydraulic power modules.
   - Type II: Pumps, purifiers, water makers, sanitation devices, life support equipment and valves.
   - Type III: Equipment not covered by Types I, II, or IV.
   - Type IV: Vane axial fans, centrifugal fans, and tube axial fans.

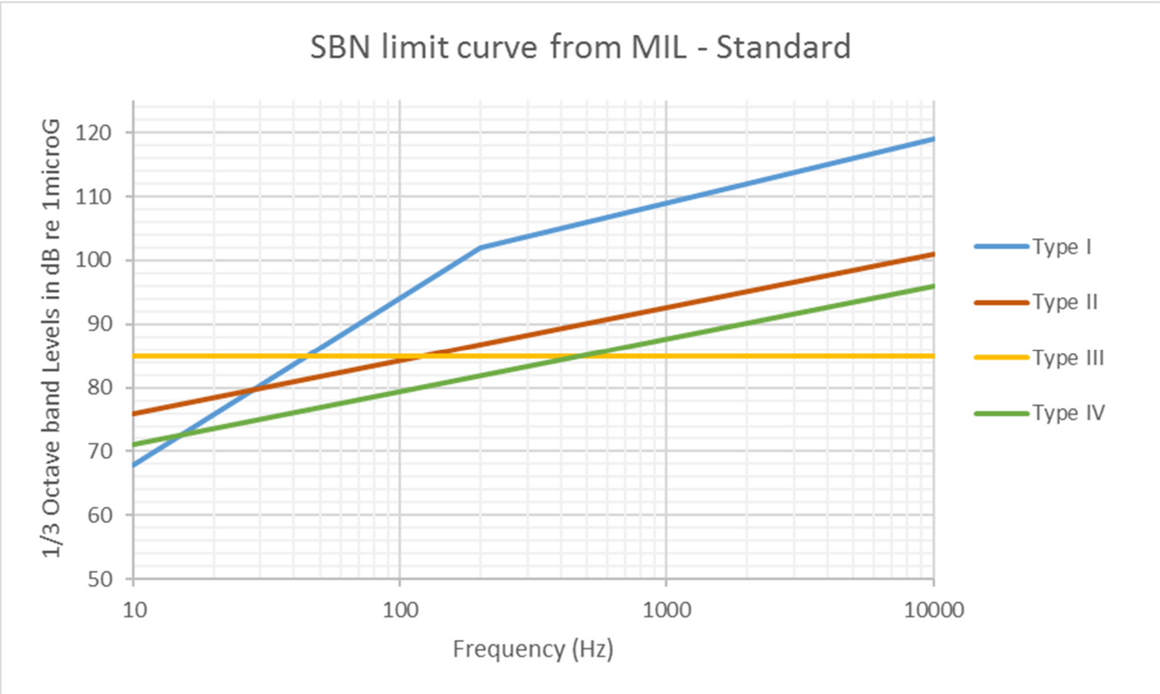


Fig. 2 - Acceptable octave band acceleration levels in dB ref. 1microG according to MIL-740-2

2. Resilient mounting [2, 3]:
   - Most effective way of decoupling the SBN from ME to the ship structure is vibration isolator, i.e. resilient mounting.
   - Properties of the mounting are determined experimentally (according to ISO 10846 [4]). The governing parameter of mounts is the force transfer through the mounts. It is given in terms of 'transmissibility' which is a ratio of output to input force.
   - Knowing the transmissibility curve of the mounts the force in the mount is found.
   - Weight of the equipment, static and dynamic stiffness of the mountings decide the force transmitted through the mounts.

- A typical transmissibility curve of a marine diesel engine resilient mounting is shown in Fig. 3, where the curve is represented in narrow band on a log-log scale. The transmissibility curve is divided into three different parts.
    - I – linear reduction of transmissibility that gives evidence of an ideal spring-like behaviour of the resilient mounting. This part of the curve is linearly extrapolated in Fig. 3.
    - II – transmissibility deviates from ideal behaviour and shows two successive peaks where transmissibility increases. This part of curve is based on the actual measurements in a typical frequency range from about 100 Hz to about 1.3 kHz with the resilient mounting properly preloaded.
    - III – it resumes its original spring like trend (extrapolated part).

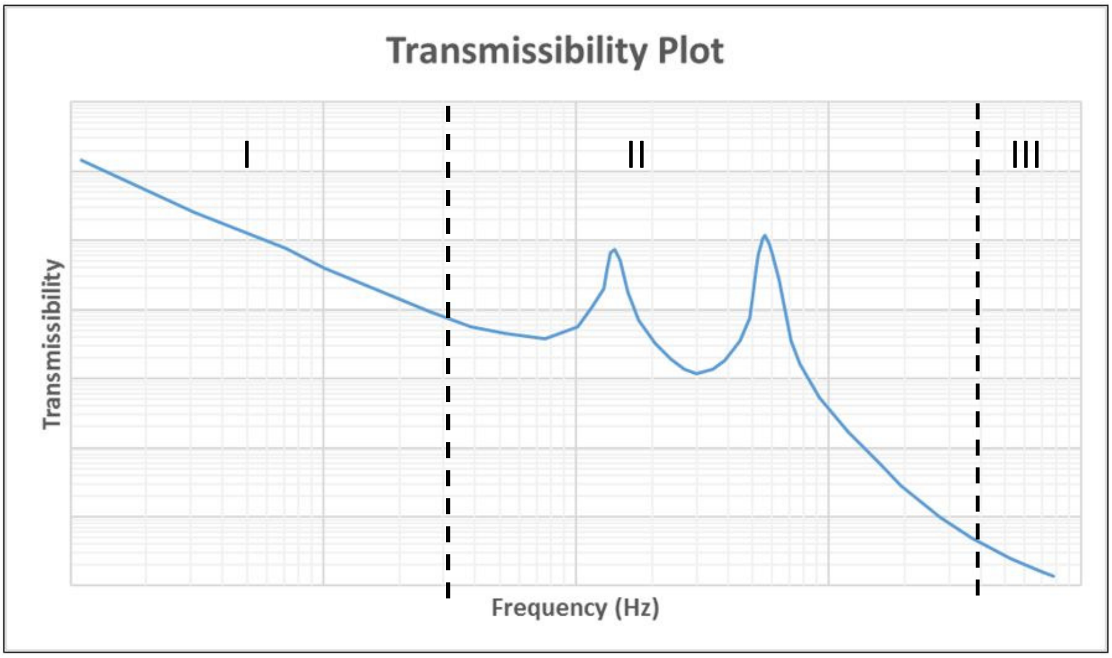


Fig. 3 – Typical transmissibility curve of resilient mounts of ME, both axes are log scale

