LONG- AND SHORT-TERM SOLUTIONS FOR MITIGATING HAZARDOUS NOISE EXPOSURE AND NOISE LEVELS ON BOARD VESSELS FROM THE SMALL-SCALE FISHING FLEET OF NEWFOUNDLAND AND LABRADOR

by © Giorgio Burella

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Abstract

Fish harvesting in Newfoundland and Labrador (NL) is prominently a small-scale industry. This is an important activity in the rural NL, providing a mean of livelihood and identity to many coastal communities. Fishing is also one of the most dangerous professions both in the province and worldwide, with high incidence of reported casualties, accidents, and injuries. Among many health and safety issues of the fish harvesting profession, elevated noise levels pose a subtle threat. Prolonged exposure to noise is known to induce noise-induced hearing loss (NIHL), and high noise levels are known to reduce the habitability of fishing vessels, increase fatigue, and ultimately add to the risk of accidents and injuries.

This PhD research aims to assess noise-related hazards on the small-scale NL fishing fleet (less than 24 m length overall) and to provide short-term (minimal vessel and gear modification, use of protection devices), and long-term (integration of an acoustic design for noise control on fishing vessels) solutions to mitigate on-board high noise levels and exposures. The research features: a) a comprehensive survey of noise levels and occupational noise exposures on-board a representative sample of 12 vessels, in order to identify the dominant noise sources, measure the in-situ acoustic insulation, assess the compliance with habitability criteria of living spaces and the risk of hazardous noise exposures; b) the study of the perception of risk of noise-related hazards from owner/operators of the fleet; c) the development of a numerical model validated using experimental data for the acoustic transmission and the study of possible noise control interventions to mitigate noise to acceptable levels on a case study vessel. In this research activity a job-based method for noise exposure

assessment was used, as opposed to the task-based method used in other studies on fishing vessels, and the noise components that lead to hazardous noise exposures were identified in order to provide effective solutions to mitigate noise exposure. Furthermore, for the first time state-of-the-art Statistical Energy Analysis (SEA) and graph theory were used to model noise transmission on a small-sized fishing vessel and reveal the dominant noise transmission mechanisms. Based on these findings, effective noise control interventions were proposed and evaluated.

These assessments are necessary to provide recommendations and guidelines, and introduce design and operational criteria to control noise levels on small fishing vessels from NL and worldwide more in general. Indeed, noise control solutions identified in the case-study vessel can be used on similar vessels, and the numerical method based on SEA as shown in this research can be applied to design of noise control on new vessels.

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Chapter 1

Introduction and overview

1.1 Problem statement

Fish harvesting is one of the most dangerous professions worldwide, with a high incidence of accidents, injuries, casualties, and vessels losses (1–3). Occupational health & safety (OHS) issues are a matter of concern for various industry stakeholders. This is also true for the fishing industry in the Canadian province of Newfoundland and Labrador (NL). Action to enhance safety in the industry led to the establishment of the Newfoundland and Labrador Fish Harvesting Safety Association (NL-FHSA) in 2012 by a co-operative effort from the NL provincial government, regulatory entities and industry representatives. NL-FHSA has a mandate to "lead the promotion of safety education and awareness initiatives in the harvesting sector of the provincial commercial fishing industry" (4). Pursuing its mandate, the association reached out to fish harvesters and owner/operators during community meetings and safety symposia to identify concerns for perceived health and safety issues and occupational injuries.

An identified outcome was that *hearing loss*, resulting from many years of *exposure* to *high noise levels*, was a concern among them. The importance and incidence of noise-induced hearing loss (NIHL) is also highlighted by the high number of hearing loss claims for compensation, making the fish harvesting sector the highest for number of claims (5). Then, NL-FHSA engaged Memorial University of Newfoundland to develop a research program on the topic of noise hazards on board small-scale fishing vessels. The collaboration led to a research project, which is the topic of this doctoral dissertation, conducted by researchers from the Faculty of Engineering and the SafetyNet Centre for Occupational Health and Safety at Memorial University to a) document occupational noise exposures on board small-scale fishing vessels from the NL fishing fleet, and, b) provide short- and long-term solutions for this issue.

This research activity is part of a wider multi-disciplinary effort to increase fish harvesting OHS that: a) investigated the influence of human and design factors in fishing vessels capsizing (6), and; b) the correlation between marine forecasts and owner/operator decision-making (7).

1.2 Overview of OHS of the fish harvesting profession

Fish harvesting at sea is an important profession that employs a large amount of workforce worldwide. United Nation's Food and Agriculture Organization (FAO) (8) has reported that there are more than 4 million professional fish harvesters globally working on the biggest commercial fleet of the world, and this number is constantly increasing over the years. 98%

of the total fleet of fishing vessels were less than 24 m length overall (LOA) (8) in 2016. Small-scale fisheries in 2004 were catching 45% of the total catch while the remainder was taken by industrial fisheries (9). It should come as no surprise that small-scale fishing enterprises employ an enormous number of people and that coastal communities largely depend on this source of livelihood.

Fishing is one of the most dangerous occupations, and there are still many improvements to be made to enhance working conditions and safety on board fishing vessels, which are mobile workplaces and have to be designed according to safety and habitability criteria (10, 11). Petursdottir et al. (12) estimate that 24,000 fatalities occur worldwide per year in fisheries, with fatality rates ranging from 3 to 30 times higher than national averages for the overall ensemble of workplaces. High incidence of injuries are linked to detrimental effects for the economic viability of fisheries, and the well-being, social integrity, and ultimately the very survival of coastal communities (13). Percin et al. (14) highlighted that poor working conditions on small fishing vessels often impact the health of fish harvesters worldwide, and that their improvement is essential to reduce occupational injuries and improve worker health, especially by including human, health factors, and the management of hazards into the design and construction of the fishing vessels.

International bodies and agencies have struggled to get a satisfactory minimum safety level. The international regulatory framework for fishing vessels is highly fragmented, depending on the length of the vessels, and often not mandatory. Indeed, for fishing vessels between 12 and 24 m LOA, the International Maritime Organization (IMO) created the Voluntary Guidelines for the Design, Construction, and Equipment of Small Fishing Vessels (15). Guidelines for the safe operations of fishing vessels under 12 m were published by FAO/ILO/IMO (16) in the Safety Recommendations for Decked Fishing Vessels of Less than 24 m in Length and Undecked Fishing Vessels. The last two documents are voluntary guidelines, thus safety regulations for fishing vessels less than 24 m LOA are left to regional and national bodies.

Safety on fishing vessels has been recognized as a key issue, and was the subject of several independent research efforts over the last few years. Several scholars focused on the identification of potential hazards, and the assessment of their associated risks in relation to vessel stability and damage (1–3, 17, 18). At the same time, several authors have focused their research on the improvement of safety of fishing vessels, covering a) optimization of fishing vessel structures (19), b) assessment of the seakeeping performance (20–22), and, c) analysis of the vessels stability (23–27). All the aforementioned studies produced indications and criteria that should be incorporated into the vessel design to obtain better performances in these areas.

1.2.1 Safety of the small-scale fishing fleet of Newfoundland and Labrador

Thanks to its proximity to the fishing grounds of the Grand Banks, the Canadian province of Newfoundland and Labrador in Atlantic Canada relies on the fish resources to develop and maintain its rural communities (28). The small-scale fisheries have faced many changes in the last half century. In the past, the industry was mainly manned by seasonal workers

(29). After the cod moratorioum of 1992 the small-scale fishing fleet was heavily limited in the access to key fisheries (30). This had tremendous repercussions on the governance of fisheries (31). Indeed the need to save, rationalize, and make small fishing enterprises economically viable led to a wide reorganization of the small-scale fishing sector (32). Fish harvesters were requested to register as professionals (33), and to be accredited through a formal training program which included safety training (34). Overall, the push for a more professionalized workforce had an effect on the safety culture of NL fish harvesters. A more professionalized workforce led to an increase of the safety culture, safety awareness, and "doing what is right" which is intended as the ability of professional to manage and adapt to unforeseen risks (35). Thus, safety on board fishing vessels under these new fishing policies and industry regime has become a rather important topic among the industry stakeholders. Efforts to quantify and enhance the safety of fish harvesters and fishing operations in the province resulted in development of research studies. Many of these have recently looked into these topic: reports on the state of the safety of fishing operations in terms of frequency of search & rescue responses (36); studies on state-of-the-art national and international safety regulatory frameworks and their effects when enforced (37, 38); analysis of the link between fishing vessel capsizing and operators training (6); and studies on risk factors on the wharves (39). In another set of studies, Murray and Dolomount (40), Power (41) and Power et al. (42) addressed the perception of risks and the state of the safety culture among fish harvesters from NL. They found that even though the workforce has become more aware of safety issues and hazards following their professionalization, the occurrence of accidents and work related injuries was still accepted as an inevitable event in a harvester's professional life (40), and that efforts to change this only resulted in the enforcement of mandatory safety training, leaving the management of day-to-day risks to fish harvesters' common sense and experience (41, 42). In this context, hazard quantification and risk management play a definite role in the prevention of emergencies and injuries, and are key to the shift towards a more safety-minded workforce. Researchers have the important role to engage in guiding and educating the stakeholders and governance of fishing industry on OHS issues (43). Using a community-based approach the knowledge mobilized from these research projects can be added to the existing professional fish harvesters commonsense and day-to-day management of OHS risks and issues.

1.3 Noise-related hazards in fish harvesting

The focus of this doctoral thesis is on hazards related to the presence of high noise levels from a diverse set of sources on board fishing vessels. In this section, the noise hazards encountered by workers in the fish harvesting industry are presented along with reasons why they are an important issue to be addressed. This is done through a comprehensive literature review, that reveals the state-of-the-art knowledge base on these issues and addresses the possible gaps that need to be filled. The research focused on two main identified groups of hazards: a) the noise exposure of fish harvesters during fishing operations at sea, and, b) the presence of noise levels that reduce the habitability on board fishing vessels.

