MARITIME RESEARCH CENTER
FOUNDATION FOR UNDERWATER DOMAIN AWARENESS

Research Note

Underwater Radiated Noise (URN) Management

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1. Introduction

The Underwater Radiated Noise (URN) Management on-board marine platforms is an interesting research area with varied stakeholder interests. The first is the ship design and manufacturing for efficient operational & maintenance related aspects. The second is the acoustic stealth related naval application for enhanced deployment efficiency to avoid detection by enemy sonars and also acoustic mine avoidance. The third is the growing marine conservation related application pertaining to Acoustic Habitat Degradation. These are multi-dimensional requirements related to safety of the ship, sustainability of the shipping operations and also growth related to the shipping sector. However, while we formulate the management strategy, one needs to formalize way ahead that can address these multiple dimensions with minimal deployment of resources. We need to understand the similarities and diversities of each of the requirements while we formulate the management framework.

The URN management has broadly, three main aspects starting with measurement & analysis that needs effective and efficient hardware and software to serve the multi stakeholder applications. The second aspect is the prediction of the URN based on available inputs for varied design and operational conditions. The third is the alteration of the URN of a specific mission requirement for acoustic stealth or to suit ecologically critical requirement in case of acoustic habitat degradation. The three distinct aspects will facilitate enhanced policy formulations, formulation of best practices & standard operating procedures and also design & development of innovative tools.

The sources of URN are broadly classified into three categories, namely the machinery noise pertaining to the auxiliary machineries for ensuring habitability, power generation & distribution and multiple other functionalities on-board. The propulsion machinery is largely associated with the propeller and the machineries driving the propeller. The third is the hydrodynamic noise pertaining to the movement of the vessel in water and also the flow of fluids inside pipes. The non-uniform wear and tear of the machineries have their own unique impact on the radiated noise. The machinery layout and the complex transmission path of the noise from the seat of the machinery to the hull of the platform with structural uniqueness of the ship design adds to this challenge.

The source-path-receiver model for URN management is extremely critical as all the three aspect have unique and complex manifestation. The source, i.e., radiated noise from the platform under varied machinery configuration has unique manifestation and can substantially vary based on the running machinery regime. The underwater medium (the path) particularly in the tropical littoral waters of the Indian Ocean Region (IOR) further adds to the complications due to the high random fluctuations. The receiver also adds to the challenges with respect to ambient noise at its location, sensor related issues and also signal processing related complications. Thus, it is imperative that we have a nuanced approach in comprehensively dealing with the URN management.

1.2 Evolution of URN Management

The evolution of URN management has multiple dimensions to it and each of these dimensions have contributed significantly to the overall progress in the knowhow and standardization. We look at few of the important aspects to get a sense of the multiple dots that eventually will connect to build the entire framework.

Models for URN Prediction Research on ambient noise was done from the time of World War II (WW II) and many researchers, starting from Knudsen proposed his curves on background noise in the ocean way back in 1944. Subsequently, Wenz also proposed his curves, which includes all natural and anthropogenic sources of ambient noise in the ocean, but they did not talk about underwater radiated noise from shipping in particular [1].

Donald Ross published his textbook "Mechanics of Underwater Noise" in 1976. This model was developed based on extensive measurement data from WW II. According to this model, propeller cavitation is the primary cause or source of radiated noise. It describes the noise source level as the function of ship parameters [2]. **Urick** published his paper in 1983 that indicated the sources of noise on ships, submarines, and torpedoes could be grouped into the three major categories: machinery noise, propeller noise, and hydrodynamic noise. He also proposed his model for estimation of URN [3]. **The RANDI model** published in1994 is a modified form of classical model of Ross. RANDI stands for "Research Ambient Noise Directionality" and it is a model for ambient noise levels and its directionalities. It was developed for use in the design of noise measurement experiments and the analysis of surveillance systems [4].

Wales and Heitmeyer proposed a model, which instead of taking ship parameters as input uses extensive noise data of ships and seeks to reduce rms error of ships with respect to the mean spectrum proposed in the paper. [5] **Wittekind** describes noise sources using a model that presents ships, as individual sources of noise, which arise from individual technical features and vessel operation [6]. The **Statistical Energy Analysis** (SEA) is a structural-acoustic method that is being used in modern days. SEA arose during the 1960's for the prediction of vibrio-acoustic response in Aerospace and Marine structures and started to build up in the military applications. Several refinements of the method have been proposed since then. The principles of SEA can be found in **Daniel's** thesis [7]. **Fahy** explains more on SEA theory [8]. There are various ways to explain the SEA method; a more modern view of the method is also proposed in 2016 [9].

The validation of the models and CFD methods for the ship in model scale have been reported in **Hallander and Johansson** , **Taniet** al. **Li et al** [10]. This work is a continuation of previous validation work, aiming to assess the prediction performance of the method for full-scale ship at design speed. Due to the regulations on ship noise,
the use of URN management is increased over the years and also, the use of computational models for analysis of various machinery has increased many fold. Many researchers are using CFD methods for analysis of the propeller. **SONIC** project and **DNV GL** have proposed various tools for preforming CFD analysis on propellers [11].

Measurement and Analysis of URN The hydrophone's origin is attributed to the

Canadian inventor Frank Massa in 1929, known as the **Fessenden oscillator**. This was a predecessor to the hydrophone that could ordinarily be used to capture aquatic sound as a unique type of recording (listening) device. Until the invention of sonars, hydrophone was also used for detecting submarines [1].

In 2000, **Aversion and Vendettas** published their first analysis of noise measurements of a bulk cargo ship M/V Oversea **Harriette**, which is a design representative of modern cargo ships. Their noise measurements became the basis of many papers in the subsequent years. They described the speed dependence of radiated noise and its omnidirectional behaviour at low frequencies [12]. In a paper published by **Kipple** in 2002, he investigated how measured sound levels, at a point ahead of the bow, changed as a function of time and bearing angle to the vessel. **McKenna** in 2002 published his paper and he had done measurement on all types of commercial ships by using dynamic ranging (CPA approach) [13].

NATO developed its first standard on measurement STANAG1136 in 1995 to standardize the measuring and reporting of the radiated noise for surface ships, submarine etc. [14]. Acoustical Society of America (ASA) has been involved in development of standards, since the end of WW II in the field of underwater acoustics, though their first standard on measurement ANSI/ASA S12.64 part 1 came in 2009, which describes about measurement of underwater-radiated noise from ships [15].
Later they developed ISO/PAS -17208 part 1 in 2012 and they worked on this standard and renewed it over the years. In 2019 they release part-2 of this standard which focuses more on measurements in deep waters and errors associated due to background noise. They also developed ISO18405 in 2016, which explains about all the parameters, required for measurement of URN from ships [16]. In addition, many classification societies like ABS, ITTC, AQUO and SONIC have evaluated these standards in their documents. In addition, they also developed their own measurement plans. AQUO in particular have also evaluated the present models for URN measurement and they published their own model for prediction of URN for all types of commercial ships. They have also evaluated current standards, stated the flaws in them, and developed a measurement method, which would provide better results [17].

Regulations The aggressive development in technology and economic growth, the commercial shipping activities has increased significantly and this has had multi lateral impacts including increasing oceanic noise pollution, particularly low frequency noise that has huge impact on marine mammals. This is the reason many regulations were imposed on noise radiated from ships. The first regulation, the US Marine Mammal Protection Act (MMPA) was imposed from 1972. The International Maritime Organization (IMO), began with addressing the effects of noise on humans aboard ships in the early 1980s, through the adoption of a **Code on noise levels on board ships** by the **Maritime Safety Committee (MSC),** which has since been updated at regular intervals [18]. At the time, it was also realized that some benefits to marine life might be derived from this instrument. In 2004, in response to the growing body of research that was emerging on the issue, the Marine Environment Protection Committee (MEPC) commenced discussions on the harmful impacts of underwater noise from ships on marine life and IMO proposed their **guidelines for reduction of URN** from ships. These are some of the regulatory bodies and regulations imposed by them [18]:

(a) The **International Union for the Conservation of Nature (IUCN)** Resolution RESWCC3.068, which was the first to deal with underwater noise pollution problem at the global level. [19]

(b) The **International Whaling Commission (IWC)** Resolution 1998–6 [20] and work by many conservation groups, such as **International Council for the Exploration of the Seas (ICES)**, limit (Mitson 1995), which is a regulatory requirement for fisheries research vessel, is compulsory at present [21].

(c) In 2010, classification **Det Norske Veritas (DNV)** released the optional **"SILENT" class notation (DNV 2010)**. The notation provides specific limits designed for four different groups of classes in which acoustic performance is important to the main task of the vessel, called Acoustic, Seismic, Fisheries and Research [22].