- Increase in transmissibility corresponds to an increase of the resilient mounting impedance level and, therefore, to an increase in structure-borne noise measured on the engine foundation. The only ways to control this behaviour is to choose the correct hardness of the rubber. Vibrational energy transfer from mounts to the foundation can be controlled by size, shape of the mounts and the stiffness of the mounts.

2. URN & Design phases

SBN transfer and associated design phases in context with underwater radiated noise are shown in Fig. 4. Equipment (machinery) and mountings have standard characteristics and only the recommendations for the same e.g. MIL standard as discussed in previous section with respect to the targeted noise levels can be made. Structural design of the vessel, especially foundation of the main machinery plays important role for noise transmission. Numerical methods can assist in early design stage to confirm acceptable design. Subsequent design iterations are required for meeting URN targets.

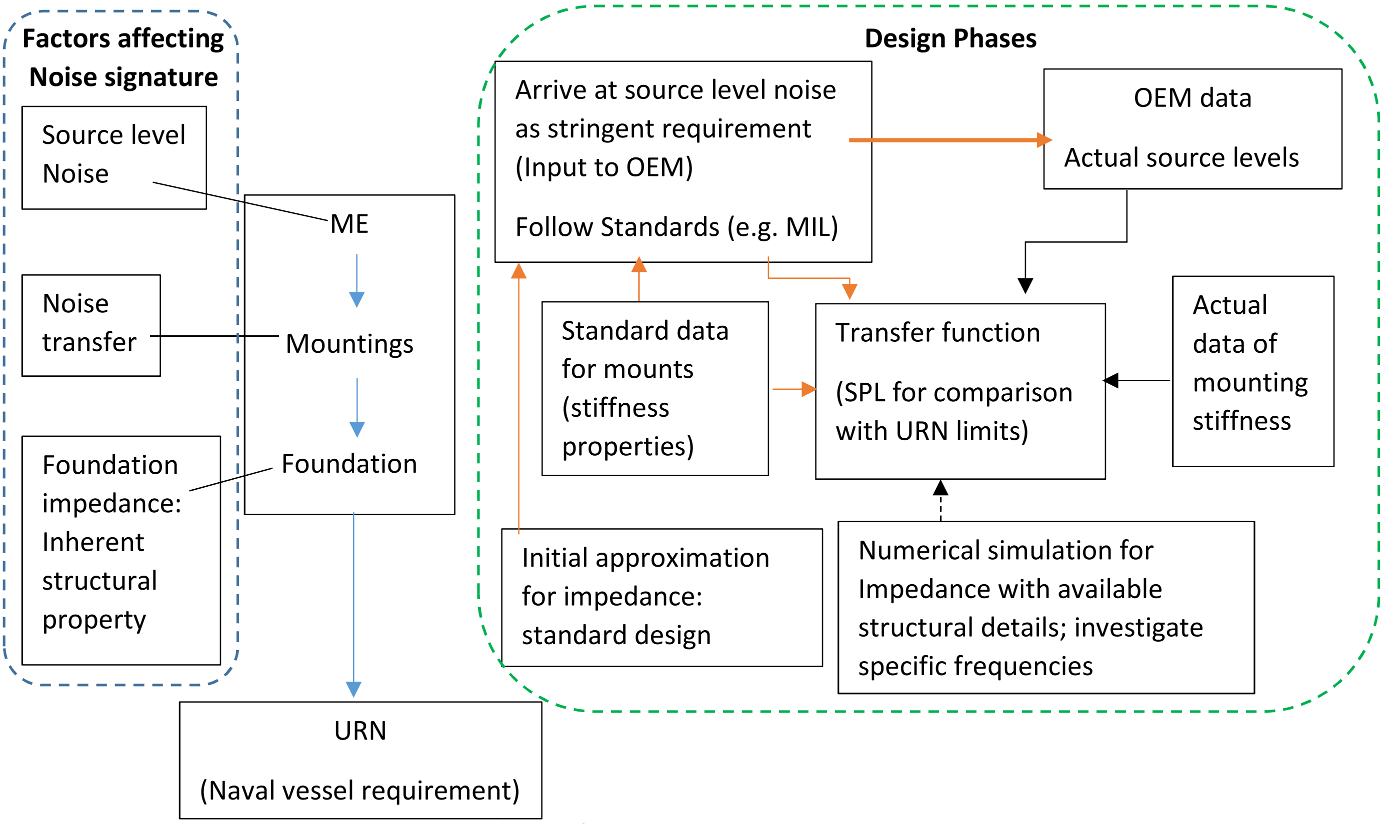


Fig. 4 – SBN propagation and design phases for URN prediction: Blue arrows – noise propagation; Orange arrows – Initial design phase; Black arrows – Final design phase; Dashed arrows – intermediate phase (fine tuning transfer function with available inputs)

3. Numerical methods

Table-1 summarizes the numerical methods used for dealing various aspects of noise transmission. Applications of these numerical methods for URN and on-board noise assessment are discussed in following sections.