1.3.1 Occupational noise exposures of fish harvesters

Hazardous exposure to occupational noise is associated with the onset of occupational noise induced hearing loss (NIHL). The risk factors for this illness are well known. Documented medical evidence has revealed that prolonged, daily exposure to high noise levels may lead to hearing impairment (44). Hearing loss has been highlighted as a risk factor that impacts the injury and fatality rate among fish harvesters due to reduced ability of perceive their surroundings (45, 46), and is also contributing in reducing the quality of life of the affected persons and their relatives and peers (47). This risk can be effectively reduced by the adoption of a hearing conservation program, aimed to reduce the hazardous exposures. The interventions adopted by these programs should be tailored to the specific case, based on the assessment of the risk and the study of the workers noise exposure (48–50). Since occupational NIHL is a widely recognized hazard in workplaces, the minimum requirements of these programs are usually codified in standards or regulations. In the maritime industry, the International Maritime Organization (IMO) sets the minimum international standard on noise hazards in their Code on Noise Levels on board Ships (51). This standard only applies to large commercial and passenger ships, excluding fishing vessels. While other aspects of safety of fishing operations are treated in other agreements (Torremolinos Protocol and Cape Town Agreement (25)), there is no international instrument to cover noise hazards encountered by fish harvesters. Their regulation is mandated to national governments; for instance, in Denmark noise hazards are covered by the OHS regulation issued by the Danish Maritime Authority (52), and in the United Kingdom fishing vessels are covered under the "The Merchant Shipping and Fishing Vessels (Control of Noise at Work) Regulations" (53). Most national regulatory frameworks do not provide standards for noise hazards on fishing vessels. However they include noise hazards in their general OHS regulations. In Canada, provincial lawmakers are responsible for providing the minimum required OHS standard for all workplaces, including fishing vessels. In NL, it is required for every employer to set up and maintain a hearing conservation program if the 8-hour equivalent noise exposure level $L_{EX,8h}$ is found above 85 dB(A), as set by the provincial OHS regulations (54, 55). It is then mandatory for the employer to abate noise to non-harmful levels via either hazard elimination, or control and provide the workers with appropriate personal protection devices. The first step to comply with such regulation is the assessment of the NIHL risk of employees on the work environment by assessing $L_{EX,8h}$ of workers.

A literature review was conducted to seek the most recent research on the topic of noise exposure of fish harvesters, the associated risk of NIHL, and the identified solutions to reduce the risk. A few research projects have been conducted in terms of noise exposures, audiometric surveys of fish harvesters covering different fisheries, different fishing gear, operations, vessel type, and vessel size from different parts of the world. Fulmer and Buchholz (56) studied the exposure to hazardous noise levels using personal noise dosimeters for Massachusetts small-scale gillnetters and lobster fishers. Neitzel et al. (46) measured the noise exposure and noise levels on board large harvester/processors. They also quantified the effectiveness of hearing protection devices (HPDs) in reducing the noise exposure levels. Paini et al. (57) studied noise exposure and audiometry for fish harvesters from small scale fisheries in Brazil. Levin et al. (45) measured noise levels on shrimp trawlers from the Mexican Gulf and conducted audiometric testing on a sample of fish harvesters. Zytoon (58) studied noise exposure on 24 different vessels from the Egyptian fleet, that included gill/trammels (LOA 12.2 ± 1.2 m), purse-seiners (LOA 15.8 ± 1.3 m), and trawlers (LOA 18.7 ± 3.1 m). Peretti et al. (59) studied noise exposures of fish harvesters, and on-board noise levels on five small to medium size vessels (LOA 14.5 m to 27.32 m) from the Adriatic Sea.

These studies can be subdivided based on the measurement methodology for the exposure surveys:

- Studies that used a task-based method (60), where noise levels associated to specific tasks were combined with the stationing duration of fish harvesters in spaces to obtain the a noise exposure level (46, 46, 57–59);
- Studies that used a full-day measurement via personal dosimetry Levin et al. (45), Fulmer and Buchholz (56), Zytoon (58). In this method, an average equivalent sound pressure level is obtained from a full day measurements using dosimeters from many workers executing a similar job, to obtain the mean $L_{EX,8h}$ of that specific group of workers performing a job.

Comparing the noise exposure levels with a limit over which exposures are considered hazardous provides an assessment of the risk of NIHL. A summary of the ranges of $L_{EX,8h}$s found in literature is reported in Table 1.1. In most cases, the reported noise exposure levels

Table 1.1: Literature values of $L_{EX,8h}$ found on board various fishing vessels per role and type of fishery/vessel found in (45, 46, 56–59).

Fishery/Type of Vessel	Role		
	Skipper	Mechanic	Crew
Trawlers (58, 59)	81 dB(A)–94 dB(A)	83 dB(A)–92 dB(A)	82 dB(A)–100 dB(A)
Gillnetter (56, 58)	84.7 dB(A)	87.1 dB(A)–91.2 dB(A)	81.6 dB(A)–87 dB(A)
Purse Seiner (58)	88.4 dB(A)	89.2 dB(A)–94.3 dB(A)	83.2 dB(A)–85.2 dB(A)
Small-scale vessels (56, 57)	-	-	75.2 dB(A)–96 dB(A)
Catcher/processer (46)	-	-	97.5 dB(A)

were higher than the widely recognized 85 dB(A) limit.

This result is also found by studying hearing thresholds of a population of fish harvesters through audiometry. Paini et al. (57) and Levin et al. (45) confirmed that there is a significant percentage of fish harvesters who are affected by hearing impairment due to noise exposure, and that prolonged exposure to high noise levels on board the fishing vessels can be a risk factor for the occurrence of such disease.

The literature shows that there is a risk for hazardous noise exposures and the occurrence of NIHL among fish harvesters. Though, most of the surveys are limited to specific fisheries, with relatively few types of fishing operations, fishing gear, and species. For small-scale fisheries, the only study available was performed by Paini et al. (57). Most of these studies suggested that continuous noise sources, such as engine(s), auxiliaries and generators have the greatest impact in overall noise exposure composition. The influence of other noise components is either not studied or neglected. Accordingly, the suggested ways to reduce the exposure of fish harvesters usually encompassed the enforcement of either regulation policies on the workplace, the usage of HPDs during noisy tasks, and application of noise control to the prevalent sources. It is also not clear which of the methods for assessing the noise exposure levels should be used in the fishing operations. Indeed, there is no clear indication on which method among task-based and full-day measurements works better for the assessment of exposures of fishing operations.

1.3.2 Continuous noise levels and noise control solutions on board fishing vessels

On-board vessels, continuous noise is generated by steady-state noise sources that run continuously, such as propulsive engine(s), electric generators, and other auxiliary machines (61). Such sources are necessary for the functioning of a vessels, since they provides propulsive and electric power, and thus they have to run continuously. Noise levels generated by continuous sources are found on board during navigation. As for other ship-based jobs, fish harvesting workers may also live on board the vessels during multiple-day fishing trips. While they are on board but off their working shifts, they could be exposed to noise due to continuous sources that is lower than occupational limits of noise exposure, but still detrimental. Indeed, high levels of noise reduce the comfort of rest time, increasing the level of physical and psychological fatigue and make the workplace on fishing vessels more hazardous compared to land-based workplaces (62, 63). If harvesters are exposed to hazardous levels of noise while fishing, they should have access to quieter areas after their shifts (59). Thus comfort and habitability of crew quarters on fishing vessels is a noise-related issue.

The assessment of noise levels on fishing vessels has been the subject of several studies, involving different species harvested, fishing gear, fishing operations, vessel type and ves-

Table 1.2: Literature values for continuous A-weighted sound pressure levels $L_{Aeq}(T)$ on board the fishing vessels found in (45, 46, 56–59, 64).

Space	$L_{Aeq}(T)$
Engine Room	85 dB(A)-111 dB(A)
Crew Spaces	60 dB(A)-83 dB(A)
Wheelhouse/Bridges	70 dB(A)-95 dB(A)
Messroom	64 dB(A)-94 dB(A)
Fishing Deck	71 dB(A)-95 dB(A)

sel size, from all over the world. Most of the studies reported in Section 1.3.1 studied to some extent the continuous A-weighted sound pressure levels $L_{Aeq}(T)$ in spaces of fishing vessels, at different vessel speeds, and due to continuous noise sources (45, 46, 56–59). Rapisarda et al. (64) also studied the sound pressure levels on six different vessels from the Adriatic sea and reported the overall noise levels, noise peak levels, and noise exposure levels from the surveyed cases. The outcomes from all these studies in terms of $L_{Aeq}(T)$s are shown in Table 1.2. These studies generally agree that the main engines are the most significant continuous noise source and highlighted that $L_{Aeq}(T)$s on vessels increase with an increase of engine power.

All of the cited papers agree that $L_{Aeq}(T)$s are high and can pose a hazard for the harvesters on board. However, the studies compared the measured $L_{Aeq}(T)$s with the maximum noise exposure limit. When addressing the noise habitability of a vessel, the common 85 dB(A) noise exposure exceedance criterion is not suitable since it is associated with the risk of hearing impairment and damage of the human auditory systems. There are no relevant criteria for noise habitability of crew quarters in fishing vessels. As already shown in Section 1.2, international level voluntary guidelines exist for the design and construction of fishing vessels, issued by the International Labour Organization (ILO) (16, 65, 66). They suggest general practical procedure to control noise on fishing vessels, however, they do not specify any target maximum noise limit for habitability of crew quarters. Since no mandatory standard is found at international level, the regulation of habitability of spaces on board fishing vessels is mandated to national level. In Canada, there are no national or provincial regulations for maximum admissible noise levels to set a minimum comfort level on board small fishing vessels that are less than 24.4 m LOA and not more than 150 GT (gross tonnes) (67). The only international regulation that sets noise limits in crew spaces is the IMO Code on Noise Levels on board Ships (51), which does not apply to fishing vessels. The Code requires a maximum level of 60 dB(A) in crew spaces, 65 dB(A) in wheelhouses and messrooms, 85 dB(A) for working decks and 110 dB(A) for engine spaces. These criteria represent a valid goal for the habitability of crew quarters for fishing vessels, as suggested by (68). The comparison of the IMO criteria values with the levels found for the state-of-the-art literature in Table 1.2 shows that most of the times there is an exceedance of the maximum acceptable $L_{Aeq}(T)$, identifying an issue of habitability of crew quarters and manned spaces.