(d) One of the major outputs of the EU-funded FP7 Framework Project **SILENV** (Ships oriented Innovative solutions to reduce Noise and Vibrations) which ended in 2012 was a "Green Label" proposal, which includes target levels for on board and emitted noise and vibration [23].

1.3 URN Management

The URN management can be useful for distinct communities. The first is the **naval** community for whom acoustic stealth is of major importance, and they are willing to use higher resources to achieve higher stealth standards. The second is the **commercial merchant marine** who need to maintain low levels of URN to comply with regulatory norms to contain acoustic habitat degradation. The third community comprises of the **ship designers and shipbuilders** who need to make sure that the newer marine platforms are compliant of the regulatory norms whether for acoustic stealth or for acoustic habitat degradation. They need to establish a direct link of every stage of the ship design and building activity to the overall URN value, at the end [24].

In this project, our main direction of study is URN management in which the main aspect is prediction or estimation of URN and towards that we evaluate the current models, which are present for prediction of URN. Comparing the results, we got from empirical models with actual measurement data to know the accuracy of these models and try to minimize the errors in these empirical models by optimizing various parameters. Also estimating URN using computational models like SEA and CFD and their comparisons with experimental results. The main study directions are

(a) URN estimation using, Modelling & Simulation (M&S) aspects and review of existing models and their suitability to our requirements.

(b) URN measurement & analysis.

(c) AI & ML based URN assessment tool to enhance the accuracy and computational efficiency. AI and ML can also open up multiple other features in data analytics that are not possible with the conventional methods.

Most of the studies of underwater noise has been mainly conducted by the military. The sensitive nature of acoustic signature limits the public availability of the data for meaningful research and validation efforts. Especially the availability of studies where calculations and measurements were compared is limited. Recent advances in the URN have made it possible to **model ship behavior in wide frequency range.** Due to increased environmental awareness, there is a growing demand for understanding the noise signature, including sound radiated from ship to underwater noise in all ships, not only in special purpose vessels. The available literature is more focused on the developed world pertaining to the European Union (EU) and North America, however the tropical littoral waters of the IOR needs far greater focus to manage the growth maritime activities.

2. Stakeholders and Applications

The effective participation of the stakeholders is extremely critical for the progress of our study and understanding of the domain. The applications across the stakeholders have a major role to play for developing the knowhow and building the appropriate tools for progressing the management of URN across the oceans. The trans-border nature of the URN management requirement demands a coherent effort.

2.2 Acoustic Habitat Degradation **Arnab Das** in his paper mentioned that acoustic signals propagate effectively and efficiently underwater, so any disruption of the soundscape causes serious acoustic habitat degradation for the marine species. The marine species adapt very well to the natural sources of the soundscape in their habitat but the **anthropogenic noise, which is coming from the activities like shipping or seismic explorations, is causing serious acoustic habitat degradation.** The rapid rise in the maritime activities has resulted in massive increase in the ambient noise having serious impact on the marine species' ability to adapt to the changes. The impact varies from minor discomfort to serious injuries and even fatalities and long-term species degradation [24].

The potential impacts of ship radiated underwater noise have been brought to the attention of the marine industry through the IMO. **Paula Kellet** in her research paper have listed several key potential impacts that are typically associated with the underwater noise radiated by transiting ships, namely Acoustic masking, avoidance, behavioural changes and Physical hearing damage [25]. **Paula Kellet** also suggested three types of approaches for assessing impact of underwater noise on marine mammals [25]:

(a) **Biologically Based Assessment** The biologically based approach is based on the use of threshold values for different types of impact in different marine wildlife species. In particular, the threshold limits proposed by the US National Marine Fisheries Service (NMFS) have been considered [25].

(b) **Rules Based Assessment** The rules-based assessment uses ship radiated noise limits, which have been proposed by various research groups and regulatory bodies [25].

(c) **Goals Based Assessment** The IMO definition of goals-based assessment is "Goal based regulation does not specify the means of achieving compliance but set goals that allow alternative ways of achieving compliance" [25].

2.3 Acoustic Stealth The acoustic stealth requirement has multiple dimensions to it. The acoustic signature management as it is called comprises of three distinct stages [24]:

(a) The first stage refers to measurement and analysis.

(b) The second stage is the prediction of the acoustic signature of any platform based on the available information.

(c) The third is the deception, where we fake the actual signature of the platform.

Acoustic Ranging System Acoustic detection and identification techniques have become more advanced and sophisticated. As they evolve, so must acoustic stealth strategies. To maintain acoustic discretion all of a vessel's noise sources must be considered, including personnel, on-board equipment and cavitation, as well as the radiated noise signature of the vessel as a whole. In recent years, there has also been a growing concern about underwater noise pollution, and thus the concept of 'green ships' is gaining importance. This has resulted in a broader interest in the analysis of underwater (ship generated) noise, resulting in attempts to specify maximum limits for noise emission [26].

Brüel & Kjær's Underwater Acoustic Ranging System provides the following main functionality [26]:

(a) Measure, record, analyse and listen to the various noise sources.

(b) Determine the Closest Point of Approach (CPA).

(c) Perform corrections to 1 m reference distance and other relevant corrections.

(d) Determine the vessels acoustic signature at different operational conditions.

(e) Provide tools for both broad- and narrow-band analysis.

(f) Perform a comparison measurement either against historical data or a specific target.

(g) Manage and report the measured data.

2.3 <u>Ship Design</u> Ship designers must consider various regulations and they need to design in a manner to ensure minimum noise to comply the promulgated norms. The few design considerations proposed for low levels of URN are listed below:

(a) Performing **computational fluid dynamics** methods to know the perfect operating load on the propeller [27].
(b) Designing the hull properly by ensuring the uniform flow on to the propeller because it can decrease the flow noise. If the flow is uniform, the chance of turbulence formation is minimum and we can control the cavitation phenomenon. [28]

(c) Uneven or non-homogeneous wake fields increase cavitation. This can be controlled by proper design of the hull. [28]

2.4 <u>Ship Construction</u> During construction of the ship, builders must consider the structural optimization to reduce the excitation response and the transmission of structure-borne noise to the hull.

Consideration should be given to selection of the on board machinery along with appropriate vibration control measures like usage of shock mounts perfectly, proper location of equipment in the hull, and optimization of foundation structures that may contribute to reducing underwater radiated and on board noise affecting passengers and crew. [28]

Designers, ship-owners and shipbuilders should request that manufacturers supply information on the airborne sound levels and vibration produced by their machinery and recommend methods of installation that might help reduce underwater noise. Also they can perform **SEA method** which can predict the noise various machinery during design stage [29].

2.5 <u>Ship Operations and Maintenance</u> IMO proposed these, although the main components of underwater noise are generated from the ship design (i.e. hull form, propeller, the interaction of the hull and propeller, and machinery configuration), operational modifications and maintenance measures should be considered as ways of reducing noise for both new and existing ships. These include, among others:

(a) **Underwater Hull Surface** Maintaining a smooth underwater hull surface and smooth paintwork may also improve a ship's energy efficiency by reducing the ship's resistance and propeller load. Effective hull coatings that reduce drag on the hull, and reduce turbulence, can facilitate the reduction of underwater noise as well as improving fuel efficiency [29].

(b) **Selection of Ship Speed** In general, for ships equipped with fixed pitch propellers, reducing ship speed can be a very effective operational measure for reducing underwater noise, especially when it becomes lower than the cavitation inception speed. For ships equipped with controllable pitch propellers, there may be no reduction in noise with reduced speed. They need to have optimum combinations of shaft speed and propeller pitch [28].

3. <u>Standards, Protocols and Regulations</u>

The standards, protocols and regulations have a very vital role in management of any domain. There are standards, protocols and regulations for each of the stages and each of them have their own relevance as discussed.

3.2 <u>Standards</u> The multiple standards in vogue for URN measurement and analysis are listed in the table below and discussed in details subsequently [30]:

International Recognized Standards	
ANSI/ASA S12.64-Part 1, 2009	Quantities and Procedures for Description and Measurement of Underwater Sound from Ships-Part 1: General Requirements
ISO/PAS 17208-1:2012, Part I	Acoustics-Quantities and procedures for description and measurement of underwater sound from ships - Part 1: General requirements for measurements in deep water
ICES Cooperative Research Report No. 209	Underwater Noise of Research Vessels, Review and Recommendation
IEC 61260	Electroacoustics – Octave band and fractional-octave band filters
IEC 60565	Underwater acoustics – Hydrophones - Calibration in the frequency range 0,01 Hz to 1 MHz
ANSI/ASA S1.11	Specification for Octave-band and Fractional-octave-band Analog and Digital Filters
ANSI/ASA S1.20	American National Standard Procedures for Calibration of Underwater Electroacoustic Transducers
ISO/IEC Guide 98-3	Uncertainty of Measurement – Part 3 Guide to the Expression of Uncertainty in Measurement

ISO-17208 (2012 and part 2 is from 2019) This part of ISO 17208, specifies the general measurement system, procedure, and methodology used for the measurement of underwater sound from ships under a prescribed operating condition. It does not specify or provide guidance on underwater noise criteria or address the potential effects of noise on marine organisms.