Table-1: Numerical methods for investigating noise transmission

Analysis		Numerical method
Foundation analysis		FE-PML (Finite Element Perfectly Matched Layer)
URN	Due to ME	FE-PML
		BEM (Boundary Element Method)
	Due to Propeller	Computational fluid dynamics (CFD) + FWH (Ffcowcs Williams Hawkins)
		CFD + BEM
On-board noise		FEM (Finite Element Method)
		SEA (Statistical Energy Analysis)

4. URN due to ME

<u>Machinery foundation</u>

The fundamental aspect of elastic coupling between ME and foundation is the detailed design of foundation. The essential aspect of foundation design is the mobility apart from supporting ME weight. It is very much required to design foundation to have low mobility, i.e. high impedance so as to transfer the least SBN. High impedance of the foundation can be achieved by optimizing the foundation plating thickness (below mounting). Impedance of the structure can be found numerically and detailed investigation can be carried out for entire frequency range.

4.1 FE-PML method

Noise from the ME (source) transmits through mounting and foundation and radiates into the water at far field. Thus for predicting noise consideration of water around the hull is very important. In general finite element (FE) modelling is used for structural solution, in this case for finding the displacement (and velocities) of the structure due to applied load. The volume around the hull is modelled as acoustic layer (3D acoustic elements) with sea water properties. The computational time increases in proportion of the number of elements and sea volume can only be modelled partly. To overcome this limitation, and to capture the far field noise, another layer is created which acts as absorbing layer. Far field radiation boundary condition is satisfied with this layer (i.e., a non-reflecting boundary condition). This additional layer is called Perfectly Matched Layer (PML), which matches with the elements of acoustic layer. The extent of both layers is decided based upon the frequency of interest. Layer length of approximately 25 – 30% of the wave length is considered sufficient to capture the water loading as well as radiation. Free surface is captured by imposing pressure release boundary condition. Fig. 5 describes FE-PML model.

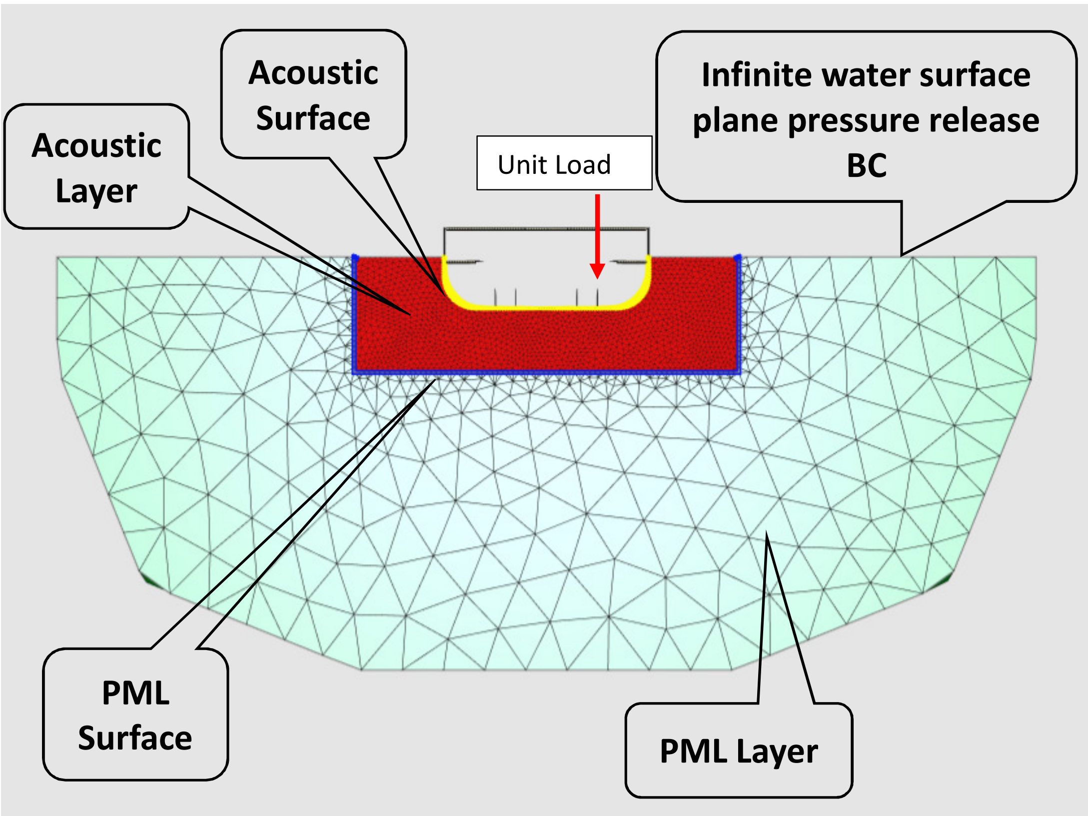


Fig. 5 - FE-PML model

Foundation Impedance calculations

- FE model is kept free-free, i.e. no boundary condition (BC) is imposed on the structure.
- To simplify the problem the FE modelling is done compartment wise, i.e. only engine room is modeled for assesing URN due to ME.
- Impedance of the ME foundation is esitmated by applying unit force at the mounting location. Actual mountings are not required to be modelled.
- The velocity levels are recorded at the same location/point where unit force is applied.
- Impedance Zi(f) is then given by:

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

  where *F* is unit Force (1N), *V* is Z-directional velocity (m/sec) at location of applied force and *f* is the frequency.
- Impedance is converted to decibel using reference impedance of 1Ns/m.
- Application of force at various mount locations is done independently and the average of all the values can be considered as the impedance of the foundation.
- Similar calculations are performed for all three principal directions.
- Based on FE-PML model the sound power level of the FE-PML system can be found
- Sound Power Level is converted to Sound Pressure Level (SPL) using the following formula.

$$p = \sqrt{\frac{Q.\rho.c.P_{ac}}{4\Pi r^2}} \tag{2}$$

  Where,

  p= Sound pressure in Pa = N/m^2
  ρ= density of water in kg/m^3
  c= speed of sound in water in m/s
  P_{ac}= Sound Power in W
  r= distance from source in m
  Q= directivity factor assumed (1=spherical)

  SPL obtained from Eq (2) is converted to dB considering reference pressure of 1µPa.