In the context of inadmissible on-board noise levels, it is thus necessary to evaluate noise control solutions. An organic and rational procedure for the study of control strategies, which is commonly used on commercial vessels, should include the following steps:

(a) measurements of on board noise levels according to the International Organization for Standardization (ISO) (69). In the case of a new vessel this is estimated based on similar vessels.

(b) characterization and identification of the continuous noise sources on the vessel (70, 71).

(c) building experimental or numerical predictive models for the evaluation of the vibroacoustic behaviour of the vessel structures and identification of hot spots on the vessel (72–74).

(d) identification of design solutions to mitigate the noise levels (75–77).

(e) evaluation of the effectiveness of the selected solutions and the compliance with the noise limits in the different ship areas. This procedure can be either done numerically or experimentally if possible.

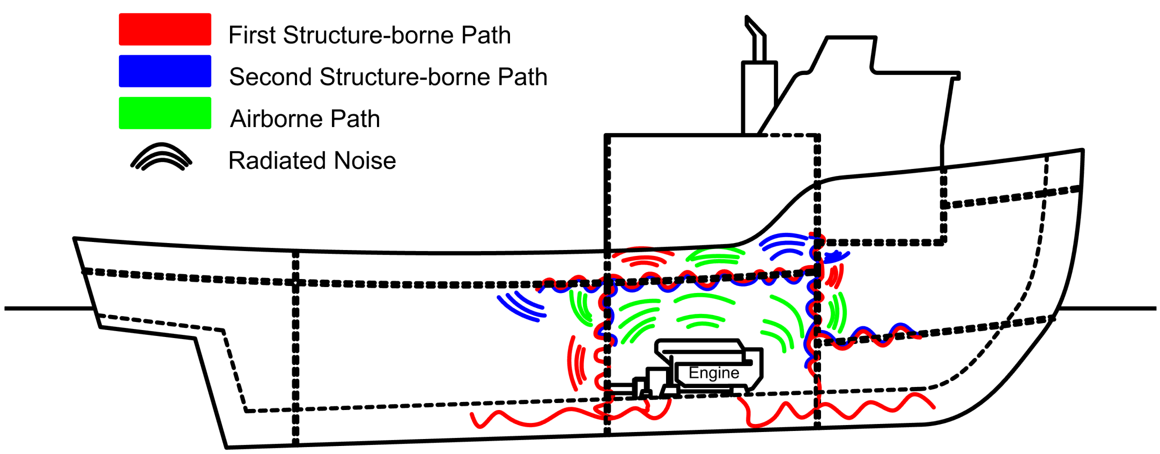

Figure 1.1: Transmission mechanisms from a source (propulsive engine) to spaces on a ship structure.

Understanding and modelling the noise transmission phenomena in fishing vessels structures is a key passage in studying effective noise control strategies. Noise in complex built-up structures can be transmitted both through the structure (structure-borne noise, or SBN), and through the air medium (airborne noise, or ABN) (78). SBN and ABN transmission mechanisms are briefly illustrated in Figure 1.1. ABN generates from sources and might be transmitted directly through the air medium to adjacent spaces, or transformed in SBN through coupling with the space surfaces in what is called second SBN path. SBN generates from sources and is transmitted through the structure, and then radiated in spaces through what is called first SBN path. Depending on the prevalence of these transmission paths, noise control solutions can then be proposed.

Noise transmission, control design, and evaluation, has been studied in few cases for fishing vessels. Both Veenstra (68), Peretti et al. (79) provided studies on the sound pressure levels and transmission characteristics on vessels limited to 16.99 m LOA or longer. They both conducted experimental surveys to explain the ABN and SBN sources contribution in terms of transfer functions, transmission losses (TL) and contribution of sources to overall noise levels. Following these considerations, they provided control approaches to reduce the noise to acceptable levels in the case studies presented. Veenstra (68) provided several noise control packages, based on studies of the transmission paths, but the analysis is limited to vessels above 24 m LOA that usually present several decks and more complex structures than small-scale vessels. Thus the proposed solutions might not work for smaller vessels. Peretti et al. (79) did not implement a thorough modelling approach to investigate the SBN and ABN transmission paths, and focused mainly on means to abate the ABN noise, neglecting the SBN paths.

One of the main issues in addressing a noise control study is to develop reliable models of

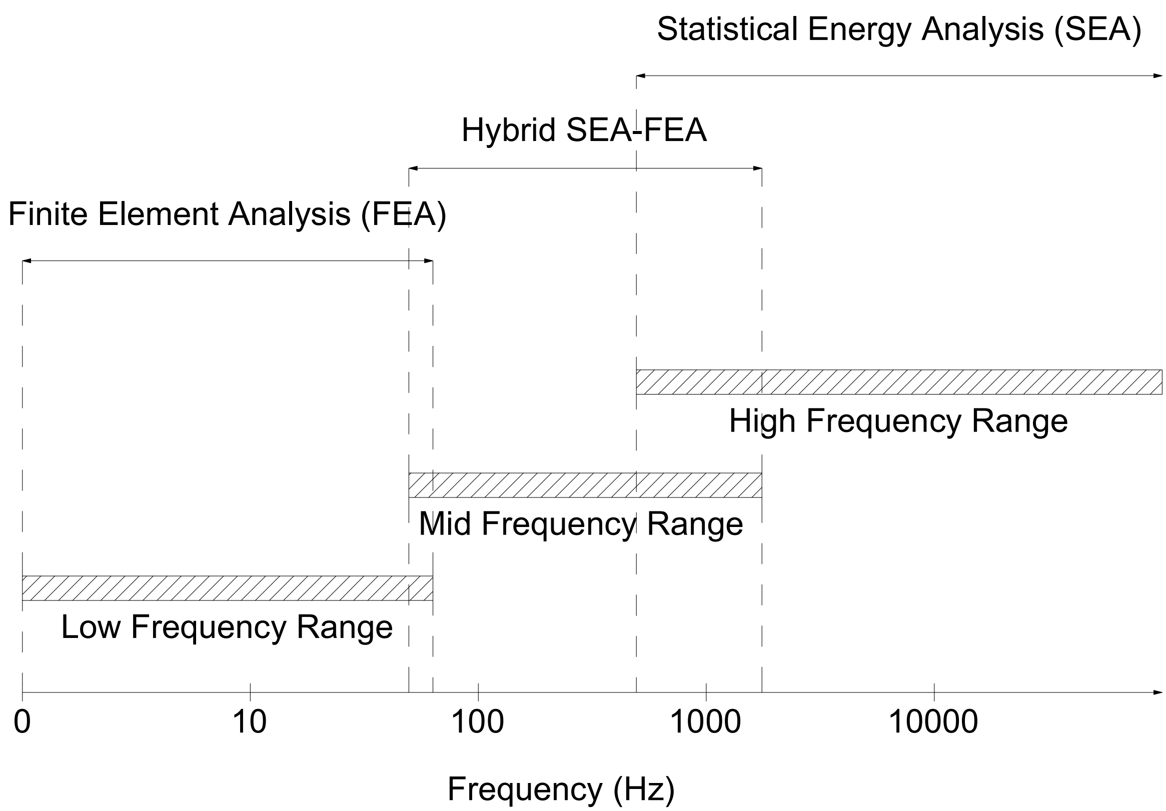

Figure 1.2: Frequency range of vibroacustic predictive models and type of numerical analysis.

the vibro-acoustic behaviour of the fishing vessel. The state-of-the-art numerical and empirical methods have different applicability, based on the frequency range of interest and the vessel type, as shown in Figure 1.2. These methods can be subdivided as follows:

- **Empirical methods**: These methods rely on statistical regressions based on data collected on a sample of similar vessels (72, 80). This approach is the base for the noise control design for commercial ships, and it provides fairly accurate predictions. These methods are limited to large commercial ships. There is no established empirical method for the prediction of noise levels for fishing vessels.

- **Low frequency range** (0 Hz to ≈100 Hz): Deterministic methods, such as Finite Element Analysis (FEA), are used to study the structural response and noise levels of ship structures to forced vibrations (73, 81, 82). FEA is popular in modal analysis of ship structures, and is usually used to study structural vibrations in the low frequency range.

- **High frequency range** (≈1 kHz to 20 kHz): Statistical methods, such as Statistical Energy Analysis (SEA) as developed in the work of Lyon et al. (83), have gained increasing popularity in high frequency vibroacoustic modelling of marine structures (74, 84–90), and is the state-of-the-art for the prediction of noise levels in complex built-up structures.

  Other methods that study the acoustic energy flow use wave energy methods (such as Energy Finite Element Analysis (91, 92)) have been applied to marine structure cases for high frequencies. These methods are less popular than SEA since their development is still quite new and they have not received much development recently.

Frequency range and applicability of these methods might overlap, depending on the type of structure, and the specific case. Overlapping in Figure 1.2 is purely indicative and serves to show this concept. These methods are currently being used in common design practice, and continuously developed to include new cases and extend their field of validity in modelling of the airborne and structure-borne acoustic behaviour of structures. There is not an established method to build predictive models for the so called mid-frequency range

($\approx$100 Hz to $\approx$1000 Hz). In these applications, hybrid SEA-FEA methods are growing in popularity, but are still the subject of research for their range of validity (93–97).