This part of ISO 17208 is applicable to all underway surface vessels, either manned or unmanned. It is not applicable to submerged vessels or to aircraft. The method has no inherent limitation on minimum or maximum ship size. It is limited to ships transiting at speeds no greater than 50 knots [31].

ISO – 18405 (2017) This document defines terms and expressions used in the field of underwater acoustics, including natural, biological and anthropogenic (i.e. man made) sound. It includes the generation, propagation and reception of underwater sound and its scattering, including reflection, in the underwater environment including the seabed (or sea bottom), sea surface and biological organisms. It also includes all aspects of the effects of underwater sound on the underwater environment, humans and aquatic life [16].

STANAG 1136 (1995) The contents of this document are mainly

(a) Terminology units, such as frequencies and noise levels, reference distance, etc.

(b) The definition of the format for reporting the measurement.

(c) Guidelines to conduct the trial and to process the data.

The standard deals both with narrowband and one-third octave band analysis. For the measurement, one or several hydrophones are considered, and it is recommended to perform the trial in deep waters. This STANAG applies both to surface ships and submarines [14, 17].

ANSI-ASA S12.64-2009 The scope is the description of general measurement systems, procedures, and methodologies used for the measurement of underwater sound pressure levels from ships at a prescribed operating condition. It contains methodology for the reporting of one-third octave band sound pressure levels. The context for the production of this standard is the need for reduction of underwater noise impact on marine life due to manmade activities, by an appropriate characterization of underwater radiated noise at sea due to shipping.

An important issue in this standard is the definition of three grades (A, B, and C) corresponding to different levels of accuracy and/or completeness of information. The main purpose is measurement of one-third octave noise levels. However, narrowband analysis is considered in grades A and B for deeper analysis. Grade C method, which is intended for survey, uses only one hydrophone [15].

ANSI-ASA S1.11 This document, mainly discusses about calculation of centre, low and high frequencies in octave, ½ octave and 1/3 octave, by taking a reference value [32].

3.3 Comparison of the Standards

Comparison of ANSI and STANAG Standards based on key Parameters As a part of AQUO project, they have evaluated all the measurement standards like ANSI and STANAG standard/ These are the differences they spotted among them [17]:

Frequency Range

STANAG - Frequency range is from 10 Hz to 100 kHz.

ANSI – Frequency range is based on Grades:

(a) Grade A – Frequency range is from 10 Hz - 50 kHz.

(b) Grade B- frequency range is from 20 kHz to 25 kHz.

(c) Grade C – Frequency range is from 50 Hz to 10 kHz.

Number of Hydrophones
STANAG - Two. **ANSI** - Depends on the Grade:

(a) Grade A – Three.

(b) Grade B – Two.

(c) Grade C – One.

Depth and Mirror Effect
STANAG - The depth of water must be sufficient to ensure that the level of bottom reflection is insignificant. They have not mentioned the exact depth [14]. **ANSI** – Depends on the Grade:

(a) Grade A – 300 m.

(b) Grade B – 150 m.
(c) Grade C – 75 m.

The measurement methods mitigate the variability caused by Lloyd's Mirror surface image coherence effects, but do not exclude a possible influence of bottom reflections [15].

Comparision of ISO and STANAG Standards
Hans Hasenpflug, Anton Homm, Stefan Schäl and Layton Gilroy in their research paper compared the measurement results of ISO and STANAG standards [33].

Radiated noise level measured by STANAG is always lesser than the ISO standard at low frequencies the reason is Lloyd mirror effect and at high frequencies the reason is difference in data window length.

The figure below, presents the major differences between the STANAG and ISO standards.

Topic	ISO 17208	STANAG 1136
Number of hydrophones	3	1
Hydrophone depth	@ 15° = 27 m @ 30° = 58 m @ 45° = 100 m	Between 9 m - 36 m
Data window angle (*Data window length*)	± 30° (*121 m*)	± 45° (*209 m*)
Distance correction at CPA	Sea surface	Nearest point on the hull

3.4 <u>Guidelines for measurement of URN</u> Various classification societies like ABS, ITTC, and AQUO have proposed their own guidelines for measurement of URN.

<u>ABS Guidelines</u> ABS proposed their guidelines for classification notation of underwater noise, and in this document they proposed URN limits of commercial and research vessels. They also proposed their measurement plan and provided test site requirements for measurement. They also provided their analysis of measurement data and proposed their measures for reducing URN. [30]

The guide is **applicable to self-propelled commercial vessels and research vessels** that are equipped with ship acoustic design technologies in their design and construction to perform specific operations. This guideline does not apply to vessels such as offshore support vessels/workboats, tugboats, towboats, dredges, drill ships, or any other vessels providing service to offshore oil and gas exploration and production [30].

<u>ITTC Guidelines</u> ITTC have proposed ITTC quality system manual recommended procedures and guidelines. In this document they have provided measurement requirement like test site, water depth and proposed corrections for background noise and transmission loss [34].
Much of the material in the guidelines are taken from currently available publications and these guidelines **only address on measurement of ship noise and does not comment on impact of ship noise** [34].

<u>AQUO Project</u> In this project, a review of the existing standards and procedures for ship URN measurements is done and their limitations are identified. Then, the main part of this section consists of identifying the key parameters driving the uncertainty and repeatability of the measurement [17].

A proposal for a new procedure for ship URN measurements is given. Two grades are defined: **Grade A for engineering purposes, with high accuracy and repeatability, and Grade B for comparison to noise limits, with medium accuracy and repeatability.** Furthermore, these two grades are split into grades A1/B1 and A2/B2, for use in shallow waters and deep waters, respectively [17].

<u>DNV Silent Class Notation</u> The main goal of this document, issued by a classification society, is to define URN limits for some classes of ships. Associated to these requirements, a measurement procedure is defined [22].

For the Silent Class Notation, the following classes of ships are considered which includes **seismic survey vessels, fishery ships, research vessels and environmental** (any vessel demonstrating a controlled environmental noise emission). They have conducted their measurements in shallow waters [22].

3.5 **<u>Regulations</u>** The regulations are based on three criterions as discussed in para 2.2 above.

<u>Biologically Based</u> The biologically based approach is based on the use of threshold values for different types of impact in different marine wildlife species. In particular, the threshold limits proposed by the US National Marine Fisheries Service (NMFS) [35]. The table below presents some of the thresholds.

Threshold Type	Limit (dB re 1µPa)
Behavioral Changes in Pinnipeds and Cetaceans	120
TTS in Cetaceans	224
TTS in Pinnipeds	212
PTS in Ceteceans	230
PTS in Pinnipeds	218

<u>NMFS Threshold Limits for certain Mammals</u> These limits were developed by an expert panel who carried out, extensive review of all the available literature of marine mammal auditory and behavioural responses, and hence comparing a vessels performance against these limits should provide a good indication of how it might affect at least on mammal species in the short term [35].

The advantages of using this kind of approach, which is based on actual marine wildlife impact is that the benefits of noise reduction are clearer, and there is a clear limits which designers can aim for.

The disadvantages of this approach are that the limits are generalised for large groups of species, where significant variations in habituation to noise, sensitivity and response may exist. The generalisation is also over a full frequency range, and so might prove to be very demanding to achieve in the lower frequencies but easier to abide by at higher frequencies, where ship radiated noise tends to have a lower sound energy content [25].

<u>Rules Based</u> The rules-based assessment uses ship radiated noise limits which have to date been proposed by various research groups and regulatory bodies.

ICES Limits The International Council for the Exploration of the Seas (ICES) limit (Mitson 1995), which is a regulatory requirement for fisheries research vessel, is compulsory at present. This limit defines the allowable acoustic performance for fisheries research vessels [21, 25].

DNV Limits Det Norske Veritas (DNV) released the optional "SILENT" class notation (DNV 2010). The notation provides specific limits designed for four different groups of classes in which acoustic performance is important to the main task of the vessel, called Acoustic, Seismic, Fisheries and Research [22, 25].

SILNEV Limits One of the major outputs of the EU-funded FP7 Framework Project SILENV (Ships oriented Innovative solutions to reduce Noise and Vibrations) which ended in 2012 was a "Green Label" proposal, which includes target levels for on board and emitted noise and vibration (SILENV Consortium 2012) [23, 25].