- SPL at far field due to equipment (ME) is found by adding the SPL (dB) as found using Eq (2) with the force in mount (dB) due to ME source level noise for each frequency.
- Similarly DG room can be modelled separelty and SPL due to DG is found. Overall SPL at far field, is found by energy additon of SPL due to all sources.
- Final URN signature of vessel @1m, is obtained by adding 20 log (R) to overall SPL (where, R is distance from far field predictions to 1m vessel).

4.2 BEM for Lloyd's Mirror Effect (LME)

URN measurements (noise ranging) of the vessel are done at a faraway distance, D_M from the vessel and depth Z_M from the sea surface as shown in Fig. 6. Noise radiating from the hull surface not only travels directly to the location Z_M (via path r1) but also indirectly via reflection path r2 [5]. Lloyd's mirror effect (LME) is the transmission loss due to reflected waves at the noise measurement location. FE-PML method as discussed in previous section, requires extended acoustic layer for computing LME. Computational resource requirement prohibits the extended acoustic layer for LME computation. Thus the simplistic approaches such as BEM are suitable for LME.

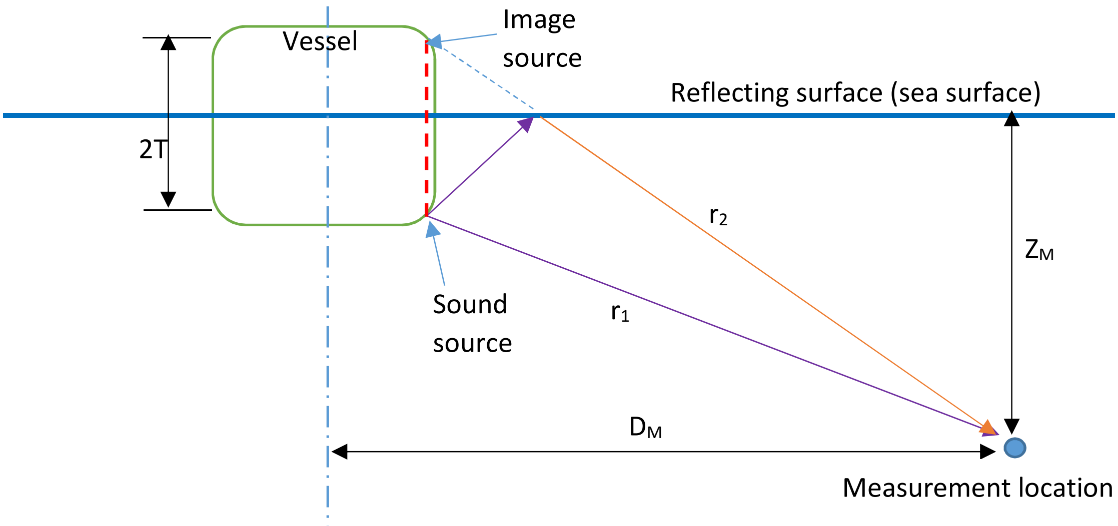


Fig. 6 – Schematic describing Lloyd's Mirror Effect [5]

Eq (3) gives the simplistic approximation for transmission loss (TL) due to LME.

$$TL = 20\log\left(R(f,\theta)\frac{\exp(-ikr_2)}{r_2}\right) \tag{3}$$

Where, $R(f,\theta)$ = reflection coefficient and for perfect mirror it is equal to -1, k is the wave number.
Fig 7 shows the sample calculations of TL due to LME

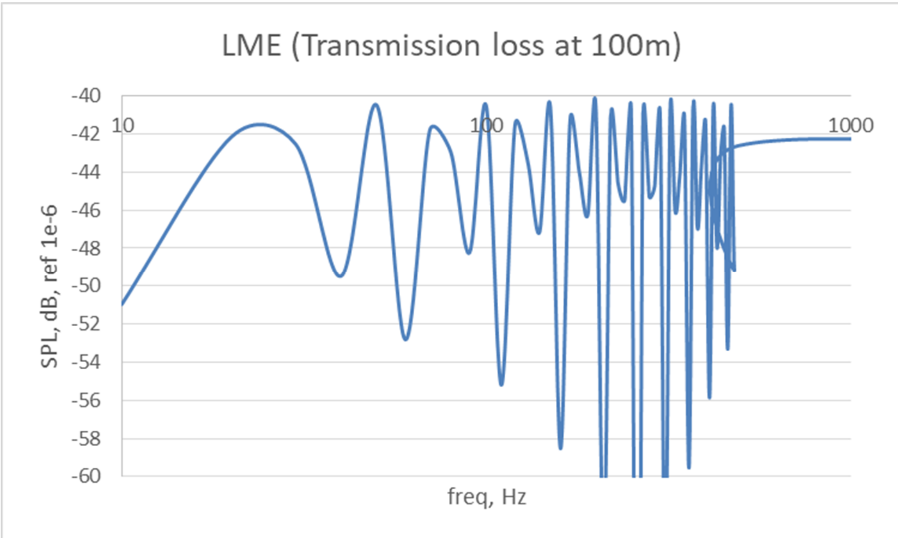


Fig. 7 – Sample calculations of transmission loss estimation (LME)

In general TL is considerably significant for frequencies up to 100 Hz. The fluctuations in TL as noted in Fig. 7 can be discarded in practice, since during URN ranging averaging is followed which cancels such effects.

4.3 ABN – investigation

Air-borne noise (ABN) from the ME transmits to the hull plating and then radiates into the water as far field noise. In some cases, ABN also poses risk for achieving URN limit of the vessel. Effect of ABN on URN can be assessed through numerical means.

Using the FE-PML model, URN due to ABN can be assessed. Source Sound pressure (ABN from ME@1 m) is applied on the hull plating of the ME room (till the waterline) as shown by red arrows in Fig. 8. The power of the FE-PML system is estimated numerically. Power is converted to SPL as discussed in previous section.