The use of SEA is compelling for building a predictive model that explains the transmission of noise through ABN and SBN paths. Due to the acoustic energy flow approach, it can provide a breakdown of the influence of noise sources on the predicted levels. Furthermore, recent application of graph theories also provides a powerful tool to study the dominance of the transmission paths in the acoustic energy flow from sources to target spaces of SEA models. This tool uses the Martin-Pascoa-Santo's (MPS) K-shortest paths algorithm (98), and the ranking of dominant transmission paths developed by (99).

1.4 Research objectives and contribution

This doctoral research investigates noise-related hazards for fish harvesters from NL working on small fishing vessels less than 24 m overall. In particular, this manuscript focuses on the study of **state of noise exposures** and the **habitability of fishing vessels from a noise standpoint**. Ultimately, this doctoral research seeks to enable the development of:

- **Short-term solutions** to mitigate the risk of occurrence of NIHL by means of *personal protection devices*, and *minimal vessel/gear modification*;

- **Long-term solutions** to increase the habitability of fishing vessels, by means of the design and evaluation of *noise control solutions* on new vessels and in retrofit.

These objectives reflect the need to enhance the OHS of fishing vessel fleet and fish harvesting operations. As reported in Sections 1.2 and 1.2.1, improving OHS of fishing operations worldwide is a major goal driven by international and national stakeholders. Their concern is also reflected in findings from the literature, which showed that the study of these topics is relevant but under-studied. This was found to be especially true for smaller vessels that are often neglected in terms of hazards from noise exposure and that are not designed for noise control.

This doctoral research project contributes to areas that still have not been addressed or are under-studied in the existing literature, as presented below.

- **Experimental study of noise levels, sources, and acoustic insulation on board fishing vessels from the small-scale fleet of NL**

  Noise levels on board have been documented, but thorough studies of noise levels, sources and transmission are scarce and limited to bigger vessels. Furthermore, the study of noise levels has been mostly performed in a noise exposure assessment context, rather than a noise control context. This is the first step in understanding the vibro-acoustic transmission phenomenon on-board the fishing vessels and it provides an assessment of the hazardousness of continuous sound pressure levels, and their impact on the habitability of crew quarters of the NL small-scale fishing fleet. This study covers a wide variety of fishing vessels so that the characterization is as general as possible.

- **Assessment of the awareness of owner/operators from the NL small-scale fleet regarding on-board noise exposure**

It is important to assess the awareness of the owner/operators of the vessels on the risks and state of the noise exposure on board their vessels. This assessment helps understanding the extent of the knowledge of industry operators on the problem, and how to address the development of short-term solutions and the dissemination of results to the wider audience of owner/operators from the NL small vessel fleet. In the chapter, this aspect is studied via structured questionnaires administered to vessels owner/operators.

- **Assessment of noise exposure of fish harvesters from the NL small-scale fleet**

  The noise exposure of NL fish harvesters has never been studied before, and a characterization of the risk is necessary. The subject fisheries are varied and provide an opportunity to study different type of fishing operations, gear and vessel type/lengths. It is unclear from the available literature what noise components have a dominant role in the overall exposure: is it mainly affected by the continuous noise sources such as the engine machinery, or is dominated by impacts, or noise generated during the working activities? It is also unclear from the literature which is the best measurement strategy for noise exposure levels in the case of fish harvesting operations. This can be studied by comparing the results of exposure levels provided by the different methods listed in the ISO 9612:2012 standard (60) and in the IMO Code on Noise Levels on board Ships (51). Once the composition of these exposure is assessed, and the relevant sources are identified, it is possible to recommend short-term mitigation solutions;

- **Development of a design procedure and assessment of noise control solutions for small-scale fishing vessels**

  The literature shows that there is a noise habitability issue on small-scale fishing vessels. Recommendations are made in order to control the noise from various sources, especially continuous noise sources (i.e. main propulsive engines, generators, and auxiliaries), but few studies dealt with the evaluation and quantification of the benefits of the proposed solutions. From the few studies that dealt with the characterization of noise transmission mechanisms, it is unclear how noise is transmitted from source to receivers, and how SBN and ABN paths and sources contribute to the overall noise levels.

  In order to study the noise transmission, it is necessary to develop predictive models of the vibro-acoustic phenomenon. The chapter will focus on the study of the noise transmission paths and behaviour of a case study vessel, whose characteristics are similar to other vessels of the NL small-scale fishing fleet. This study is necessary to provide designers with useful guidelines on which noise control solutions are the best to implement on board similar fishing vessels. Given the high level of expertise, time, and high cost required for conducting a noise control study, designers and owner/operators are unlikely to include noise habitability criteria in their designs.

  The SEA analysis and the MPS algorithm are used a) to build a predictive model of the vibroacoustic phenomenon on board fishing vessels, and; b) to study the transmission paths and provide a rational base for noise control interventions. SEA is also used for the study of the effectiveness of proposed solutions, by including changes in the insulation plan of the vessels on the validated model.

1.5 Chapters outline and organization

This thesis is organized using a "manuscript" format. Chapters 2 to 6 are thus standalone pieces that either have been published as peer-reviewed journal articles or conference papers, or are undergoing a peer-review process, or they will be considered for future publication in journals. The following description will outline how the chapters are linked and how they contribute to the doctoral research objectives.

Chapter 2, named *"Noise sources and hazardous noise levels on fishing vessels: the case of Newfoundland and Labrador's fleet"* reports the study of noise levels and noise sources on-board a relevant sample of small NL fishing vessels. The chapter provides a study of the composition of the NL small-scale fishing fleet under 24 m LOA, in order to compose a relevant sample of fishing vessel to be surveyed. In the study of the fleet, typical vessels layout and fishing operations are discussed. Continuous A-weighted sound pressure levels have been measured and relevant sources identified via the study of the signals spectra and order analysis. Chapter 2 functions as an introduction to the noise related hazards of small-scale fisheries and provides the reader with: a) a general knowledge of the structure of the fleet, the type of vessels and operations carried on board, b) a study of continuous noise levels and the level of hazard from a noise exposure and habitability perspective, and, c) the contribution of steady-state continuous noise sources to the overall noise levels. This chapter is the first step in studying the noise hazard and control issue on the fishing vessel. Chapter 3, named *"Is on-board noise putting fish harvesters hearing at risk? A study of noise exposures in small-scale fisheries in Newfoundland and Labrador"*, presents the study of the risk of hazardous noise exposures of fish harvesters of a sample of 36 harvesters working on 12 fishing vessels under 24 m LOA. Several types of gear (gill-nets, trawls, jiggers/hand-line, pots, purse-seines) and species harvested (cod, whelk, lobster, crab, capelin, shrimp, and squid) were covered. The sample is built from the study of the fleet done in Chapter 2, and covers the most relevant small-scale fishing operations found in NL. Firstly the chapter reports the results from a structured questionnaire survey that aims to study the perception of risk to hazardous noise exposure from an owner/operator's perspective. The assessment is performed using a job-based method according to the ISO 9612:2012 standard (60), and reports the noise exposure levels in terms of $L_{EX,8h}$ of the harvesters, divided by group of workers. Furthermore, the research included a study the composition of the exposures through a tasks breakdown. This chapter deals with the OHS issue of hazardous noise exposures and provides the reader with: a) an assessment of the perception of the risk of hazardous noise exposure, necessary to understand the current management of this risk on board vessels from the small scale NL fishing fleet, b) an assessment of the risk of noise exposure for a relevant sample of fishing vessels that represents the small scale NL fishing fleet and operations, and, b) a breakdown of the most relevant sources of exposures for harvesters, that is used to provide tailored short-term solutions to be applied in order to reduce the exposure.

Chapter 4, named *"A comparative study of the methods to assess occupational noise exposures of fish harvesters "* presents a comparison between the several available methods for the assessment of noise exposure levels for fish harvesting activities on board small-scale fishing vessels. Three different methods from the ISO 9612:2012 and the IMO Code on noise levels on ships (51) are used and compared against full-day measurement of the exposure. This chapter provides the reader with a data driven assessment of pros and cons of the various methods, and recommends a preferred method for the assessment of noise exposure levels for small-scale fish harvesting operations.

In order to travel on board the vessels and conduct noise exposure measures reported in Chapters 3 and 4, an ethics clearance was obtained from the Interdisciplinary Committee on Ethics in Human Research (ICEHR) of Memorial University. The application for the ethics clearance is reported in Appendix A.

Chapter 5, named *"A study on the acoustic transmission characteristics of small-scale fishing vessels from Newfoundland and Labrador"* presents the study of the acoustic insulation of surfaces on a sample of NL fishing vessels less than 24 m LOA. The sample was composed from the study of the fleet conducted in Chapter 2, and is composed by relevant type of vessels found in the small-scale fishing fleet of NL. Noise levels measurements were used to obtain the in-situ transmission loss characteristics. These curves shows the ability of surfaces to reduce or insulate the receiver spaces from the main noise sources (main propulsive engine, auxiliaries and electric generators) in the frequency range of interest. This chapter provides the reader with insights into some design issues on the noise insulation between spaces of the NL small-scale fishing vessels, and their impact on noise levels measured on board. This study also provide a comparison of insulation performances on different vessels, based on their structural layouts, to identify commonalities and differences in their noise transmission behaviours.

Finally, Chapter 6, named *"Design solutions to mitigate high noise levels on small fishing vessels"*, presents the study of noise transmission paths from continuous noise sources to receiver spaces, and noise control solutions are hypotised to reduce sound pressure levels and increase the habitability of fishing vessels. From the study of the fleet in Chapter 2 a relevant case-study fishing vessel was selected. A predictive model for the vibroacoustic behaviour of the vessel structure built and validated using SEA and the MPS algorithm. The model then was used to: a) study the structure-borne and airborne transmission paths and identify hot-spots in the noise insulation, and, b) evaluate several tiers of intervention for controlling the noise levels. This part provides long-term solutions for new design and retrofit to be applied on similar vessels of the fleet.

Table 1.3 illustrate the work and research objectives achieved in each chapter. Given multiple vessels sampled in Chapters 2 to 5, for completeness Table 1.4 provides an outline of the complete sample of vessels used and possible cross-overs of vessels.

