Research Note

Noise & Vibration Management on-board Marine Vessels

Onkar Randad, UDA Project Fellow, Dr. (Cdr) Arnab Das, Founder & Director
Maritime Research Centre (MRC), Pune

1. Introduction

Noise and Vibration (N&V) on-board marine platforms is a critical research area that has multiple applications to it. The first is the crew comfort on-board the platforms that would determine the health hazards for the crew and passengers due to long and short exposure to the running machinery noise. The second is the Condition Based Preventive Maintenance (CBPM) or failure analysis that ensures optimum availability of the running machineries for sustained operations of the platform over long periods of time. The third is the Underwater Radiated Noise (URN) management aspect that impacts the marine mammals or the acoustic stealth of naval platforms. All these aspects need to be understood and we need to find the similarities and diversities in all of them. One may also make a clear distinction between naval warships and merchant vessels while attempting to undertake N&V management on-board marine vessels.

The noise is the sound or pressure wave that propagates in the fluid medium, whereas the vibration is the mechanical oscillations that propagates in a solid medium. The noise can induce vibrations and vice-versa, but the intensity is greatly reduced at the medium boundary and may become insignificant. The origin of both is the running machinery operations, however the manifestations are varied and even transmission mode is diverse. The marine vessel represents a very complex system of N&V sources determined by the operation of numerous on-board installations and specific activities of crew and passengers.

The N&V management on-board marine vessel has multiple dimensions, right from the measurement & analysis, transmission path through the diverse medium characteristics and then the coupling with the water medium for conversion as Underwater Radiated Noise (URN). Multiple stakeholders have their specific application related requirements and demand their own management protocols. The diversity of stakeholders and supply side aspects translates to certain regulatory frameworks and best practices to standardize the operations and other management issues.

The real field measurement and analysis can never capture all the diversities of source-path-receiver model and thus modelling & simulation is inescapable. There are multitude of models developed by researchers for specific problem solving requirements and are limited their applicability across other users. The development of new high-end science & technology tools and measures across other applications and sectors may have potential to significantly boost our own research efforts. Thus, there is a serious opportunity to review the available literature to establish the state-of-the-art and then build the research directions before we finalize our aim and scope of the project. This research note is an exercise to establish the comprehensive problems that can add value to the efforts at effective N&V management on-board marine vessels.

1.2 Evolution of N&V Studies

Noise and vibration study is a crucial part of multilateral industries and practices. The first studies on shocks and vibrations were carried out at the beginning of the 1930s to improve the behaviour of buildings during earthquakes. We have come a long way now and there is merit in understanding the entire process of evolution of N&V measurement & analysis, protocols, standards and more. We have tried to put the evolution is a chronological order:

(a) In the early 1900s, most vibration measurements were made using mechanical or optical devices. With mechanical devices only measurable parameter was peak-to-peak displacement with the advent of electronics in the 1920s, transducers that converted mechanical into electrical signals were developed. In 1917, AT&T produced a sound-level meter [4].

(b) Electronic instruments for measuring vibration on industrial rotating machinery did not become readily available until the late 1940's and early 1950's, although the significance and importance of measuring vibration as an indicator of machinery condition had been well known for decades. In 1950, Swept sine tests were introduced to simulate variations in engine speed, or to excite all of the resonance frequencies of the test item [4].

(c) In the late 1960s, with the advent of powerful computers, the acoustical finite element method (FEM) became feasible. The FEM has been widely used to study the acoustical performance of elements in automobile mufflers and ship cabins [5].

(d) Statistical energy analysis was introduced in early 1960s. Since its introduction, SEA, has gained acceptance as a method of analysis for structural acoustical systems [5].

(e) First Sound Level Meter (SLM) standard, IEC 123 were published in 1961. First handheld sound level meter used transistor technology. Until the late 1970s, frequency analysis mostly was carried out with dedicated instruments that incorporated analog filters. Standard **IEC 60651:1979** emerged for Specification for sound level meters in 1979. Emergence of microprocessors and storage data in 1980s reduced size of sound level meters. The 1990s saw the growth of digital signal processing, which, combined with greater computing power made it possible to process more data in real-time [4].

(f) With digital signal processing, real-time 1/3-octave band frequency analysis became a possibility, measuring all frequency bands simultaneously. As digital signal processing became widespread among SLM providers, more detailed analyses like FFT became possible in a handheld platform [4]. Development of vessel-based AIS (Automatic identification system) transceivers (developed in 2009) and information platforms made data acquisition for vibrational analysis more readily available [5].

(g) Modern SLMs can even connect wirelessly to Wi-Fi networks, making remote control from a smartphone possible, along with cloud-based services for data storage and sharing [4].

(h) The two most widely distributed documents concerning ship board noise are IMO's Resolution A.468(XII), "Code on Noise Levels On-board Ships," issued in 1981 and the USCG's Navigation and Vessel Inspection Circular (NVIC) 12- 82, "Recommendations on Control of Excessive Noise," issued in 1982 [6].

(i) Methods for acoustic modelling of shipboard noise have been available since the early 1980s. Developed and published by the Society of Naval Architects and Marine Engineers (SNAME) [6].

(j) “SNAME Design guide for shipboard noise control” was published in 1983 provided noise prediction methodology to predict shipboard noise levels based on design information. In SNAME guide, each marine source level is described by equations based generally on operating speeds, mass, type of equipment, operating speed relative to design speed, and so on. Similarly, equations and tabular data are used to describe losses along both airborne and structure-borne paths [7].

(k) A more recent supplement to this guide was issued in 2000 by Fischer and Boroditsky. The supplement added new noise calculation algorithms including propeller-induced noise, structure-borne noise paths, and mechanical source updates. The drawback of this approach is that each compartment of interest requires an independent calculation from each influencing source and each potential path, which is a laborious process [7].

(l) HVAC Noise modelling methods are being developed since 1980s. The noise prediction methods are mostly all empirical approaches wherein each element in a ducted HVAC system produce and/or attenuate a certain sound power level. The methodology involves simply adding the sequential set of sound power or sound attenuation to come up with a resulting sound power level coming out of the diffuser. These methods account for sound generation both by the system fan and by flow within the ducting system, with such noise only being generated at turns and branches. Numerous organizations including SNAME and ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) are working on HVAC modelling [5, 7].

(m) In Seiler & Holbach (2013) the A-weighted sound pressure level is put under discussion to check, if it is still a suitable parameter for the judgment of the overall noise comfort on board. They concluded that A-weighted SPL is best valid parameter [8].

(n) Stritzelberger (2013) proposed an alternative method to the classical FEA/SEA (Finite Element Analysis/Statistical Energy Analysis) based numerical approaches, namely the wave-based Energy Finite Element Method (EFEM). This method is capable of handling big sized/high frequency models [8].