Although this assessment gives insight into the dominating frequencies which need to be dealt at the early stage of design the methodology has certain limitations as below –

- The uniformly applied pressure is on hull plating results in very conservative results.
- The sound pressure in practice when acting on the hull surface exhibits phase differences at each location. This effect cannot be accounted.
- Diffusion effects of ABN are challenging to account in general.

Above factors may lead to the resultant SPL very close to or beyond the URN targets, which may not be the reality. However, based on these studies early investigation of probable effects of ABN on URN can be made.

SEA method for investing ABN contribution for URN remains challenge, and authors believe further investigations on the methodology are required.

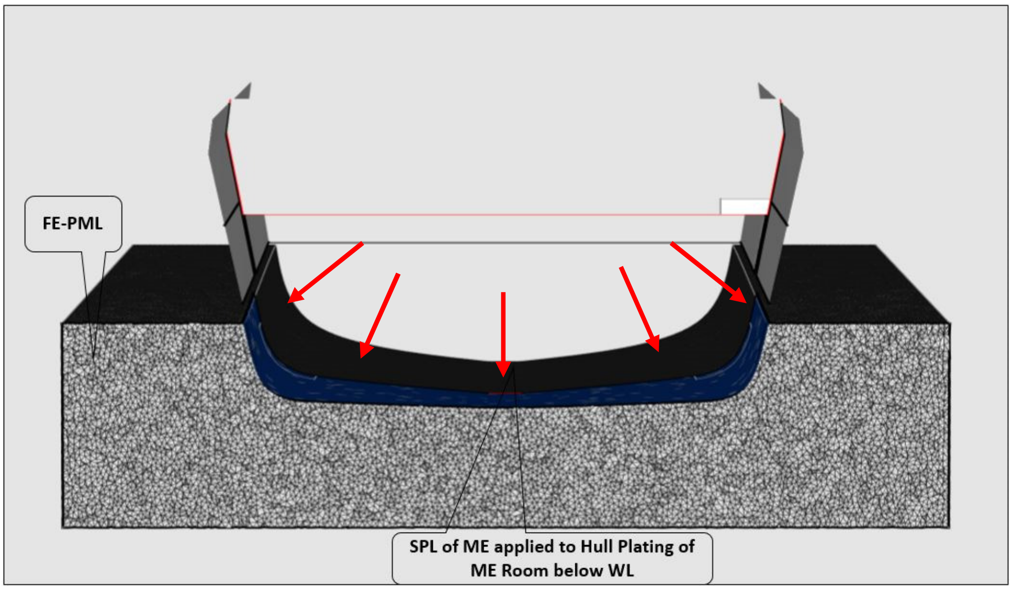


Fig. 8 Model for URN prediction due to ABN

4.4 URN case study

Numerical aspects of noise transmission are elaborated with the help of sample case in Fig. 9. Following can be noted from Fig. 9

- Ideal spring like impedance is shown with orange line (Fig. 9a). Numerically computed impedance for the actual structure is shown in blue colour. In the lower frequencies (20 – 40 Hz) and the frequencies in the range of 140 – 180 Hz the computed impedance is noted to be lower than the expected.
- Lower impedance results in higher URN and can be noted in Fig. 9a (maroon curve).
- Effect of loss due to reflections from sea surface (LME) is also shown.
- At a frequency near 300Hz the URN due to ABN is dominating (Fig. 9a). Effect of ABN on URN at higher frequencies is shown in Fig. 9b. It can be noted that at nearly 1300Hz ABN contribution to URN is high and may require detail investigation.
- Above noted frequencies are to be dealt with caution during the initial design as well as subsequent phases. Mitigations are discussed in summary section of this paper.

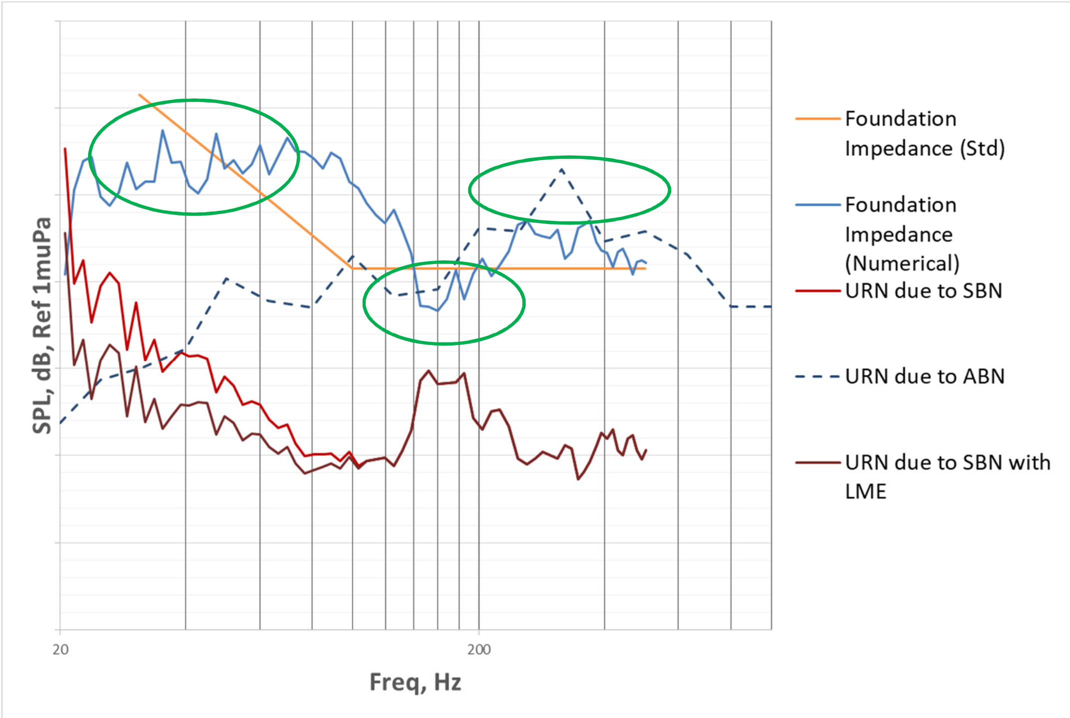


Fig. 9a – Sample URN predictions. Frequencies of concern are highlighted with green ellipse.