The advantages of using these limits for assessing the acoustic performance of vessels is that whilst they may be stringent, they should be achievable for the majority of vessels. The limits also take into account variations in typical spectra between the lower and higher frequency sections. Furthermore, being able to use a recognised Class notation for a vessel may make it more appealing to designers and ship owners
[25].

The disadvantages are that in the case of the ICES limit, it has been designed for a very specific purpose and so has limited applicability for different vessels. The DNV and SILENV limits are intended to be applied to commercial vessels in general and are less specific however, they do not consider marine wildlife impact. It could therefore be difficult to demonstrate whether vessels complying with these limits are "better" in terms of minimising impact on wildlife [25].

Goals Based The advantages of this type of approach is that it specifically takes into account the marine wildlife aspects. In addition, this approach does not apply a general limit for all cases. It allows appropriate measures to be applied for a given set of conditions and scenarios. This means that excessive time and cost is not incurred in addressing the acoustic performance of a vessel [25].

The disadvantages of this approach are that it is not as prescriptive as the other approaches, and therefore requires more effort on the part of the designer and ship owner. There is also likely to be some discrepancy between what a designers or ship owner view as appropriate measures, and what a marine biologist would feel was suitable [25].

These are some of the regulations for ship design and construction:

SOLAS The IMO Convention for the Safety Of Life At Sea (SOLAS) Regulation V/19.2.4 requires all vessels of 300 GT and above engaged on international voyages and all passenger ships irrespective of size to carry **AIS on-board** which supports the IMO defined MDA (Maritime Domain Awareness) Framework [18].

International Regulations for the Safety of Fishing Vessels This document provides various regulation for fishing vessels in categories like [36]:

(a) General Provisions.

(b) Construction, Watertight Integrity and Equipment.

(c) Stability and Associated Seaworthiness.

(d) Machinery and Electrical Installations and Periodically Unattended Machinery Spaces.

(e) Fire Protection, Fire Detection, Fire Extinction and Fire Fighting.

(f) Life-Saving Appliances and Arrangements.

(g) Emergency Procedures, Musters and Drills.

(h) Shipborne Navigational Equipment and Arrangements.

3.6 Regulatory Bodies Multiple regulatory bodies, with diverse mandates have their relevance to the URN management. We have listed these below:

IMO The International Maritime Organization's (IMO) work, in relation to noise began with addressing the effects of noise on humans aboard ships in the early 1980s, through the adoption of a Code on noise levels on board ships by the Maritime Safety Committee (MSC), which has since been updated at regular intervals. In 2004, the Marine Environment Protection Committee (MEPC), commenced discussions on the harmful impacts of underwater noise from ships on marine life. It was noted that continuous anthropogenic noise in the ocean was primarily generated by shipping, and since ships routinely cross international boundaries, management of such noise required a coordinated international response. Consequently, MEPC, at its 58th session in October 2008, approved the inclusion of a new item on "Noise from commercial shipping and its adverse impacts on marine life" in the agenda of MEPC 59 (July 2009) [18].

IUCN The International Union for the Conservation of Nature (IUCN) Resolution RESWCC3.068, which was the first to deal with underwater noise pollution problem at the global level. Their mission is "influence, encourage and assist societies throughout the world to conserve nature and to ensure that any use of natural resources is equitable and ecologically sustainable" [37].

ICES The International Council for the Exploration of the Sea (ICES) is an intergovernmental marine science organization, meeting societal needs for impartial evidence on the state and sustainable use of our seas and oceans [38].

IWC The International Whaling Commission (IWC) was set up under the International Convention for the Regulation of Whaling, which was signed in Washington DC on 02 Dec 1946. The preamble to the Convention states that its purpose is to provide for the proper conservation of whale stocks and thus make possible the orderly development of the whaling industry [39].

The present standards, which are in practise for measurement of URN, are very useful for measurements, which are carried out at deep waters. For shallow water, new standards are to be developed and many classification societies need to evaluate these standards so that others can use the standard, which is covering all aspects and providing better methods for measurement. Also **Christian Audoly and Valentin Meyer** in 2017 have done their study on Lloyd mirror effect and they have found out that a variation of 3 dB is found due to this effect which is quiet high as per the present standards except ISO 17208 (updated in 2019) have not considered this effect. Regulations must have precise cause and effect inputs, which is not available today [40].

4. Prediction or Estimation of URN

Prediction or estimation is a very critical step towards management of any domain as it brings the structure of the study in a comprehensive manner. Prediction/estimation models are best handled with modelling and simulation as discussed below.

Modelling & Simulation (M&S) Modelling is a method to systematize the knowledge build up through observations or deduced from underlying principles, also modelling is a mechanism by which researchers and analyst can simulate performance in laboratory conditions. Modelling is necessary to analyse the data collected in field experiments and forecast acoustic conditions for planning at sea experiment [41]. Mathematical models include both empirical models (those based on observations) and computational models (those based on mathematical representations of the foremost physics). Figure-1, explains the details.

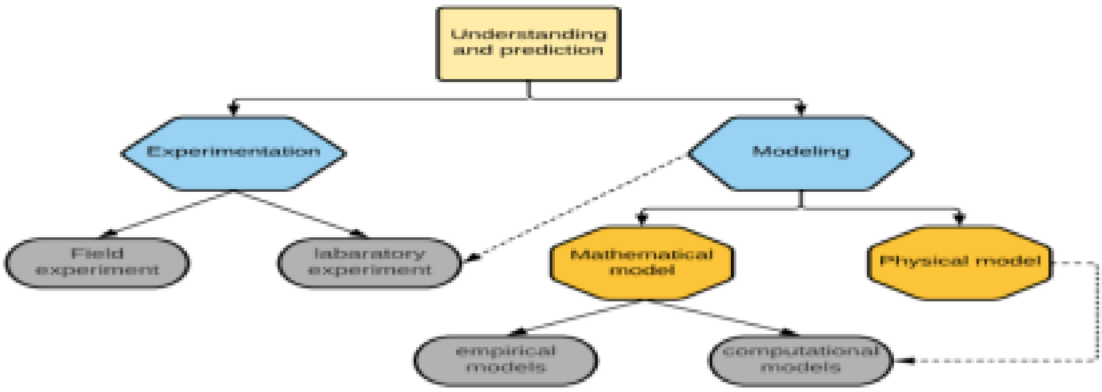

Fig. 1 Flow chart to explain the key aspects of modelling and schematic relationship between experimentation and modelling.

4.2 Empirical Vs Computational Models

Empirical methods, if available are always best however, these are impossible to achieve in some cases, hence numerical methods become useful. Computational methods are mathematical way to solve certain problems. Whether the equations are linear or non-linear, efficient numerical methods can be used to solve the equations. However, when the equations of fluid flow are complex it is difficult to solve them by empirical methods in such case they can be solved by computational or numerical methods like Computational Fluid Dynamics (CFD). Computational methods are used for deeper understanding to predict the anomalies, which are not possible in the analytical methods. [41]

Empirical Models Multiple empirical models have been proposed by researchers for varied applications and we analysis them for their relevance to our project.

The Ross Model The model proposed by Donald Ross, in his book *Mechanics of Underwater Noise,* assumes that the radiated spectra of surface ships are primarily due to the phenomenon of propeller cavitation. Thus, for speeds greater than that required for cavitation inception, the source level of noise as a function of ship parameters is given by

$$(f) = S_0(f) + S'$$

Here, S_0, the base spectral level, applies to all ships moving at service speeds regardless of their type. The second term S' is the scaling term that takes into account various ship parameters [2]. The value of the base level can be calculated from the following expression

$$S_0(f) = 20 - 20\log_{10}(f)$$

Where, f is the frequency at which the level is desired. In his book, Donald Ross cautions that this formula works only for frequencies over 100Hz. For the scaling term S', Ross gives the following two expressions

$$S_0 = 134 + 60\log_{10}\left(\frac{V}{V_{ref}}\right) + 9\log_{10} D_T$$
$$S_0 = 112 + 50\log_{10}\left(\frac{V}{V_{ref}}\right) + 15\log_{10} D_T$$

Where, D_T is the displacement tonnage, V is the speed of the ship and V_{ref} is taken to be 10 knots. Ross recommended that the scaling formula should not be used for ships over 30,000 tons.