(o) Boroditsky & Fischer (2012) presented an algorithm based on the Smith’s transfer function prediction procedure, relating the vibration response to an airborne noise excitation [8].

(p) Software and tools like PULSE from B&K & WAVE6 from Dassault systemes are used for noise modelling and data analysis. PULSE 14 is latest software from B&K for base measurement and analysis and Wave6 software from

Dassault provides unique Analysis Methods for efficiently and accurately simulating noise and vibration across the entire audible frequency range. [9].

1.3 Purpose of N&V Study on-board Marine Vessels

The marine vessel is a complex mix of equipment and fittings on-board with varied level of exposure to the operating environment and also inter-connections with other machineries. The N&V studies mean different things to different stakeholder on-board the platform. It may be important to understand the varied requirement of studies based on the stakeholder expectation. We discuss the purpose of study:

Crew Habitability

Shipboard noise can cause discomfort to passengers and hearing damage to the crew and in this regard the demand for a safe work environment is growing both from the regulatory perspective and also the operators. Permanent hearing loss is one of the most common disabilities among sailors. For 1999, the hearing compensation claims paid to veterans totalled $291.7 million, and for 2004 this number increased to $633.8 million. Given the enormity of the increase in spending by organizations, noise source identification and mitigation are of utmost importance. International, national, and local criteria exist for habitability noise, habitability vibration, and underwater radiated noise [5]. There is growing demand to identify and contain on-board noise.

Fatigue Failure of Equipment

Fatigue and fracture are significant failure modes of ships. Fatigue and fracture became significant in the middle of the twentieth century. Well known are brittle fractures of several standard ships such as Liberty freighters and T2-tankers built during the Second World War, where material with low fracture toughness was used. Enlarged local loads acting at super tankers built in the 1960s and 1970s exaggerated the problem of fatigue failures, resulting in thousands of cracks in several ships after few years of service [5].

Propulsion-induced loads and vibrations are among main causes of fatigue on ships. Higher frequent loads caused by engines and propellers result in forced vibrations with high number of load cycles, are main cause of fatigue. The majority of past fatigue failures can be attributed to wave-induced loads, particularly in structural members at the ship’s sides and longitudinal members of the hull girder, particularly on deck [5].

Condition Based Preventive Maintenance (CBPM) is a term often used as a mechanism to minimize the fatigue failure on-board marine vessels, where the N&V measurement & analysis can precisely identify the maintenance requirements. CBPM enable’s optimization of the maintenance schedules for on-board running machineries and prevents break down of critical and high value equipment.

Acoustic Stealth of Warships

Excessive noise can cause concern to acoustic stealth required for military purposes such as to avoid detection by sonars deployed by their adversaries and also to minimize risk of triggering acoustic mines [5]. There is merit in managing the N&V on board to contain the overall Underwater Radiated Noise (URN). The URN is critical for managing both Acoustic Stealth of military platforms and also Acoustic Habitat Degradation for all forms of marine vessels in the water. The navies throughout the world give very high priority to Acoustic Stealth and post the World War II, massive progress has been made in acoustic stealth.

1.4. Noise and Vibration Management

The modelling of on-board noise analysis for ships requires three key elements namely the “Source”, the “Path”, and the “Receiver”, and the procedure is described as **Source-Path-Receiver modelling** [10].

Sources- are the equipment which generates airborne noise and structure-borne noise, such as main engines, propellers, compressors, and fans. **Path**- are the air, fluid, or solid structures such as decks and bulkheads through which sound propagates. **Receivers**- are the compartments of interest, such as crew cabins, workspaces, and offices. [11]

This modelling scheme takes three key elements into consideration: **noise sources, transmission paths, and the receiver acoustic characteristics.** Empirical methods and numerical analysis methods can be used to calculate the sound attenuation from Sources to the Receivers through different transmission Paths [11].

The recommended way to meet noise and vibration criteria is to undertake noise and vibration analyses early in the design process and apply appropriate controls to mitigate areas of potential concern. Noise and Vibration management is crucial on ship for the CBPM and improving habitability in spaces as per guidelines by regulatory bodies. Noise and **Vibration management plan should include** [5]:

(a) Identifying sources of noise and vibration.
(b) Modelling noise and vibration within the vessel.
(c) Calculation of exciting forces (frequency and amplitude).
(d) Modelling the source-path-receiver phenomenon.
(e) Using this information to review the existing design for opportunities to improve noise and vibration levels.

Source of Noise On-board

On-board ship noise generating machinery contains equipment for heating, ventilation, air-conditioning, main engine, generator, bow thruster, and the HVAC system [5]. Each of these have their unique mechanism for generating and transmitting the noise.

The principal mechanisms that generate vibratory forces involve mechanical imbalance, electromagnetic force fluctuations, impact, friction, and pressure fluctuations. The classes of machinery that produce noise may be categorized according to their functions, such as:

(a) **Propulsion machinery** (diesel engines, steam turbines, gas turbines, main motors, reduction gears, etc.).

(b) **Auxiliary machinery** (pumps, compressors, generators, air-conditioning equipment, hydraulic control systems, etc.)

Each machinery noise source generates both airborne noise and structure-borne noise. The major cause of underwater noise are the main propulsion engines [5, 11] with their unique noise and vibration generation mechanism. Some are discussed below to better appreciate the characteristics:

Slow Speed Diesel Main Engines

Slow Speed Diesel engines are usually selected as the main engine in large cargo ships for reasons of power and economy, however, they usually have significant imbalances at several frequencies, and as they have to be bolted directly on to ship structure due to their invariably large size and mass, vibration excitations can be fully transmitted into the ship. This type of engine is direct drive to the propeller shaft, i.e., there is no gearbox. Hence, engine crankshaft frequency and propeller shaft frequency are the same. ‘Slow speed’ usually implies an operating RPM that is somewhere in the region of 70 to 130 RPM [12].

Medium and High-Speed Diesel Main Engines

Medium speed diesel engines operate in the region of 500 RPM and high-speed diesel engines in the region of 1000 RPM, through reduction gearboxes to the propeller shaft. They are significantly smaller and lighter than slow speed diesel engines. Engine manufacturers normally state for these types of engines that there is no significant external imbalance that could affect overall ship vibration, and they normally specify resilient mounts together with suitable system connections [12].

Diesel Electric and Auxiliary Machinery

Electric motors do not constitute a significant source of vibration within the frequency range applicable to overall ship vibration [12].