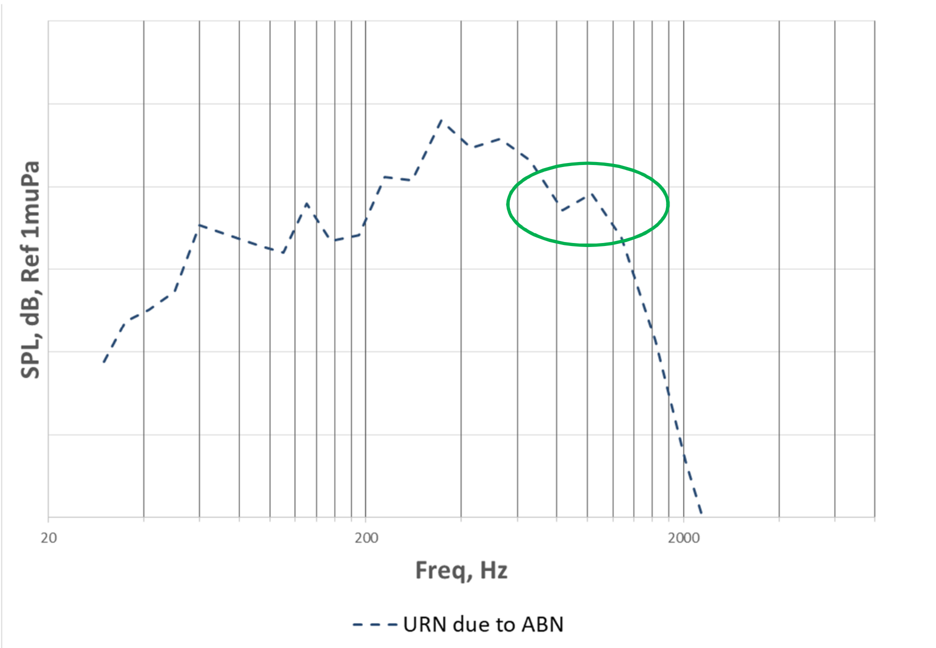


Fig. 9b – Sample URN predictions- investigation of ABN contribution to URN (LME is not considered)

5. URN due to propeller

FWH and BEM approach

Noise generated due to propeller rotation, radiating at far field, can be estimated using Ffowcs Williams Hawkins (FWH) as well as BEM model of noise prediction in conjunction with CFD simulations.

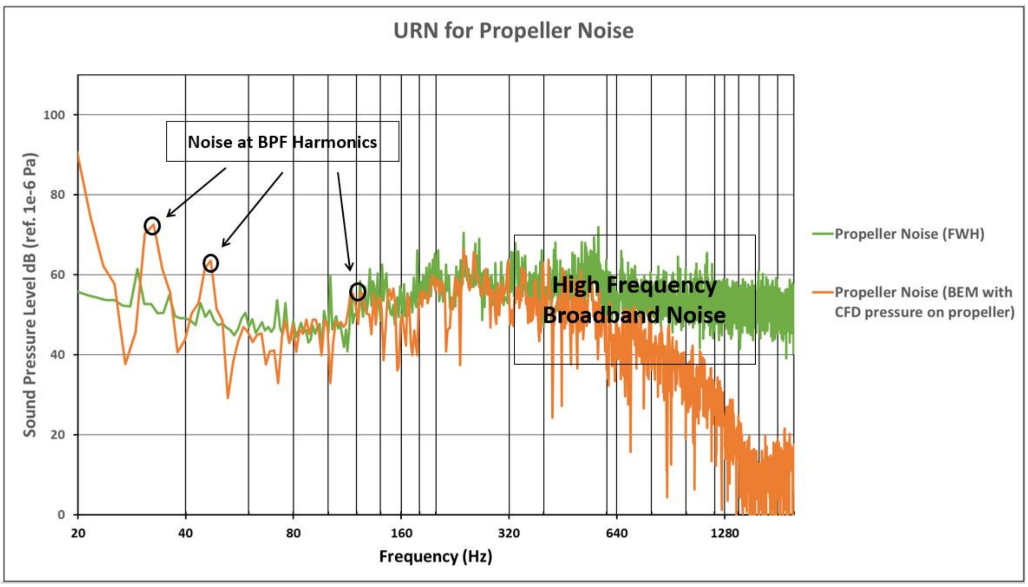
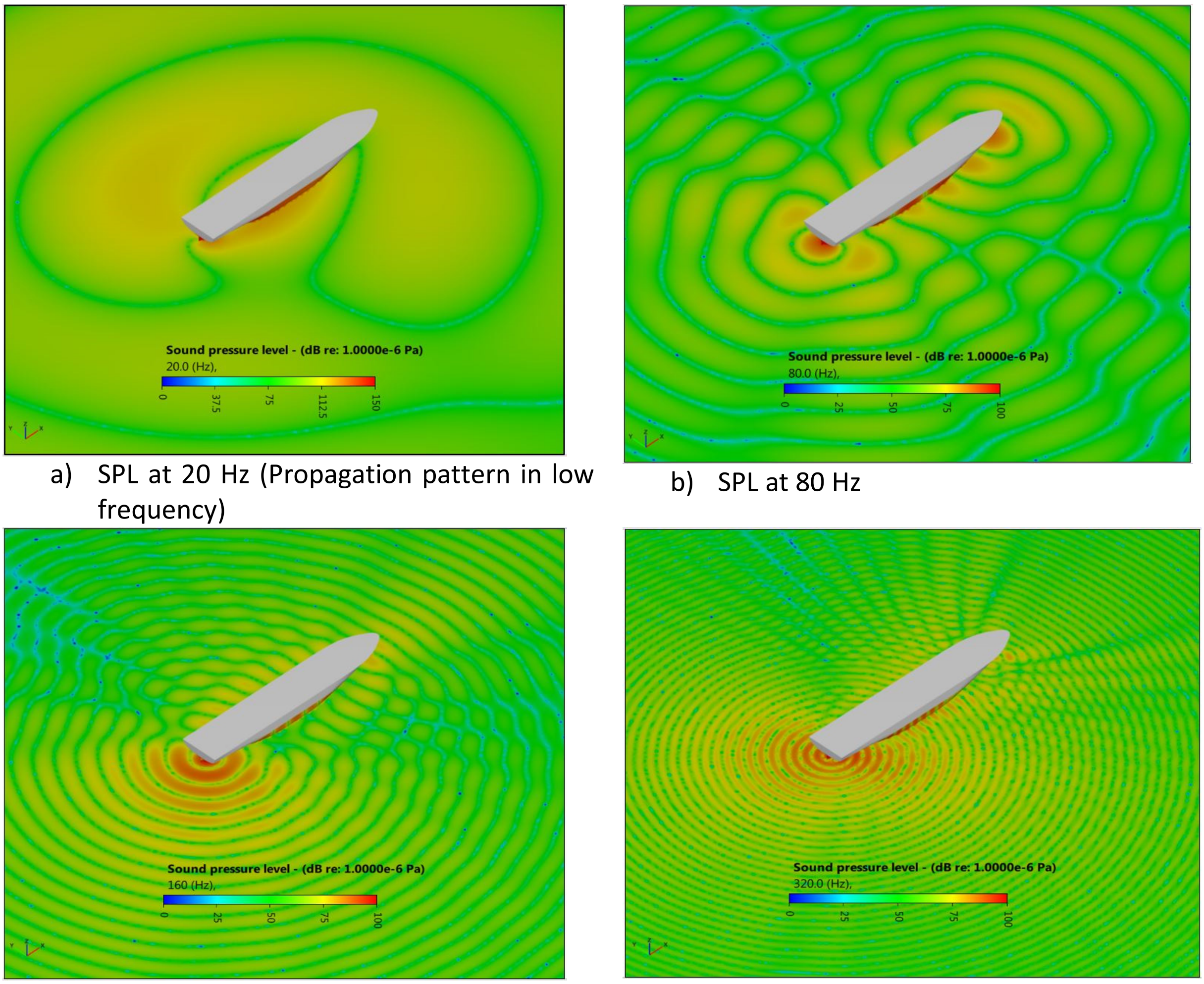