Table 1.3: Organization of manuscript thesis.

Chapter		**Research objectives**	**Associated tasks**
1	Noise sources and hazardous noise levels on fishing vessels: the case of Newfoundland and Labrador's fleet	• To study continuous sound pressure levels on board vessels from the NL small-scale fishing vessel fleet. • To identify continuous noise sources on board vessels from the NL small-scale fishing vessel fleet.	• Study of the composition of the NL small-scale fishing fleet • Didascalic description of NL small-scale fisheries, fishing vessels, and fishing operations • Study of continuous sound pressure levels from a relevant sample of fishing vessels • Identification of the main continuous noise sources
2	Is on-board noise putting fish harvesters' hearing at risk? A study of noise exposures in small-scale fisheries in Newfoundland and Labrador	• To study the perception of the risk to hazardous noise exposures from the point of view of vessels owner/operators • To assess the state and risk of noise exposures of fish harvesters from the NL small-scale fishing fleet • To provide short-term solutions to mitigate noise exposure	• Analysis of structured questionnaires on awareness of noise hazards • Surveys of noise exposure on relevant sample of fishing vessels • Breakdown of tasks and their influence on noise exposure • Proposal of short-term solutions
3	A comparative study of the methods to assess occupational noise exposures of fish harvesters	• To find the most suited method for assessing noise exposure of fish harvesting	• Comparative study of 3 different method of noise exposure assessments for a relevant sample of fishing vessels
4	A study on the acoustic transmission characteristics of inshore fishing vessels from Newfoundland and Labrador	• To study the acoustic insulation characteristics of vessels from the NL small-scale fishing fleet	• Survey of transmission losses for a relevant sample of fishing vessels • Comparison of transmission losses characteristics of vessels from the sample

5	Design solutions to mitigate high noise levels on small fishing vessels	• To study the vibroacoustic behaviour of noise transmission on board a small-scale fishing vessel • To propose long-term noise control solutions to enhance habitability of the vessels	• Development of a predictive SEA model for a case-study fishing vessel • Study of the structure-borne and airborne noise transmission paths • Identification of hot-spots in the noise insulation of fishing vessel • Propose tailored noise control solutions

Table 1.4: Vessels samples in different chapters and crossovers.

Chapter 2	**Chapter 3**	**Chapter 4**	**Chapter 5**
FSH001	FSH001	FSH001	-
FSH002	FSH002	-	-
FSH003	FSH003	FSH002	Vessel 1
FSH004	FSH004	FSH003	Vessel 3
FSH005	FSH005	FSH004	Vessel 2
FSH006	FSH006	FSH005	Vessel 4
FSH007	FSH007	FSH006	Vessel 7
-	FSH008	FSH007	-
-	FSH009	FSH008	Vessel 5
-	FSH010	FSH009	Vessel 6
-	FSH011	FSH010	-
-	FSH012	FSH011	-
FSH008	-	-	-
FSH009	-	-	-
FSH010	-	-	-
FSH011	-	-	-
FSH012	-	-	-

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Chapter 2

Noise sources and hazardous noise levels on fishing vessels: the case of Newfoundland and Labrador's fleet

2.1 Co-authorship statement

The chapter has been published as a peer-reviewed journal paper in January 2019 on *Ocean Engineering* (1) and was authored by Giorgio Burella, Dr. Lorenzo Moro, and Dr. Bruce Colbourne. Giorgio Burella led the writing of this paper, and conducted the noise surveys on board the study vessel. Dr. Lorenzo Moro helped in surveying the vessels during dock visits. All authors participated in discussions that helped enhance the concepts presented in the discussion section of this paper. All authors revised, edited, and made recommendations for improvements to earlier drafts of this paper.

2.2 Introduction

Sustainability of fisheries is a growing concern for governments, international agencies, and industry worldwide. According to the latest statistics issued by the Food and Agriculture Organization (FAO) of the United Nations (2) 37,881,000 people are professional fish harvesters, which represents an increase of more than 25% over the last 20 years. In addition the worldwide fishing fleet consists of about 4,515,000 vessels, thus forming the biggest commercial fleet in the world, and the world production of fish and fish products reached 133 billion USD in 2015. Of the 37,881,000 fish harvesters, 86% are in Asia, 8.6% in Africa, 3.35% in South America and the Caribbean, 1.22% in North America, 0.63% in Europe, and 0.55% in Oceania. Moreover, the world fleet of fishing vessels has increased by 11% since 1995. The fleet distribution is 75% of vessels in Asia, followed by Africa, Latin America and the Caribbean, North America, and Europe. Sixty one per-cent of fishing vessels are engine-powered and 85% of the motorized vessels are less than 12 m in length overall (LOA). About 90,000 vessels are 24 m LOA and above, and thus 98% of the total fleet of fishing vessels are less than 24 m LOA (2).

The growth of the fishing industry has entailed higher exploitation of marine resources, with repercussions on ecosystems, productivity, and society (3). Over the last few years, the drive for more sustainable fisheries has led designers and researchers to focus on new design solutions for fishing vessels which aim to reduce air pollution generated by exhaust gases (4–6), improve the energy efficiency of fishing vessels (7, 8) , and contain garbage (9) and waste oil pollution (10). Furthermore, international agencies have issued guidelines on sustainable management of fisheries (11–13) in order to encourage the development of an industry that will be able to satisfy rising fish demand at more than 2.5% a year (3, 14, 15). Sustainability of fisheries also implies an improvement of working conditions and safety

(11, 13). Fishing is still one of the most dangerous industrial activities, and guidelines and regulations issued by international agencies to improve safety on fishing vessels struggle to improve on board safety. The international regulatory framework on safety of fishing vessels is fragmented and not mandatory. As recently highlighted by González and Bulian (16), fishing vessels 24 m LOA and above are covered under the Torremolinos Protocol (17), Part B of the Code of Safety for fish harvesters and Fishing Vessels, and the Cape Town Agreement (18). Fishing vessels between 12 and 24 m LOA should be designed according to the Voluntary Guidelines for the Design, Construction and Equipment of Small Fishing Vessels (19). Fishing vessels under 12 m LOA should be in agreement with the Safety Recommendations for Decked Fishing Vessels of Less than 24 m in Length and Undecked Fishing Vessels (20). These international regulations are not mandatory and thus rules for the design of fishing vessels are set by regional and national bodies, with the consequence that the level of safety on fishing vessels depends on the vessels' flag state.

Over the last few years, safety on fishing vessels has been the subject of several studies. An analysis of accident data gathered from Marine Accident Reports in the 1990s, shows that machinery damage, foundering and flooding, and grounding are the most probable accidents (21). Another analysis performed on the determinants of vessel losses in the United States show that the probability of a total loss is greatest for a capsizing, followed by a sinking accident (22). Later, Jin and Thunberg studied accidents off the northeastern United States and showed that accident probability is affected by weather conditions, vessel location, and vessel characteristics (23, 24). A study conducted by Jensen et al. (25) confirms these findings and shows that causalities occur in a large percentage on small fishing vessels.

At the same time, several authors have focused their research on the improvement of safety on fishing vessels, optimizing the fishing vessel structures (26), assessing the seakeeping performance (27–29), and the vessels stability (16, 30–33). All the aforementioned studies produced standards, indications and criteria that need to be incorporated if fishing vessels are to be better designed for structural strength, stability and seakeeping performance.

Another criterion to improve safety on vessels is the ergonomics of the platform. This aims to make the workplace more efficient, more comfortable and safer, so that the occurrence of work-related injuries and diseases can be reduced or avoided. Percin et al. (34) highlighted the poor working conditions on small fishing vessels and how these conditions impact the health of fish harvesters. They suggest improving working conditions on board in order to reduce occupational injuries and improve worker health.

Exposure to hazardous noise levels is a significant safety issue on fishing vessels. Studies on the history of hospital contacts (35), surveys on health conditions (36), and follow-up audiological tests on samples of fish harvesters (37) show that hearing problems and noise-induced hearing loss are major issues amongst fish harvesters. The assessment of noise levels on fishing vessels and noise exposure of fish harvesters has been the subject of several studies, involving different species, fishing gear, fishing operations, vessel type and vessel size, from all over the world. Fulmer and Buchholz (38) studied the ergonomic risks associated with fishing activities, and measured the noise exposure for small-scale gillnetters and lobster fishers from Massachusetts, using personal noise dosimeters. Neitzel et al. (39) measured the noise exposure and noise levels on board large harvester/processors. Paini et al. (40) studied noise exposure and audiometry for fish harvesters from small scale fisheries (engine power $8-13$ HP) from Brazil. Levin et al. (41) measured noise levels on shrimp trawlers from the Mexican Gulf and conducted audiometric testing of individual fish harvesters. Zytoon (42) studied noise levels in various stations on 24 different vessels from the Egyptian fleet, that included gill/trammels (LOA 12.2 ± 1.2 m), purse seiners (LOA 15.8 ± 1.3 m), and trawlers (LOA 18.7 ± 3.1 m). He also assessed the noise exposure of fish harvesters using personal noise dosimeters and sound level meters. Peretti et al. (43) studied the noise exposure of fish harvesters, and on board noise levels on five small to medium size vessels (LOA 14.5 m to 27.32 m) from the Adriatic Sea. Rapisarda et al. (44) also studied the sound pressure levels on six different vessels from the Adriatic sea and reported the overall noise levels and noise peak levels for the different areas of the tested vessels.

The outcomes of all these studies show that noise levels on different fishing vessels ranges from ≈ 75 dB(A) in crew spaces up to ≈ 105 dB(A) in the engine room. The noise levels on fishing decks were reported as high as ≈ 95 dB(A), and in most of the cases, the 8-hours equivalent noise exposure level ($L_{ex,8h}$) was reported higher than the limit of 85 dB(A) recommended by the Rosenstock (45).