2. Measurement and Analysis

Noise is often produced by the radiation of sound from vibrating surfaces. The noise can be related by a physical transfer function to the surface vibration. Analysis of the noise and vibration signals is usually done to extract parameters that best characterize the signals for the purpose of the practical application [5]. In some cases, it is necessary to study the resonant response of excited structures or systems to which the signal is applied. In such cases, simple signal strength is not the only important factor, but also how the noise and vibration is distributed with frequency. Hence, frequency analysis by Fourier transform techniques and filters is often used [5].

2.1 Measurement Parameters

Measurement of noise and vibration is crucial for studying the effects of noise on board and link it to intensity of vibration of individual equipment. Vibration can be measured in displacement (± mm), velocity (± m/s) or acceleration (± m/s^2). Displacement tends to emphasise the lower frequencies, whilst acceleration emphasises the higher frequencies [13]. Some of the noise parameters are:

(a) **Sound Pressure Level, L_p** Sound pressure level (SPL) or acoustic pressure level is a logarithmic measure of the effective pressure of a sound relative to a reference value.[5]

(b) **A-weighted Sound Pressure Level,** L_{pA} the A-weighted frequency filter is used to reproduce the frequency response of the human ear.[5]

(c) **Equivalent Continuous Sound Level, L_{Aeq}** This is the notional A weighted, continuous, steady sound pressure level that, within a specified time interval T, has the same mean square sound pressure level as a sound whose level varies with time.[5]

2.2 Measurement Tools

Sound is measured by a pressure sensing device, usually a microphone, connected to a Sound Level Meter (SLM) or an acoustic analyser. The range of noise levels which can be measured on the modern vessel is between 30 and 130 dB(A) [10]. To account for sensitivity range of the ear, sound meters contain a filter with a frequency response similar to that of the human ear. These are known as weighting filters. If the weighing filter is turned on by using A scale, sound pressure levels are read as dB(A). If other scales are used like C then dB(C) or dB(B), depending on the scale. But dB(A) is relatively easy to measure therefore is used worldwide [1].

Measurements, should be made with an electronic system employing transducers which generate signals proportional to velocity or acceleration. Integrators may be used for conversions of velocity signals to displacement, or acceleration signals to velocity or displacement [5]. Accelerometers, Velocity Gauges, Proximity Probes, Strain Gauges are used, depending on frequency of machine operating.

2.3 Analysis

Analysis of the noise and vibration signals is usually done to extract parameters. These parameters majorly involve rms values that can be used to assess signal strength or the potential of the noise or vibration to cause damage [5]. The type of data that is to be recorded (displacement, velocity or acceleration) depend on the appropriate frequency range. For example, for frequencies measure:

(a) Below 300 rpm displacement is to be measured.

(b) Between 300 rpm and 6,000 rpm velocity is to be measured.

(c) Above 6,000 rpm acceleration is to be measured.

To be able to predict the noise levels due to different classes of machineries, machine specific parameters are required. For a deeper and clearer understanding of the noise being generated in different accommodation spaces, all the different kinds of machineries, whose vibrations contribute to the noise on board should be considered [7]. The engineering estimates for noise prediction requires the following inputs [5]:

(a) Diesel Machines:

- (i) w - the gross weight of the machine.
- (ii) KW - the rated power.
- (iii) RPM - the given rotational speed.
- (iv) RPM_0 - the rated rotational speed.

(b) Reduction Gears: Only the rated power (KW) is required.

(c) Generators: The rated power (KW) and the given rotational speed (RMP) is required.

(d) Pumps: Only the rated power (KW) is required.[5]

2.4 Tools for Analysis

Using the traditional noise model, various engineering estimates have been developed to predict the noise generated by different types of machinery. Source level algorithms are developed considering the transmission path dynamics and using transfer functions which estimates the transmission loss in noise, as it is transmitted from the hull and foundation. These estimates were developed for SNAME (Society of Naval Architects and Marine Engineers) [4]. The analysis tools are:

(a) Data acquisition system software like LAN XI from B&K can be used to get real time data from ship.

(b) Analysis tools like SEA and FEM/BEM are discussed in Noise and Vibration model section.

3. Sound Transmission Path

Transfer path analysis is a procedure based on measurements and has been developed to allow tracing the flow of vibration and acoustic energy from the source, through a set of structure and airborne pathways, to a given receiver location. Acoustic transmission is the transmission of sounds through and between materials, including air, wall and other structural elements [11]. The purpose of path modelling is to calculate the sound attenuation from sources to receiver rooms. Sound can be transmitted from a source to a receiver in 4 ways [11]:

(a) Airborne path where sound propagates through air.

(b) Structure-borne path where sound propagates through the structures.

(c) Duct-borne path where sound is transmitted through the HVAC duct system.

(d) Fluid-borne path.

3.2 Airborne Path

Airborne noise is usually the machinery casing noise. For main engines and diesel engines, besides the casing noise, airborne noise also includes the sounds emitting from air intakes and air exhausts. When airborne sound propagates in a free field, it gradually attenuates over the distance it propagates. However, when it meets a solid object, such as a steel plate, the attenuation increases significantly.

Noise sources producing airborne sound could influence open deck areas and locations close to these openings. Due to the high attenuation of the decks and bulkheads in ships and offshore units, the airborne path is usually a critical factor only within a source space itself and the compartments directly adjacent [11].

3.3 Structure-borne Path

Structure-borne paths often carry acoustic energy to everywhere on the vessel/unit, including remote spaces and spaces adjacent to the area where the source is located [1]. Structure-borne sound will usually attenuate gradually in a continuous structure. However, obstacles or discontinuities, such as deck/bulkhead intersection and frames, can attenuate significantly. The structure-borne noise generated by a machine depends on the characteristics of the source, along with the characteristics of the coupling elements (i.e. the resilient mounts) and the dynamics of the receiving structures [5].

The elements of the structure-borne path in ships and offshore units can be divided into four groups, as listed below. The total structure-borne sound transmission loss from the source to the receiver is the arithmetic sum of all the losses throughout the transmission path [11].

(a) **Structures within the source room** Structure-borne transmission loss from an effective source area to the source room boundary mainly depends on its shape, orientation, and distance to the compartment boundary. For machinery equipment, the effective source area is the deck region immediately below the machinery's foundation.

(b) **Structures beyond the source room** For structures beyond the source room, the structure-borne transmission loss depends on the damping loss factor of the structure, the size of the structure, and the distance from the source to the structure of interest. The larger the damping loss factor and the larger the distance from the source to the structure of interest, the higher the attenuation of the structure-borne sound.