The Urick model Urick gives some typical radiated source levels that were measured on various classes of ships, during World War II. It is based on 157 measurements from 77 ships belonging to 11 different categories (mostly freighters, tankers and large warships). The underwater noise for these ships is dominated by propeller cavitation noise. The source levels were summarized in an empirical formula in terms of the propeller tip speed UT (in feet/s), the displacement T and the frequency f in Hz. In principle, it is only applicable at frequencies above 1 kHz where propeller cavitation is the principal source of noise [3].

$$SL(f) = 46.5 + 51\log U_T + 15\log T - 20\log f, \text{ in dB ref. } \mu Pa^2/Hz \text{ @ 1 m}$$

The RANDI Model This model is a modified form of the classical model proposed by Donald Ross. It was designed to predict the response of low- to mid-frequency sonar receivers to the ocean acoustic noise field in locations with highly variable bathymetry and range-dependent sound speed structure. Such environments are common in shallow water areas. This model uses parabolic equation propagation loss models to propagate energy from individual ships to the receiver array [4]. According to this model, the noise level comprises of the following three terms:

$$S_{RA}(f) = S_0(f) + S'(V, L) + S''(f, L).$$

The qualitative discussion of these terms is given below: S_0 is the base spectrum of the RANDI model.

S' is the ship parameter based scaling term.
S'' is a correction term that is applicable only to frequencies below 200Hz.

The Wales-Heitmeyer Model The model proposed by Wales and Heitmeyer seeks to reduce the rms error of the classical Ross Model. The paper argues that the

Ross model cannot describe the surface interaction propagation effects observed in the radiated noise spectrograms for some of the larger ships. Instead of using ship parameters as inputs, the Wales-Heitmeyer model uses extensive noise data of ships [5].

Wales-Heitmeyer divide the source spectrum into two parts: 50-400 Hz and 400-1200 Hz. The justification given for this is that for frequencies above 400 Hz the source spectra showed a simple power law dependence, conversely, for frequencies less than 400 Hz, many of the source spectra exhibited a more complex frequency dependence and there was a much greater variability in the spectra across the ensemble [5].

It uses a rational spectrum model whose parameters are determined by the statistical analysis of the collected noise data. The rational spectrum model provides a ship dependent spectrum that consists of linear combination of approximating functions. This model gives a better estimation of both the individual spectra and the variability than the Ross Model does, as claimed by Wales and Heitmeyer in their original paper [5].

Wittekind Model This model breaks down ship radiated noise into three components namely:

(a) Low frequencies from propeller cavitation.

(b) Medium to high frequencies from propeller cavitation.

(c) Medium frequencies from four-stroke diesel engines.

Hence, the following parameters of the ship are considered in the model:

(a) Displacement.

(b) Speed relative to cavitation inception speed.

(c) Block coefficient as an indicator for wake field variations.

(d) Mass of diesel engine(s).

(e) Diesel engine resiliently mounted yes or no.

Source levels in the Wittekind model are given in terms of 1/3 octave band levels instead of source spectrum levels

$$SL = 10log_{10}\left(10^{\frac{SL1(f_k)}{10}} + 10^{\frac{SL2(f_k)}{10}} + 10^{\frac{SL3(f_k)}{10}}\right)$$

The first contribution, SL1 (f_k), represents the low-frequency cavitation noise, SL2 (f_k) represents the high-frequency cavitation noise, and SL3 (f_k) the diesel engine noise [6, 17].

Gaps in Research One possible interpretation is that some of these models were established a long time ago, with a majority of vessels from the WW II period. In addition, Wales's model gives higher levels at very low frequencies, probably due to correction from Lloyd's mirror effect, which is not taken into account in other models, except Wittekind's.

All these models assumes propeller cavitation as a major source of URN, so when the ship operates at low speeds these models may not be that accurate. Also, for Wittekind's model, we need to have lot of parameters, which are difficult to find. Several ship dependent parameters, which contribute to radiated noise levels, were not included in the model devised by Wittekind. These include draft of the ship (small or full), positioning of the propeller, sinkage, trim, and height of stern wave etc.

A study can be done on the types of ships present in the Indian Ocean Region (which is a tropical littoral region), and the Wittekind model can be tuned accordingly, to give the most accurate results possible for ships in the IOR. All the current estimation models only use a handful of ship parameters (mostly related to its operating conditions) as inputs.
McKenna et.al. Recommend that the number of ship parameters (relating to both design and operating conditions) be increased and oceanographic conditions be considered while devising noise models [13].

Computational Models Here we discuss the computational models to ascertain their relevance to the URN management initiative.

Statistical Energy Analysis (SEA) Method The SEA is a structural-acoustic method that is being used in modern days. SEA arose during the 1960´s for the prediction of vibro-acoustic response in Aerospace and Marine structures started to build up in the military applications. Several refinements of the method have been proposed since then. In SEA, each system is divided into several physical elements of a suitable size. For example, in traditional SEA these elements would be divided so that the vibro-acoustic characteristics are similar over them, such as damping, excitation and coupling properties. These elements are called subsystems [9].

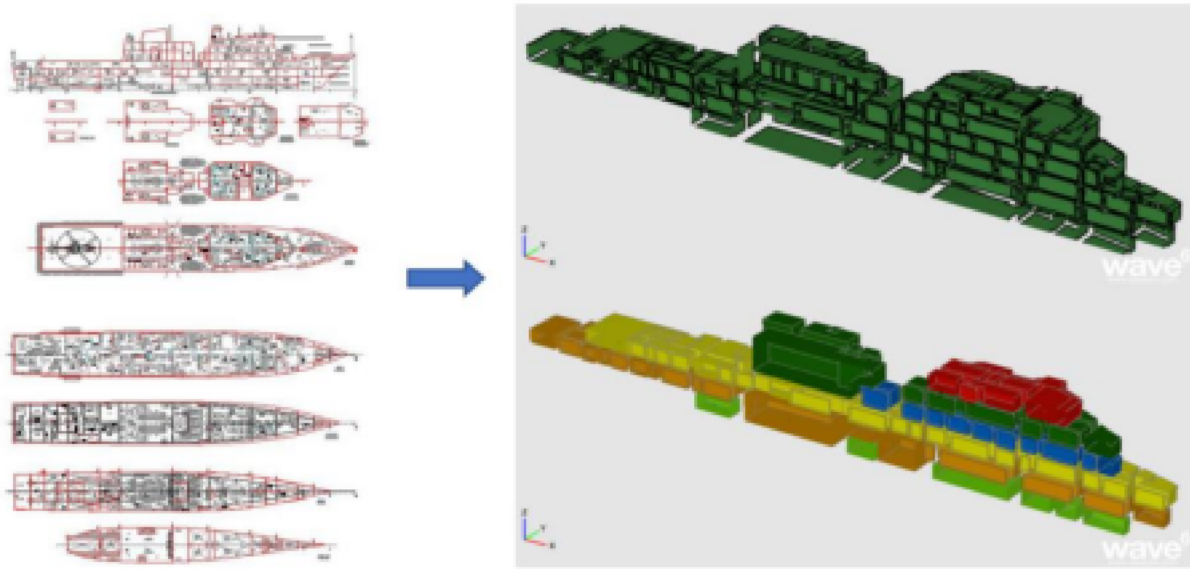

Fig.2 Schematic Representation of the SEA Method

As shown in the figure 2, for implementing SEA we need to create a CAD model of the ship which we want to analysis and that CAD model in wave6 software is converted into 2D SEA (top right) and 3D SEA (bottom right) subsystems [9].

Finite Element Analysis (FEM) The Boundary Element Method (BEM), Infinite Element Method (IFEM), and Automatically Matched Layers (AML) are common numerical methods for calculating structure radiated noise in the mid and low frequency band. The BEM combines classical integral equations and finite element theory. The integral equation may be regarded as an exact solution of the governing partial differential equation. The BEM attempts to use the given boundary conditions to fit boundary values into the integral equation. Once this is done, in the post processing stage, the integral equation can be used again to calculate numerically the solution directly at any desired point in the interior of the solution domain [42].
The IFEM is a modification of the FEM. The method divides the domain concerned into infinitely many sections. The structure of the acoustic IFEM is composed of two parts: the finite inner region of the envelope structure model and the semi-infinite outer region. The limited inner region is dispersed by finite elements, the semi-infinite outer region is dispersed by divergent infinite elements, and the nodes are coupled at the interface to ensure continuity in the process of outward propagation of sound pressure
[42].

The AML is a new type of finite element method. The calculation principle is to artificially set a finite thickness medium layer to absorb sound waves at the acoustic finite element boundary. The absorption layer makes sound waves decay rapidly in exponential form. Therefore, the sound intensity at the boundary of the medium layer is near zero [42].

Figure-3, pictorially represents the BEM, IFEM and AML methods.