These studies have provided insights into the noise exposure on small fishing vessels and highlighted that noise exposure of fish harvesters is an issue worldwide. Furthermore, most of the cited papers agree that the main engines are the most significant noise source and highlighted that noise levels on vessels increase with an increase of engines power. However, few authors provide information about the acoustics characteristics of the ships in order to provide design solutions to mitigate the noise levels. Among the cited papers, Peretti et al. (43) performed tests for the acoustic characterization of several on board areas and provided practical suggestions for the mitigation of on board noise. Zytoon (42) also proposes possible interventions for medium to small-size vessels such as engine replacement and the reduction of the noise transmission by soundproofing the engine space and the use of resilient mounts. Veenstra (46) provided 1/3 octave band spectra of noise measured on dutch cutters and large trawlers (LOA $\geq 24\,\mathrm{m}$) and suggests some practical solutions to mitigate noise levels.

Generally noise assessments, performed to evaluate noise exposure of fish harvesters, are compared with the occupational noise exposure limits required in the region where the surveys were performed. As for other ship-based jobs, fish harvesting workers may also live on board the vessels for multiple-day fishing trips. Therefore, while they are on board but off their working shifts, they could be exposed to noise levels that are lower than occupational limits of noise exposure, but still detrimental to their long term health. Indeed, high levels of noise reduce the comfort of rest time, increasing the level of physical and psychological fatigue and making the workplace on fishing vessels more hazardous compared to land-based workplaces (47). Moreover, if harvesters are exposed to hazardous levels of noise while fishing, they should have access to quieter areas after their shifts (43). Nevertheless, the only international regulation that sets noise limits in crew spaces is the IMO Resolution MSC.337.91 issued in 2012 (48), but these limits do not apply to fishing vessels. For the latter, there is no international regulatory framework, and the only reference are the guidelines issued by the International Labor Organization (ILO) which suggest general practical procedure to control noise on fishing vessels, but does not specify any noise limit (20, 49, 50).

In the Canadian province of Newfoundland and Labrador, fishing is traditionally one of the main working activities, with 3787 licenses issued by the Department of Fisheries and Oceans in 2015 (51) and almost 9,500 fish harvesters in 2017. Noise exposure has been recognized as an issue. According to WorkplaceNL, the provincial agency that process work-related injury claims and compensation, fish harvesters are the second most frequent work class filing hearing-related claims, with a total of 8.9 % of the overall claims in the province (52). On the regulatory side, there is a requirement from the provincial government for a maximum $L_{ex,8h}$ to be lower than 85 dB(A) in all workplaces (53), but no data are available on the noise exposure of fish harvesters, and there are no national regulations for the maximum admissible noise levels on board small fishing vessels that are less than 24.4 m in length and not more than 150 GT (54).

A multi-disciplinary research activity that involves researchers from the Department of Ocean and Naval Architectural Engineering and the SafetyNet Centre for Occupational Health and Safety Research of Memorial University of Newfoundland, in partnership with the Newfoundland and Labrador Fish Harvesting Safety Association (NL-FHSA) aims to find short and long term solutions to mitigate noise exposure of fish harvesters. This include a cross-sectional study for the assessment of noise exposure of fish harvesters with the consequent identification of ergonomic hearing protection, and also the implementation of a design study to identify practical solutions and guidelines to improve the acoustic characteristics of vessels by reducing noise levels on the fishing deck as well as in the living areas.

The authors recognize that there is a gap in the literature in noise control on board small scale fishing vessels ($\leq 65'(19.81\,\mathrm{m})$). This would generally involve work to identify hazardous noise levels, their sources, analyze the acoustic transmission through vessels spaces and identify solutions to abate noise to satisfactory levels, both for comfort and noise exposure hazards. This can be achieved if the following procedure is implemented:

(a) measurements of on board noise levels according to the International Organization for Standardization (ISO) (55), in the case of a new vessel this is done on similar vessels;

(b) characterization of the noise sources on the vessel, which includes airborne noise (56) and structure-borne noise sources (57);

(c) experimental or numerical evaluation of the acoustic characteristics of the vessel structures and identification of hot spots on the vessel (43, 46). The authors intend to perform trials on board the vessels to measure transmission losses and transfer functions for the visited vessels. Also, they intend to develop a Statistical Energy

Analysis model and FEM model of a case study vessel to model the vibro-acoustic characteristics of the structure;

(d) Identification of design solutions to mitigate the noise levels (58–60);

(e) on board measurements for the evaluation of the effectiveness of the selected solutions and the compliance with the noise limits in the different ship areas.

This approach provides an orderly and previously untried process for the design and assessment of noise mitigation solutions for small fishing vessels by application of the above procedure, which is the standard applied to predict and control noise levels on commercial ships.

Since the fleet of fishing vessels in Newfoundland and Labrador is composed of 6432 vessels (51), the composition of this fleet was initially analyzed in order to identify typical vessels, covering different machinery, fishing gear, and fishing operations. The current research concentrated on the small scale fisheries for vessels lengths $\leq 65'(19.81\,\mathrm{m})$.

This paper presents the results obtained implementing phase a) and b) of the above procedure for seven vessels selected as typical based on the analysis of the fleet. These steps provide understanding of noise sources and noise levels in the different areas of the vessels. These are the first steps in a thorough analysis of the acoustic characteristics of the vessels, and the later steps are needed in order to provide effective solutions to mitigate noise levels and improve safety on fishing vessels.

2.3 Methods

This section consists of three parts. The first explains how the NL fishing vessel fleet composition was analyzed to compile an initial representative sample of the fleet for the acoustic surveys. The second part describes how inspections and sound level measurements were performed, in order to obtain data on noise levels and noise sources. The last part describes how the collected data from the noise surveys and vessel inspections were handled and processed, to characterize the sources of the noise and provide sound pressure levels.

2.3.1 Study of the NL fleet characteristic and definition of the study sample

The choice of vessels to be surveyed in this research comes from a study of the composition of the Newfoundland fleet, in terms of length, gross tonnage, building material, installed propulsive power, type of vessel, type of fishing gear used, fisheries licensing data, and fisheries landed data. These data were drawn from two different database provided by Fisheries and Oceans of Canada (DFO) and Transport Canada (TC).

The data kindly provided by the Department of Fisheries and Oceans of Canada (DFO) give information on the vessel length from 6405 registered fishing vessels and on 3787 fishing licenses registered in 2015 in Newfoundland and Labrador. A fishing license is issued to a fishing enterprise, run by its owner/operator, with its linked vessels, and permits fishing for a given species. In order to register a vessel with DFO, the operator has to provide the length of the operated vessels. Thus, two figures can be extracted from this: the number of the vessels and the distribution of vessel lengths linked to the fishing licenses. Theoretically the DFO database have information on every operated vessel in the province, and thus is the most complete database available for the vessel lengths. Furthermore, to understand the concentration of fishing effort in NL, the data for landed quantities and values by fishery, provided publicly by DFO (61), were also analyzed.

Data on the vessels length distribution only is limiting to properly describe the fishing fleet from the province. To further characterize it is necessary to gather data on construction types, gross tonnage, construction material, installed power, and structural layout. This information is available within Transport Canada's (TC) registry of vessels, that only counts 1414 entries as of June 2017, compared to the 6405 of the DFO database. Figures on vessels' overall length are also available in this database. The latter data are available via the TC website (62).

The data from the DFO and TC databases were analyzed and presented in terms of histograms of length, construction material, gross tonnage, landed values and quantities. From the TC data, correlation of length, gross tonnage and installed propulsive power was obtained and presented in scatter diagrams and fits obtained via linear regression. The data collected and analyzed have been used to compose a sample of fishing vessels of length $\leq 65'(19.81\,\mathrm{m})$ for the noise surveys to represent the section of interest for the fishing vessel fleet.

Vessels with the required representative characteristics were identified through contacts provided by the NL Fish Harvesting Safety Association (NL-FHSA) and arrangements made with individual vessel operators to conduct inspections and measurements during a regular fishing voyage. These measuring trips were scheduled based on the operations of the vessel and the availability of researchers and thus some details like weather could not be selected or controlled.

2.3.2 Inspections and noise measurements

For a typical vessel visit/trip the vessel was inspected at the wharf prior to the voyage and during the voyage, measurements of the sound pressure levels in different locations of the vessel at different sailing speed and for different fishing activities were recorded. The pre-trip inspection covered the vessel structure, spaces and equipment to highlight noise sources, and the layouts of possible noise transmission mechanisms. During inspections, the owner was asked questions about the propulsion machinery such as the expected rotation rate at different typical vessel speeds, the gear-ratio of the gearbox, the number of propeller blades and the presence of other machinery that may generate noise (such as hydraulic and electrical power generators and hydraulic machinery). Also, the owner was asked what typical fishing operations were to be expected during the trip. With this information, a measurement plan was laid out according to the presence of different noise sources and anticipated fishing activities. The measurement plan was tuned so that meaningful noise levels could be acquired.

Sound pressure levels were acquired using a data acquisition system composed of a hardware and a software end. The hardware end of the data acquisition system was made up of a Class 1 PCB Piezotronic ® mod. 378B02 ICP free field microphone connected to a National Instrument ® mod. 9234 BNC input card, that was connected via USB to a Toshiba ® Toughbook laptop computer. The sound pressure level was acquired continuously with a a sampling rate of 52.6 kHz. The software end of the acquisition system was coded using LABView®. A fast Fourier transform (FFT) of the sound pressure signal was provided live. The time domain signal was also recorded for later post-processing.

During trials of undecked vessels, where the installation of the data acquisition system was not feasible due to weather exposure, sound pressure levels were recorded using a hand-held noise dosimeter from Bruel&Kjær ®. This instrument is not able to record in the time domain but provides one minute averages of A-weighted equivalent sound pressure levels $L_{A,eq}$.