(c) **Intersections of structures** For the intersection of structures, such as the junction of two bulkheads, bulkhead and deck, or a deck and the hull, the structure-borne sound transmission loss can be significant. The transmission loss of the intersection depends primarily on three factors: the shape of the intersection, the plate thickness, and the material. Most intersections of structures are right-angles, cross junctions or T junctions. The higher number of intersections between the source and the receiver along the transmission path, the more the structure-borne sound attenuates.

(d) **Pillars** Pillars usually act as a rigid coupling between decks at most frequencies of interest. The transmission loss between decks connected by a pillar is almost zero. Therefore, the pillars, especially those located in the vicinity of vibration sources cannot be ignored in the noise analysis as the acoustic energy can transmit through the pillar with almost no dissipation.[11]

3.4 Duct-borne Path

The duct-borne path is where the HVAC system transmits sound from air conditioning equipment such as the Air Handling Unit (AHU) to the duct outlets [11]. When the sound transmits via ducts, it attenuates due to the following six factors, namely Plenum, Silencers, Straight Duct Attenuation, Branches where Flow Divides, Turns where Flow Changes Directions by More than 30 Degrees and End Reflections at Duct Openings.

The total sound attenuation from source to outlet via ducts is the sum of the attenuation caused by the six factors is [11]:

$$T_{duct} = T_{plena} + T_{silencer} + T_{straight} + T_{branch} + T_{turn} + T_{end}$$

3.5 Fluid-borne Path

The hydro-excitation sources such as propeller, thruster, and wave-slap transmit the hydro-acoustic pressure to the hull by water and result in hull pressure force. The fluid load of ships and offshore units can be divided into two major groups:

(a) Ocean water outside the structure.

(b) Fluid inside the structure such as ballast water.

Normally, the effect of the fluid inside the structure on the on-board noise is slight and can be ignored. Although the water will increase the damping loss factor of the structures by several times [11], the damping is still too small to affect the compartment structure-borne noise. Ocean water is recommended to be considered. Although its effect on the high frequency range is slight, it may be significant in the low frequency range [11].

Transmission Path Analysis is crucial for source-transmission-receiver modelling and use of more precise empirical formulas for error minimizing model is crucial. If Transmission losses could be calculated more precisely then errors will be minimized nonetheless. Effect of various structure design on transmission losses can be calculated in early design phase to provide the designer early useful information for structure design and selection of machinery.

4. <u>Standards, Regulations & Protocols</u>

Regulations, standards and laws of the sea are crucial for protecting global shipping, sustainable resource extraction and ensuring safety of seafarers. Regulations concerning shipping are developed at the global level as shipping is inherently international. It is vital that shipping is subject to uniform regulations on matters such as construction standards, navigational rules and standards of crew competence [15].

4.2 <u>Regulatory Bodies</u>

Shipping is one of the most heavily regulated industries and was amongst the first to adopt widely implemented international safety standards. United Nation’s International Maritime Organization (IMO) plays an important role in handling all international maritime affairs with support from the maritime nations of the world. As a specialized agency of the United Nations, IMO is the global standard-setting authority for the safety, security and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented. The International Labour Organisation (ILO) is also responsible for the development of labour standards applicable to seafarers worldwide.

4.3 <u>Standards</u>

A standard is a document approved through consensus by a recognized (standardization) body that provides, for repeated and common use, rules and guidelines. Compliance to standard is not mandatory. Standardization provides a basis for technical/trade agreements and technical regulations [16].

All nations require certain standards be met by ships and other marine structures which fly their flag. A classification society, or "Class", is a non-governmental regulatory association which regulates construction of vessels and offshore structures in the maritime industry. The society is responsible for establishing regulations for the construction and classification of ships and offshore structures [16]. Many classification societies are in operation around the world. The largest are DNV, (Det Norske Veritas), Lloyd's Register, Germanischer Lloyd, Nippon Kaiji Kyokai, RINA and ABS (the American Bureau of Shipping).

Major International Standards for Measurement:

(a) **ISO 4866:2010** Mechanical Vibration and Shock — Vibration of fixed structures — Guidelines for the measurement of vibrations and evaluation of their effects on structures.

(b) **ISO 20283-2:2008** Mechanical Vibration — Measurement of vibration on ships — Part 2: Measurement of structural vibration.

(c) **ISO 20283-5:2016** Mechanical Vibration — Measurement of vibration on ships — Part 5: Guidelines for measurement, evaluation and reporting of vibration with regard to habitability on passenger and merchant ships.

(d) **ISO 10816-6:1995** Mechanical Vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 6: Reciprocating machines with power ratings above 100 kW.

(e) **ISO 17208-2:2019** Underwater Acoustics — Quantities and procedures for description and measurement of underwater sound from ships — Part 2: Determination of source levels from deep water measurements.

(f) **PD 12349:1997** Mechanical vibration guide to the health effects of vibration on the human body.
(g) **IEC 61672 Ed. 2.0 (2013)** Sound Level Meters.

(h) **ISO 3382-1:2009** Room Acoustics. Measurement of Room Acoustic Parameters Part 1: Performance Rooms.

4.4 Protocol

A convention is formal agreement between states and is usually an instrument negotiated under an international organisation. A protocol is one of the ways in which a convention can be modified.

The amendments by protocols are not binding on all the states that have ratified the original convention. The amendments by the protocols are only binding to the states that ratify the new protocol [15].

4.5 Regulations/ Resolutions by IMO

Resolutions are the finalized documents which are accepted by the IMO or any of the main body under IMO. They generally result from an agreement on a recommendation or amendment. Regulation is the management of complex systems according to a set of rules and trends.
No consensus is necessary for establishment of the regulation. The difference between a standard and a technical regulation lies in compliance. While conformity with standards is voluntary, technical regulations are by nature mandatory [15].

Legal Framework for Crew Habitability and Human Fatigue The IMO's 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. Legislation has been introduced to improve the working/living conditions of seafarers, including measures to address fatigue-related issues.

International Labour Organization (ILO), Convention No.180 adopted in 1996 was an important development in improving safety at sea and implementing limitations on hours of work and rest for vessels whose flag states ratified it [14]. IMO published recent document, addresses the human fatigue on-ship concerns (MSC.1/Circ.1598) and listed vibration as cause of fatigue in ship specific reason of fatigue [18]. The ILO Maritime Labour Convention (MLC) 2006, was ratified and came into force in August of 2013 by port States having adopted the Convention. Within the maritime sphere, the ILO provides legal instruments, aimed at protecting and improving seafarers' working and living conditions [16, 17 and 19].

Summary of Major Guidelines and legal frameworks

(a) IMO Resolution A.468 (XII) limits for noise levels in each compartment of the ship -1981.

(b) ILO, MLC 2006.