Fig. 10 - FWH and BEM based predictions. Blade pass frequencies captured using BEM are highlighted with black circles.



a) SPL at 20 Hz (Propagation pattern in low frequency)

b) SPL at 80 Hz

c) SPL at 160 Hz

d) SPL at 320 Hz (Propagation pattern in high frequency)

Fig. 11 - Sound propagation pattern in fluid domain due to propeller rotation. (Sound travels far away in low frequencies)

FWH model calculates the far field sound signal that is radiated from near field flow data obtained from CFD solution. The small amplitude acoustic pressure fluctuations at the locations of receiver are captured. Noise in terms of surface terms i.e. monopole, dipole noise sources and volume term i.e. quadruple noise source is distinguished. Monopole term is so called thickness noise i.e. the sound due to the kinematics of the body, dipole term is due to the unsteady pressure fluctuations upon emitting body surface (loading noise). Quadruple noise represents flow field sources. For propeller induced noise, the volume terms are not important, thus the Boundary Element Methods, which do not deal with volume terms can also be applied for propeller noise. Detail discussion on these methods can be found in literature, e.g. ITTC [6]. The prime advantage being the less computational time. Another advantage of BEM is that the other contributing surface such as hull, rudder, etc. can also be included for noise prediction. Differences in the predicted sound levels utilizing two approaches is depicted in Fig. 10 for sample propeller case [7].

Sound propagation patterns at various frequencies can be obtained with BEM technique. Fig. 11 shows the sound pressure levels for various frequencies and the sound propagation pattern in fluid domain due to propeller rotation.

6. On-board noise: SEA techniques

Criteria such as IMO Resolution 468 [8] are generally followed for compartment noise. Similar or stringent criteria may be followed for naval vessels for various working areas on-board the vessel. These noise levels are to be met as an average over wide band of frequencies (20 Hz – 10 kHz). General FE based solutions are computationally expensive w.r.t. the computational resource and time taken for the purpose. Thus the technique called Statistical energy analysis (SEA) is used which is based on energy principles. Calculation of energy and transfer of energy through air and structure is estimated to arrive at the acoustic pressure at the receiver location, i.e. the desired compartment. Entire vessel is discretized into various size volumes, so called cavities, and the energy transfer takes place through these cavities. The sound level at the compartment is found as an average over the volume (of the desired compartment). The properties of the structure along with the absorbing material (insulation), if any, can be taken into account. Thus the transfer of noise as well as effect of the insulation can be investigated with this technique. Fig. 12 shows the results for sample case.