ISO 2923 (55) was used as the standard for measurements of noise levels. For each recording, the power spectrum of the acquired signal provided by the software was used to assess the frequency content of the sound pressure level. Once the main periodic noise sources were identified from the frequency spectrum and machinery rotation rate readings, care was taken so that the recorded sound pressure levels were long enough to contain the frequency component of the lower periodic noise source. Practically this meant that sound pressure levels were recorded for at least 60 seconds.

Each sound pressure signal record was repeated at least twice to have enough data to process a signal free from unwanted noise components. Space averaging of sound pressure level was obtained by slowly waving the hand-held microphone in an infinite-sign pattern around the compartment, standing in the center of the space.

Sound pressure measurements were performed at all significant workstations and spaces where crew are expected to be during fishing activities. Records of sound pressure levels were done for different engine speeds (slow-downs and transfers) and combinations of noise sources (the presence of engine, electric power generators, and hydraulics) in order to include the steady state noise from periodical sources. The propulsive engine speed was recorded before each take, as well as the one from other rotating machines operating, when possible.

2.3.3 Noise level processing

The post-processing of the data signal was performed by means of LABView ®. Each data record was cut so that spurious sound components in the time domain were eliminated (casual impacts, unwanted presence of speech, etc.). In this way, the steady state noise levels were assessed and the main contributions of periodical steady state sources were identified. Signals were first processed without a weighting filter. Then, an FFT was performed on the processed signals to obtain the one-sided power spectrum of the signal, using Hanning windowing to decrease spectral leaking. Spectral averaging was performed to decrease the noise floor of the computed spectral quantities. The one-third octave band spectra were calculated on the same signal as well. Peaks in the narrow band were identified using the engine rotation rate to identify the cylinder firing rate, the gear-box speed reduction ratio to identify the shaft rotation rate, and the number of propeller blades for the blade passage frequency (BPF). Order analysis was performed on the relevant fundamental excitation frequencies (engine firing rate, shaft rotation rate, BPF, electric generators engine firing rate) to assess the fundamental and higher harmonic peaks associated with the noise sources. The following formulas were used to identify all the aforementioned frequencies and rates (63, 64):

$$f_{eng,N} = n_{eng} \times N/(60\,s) \qquad \text{engine firing rate} \tag{2.1}$$

$$f_{gen,N} = n_{gen} \times N/(60\,s) \qquad \text{generator engine firing rate} \tag{2.2}$$

$$f_{prop,N} = f_{eng,1} \times r_{gb} \times N \qquad \text{propeller rotation frequency} \tag{2.3}$$

$$f_{BP,N} = f_{prop,N} \times Z \qquad \text{blade passage frequency} \tag{2.4}$$

where $N = 2, 3, 4, \ldots$ is an integer number representing the harmonics of the fundamental frequency (found at $N = 1$), $s = \{1, 2\}$ for a 2 or 4-stroke engine respectively, n_{eng} and n_{gen} are the rotation rate in rpm of the propulsive engine and electric generators respectively, r_{gb} is the gear-box speed reduction ratio, and Z is the number of propeller blades.

A-weighted time-integrated equivalent sound pressure levels ($L_{A,eq}$) were also calculated over the whole available frequency band using the whole available time measurement, as shown in Eq. (2.5). The A-weight filtering of the signal was used since it is relevant for comparison with noise levels required by IMO regulations for ships between 1600 and

10000 GT (48). Even if these noise levels do not apply to fishing vessels, and the vessels inspected in this study are lower than 1600 GT, this IMO Code sets a fair comparison standard.

$$L_{A,eq} = 10\log_{10}\left(1/T\int_0^T \left(p(t)_A^2/p_0\right)\,\mathrm{d}t\right) \tag{2.5}$$

In Eq. (2.5) the A-weighted sound pressure signal $p(t)_A$ is sampled for $0 \leq t \leq T$. The reference level of the pressure is usually set to $p_0 = 20\,\mu\text{Pa}$.

The logs from the noise dosimeters containing the broadband time-integrated A-weighted $L_{A,eq}$ were also inspected, and cleaned of spurious noise components (casual impacts, unwanted presence of speech, etc.) according to any registered presence throughout the measurement time span.

2.4 Results

This section presents the results from the research as outlined in the methods section. The first part presents analysis of the composition of the NL fishing vessel fleet that led to the choice of the sample of visited vessels. The second part discusses the qualitative aspects of the visited vessels' characteristics, fishing operations, structure, noise sources and acoustic transmission. The third part identifies the locations and vessel speeds at which the measurements were taken. Lastly the measurements and sound power spectra are presented, in order to characterize the noise sources and identify the sound pressure levels in the various vessels' locations and at different vessel regimes.

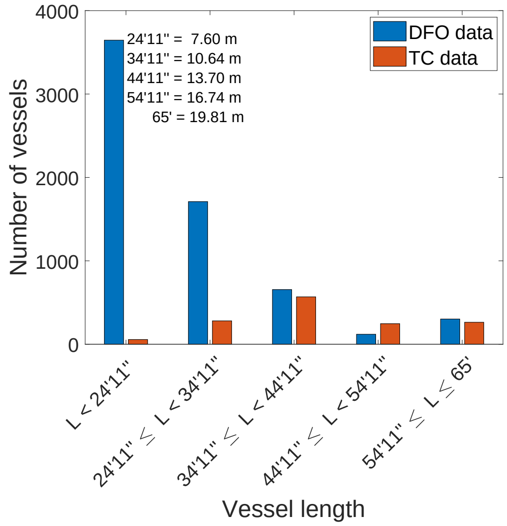

Figure 2.1: Distribution of the Newfoundland and Labrador fishing vessels' fleet based on length, vessels $\leq 65'(19.81\,\text{m})$, data from DFO 2016, TC 2017.

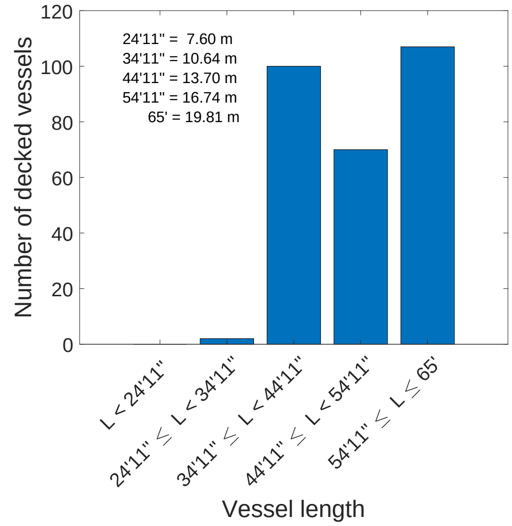

Figure 2.2: Distribution of the Newfoundland and Labrador decked fishing vessels' fleet based on length, vessels $\leq 65'(19.81\,\text{m})$, data from TC 2017.

2.4.1 Analysis of the composition of the Newfoundland and Labrador fishing fleet

Figure 2.1 shows the distribution of fishing vessel lengths for the registered vessels $\leq 65'$ (19.81 m) from both the DFO and TC databases. A separations of fleet lengths is provided by DFO, that in Newfoundland and Labrador recognizes two segments of fleet: less than $40'$ (12.2 m), and more than $40'$ but less than 65 (19.81 m). The authors chose the bin sizes as in Figure 2.1 because, according to consultations with the NL-FHSA and the Fish, Food and Allied Workers Union (FFAW-Unifor), this was more adherent to the distribution of vessel structural type (skiff for smaller vessels, decked for intermediate, and double-decked vessels in the longer vessels range). Using this subdivision, it can be clearly seen that the majority of the fleet is under 13.70 m. Due to the difference in numbers of entries between the TC and DFO databases, some discrepancies in the length distributions are expected, as shown in Figure 2.1. The TC database matches the DFO database well for the count of vessels for bins of length $\geq 10.64\,\text{m}$, suggesting that some smaller vessels are not registered in the former database. As a matter of fact, TC requires registration to the national registry only for non-pleasure vessels with engine of more than 7.5 kW, but before 2008 they required registration for vessels with tonnage ≥ 15 GT (gross tonnes) Centre for Fisheries Ecosystems Research (65). This suggests that the new registration requirements from TC are yet to be fulfilled by the larger fleet, especially for smaller vessels.

The distribution of the vessel lengths does not reflect the number of workers involved in each bin. Even though no data are available, intuitively a relatively larger fraction of the workforce will be concentrated on bigger vessels that require more crew to operate.

The bins of length under 10.64 m mainly contains skiffs and undecked vessels powered by outboard engines and used for coastal fishing. All the other classes can be assumed to be composed of decked vessels, as demonstrated from the distribution of decked vessels in Figure 2.2 from the TC database. It can be seen that the most of the vessels registered as decked are in the bins $\geq 10.64\,\text{m}$. The distinction between decked and undecked vessels is important and differentiates the layout of the vessel's structure and the presence of different fishing gear:

- Undecked vessels are open boats or skiffs propelled by an outboard engine, usually in standardized power sizes. They are mainly used for coastal fishing in sheltered waters. If hydraulic or electric equipment is needed in the fishing operations, additional hydraulic or electrical power generators can be present in the boat.

- Decked vessels present a more complex structure, with divided spaces such as cabins, holds, and engine space under the deck. These vessels are used for all kind of fisheries, and provide a more robust platform than open boats. The propulsion system consists of an inboard engine with a reversible gearbox that drives the propeller. In the engine room there are usually hydraulic pumps and in larger vessels, electric power generators. The installed power is higher than undecked vessels.

In the selection of the sample of vessels to visit, the length distribution has to be considered in order to cover both undecked and decked vessels.

Figure 2.3 shows the distribution of construction material per vessels' length bins registered in the TC database. The glass reinforced plastic vessels (GRP) are the most common material for all vessel lengths, but mainly used in vessels $\leq$ 13.70 m. Wood is used more for bigger vessels, but still a popular material for smaller vessels. Metal vessels (steel and aluminum) represent a small percentage of the vessels, becoming more used for vessels around 20 m. Construction materials diversification has to be considered in the choice of the sample, even though for the current study, metal vessels are neglected.