(c) IMO MSC 83/25/13 – Proposal for protection against noise on board ships. IMO Maritime Safety Committee 2007.
(d) IMO DE 53/10 Amendments of SOLAS regulation II-1/36 and for a revision of the 2007 Code on noise levels on board ships- 2009.

(e) IMO MSC – 337(91) amended in July 2014.

MSC 337(91)
Maritime Safety Committee (MSC), after reviewing the previous regulation from 1981 - "the Code on noise levels on board ships A.468 (XII)" decided to revise it in October 2007. The revision was completed in November 2012 and its amended into effect in July 2014. The purpose of the Code is to limit noise levels and reduce worker exposure. The revised noise limits distinguish between two ship sizes:

(a) 1,600 up to 10,000 GT.

(b) 10,000 GT and above.

The Code applies to new ships of a gross tonnage (GT) of 1,600 and above. The Code is not intended to be applied to passenger cabins or other passenger spaces, except insofar as such spaces are work areas, in which case they remain within the scope of the Code [17].

Classification Society Regulations on Noise
Classification Societies have included in their Regulations, a notation aimed at assessing comfort (the COMF notation) with respect to noise and vibration on board, making on-board comfort more realistic. Ship-owners and shipyards find it convenient to use the standards of classification societies as a set of objective criteria on which to base the shipbuilding contract [23]. The following Noise Standards are frequently used by Classification Societies:
(a) **IMO- MSC 337 (91) (2014)** - "Code on noise levels on board ships". (b)

ISO 2923- (1997), "Acoustics - Measurements of noise on board vessels.

(c) **ISO 16283 (2015)**, in particular Part 4 (Field measurements of airborne sound insulation between rooms) and Part 7 (Field measurements of impact sound insulation of floors).

(d) **ISO 717-1 (2013)**, in particular Parts 1 (Airborne sound insulation in buildings and interior elements) and 2 (Impact sound insulation).

Major EU Directives on Noise

(a) Through its "Green Policy", the European Union has imposed increasingly stringent requirements to reduce the environmental impact of all types of transportation.

(b) This has been accompanied by the emergence of new Directives [23].

Specific Regulations for the control of noise radiated from ships

(a) **2006** - **Directive 2006/87/EC**. The noise generated by a vessel under way shall not exceed 75 dB(A) at a lateral distance of 25 m from the ship's side and the noise generated by a stationary vessel shall not exceed 65 dB(A) at a lateral distance of 25 m from the ship's side, apart from transhipment operations.

(b) **2007** - **EN ISO 14509-2:2007**. This specifies procedures for assessing the maximum noise emitted by powered mono-hull recreational craft of up to 24 metres in length.

(c) **2009** - **EN ISO 14509-1:2009**. This standard evaluates emitted noise using calculation and measurement procedures.

Specific regulations for the ship underwater radiated noise

The emergence of international, national and regional associations for the protection of marine mammals has led to the drawing up of a series of regulations that address underwater radiated noise and its potentially adverse effect on marine life. International Council for the Exploration of the Sea (ICES), Requirement 209 sets a limit to the level of lateral noise radiated underwater by the vessel at 1 m from the ship's side [23]. According to IECS 209 the noise radiated by the ship hull at 1 metre from the hull should not exceed 132 dB. Directive 2008/56/EC comprises an international legal instrument which includes human-induced underwater noise in the definition of pollution [21].

Evolution of Noise Regulations on Ship

Year	Noise on board	URN
1974	SOLAS (Protection against noise)	International Union for Conservation of Nature RESWCC-30638
1975	IMO A.343(XII)	
1981	IMO A.468(XII)	
1990	Comfort class notations	
2002		IECS - 209
2003	Directive 2003/10/EC ILO MLC Convention	
2006	Directive 2006/87/EC ILO MLC Recommendations	

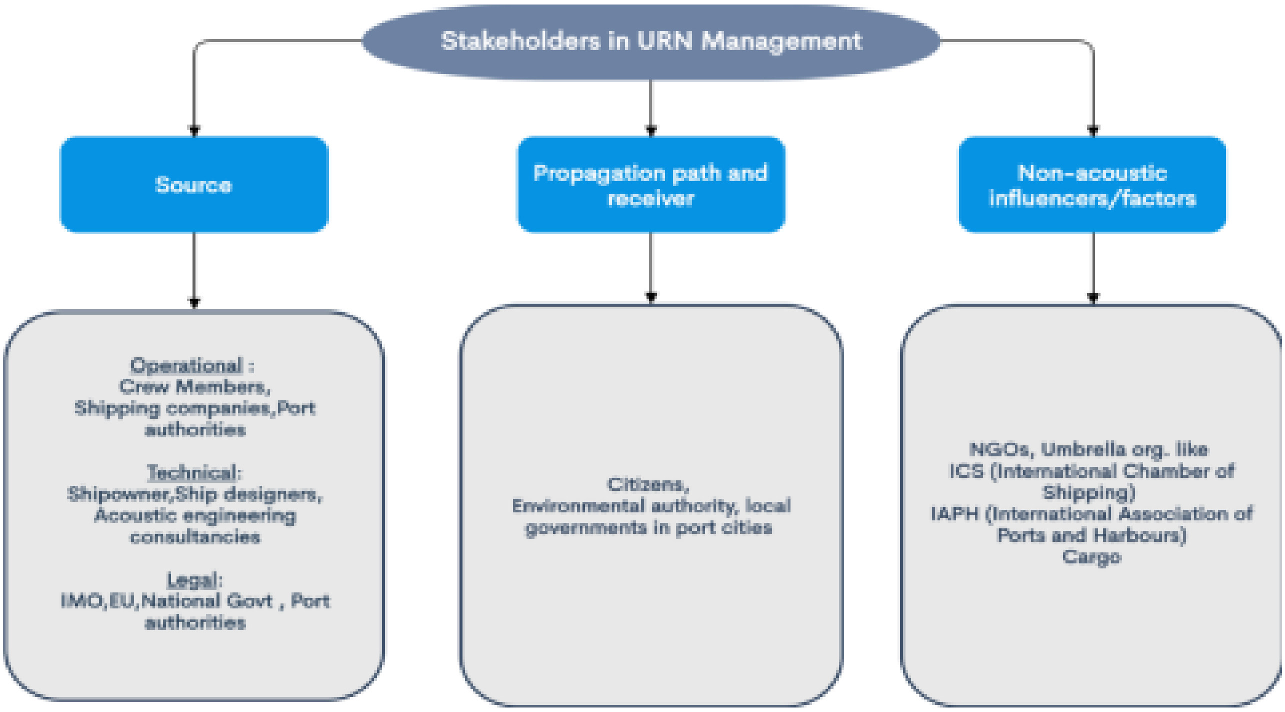
2007	Review IMO A.468(XII)	Directive 2008/56/EC
2009		Silent Class
2012	MSC 337(91)	

5. Stakeholders

When considering ship-generated airborne noise, its impact on the environment and its mitigation, many stakeholders can be identified. We can differentiate between stakeholders on basis of area of influence of noise:

(a) Source.