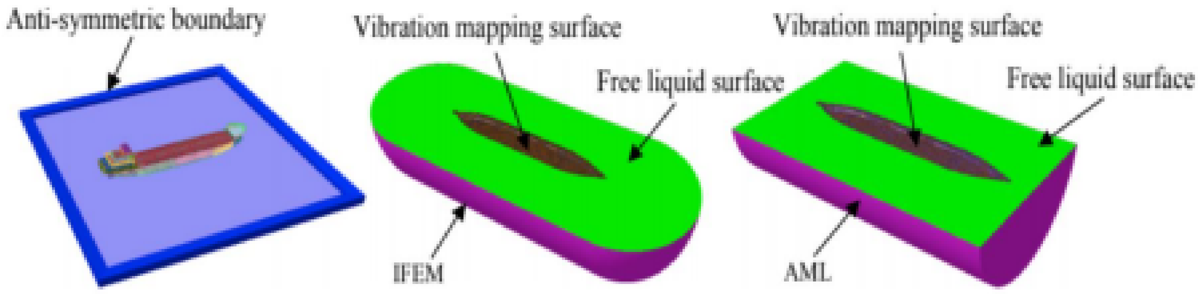

Fig. 3 Pictorial Representation of the IFEM and AML Methods

Computational Fluid Dynamics (CFD) The CFD method is one of the most advanced computational tools that is able to give more insight into the flow physics. It can be very useful in predicting and visualizing flow characteristics around the hull and, generating the wake field in which the propeller operates. For computation of the unsteady flow around the propeller, the unsteady flow around it has to be stimulated first. Once the flow around the propeller is solved, acoustic computations are performed to predict the radiated noise [27].

Initially CFD model is validated with following studies

(a) Resistance prediction.

(b) Propeller open water characteristics.

(c) Propeller behind hull simulations: thrust prediction.

Finally radiated noise prediction is done by using **FWH solver.** The Acoustic spectra prediction was conducted by applying the built-**in Ffowcs-Williams Hawking's (F WH) solver**. The solver applied Farrassat Formulation 1A for thickness and loading noise sources.

In recent times majority of the research work in this field is focused on the application of the Ffowcs-Williams Hawking's (FWH) equation to hydro acoustic problems. This was originally developed for aeroacoustics. More recently, this equation has been applied to other fluids, namely water, for the noise generated by marine propellers. If the turbulent data in the near field is available, then the Ffowcs-Williams Hawking's equation can also be used for broadband noise prediction [9].

4.3 Case Studies Here we discuss some case studies on model validation and conceptualization.

Comparing Ship Underwater Noise Measured at Sea with Predictions by Empirical Models In this paper, with the aim of verifying the reliability of a selection of available empirical models for the ship radiated noise, a comparison of predictions with measured noise spectra for a small set of ships is carried out. The empirical models considered are Ross and Randi. It follows that both the models appear not suitable to predict the radiated noise spectrum of a modern merchant ship [43].

AQUO SHIP Underwater Radiated Noise Patterns In this document, they have compared all the existing models for estimating URN, which includes Ross, Randi, Wales and Heitmeyer, Urick and Wittekind. The comparisons are shown in the table below [44].

Model	Speed dependence	Size dependance	Ship categories and list	Min freq.	Max. freq.
Urick	X	X	None	100	10000
Ross	X	X	None	100	10000
Wales			None	10	1000
ANATRA			"Noise" (Silent, Standard, Noisy)	10	10000
RANDI and RANDI 3.1	Related to category	Related to category	Supertanker, Large tanker, Tanker, Merchant, Fishing	10 10	1000 10000
Wittekind	X	X	Merchant ships	10	10000

Underwater Radiated Noise model - V. M. Kumbhar, S.S. Jagdale, R. K. Shastri In this paper, the radiated ship noise model is used for analysing the noise level for the frequencies varying from 100 Hz to 5 kHz. The result shows that noise level is dominant at low frequencies. This spectral analysis using real time data shows that noise is dominant at low frequencies and at higher frequencies noise level decreases [45].

Numerical Cavitation Noise Prediction of a Benchmark Research Vessel Propeller This study presents the initial results of URN predictions for the Princess

Royal model propeller in the uniform flow conditions, and are compared with experimental results from cavitation tunnel tests. The results of the noise simulations give a rather acceptable prediction with respect to the experimental data in terms of the BPF values and shape of the spectrum [22].

Prediction of On-board and Underwater Sound Level Using Computational Methods - performed by Akula Chaturvedi (Surveyor, IRCLASS) The use of numerical methods based on SEA has been investigated. However, the human time spent on such calculations is a critical concern. Using the SEA technique, it is possible to efficiently use existing inputs that are anyway produced for other departments of the ship designer. Virtual variants of the ship can then be easily considered, and design decisions can be quickly taken. Absolute level predictions would require detailed information about all the noise and vibration sources of the ship, including the structural excitations, plus detailed information about the materials and ship assembly [9].

Initial study for URN predictions are performed using CFD and Ffowcs-Williams Hawking's (F-WH) solver and the results have been compared with the measured data from the EU-AQUO project. Few limitations have been identified in the F-WH solver and further study may be required to accurately predict URN [9].

Study on Prediction Methods and Characteristics of Ship URN To calculate the ship URN in the middle and low frequency, the finite element and boundary element method (FE-BEM), finite element and infinite element method (FE-IFEM), and finite element and automatic matching layer (FE-AML) were used, respectively. It is found that the FE-BEM is the preferred method for calculating ship URN in modelling scale and computational efficiency. The calculation of hull vibration and URN in the high frequency were performed by using the Statistical Energy Analysis (SEA). Full frequency underwater radiated noise prediction of the oil tanker was completed [42].

Lu et al. (1982) compared finite element method, statistical energy analysis, and experimental results for broadband vibrations to provide understanding in modelling machine borne vibration of ships. The test specimen consist of plates in similar shape to ship hull. In the low frequencies, finite element method provided results close to those measured. Statistical energy analysis provided averaged results, at the range of the greatest response. As frequency was increased, accuracy of single finite element method reduced dramatically, but using Monte Carlo analysis, the frequency range available to finite element analysis was extended to 1000 Hz. The statistical energy analysis become more accurate when frequency was increased, proving results slightly larger than measured [46].

Gaps in Research The various case studies and methods shown here cannot predict the complete URN from ships. Computational models like SEA or FEM cannot predict the noise generate due to propeller cavitation and high computational power and time required for performing these methods.

5. <u>Measurement and Analysis</u>

The procedures and methods for full-scale noise measurement are dictated by the objectives and purpose of measurement program. For example whether the measurements are made on commercial, military or possibly research vessels. The ANSI and ISO standards provide measurement standards that depend on quality of measurements needed. Specifications of three grades of quality are [27]:

(a) Precision grade.

(b) Engineering grade.

(c) Survey grade.

5.2 <u>Measurement Parameters</u> The major parameters in use for noise measurement are:

(a) Sound pressure level.

(b) One third octave bands.

$$f_{max} = 1.25992\ f_{min}$$

(c) Propagation or transmission loss.

(d) Range and reference distance.

(e) Radiated noise level.

Sound Pressure Level + Transmission or Propagation Loss

5.3 <u>Measurement Systems</u> Measurement systems are critical in terms of their hardware & software aspects and more importantly their deployment challenges. We discuss the state-of-the-art in measurement systems available.

Andrew M. Patterson; Jesse H. Spence; Raymond W. Fischer in their research paper mentioned various systems which are present now for measuring URN. The major systems they mentioned are

(a) Permanently Installed Ranging Facilities.

(b) Bottom Moored Hydrophone with a Support Vessel.

(c) Surface Supported Hydrophone with Support Vessel.

(d) Near Shore Measurements.

They have listed pros and cons of these systems and they have proposed a new measurement system known as **The Buoy Acoustic Measurement System (BAMS)** also listed the pros and cons of this system [47].

National physics laboratory in their practise for "good practise guide for underwater noise measurement "proposed three systems, which are:

(a) Vessel based systems.

(b) Static systems.
(c) Drifting systems.

Vessel Based Systems The method has the advantage that deployments can be quick and mobile, and a relatively large area may be covered cost-effectively. The risk of losing instrumentation is low, the data can be monitored as they are acquired (often in real time), and instrument settings may be adjusted in real time to provide the optimum settings to ensure high quality data. However, there are some disadvantages, the most obvious being that it is usually **not cost effective for the vessel** (and the researchers) to **undertake long-term deployments** (for example, weeks, months or years), so the deployments tend to be relatively short [48].

Static Systems Static systems are more appropriate for longer-term deployments, and these can be used for monitoring, using either continuous recordings, or time sampling with a specific duty cycle for periods of weeks or months. This enables the measured data to be sampled for a range of tidal cycles, weather conditions, operational states, etc. Static deployments have the disadvantage that they are by definition static, and so measured in only one location. They also have a **higher risk of data loss** [48].

Drifting Systems These systems are highly suitable in **high tidal flow areas** (such as those encountered in the locations of tidal stream energy developments) for both baseline measurements of background noise, and assessment of radiated device noise. Typically, the system will consist of a hydrophone and recorder attached to a drogue or sea anchor, which causes the whole system to drift with the prevailing current. **A GPS receiver** is sometimes used to provide a log of positional data. Note that a synchronised time stamp on the audio-track is needed to accurately link to the GPS time. Such systems have the advantage of being less susceptible to flow noise, but may still suffer from parasitic noise from moorings and floats. Drifting systems are not suitable for **long-term deployments** [48].