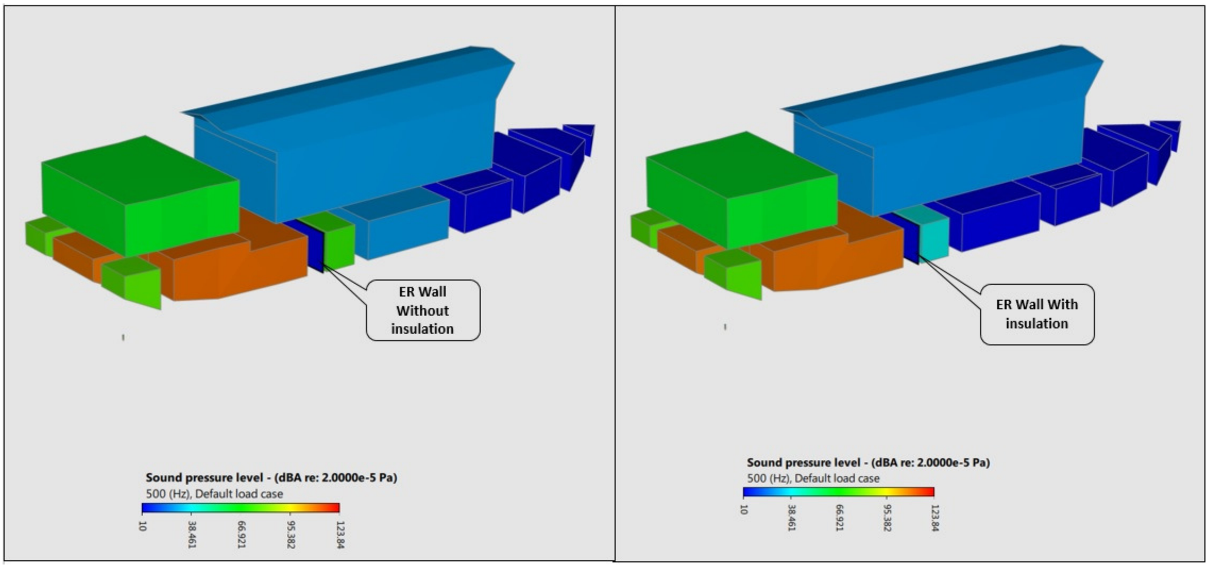


Fig. 12a – Sample case of on-board noise analysis using SEA technique (Difference in SPL levels in compartment next to ER wall can be noted).

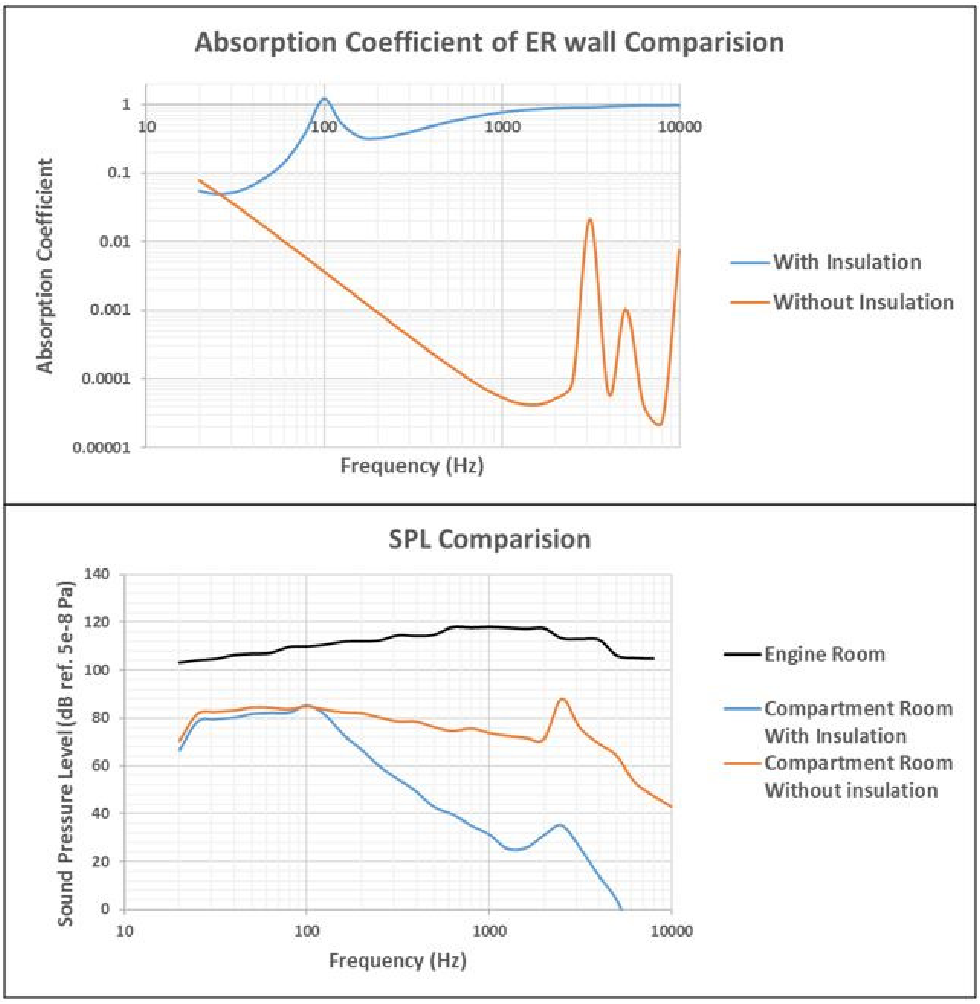


Fig. 12b – SEA based noise prediction – effect of insulation

7. Summary

Fundamentally the noise predictions are associated with deriving noise transfer functions utilizing state of the art methods. Present paper confers the numerical aspects of such methods. Standard practices and practical implementations of numerical techniques can be summarized as –

- Foundation impedance is the inherent property of the vessel structure and to start with 'Foundation impedance (Std)' as shown in Fig. 9a can be assumed. Accordingly the noise transfer function is derived which forms the basis of URN prediction.
- Limits of source level noise with respect to URN requirements can be derived based on transfer function and the standard mounting properties.
- The numerical calculations of foundation impedance can help in finding the frequencies of concern where the URN is likely to result in higher values. Dynamic stiffness and the overall mounting arrangement will require attention at final design stage to meet URN requirements.
- SBN generally diminishes with increased frequency. However, drop in the impedance results in increased SBN, resulting in higher URN. It can be investigated at an early design stage with numerical predictions.
- ABN on the other hand, increases with frequency and can be dominating for URN contribution in some cases. Such features can be investigated with numerical studies. Findings from numerical

studies can assist in decision making regarding engine enclosure or other insulation means to mitigate ABN.

- Methods such as FWH and BEM can be used for predicting propeller induced noise. Aspects such as contribution due to all radiating surfaces (hull, rudder), investigating blade pass frequencies, etc. can be studied with these methods.
- On-board noise can be predicted with SEA based methods, which can be helpful in early design stage as well as after construction of the vessel to deal with the noise issues. Decision on noise absorbing materials can be taken from predictions based on SEA method.

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