(b) Propagation path and receiver.
(c) Non-acoustic influencers/factor.



5.2 Broad Applications

Crew habitability and human fatigue on ship

Human fatigue is a common problem in all modes of transportation and maritime transport is no exception. According to the IMO, fatigue can be described as a state of feeling tired, weary and sleepy which results from mental and physical pressure over a period of time. It can be augmented by exposure to harsh environment [5].

The consequences of fatigue at sea are; increased personal injuries, groundings, collisions, health decrement and adverse physiological effects. A high noise level generated on ship not only impacts the hearing. This noise also impacts the body and the way it functions and often the psychological consequences are much worse than the physiological [24].

Noise reduction becomes crucial on marine vessel because, a slight change in the sound pressure level/noise level might have a significant impact on how damaging the noise is, to get an idea about how small noise reduction will improve habitability on ship. It is just as damaging to be exposed to 110 dB for 5 minutes as it is to be exposed to 90 dB for 8 hours [2].

5.3 Failure Analysis

Vibration fatigue describes material fatigue, caused by forced vibration of random nature. An excited structure responds according to its natural-dynamics modes, which results in a dynamic stress load in the material points [11]. The analysis of historical failure data from Lloyd's register shows that general cargo ships have the highest propulsion system vibration defects, followed by oil tankers. The process of material fatigue is thus governed largely by the shape of the excitation profile and the response it produces. Fatigue failure can be minimized by vibrational analysis of machinery and

Optimisation of machinery components' maintenance can majorly contribute to the sustainability and profitability of a vessel. Specifically, this optimisation concerns the selection of aspects from both preventive and reactive (run-to-failure) maintenance for uptime maximisation and cost minimization [25].

Vibrational analysis has been used to non-intrusively diagnose motor and bearing problems without the need to interrupt operation of the motor or drive system. Various motor and bearing problems are known to relate directly to the presence of excessive vibration at frequencies related to the motor speed, typically expressed in RPM (revolutions per minute). For example, vibration at twice (2×) the motor RPM frequency often indicates mechanical bearing looseness. A vibration at a frequency of three times (3×) the motor RPM frequency often indicates misalignment of the bearings as related to the shaft [26].

5.4 Underwater Radiated Noise

It has been recognized that the underwater radiated noise, which has been increasing since the industrial era, has devastating effects on marine habitat. This anthropogenic ocean noise is the cumulative result of the human maritime activities including seismic exploration by the oil and gas industries, military and commercial use of sonar, recreational boating and shipping traffic [1]. Explosives detonated for seismic exploration or scientific research produce noise in a wide spectral range. Military or commercial sonars have frequencies ranging from 0.1 Hz to 30 kHz, generating source levels exceeding 200 dB.

Sound generated by ships is primarily due to hydrodynamic flow, interaction between hull and water and propeller cavitation, is generally in the low frequency range [2]. Low frequency noise i.e., less than 1,000 Hz could affect several marine mammal species, specifically the big whales, whose auditory range overlaps [27]. Over 90% of the world trade is carried out through commercial vessels. Therefore, it is of utmost importance for the marine engineers to reduce the ship's radiated noise in order to protect the marine habitat from devastation and also to enhance the military requirement of acoustic stealth [11].

Erbe (2012) developed a simple method to derive a largescale noise map of the oceans, matching AIS data from ships with marine wildlife distribution maps thus providing a tool to establish areas where the underwater noise is - or is not- a problem for different kind of ships. The equation is a simple and useful tool to input shipping noise in modelling the marine environment [8].

Traverso & Trucco (2014) presented a method to measure the underwater noise emitted from a ship, measured from the ship's bow. The method has the advantage to measure the radiated noise directly close to its origin, avoiding the uncertainty connected to the calculation of the transmission loss [8].

5.5 Synergy between CBPM and URN Management

The vibrations measured externally on operating machines contain much information as to their condition, as machines in normal condition have a characteristic vibration signature, while most faults change this signature in a well-defined way. Thus, vibration analysis is a way of getting information from the inside of operating machines without having to shut them down [5]. The analysis of the condition of the equipment based on the machinery data and then planning the maintenance to prevent major break down and enhance the operational efficiency is a very cost effective and efficient way. This process is known as Condition Based Preventive Maintenance (CBPM).

Information about condition of ship is gathered through performance data (often gathered by different sensors and/or tools). The most common conditions measured in CBPM are temperatures, vibration, pressure, noise and lubricant status. CBPM uses vibration analysis as it the most commonly used monitoring technique for rotating equipment (e.g. compressors, centrifugal pumps, motors). Installed vibration sensors monitor axial, vertical, or horizontal movement and send notifications when vibrations becomes excessive [17]. CBPM is an extended version of Predictive Maintenance where automatic triggering alarms are activated before obtaining any breakdown. Multi-variable complex methods and algorithms are being used to satisfy condition whether to apply CBPM [28].

Two main approaches to condition monitoring [5]:

(a) Monitoring the relative displacement of a rotating machine shaft or bearing with a proximity probe.

(b) Monitoring the vibration of the cover of a machine.

In CBPM policy, the predictive threshold is assumed as degradation-based failure that must cut down to an acceptable level for better efficiency. It projects future components health by signal processing techniques that provide decision support for Predictive Maintenance. Real-time prognostics and data acquisition help to predict a sign of possible hazard and prevent them from happening. Most electrical equipment on-board includes embedded sensors or provides data such as temperature, pressure, current power (medium voltage) and switchboards. They are equipped with protection relays, current and voltage transformers or power meters providing comprehensive data. Power transformers can be equipped with embedded temperature sensors [28].

This data is primarily used for ship control and monitoring systems. However, it could easily be made available for external monitoring. Data loggers can be installed for CBPM on-board to collect the data and send it to the remote server through a network connection [28]. The configuration of this communication system will be highly dependent on the number of monitored assets and on the frequency of data exchange. This data can also be used for URN analysis.

Stakeholders in URN noise aspects have to be combined to gain better resource management and synchronous efforts for mitigating risk of habitat degradation, stealth, crew habitability concerns and various guidelines should come out of it.