5.4 Measurement Requirements The acoustic measurement of URN has multiple pre-conditions to be met before we commence the actual measurements [30].

Test Site Requirements The key factors to consider when selecting a suitable test site are the geographical location and the seasonal weather when carrying out the planned acoustic measurement activity. Other factors include, but are not limited to, salinity, water temperature, water depth, sea conditions, weather conditions, a safe zone and low background noise (considering the surrounding shipping activities at or near the vicinity of the proposed test site) [30].

Test Site Water Depth In order to minimize the bottom surface effects in the oceans, ANSI and ISO standards recommends [15, 31]:

(a) Highest Grade Measurements: Tests should be conducted with a minimum water depth of 300m or three times ship length.

(b) Middle Grade Measurements: 150 m depth or 1.5 times Ship’s length depth.

(c) Lowest Grade Measurements: 75 m depth or 1 times ship’s length depth.

Background Noise The background noise at the test site is to be monitored at least at the start and end of the measurement survey. When the background noise is measured, the ship to be tested is to drift in an area away from the hydrophone. The background noise is to be measured for at least 2 minutes. During the measurement, the stability of the real-time signal is to be checked to ensure the reliability of the measurement [30].

5.5 Analysis of Measurement Data The measured underwater radiated sound pressure level from the vessel under test has to undergo a post-processing phase to account for background noise adjustment, sensitivity adjustment and distance correction [30].

Background Noise Correction ABS suggested that a set of background noise data is to be collected at the beginning and at the end of each measurement run. This is to enable the comparison of the sound pressure level radiated from the vessel under test to the background noise level during the period of the measurement test [30]. The steady-state background noise is to be checked in order to ensure that the maximal error due to the background noise correction does not exceed two Db [49].

Bottom Effect Correction If the distance between the hydrophone and the bottom is less than 0.2 m (0.66 ft), a 5 dB reduction to the underwater sound pressure level can be made to correct for the sound reflection from the sea bottom. [30]

Sensitivity Adjustment The adjusted underwater sound pressure level taken into account the background noise correction is also required to consider the sensitivity aspect of the hydrophone. Ideally, the sensitivity of the hydrophone and measuring system should be chosen to be an appropriate value for the amplitude of the sound being measured. The aim in the choice of the system sensitivity is to avoid poor signal
to-noise ratio for low amplitude signals avoid nonlinearity, clipping and system saturation for high amplitude signals [48].

Distance Correction The final underwater sound pressure level is to account for the transmission loss that is to be corrected to a reference distance of 1 m (3.28 ft) for each hydrophone.

Transmission Loss Ross in his book said that a simple propagation law could obtain transmission loss. When measuring the transmission loss directly, the known source is to be towed along the same path as the vessel under test [2]. For numerical estimation, it is necessary to consider the geo-acoustic properties of the sea bottom. A simple expression for transmission loss is found in ABS guidelines, which has been shown below [30]:

$$TL = 20\log\left(\frac{D_{Total}}{D_{ref}}\right) \quad \text{(6)}$$

$$D_{Total} = \sqrt{D_{vertical}^2 + D_{horizontal}^2} \quad \text{(7)}$$

where

D_{Total} = total distance from the acoustic center of the vessel under test to each of the hydrophones, in m (ft)

$D_{vertical}$ = depth of the hydrophone from the sea surface, in m (ft)

$D_{horizontal}$ = horizontal distance from the sea surface above the hydrophone(s) to the acoustic center of the vessel under test, in m (ft). This distance could be verified by means of using any distance measurement device (i.e., laser rangefinder, ultrasonic ranging module (sonar, echo-sounding), radar distance measurement, or a GPS system).

$D_{ref}(m)$ = standard reference of distance = 1 m (3.28 ft).

Recently **Sipilia Tuomas, Viitanenn Villi** and **Uosukainen Scppo** have performed their analysis on underwater noise of icebreaker. They have carried out the transmission loss measurements by using one hydrophone at the bottom and three hydrophones at intermediate depths. However, they found out that the measured and simulated transmission loss levels were similar and showed an increasing trend towards higher frequencies [49].

6. Research Directions

Based on the research note, the following three research directions are proposed:

URN estimation, Modelling & Simulation (M&S) aspects and review of existing models and their suitability to our requirements Focus is on comparing the predicted noise with the actual measurements of noise. All the parameters required for the models are not easily available (or not directly a part of the AIS data of the ship). In that case, try to derive the unavailable parameters form data, which is available. All the current estimation models only use a handful of ship parameters (mostly related to its operating conditions) as inputs. McKenna et.al. Recommend that the number of ship parameters (relating to both design and operating conditions) be increased and oceanographic conditions be considered while devising noise models.

Try to use computational models for estimating URN and compare the results with actual noise measurements. Existing numerical tools tend to be good at prediction low-frequency noise, but are lacking accuracy for the higher frequencies. Therefore, numerical analysis techniques should be improved in order to achieve more accurate noise predictions.

URN Measurement & Analysis Ship radiated noise levels cannot yet be regulated, because there is no practical standardised measurement procedure available. Ship noise can be measured on a sound range, but these ranges are fixed in location and often not close to the shipyard or the trial location. Therefore, such a standardised procedure is required.

Experimental facilities are more accurate for the higher frequencies as the lower frequencies are typically influenced by wall reflections in the basin, which need to be corrected for. Therefore, measurement techniques need an upgrade so that we could very well perform measurements in the shallow regions as well.

AI & ML based URN assessment tool to Identify Noisy trends in Merchant Vessels There is a lack of an open database of the ship parameters required for the URN study. Such a database could be built up which will be a huge help to the researchers.

[1] "Discovery of sound in the sea" – official website
https://dosits.org/people-and-sound/history-of-underwater-acoustics/

[2] Donald Ross "Mechanics of underwater noise" ISBN 978-0-08-021182 4 Elsevier,1976
http://libgen.rs/book/index.php?md5=7D354D5E9C05F76ED9D65DFF4C6F8 F24

[3] R. J. Urick, "Principles of Underwater Sound", New York: McGraw-Hill,1983
https://renuanhusis.wixsite.com/tiarasadum/single-post/2018/02/18/Urick Principles-Of-Underwater-Sound-Pdf-19

[4] Breeding Jr, J. E., Pflug, L. A., Bradley, M., & Warlord, M. H.” Research Ambient Noise Directionality (RANDI) 3.1 Physics Description (No. NRL/FR/7176--95- 9628).” Naval Research Lab Stennis Space Centre MS., 1996
https://www.researchgate.net/publication/235092174_RANDI_31_User%27s_Guide

[5] Wales, S. C., & Heitmeyer, R. M.” An ensemble source spectra model for merchant ship-radiated noise.” The Journal of the Acoustical Society of America, 111(3), 1211-1231. 2002
https://asa.scitation.org/doi/10.1121/1.1427355

[6] D. K. Wittekind. ” A simple model for the underwater noise source levelof ships.” Journal of Ship Production and Design, 30(1):1–8, 2014
https://www.semanticscholar.org/paper/A-Simple-Model-for-the-Underwater Noise-Source-of-Wittekind/d64d86d050889ac335a6a68fdd23ed2a2715d09b

[7] Daniel johnasson Peter comnell “Statistical Energy Analysis software Development and implementation of an open source code in Mat lab/Octave” CHALMERS UNIVERSITY OF TECHNOLOGY, 2010
https://docplayer.net/8165507-Statistical-energy-analysis-software.html

[8] Frank J. Fahy ” Statistical Energy Analysis: A Critical Overview” Published By: Royal Society 2, 1994
https://www.jstor.org/stable/54287?seq=1

[9] Akula Chaturvedi (Surveyor, IRCLASS), Ram Kumar Joga (Surveyor1, IRCLASS), Karan Doshi (Surveyor1, IRCLASS), Sharad Sham Dhavalikar (Principal Surveyor, IRCLASS), A. R. Kar (Sr. Principal Surveyor, IRCLASS) “Prediction of On-board and Underwater Sound Level Using Computational Methods”. INMARCO, 2018
http://inmarco.in/images/46AAkula%20Chaturvedi,%20Ram%20Kumar%20Joga,%20Karan%20Doshi,%20Sharad%20Sham%20Dhavalikar,%20A.%20R.%20Kar_Prediction%20of%20ON BOARD%20AND%20UNDERWATER%20SOUND%20LEVEL%20USING%20COMPUTATIONAL%20METHODS.pdf