6. Model Analysis

Historically, sonar technologists initiated the development of underwater acoustic modelling to improve sonar system design and evaluation efforts, principally in support of naval operations. Models originally developed for traditional sonar applications have matured and rapidly evolved over the past several years to support a much more diverse community of users. Underwater acoustic models now serve as enabling tools for assessing noise impacts associated with the installation and operation of marine
hydrokinetic energy devices in coastal regions.

Understanding of sound in the sea into mathematical models that can simulate the performance of complex acoustic systems operating in the undersea environment. Modelling and simulation become crucial in this field because experimental measurements in the physical sciences are generally expensive due to instrumentation and facility-operation costs. In the case of oceanographic and underwater acoustic data collection, this is particularly true because of the high costs of platform operation. Modelling has been used extensively to advance scientific understanding without expending scarce resources on additional field observations [26].

Acoustical modelling needs to account for [5]:

(a) Source noise and vibration levels for critical equipment.

(b) Noise transmitted over airborne, structure-borne, and secondary structure borne paths.

(c) Noise radiating from the structure forming the compartment of interest.

(d) Room acoustical characteristic of the receiver compartment.

6.2 N&V Models

Noise and Vibration Model analysis is crucial for noise and vibrational aspect because it simplifies the complex structural system in simple structure. The shipping industry has relied on empirical models to predict vibration and sound pressure throughout a vessel for many years. Empirical methods have proven useful when the ship to be studied is built of similar material, has similar general arrangement plan and has conventional sources as the numerous ships used to build the empirical models. Furthermore, some shipbuilding companies also used FEM to predict first few global modes of the ship and making sure the different sources would not excite the structure with the same frequencies to avoid major resonance problems [11].

FEM/ BEM Noise Model

In the late 1960s, with the advent of powerful computers, the acoustical finite element method (FEM) became feasible. In this approach the fluid volume is divided into a number of small fluid elements (usually rectangular or triangular), and the equations of motion are solved for the elements, ensuring that the sound pressure and volume velocity are continuous at the node points where the elements are joined [5].

The FEM has been widely used to study the acoustical performance of elements in onboard machinery e.g. propulsion system like diesel engine and crew cabins. The first indication that the FE approach could be applied to acoustics came with pioneering work by Gladwell, Craggs, Kagawa, and others in the late 1960s and early 1970s [5].
The Boundary Element Method (BEM) was developed a little later than the FEM. In the BEM approach the elements are described on the boundary surface only, which reduces the computational dimension of the problem by one. This correspondingly produces a smaller system of equations than the FEM. BEM involves the use of a surface mesh rather than a volume mesh.

Boundary element results can be viewed and assessed in a number of different ways. The BEM matrix solution only computes the acoustical quantities on the surface of the boundary element mesh. Thus, only the sound pressure and/or normal velocity is computed on the boundary using the direct method.

FEM & BEM Comparison

Computations with FEM are generally less time consuming than with BEM. In BEM model, noise sources can be modelled as a point source, if they are acoustically small (i.e., the dimensions of a source are small compared to an acoustic wavelength) and omnidirectional.

For sound propagation problems involving the radiation of sound to infinity, the BEM is more suitable because the radiation condition at infinity can be easily satisfied with the BEM, unlike with the FEM. However, the FEM is better suited than the BEM for the determination of the natural frequencies and mode shapes of cavities [5].

SEA Noise and Vibration model

Statistical Energy Analysis (SEA) is commonly used to study the dynamic response of complex structures and acoustical spaces. SEA method is increasingly used in the marine sector to design interior insulation, SEA can be applied on a wide frequency range from a few hundred hertz to 10,000 Hz.

A statistical approach is used in SEA to develop a prediction model. The properties of the vibrating system are assumed to be drawn from a random distribution. This allows great simplifications in the analysis, whereby modal densities, average mobility functions, and energy flow analysis can be used to obtain response estimates and transfer functions [5].

A SEA program's ability to consider in a single framework, a large, three-dimensional complex array of sources, structural elements, and their interactions is beneficial. The ability to accurately predict noise levels in a multitude of compartments with contributions transmitted over the airborne and structure-borne path from every significant source has a great potential for noise control. The use of automated computer programs has also greatly improved the speed of calculation, thereby doing away with worksheets and notebook calculations discussed in the above section. Furthermore, SEA models can typically cover the audio range from low to high frequencies.

The SEA method calculates the diffusion of acoustic and vibration energy in complex acoustic systems using energy flow relationships. It predicts the average response of the structure, which avoids a large quantity of calculations. In the SEA method, the entire structure is considered as a system, which can be divided into a number of coupled subsystems, such as plates, beams, and cavities. Each subsystem represents a group of modes with similar characteristics and a storage of energy.

The SEA subsystems can be considered to be “control volumes” for vibratory or acoustic energy flow [6]. SEA Model building has been greatly simplified by the use of automation [6]. US Navy has built a tool using SEA called Designer NOISE in 2015 for ship noise modelling.

FEM & SEA Comparison

FEM is deterministic analysis on the contrary, SEA is the total opposite of the deterministic analysis. SEA was developed because of the inability of deterministic analysis to model the behaviour of the structure at higher frequencies. SEA does not require as much detail as FEM and has a brief computational time [23].

6.3 Empirical Models

The empirical models are developed based on measured data from laboratory experiments, shipboard investigations and an extensive databank of the vessels. SNAME Model and TNO Cabin are one of the most established empirical models for ship noise. In general, both of them use the same scheme to predict the sound in the receiver location [23].

TNO Cabin In TNO Cabin model, the empirical formulas for structure-borne noise calculation are derived for various equipment. TNO cabin uses the octave band centre frequency ranging from 63 – 2000 Hz. The airborne noise sources taken into account are only the diesel engine. The TNO cabin assumes that the diesel engine noise is masking other airborne noise sources inside the engine room. Moreover, it can contribute significantly to the noise level in a room adjacent to it. This contribution means that if the receiver located in another room close to it, the sound pressure level experienced by the receiver is added by the airborne noise generated from the diesel engine [23].

SNAME Model The range of frequencies of SNAME is the octave band centre frequency from 31.5 – 8000 Hz. In SNAME Model, the airborne noise sources will be measured in sound power level instead of sound pressure level. In the airborne transmission path, the sound power level will be converted into the reverberant and the free field sound pressure level [23]. The structure-borne noise sources are described by the free acceleration levels.

SNAME & TNO Cabin Comparison The small frequency range (31.5 – 2000 Hz) of TNO Cabin imply that it is not suitable anymore, to comply it with the recent regulations of IMO 337(91) range (31.5 Hz – 8000 Hz). TNO Cabin also has less variety of equipment in its empirical model compare to SNAME Model. TNO Cabin assumes that the airborne noise source level in an engine room is only the main engine, neglecting other heavy equipment such as gearbox and electrical motor [23].