[10] Da-Qing Li Jan Hallander, Torbjorn Johansson“ Predicting underwater radiated noise of a full scale ship with model testing and numerical methods “ Elsevier, 2018
https://www.sciencedirect.com/science/article/abs/pii/S002980181830266X

[11] SONIC (Suppression Of underwater Noise Induced by Cavitation) European Commission within the Call FP7
https://cyberleninka.org/article/n/1439329

[12] Arveson, P. T., and Vendittis, D. J. “Radiated noise characteristics of a modern cargo ship,” J. Acoust. Soc. Am. 107, 118–129, 2000
https://asa.scitation.org/doi/10.1121/1.428344

[13] McKenna, M. F., Ross, D., Wiggins, S. M., & Hildebrand, J. A. “Underwater

radiated noise from modern commercial ships." The Journal of the Acoustical Society of America, 131(1), 92-103. 2012
https://asa.scitation.org/doi/10.1121/1.3664100

[14] NATO STANAG 1136 " standards for measurement ", 1995
https://standards.globalspec.com/std/165070/STANAG%201136

[15] ASA - S12.64 PART 1 "American National Standard Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements" , 2004
https://standards.globalspec.com/std/14215545/ANSI/ASA%20S12.64%20PA RT%201

[16] "ISO official website - ISO 18405", 2018
https://www.iso.org/obp/ui/#iso:std:iso:18405:ed-1:v1:en

[17] AQUO PROJECT " URN measurement method", 2015
https://documents.pub/document/d31-european-urn-standard-measurement method-aquoeudownloadsaquod31-european.html

[18] "IMO and anthropogenic noise"

https://www.un.org/depts/los/consultative_process/contributions_19cp/IMO.pd f

[19] "IUCN official website"

https://www.iucn.org/

[20] "IWC resolution 1998(6)
https://archive.iwc.int/pages/search.php?search=%21collection72&k=

[21] "ICES cooperative research report " , 2009
http://www.ices.dk/sites/pub/Publication%20Reports/Cooperative%20Resear h%20Report%20(CRR)/CRR299.pdf

[22] Det Norske Veritas (DNV) " silent class notation", 2010
http://www.docsford.com/document/2823195

[23] SILENV Consortium. Green Label. 'Noise and Vibration label proposal', 2012
http://www.silenv.eu/

[24] DR arnab das " acoustic habitat degradation due to shipping in the indian ocean region " in tech open, 2019
https://www.intechopen.com/books/changing-ecosystems-and-their services/acoustic-habitat-degradation-due-to-shipping-in-the-indian-ocean region

[25] PAULA KELLET "Underwater Noise and Marine Wildlife: Current and Future Implication and Assessment" Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, 2014 https://www.researchgate.net/publication/303179352_Underwater_noise_a n arine_wildlife_current_and_future_implication_and_assessment

[26] Bruel and kjaer case studies "Underwater Acoustic Ranging System" https://www.bksv.com/-/media/literature/System Summary/bu3099.ashx?la=en&hash=357E13F9FF8616AF57D20BE2292EF 8 1C15134DCF#:~:text=Underwater%20Acoustic%20Ranging%20System%20 The%20Br%C3%BCel%20%26%20Kj%C3%A6r,acoustic%20stealth%20of% 20their%20submarine%20and%20surface%20fleet.

[27] Savas sezen Mehmet atlar "Numerical Cavitation Noise Prediction of a Benchmark Research Vessel Propeller" research gate, 2015 https://www.researchgate.net/publication/336717443_Numerical_Cavitation_ Noise_Prediction_of_a_Benchmark_Research_Vessel_Propeller

[28] IMO "GUIDELINES FOR THE REDUCTION OF UNDERWATER NOISE FROM COMMERCIAL SHIPPING TO ADDRESS ADVERSE IMPACTS ON MARINE LIFE", 2014 https://www.imo.org/en/MediaCentre/HotTopics/Documents/833%20Guidance %20on%20reducing%20underwater%20noise%20from%20commercial%20s h ipping%2C.pdf

[29] "Ship underwater radiated noise technical report and matrix Submitted by Canada" MARINE ENVIRONMENT PROTECTION COMMITTEE 74th session, 2019

[30] American bureau of shipping "guide for classification of underwater noise",2018 https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/295 - classification-notation-underwater-noise/295-guide-classification-notation underwater-noise-uwn-July-2018.pdf

[31] "ISO official website – ISO17208" , 2016 https://www.iso.org/obp/ui/#iso:std:iso:17208:-2:ed-1:v1:en

[32] "Frequency Limits for Octave Bands, 1/2- and 1/3-Octave Bands" https://courses.physics.illinois.edu/phys406/sp2017/Lab_Handouts/Octave_ B ands.pdf

[33] Hans Hasenpflug, Anton Homm, Stefan Schäl, Layton Gilroy "Evaluation of range standards for underwater radiated noise in beam aspect" ICA2009, 2013 http://pub.dega-akustik.de/ICA2019/data/articles/001481.pdf

[34] ITTC guidelines " underwater noise full scale measurements", 2017 https://www.ittc.info/media/8183/75-04-04-01.pdf

[35] Hildebrand, J.A. 'Impacts of Anthropogenic Sound on Cetaceans'. Sorrento,

Italy, 2004
https://www.researchgate.net/publication/237740051_Impacts_of_Anthropog e nic_Sound_on_Cetaceans

[36] "INTERNATIONAL REGULATIONS FOR THE SAFETY OF FISHING VESSELS" from IMO website
https://www.imo.org/en/About/Conventions/ListOfConventions/Documents/Consolidated%20text%20of%20the%20Agreement.pdf

[37] IUCN – Wikipedia page

https://en.wikipedia.org/wiki/International_Union_for_Conservation_of_Natur

e [38] ICES – Wikipedia page

https://en.wikipedia.org/wiki/International_Council_for_the_Exploration_of_th e Sea

[39] IWC – official website
https://iwc.int/home

[40] Christian Audoly and Valentin Meyer " measurement of radiated noise from commercial ships and influence of sea reflection coefficient on Lloyd mirror effect " acoustics, 2017
https://www.acoustics.asn.au/conference_proceedings/AAS2017/papers/p31 . pdf

[41] Paul C. Etter "Underwater Acoustic Modelling and Simulation: (Fifth Ed.)", 2018
https://www.researchgate.net/publication/215514525_Underwater_Acoustic_Modeling_and_Simulation

[42] Bo zhang, Yang xiang "Study on prediction methods and characteristics of ship underwater radiated noise within full frequency" Elsevier, 2015
https://www.sciencedirect.com/science/article/abs/pii/S0029801818306905

[43] T. Gaggero, E. Rizzuto, F. Traverso, A. Trucco "COMPARING SHIP UNDERWATER NOISE MEASURED AT SEA WITH PREDICTIONS BY EMPIRICAL MODELS", 2014
https://www.researchgate.net/publication/269629700_Comparing_ship_underwater_noise_measured_at_sea_with_predictions_by_empirical_models

[44] "AQUO underwater noise patterns ", 2015
http://www.aquo.eu/

[45] V. M. Kumbhar, 2 S.S. Jagdale, 3 R. K. Shastri Department of E&TC, VPCOE, Baramati UNDERWATER SHIP RADIATED NOISE MODEL technical research organisation India, 2015
https://www.researchgate.net/publication/313839552_UNDERWATER_SHIP_RADIATED_NOISE_MODEL

[46] Mikko Köykkä “Modelling of ship structure-borne underwater radiated noise” Aalto university, 2015
https://aaltodoc.aalto.fi/bitstream/handle/123456789/20515/master_K%C3% 6ykk%C3%A4_Mikko_2016.pdf?sequence=1

[47] Andrew M. Patterson; Jesse H. Spence; Raymond W. Fischer(2013) “Evaluation of Underwater Noise from Vessels and Marine Activities” IEEE/OES RIO Acoustics, 2013

https://www.researchgate.net/publication/259331456_Evaluation_of_Underwa ter_Noise_from_Vessels_and_Marine_Activities

[48] National physics laboratory “ good practice guide for URN measurement
https://www.npl.co.uk/special-pages/guides/gpg133underwater

[49] Bureau Veritas “NR 614 Underwater Radiated Noise (URN)”, 2018
http://erules.veristar.com/dy/data/bv/pdf/614-NR_2018-07.pdf

[50] Sipilia tuomas ,Viitanenn villi and Uosukainen Scppo “shallow watereffects on underwater noise measurements “ MADRID noise control for better environment, 2019

http://www.sea
acustica.es/fileadmin/INTERNOISE_2019/Fchrs/Proceedings/1707.pdf

Reference Link:

To support documentation to this research note that covers all aspects of underwater radiated noise management in ship is available for reference.

https://drive.google.com/drive/folders/1ZQYX4K_sYy-dYYjkksFzBzpjSpBzrV x?usp=sharing