Following Table summarise the different models

	Level of details required	**Calculation time**	**Accuracy**	**Frequency Range**

FEM	High	High	High	**0-250 Hz**
SEA	Moderate	Fair	Fair	**>500 Hz**
TNO Cabin	Low	Low	Fair	**31.5 – 2000 Hz**
SNAME	Low	Low	Fair	**31.5 – 8000 Hz**

6.4 Transfer Path Models

Transfer Path Analysis (TPA) designates the family of test-based methodologies to study the transmission of mechanical vibrations. Since the first adaptation of electric network analogies in the field of mechanical engineering a century ago, a multitude of TPA methods have emerged and found their way into industrial development processes [31].

In transfer path analysis, the receiver and sources are normally considered to consist of two different subsystems. In structure-borne transfer path analysis, the two subsystems are assumed to be connected by several quite stiff connections—called the transfer paths. TPA concerns a product's actively vibrating components (such as engines, gearing systems or turbochargers) and the transmission of these vibrations to the connected passive structures. TPA is particularly useful when the actual vibrating mechanisms are too complex to model or measure directly, as it allows us to represent a source by forces and vibrations displayed at the interfaces with the passive side [6].

The noise radiated in water by one machinery item is obtained by summing up the contributions from each transmission path. For paths and, the result depends greatly on the radiation efficiency of the hull, which depends on its geometry and mechanical characteristics and on frequency. In general, for commercial vessels, the vibratory path is the dominant one, followed by the airborne acoustic path. Total machinery underwater radiated noise for the ship is obtained by summing up the contributions from all noisy equipment [7].

Estimation of Noise Transfer Functions (NTFs) can be achieved directly or reciprocally on the account of linearity assumption, if it holds in the frequency bandwidth of interest. The transfer functions for the resilient mount and the interaction between the foundation and the structure can be obtained by experimental testing, numerical analysis, or empirical estimation [32].

6.5 URN Prediction

To be able to predict the noise levels due to different classes of machinery, machine specific parameters are required. For a deeper and clearer understanding of the noise being generated in different accommodation spaces, all the different kinds of machinery whose vibrations contribute to the noise on board should be considered.

Underwater sound is heavily affected by the propeller design rather than choices of the propulsion system and machinery on-board [5]. One of the main sources of radiated noise is the propulsion system machinery. The level of radiated noise depends on the transmission path from on-board noise to the underwater noise. This path is affected by the high level of ship structure details.

Using the traditional noise model, various engineering estimates have been developed to predict the noise generated by different types of machinery. Source level algorithms are developed considering the transmission path dynamics and using transfer functions which estimates the transmission loss in noise, as it is transmitted from the hull and foundation. These estimates were developed for SNAME (Society of Naval Architects and Marine Engineers) [7]. From on-board machinery there are three main transmission paths to URN:

(a) Airborne path.

(b) First Structure-borne path, and

(c) Secondary Structure-borne path.

The latter one is the incident airborne noise diffuses on the boundary surface creating vibration in the hull structure.

6.6 N&V to URN Proposal

Multiple noise sources on-board ship contributes to the URN. The vibration transmission from multiple noise sources will be strongly influenced by the dynamic behaviour of the structure between the source and the submerged shell plates as well as on the frequency response of the shell plates. The vibration of the shell plates causes pressure fluctuations in the water some of which is radiated as sound to the far field [33].

The actual radiation to the far field will depend on the modal pattern at each frequency and the structural properties of the plates. Due to these filtering processes the noise radiation may not necessarily be strongest at locations close to the source causing the vibration and may have frequency dependent radiation causing the noise to vary in strength and frequency content from location to location [33]. The structure-borne noise may spread over large areas. Low frequency noise may be associated with global vibration of large hull areas moving in phase at the same frequency, whereas local vibration modes of smaller hull areas will be more typical for vibration at higher frequencies. For low power vessels or for vessels with firmly mounted machinery,
structural noise radiation may be dominant overall or in parts of the frequency range. Significant machinery sources may be located throughout the length of the hull [33].

The criticality of background noise will depend on the source strength of the ship noise sources in relation to the background noise in the area of observation. The criticality will increase for a relatively quiet ship in a noisy area. Keeping in mind that the theoretical spherical spreading loss will be 40 dB at 100 m distance a relatively quiet ship may struggle with background noise already at a distance of this magnitude whereas a noisy ship may easily be observed at distances many times longer [33].

7.1 Challenges and Gaps in Research

Previous studies of underwater shipping noise provided important details on noise levels from individual ships operating under various conditions. Some of these studies by D. Ross, Arveson and Vendittis, Heitmeyer; investigated functional relationships between radiated noise and operating conditions [1, 36, 37]. These measurements, however, were made on older ships and in narrower frequency bands. Therefore, making direct comparisons with previous studies is not appropriate given that ships reported in this study are newer (built after 1985) and larger ships (>10 000 GT), and acoustic measurements for these ships cover a wider frequency band (20–1000 Hz). Because of these prominent differences, we only make general comparisons with previous studies.

Lack of an open database of the ship parameters required for the URN study is crucial problem because most of ML models require extensive data for training and most of data in this field is not available for general research purpose. Many organizations like IBM, Microsoft provides data required for training models for general purposes. Lack of such repository is bottleneck in automation process.

Effects of choice of propulsion system on underwater radiated noise in early design phase are not well analysed. Consequences of early design choices for the propulsion system on the underwater noise needs to be done as there is a strong correlation between the structure-borne noise and the underwater noise.

7.2 Direction of study

The motive of our study of the noise and vibration on-board, underwater radiated noise and the connection between them, has largely been to combine their applications into a GUI software. This will lead to the automation of the whole noise and vibration study. Noise and vibration analysis require data processing and data science algorithms. The automation of the whole process of N&V analysis can make the whole process very efficient. It would become more efficient if the data required as input can be directly imported from hardware i.e. measuring instruments into the software. Data acquisition software is used for such purposes. It begins with the physical phenomenon to be measured like sound pressure levels, vibrations, etc. SPL measured through hydrophones.

7.3 Research Problems

(a) Identifying different noise generating sources and model them in Source Path-Receiver modelling and link the on-board noise with underwater radiated noise.

(b) Noise and vibration analysis of significant noise making equipment on board.

(c) Analysis of acoustic transmission path and impact of ship structure design in transmission path.

(d) On-board noise impact on underwater radiated noise and study transmission paths from on-board noise to underwater noise.

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To support documentation to this research note that covers all aspects of noise onboard ship is available for reference.

https://drive.google.com/drive/folders/1yjlnG8Wexfl7QxHc2TEcRZewmchXk HoN?usp=sharing