Figure 2.4 shows the distribution of registered gross tonnage (GT) for vessels in the TC database. Unexpectedly, the bulk of the registered gross tonnage is for vessels $\leq$ 15 GT, vessels that before 2008 were not required to register.

InFigures 2.5 and 2.6, the correlation between the length of vessels and gross tonnage and power are presented. A positive correlation can be seen in both scatter diagram, even though a bias can arise in the GT distribution due to the Assigned Formal Tonnage. As

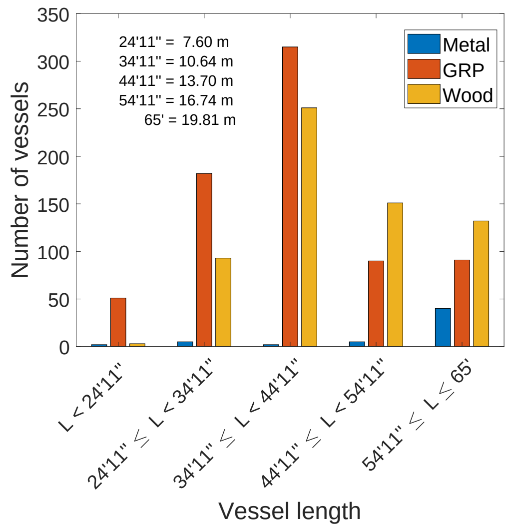

Figure 2.3: Distribution of the Newfoundland and Labrador decked fishing vessel fleet based on length and construction material, Metal (aluminum and steel), GRP (Glass Reinforced Plastic) and Wooden vessels $\leq 65'(19.81\,\mathrm{m})$, data from TC 2017.

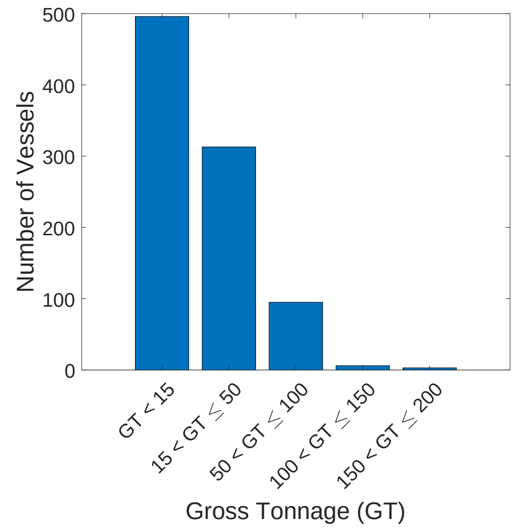

Figure 2.4: Distribution of the Newfoundland and Labrador fishing vessel fleet based on Gross Tonnage (GT), vessels $\leq 65'(19.81\,\mathrm{m})$, data from TC 2017.

a matter of fact, for Canadian vessels of not more than 12 m (39′) in length, the tonnage assignment can be done according to a formal tonnage which links the only length to a tonnage value, without the need to perform a tonnage assessment Transport Canada (TC) (66). This biases the distribution for the shorter vessels' range, as shown in Figure 2.5, where the dashed-dot line represent the formal tonnage assignment.

Installed propulsive power roughly follows a quadratic trend with the length. Also in this distribution there is the presence of cluster of points that are not randomly distributed. This bias is probably due to the fact that the size of propulsive engines is standardized and similar vessels in length would install identical powers. Also, the propulsive engine size selection is done without any experimental of analytic study of the real powering needs, resulting hence in biased distribution of power vs length.

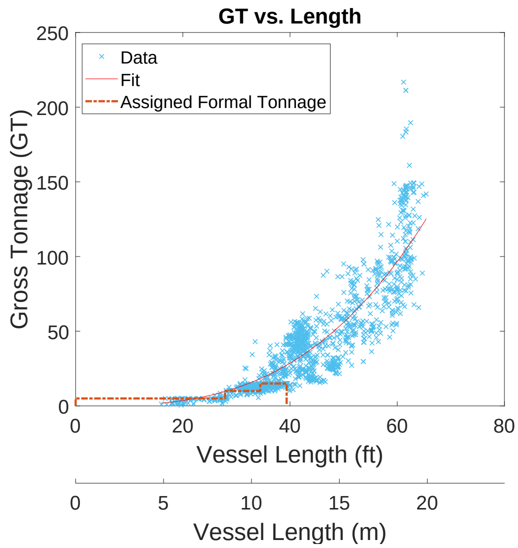

Figure 2.5: Correlation between gross tonnage and vessel length of Newfoundland and Labrador vessels $\leq 65'(19.81\,\mathrm{m})$, data from TC 2017.

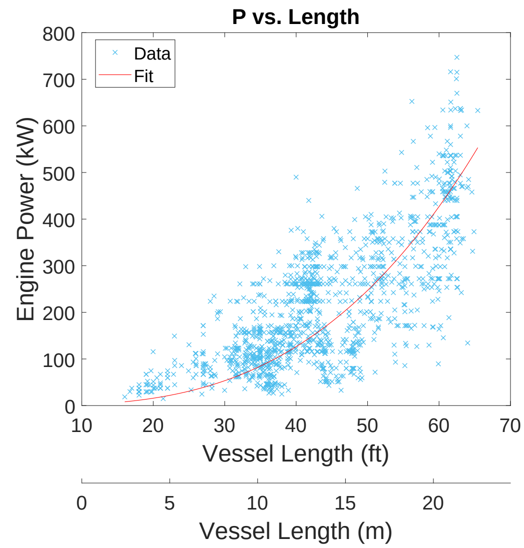

Figure 2.6: Correlation between installed propulsive power and vessel length of Newfoundland and Labrador vessels $\leq 65'(19.81\,\mathrm{m})$, data from TC 2017.

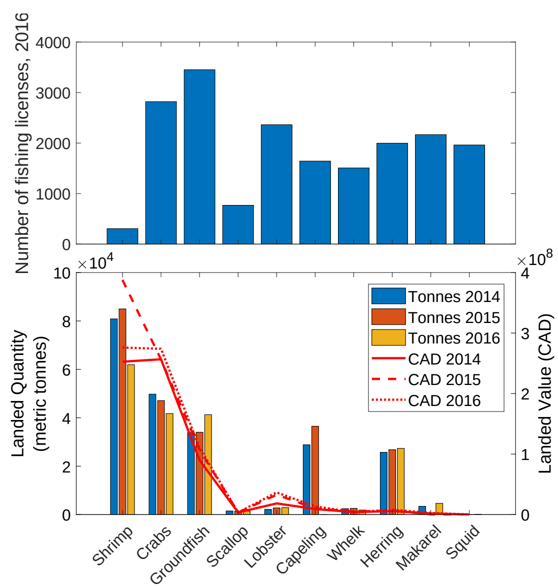

Figure 2.7: Distribution of the Newfoundland and Labrador license number, landing values and quantities per fish species, all vessels lengths, DFO 2014, 2015 and 2016.

Figure 2.7 shows the distribution of the 10 most common fishing licenses per fished species in 2016, as well as the values of the weight of landed species and value in 2014, 2015 and

2016. Each type of license roughly represents a fishery. As stated above, the number of licenses does not reflect the number of people working in that fishery, but can give a rough indication of the most active sectors in the fishing industry. The landed quantities and values per species can provide further indicators of where fishing activities are concentrated considering the full range of vessel lengths. Figure 2.7 was used to focus the noise measurement study.

For each fishery, specific fishing gear and techniques are used to harvest the fish. This means that each fishery presents different noise sources or combination of sources with engine and propulsion machinery always present. According to the Fisheries and Aquaculture Department (67), for each of the licenses presented in Figure 2.7, the following list of vessels types, fishing gear, and fishing techniques can be listed:

- *Shrimp* is caught using trawlers that use bottom trawls. Setting and hauling the trawls requires large hydraulic winches. Usually the size of the boat is $\geq 15\,\text{m}$ ($50'$) and installed power ≥ 90 HP.

- *Crab*, *lobster* and *whelk* are caught using pots that require hydraulic winches to recover pots from the sea bottom to the vessel. The vessels can be either decked or undecked (with undecked more common for the lobster fishery). Usually shrimp trips span over a 3 to 5 days at sea.

- *Groundfish* (such as cod, turbot, flatfish, halibut, redfish, haddock, hake, pollock and skate) is harvested mainly via longlines, gillnets or handlines (65). Longlines can be operated manually or with hydraulic winches. Gill nets require hydraulic winches to recover the net. Handlines are operated manually from the vessel or by means of hydraulic winches. The vessels can be either decked or undecked. A fishing for these species can either last a day or several days at sea, depending on the fish stock location.

- *Squid* is harvested using hand operated handlines that only require fish harvesters manpower, and is usually performed in undecked vessels near the coast. The fishery consists of daily trips

- *Mackerel*, *herring* and *capelin* are harvested using purse seines, tuck seines, gill nets and fish traps . Purse seines are a kind of mobile gear that require hydraulic winches to recover the net, and the auxiliary aid of a skiff to set the seine to trap fish schools. Fish pumps can be used to vacuum the catch from inside the seine. Tuck seines and fish traps are fixed gear that require hydraulics to haul in fish and/or fish pumps to vacuum the catch on board. Boats are typically decked with lengths $\geq 15\,\mathrm{m}$ ($50'$) and installed power ≥ 90 HP. Such trips span over several days out at sea

- *Scallops* are harvested using dredges, that are dragged on the sea bottom and hauled by means of hydraulic winches. The vessels are usually decked, and trips can span over several days.

Vessel owners tend to use the same vessel for different fisheries and refit the equipment on the deck as needed when switching between species during a season.

Table 2.1: Characteristics of the surveyed vessels. GRP stands for Glass Reinforced Plastics (fiberglass made vessels). OB stands for Outboard, IB stands for Inboard, 4s stands for 4 strokes.

Vessel ID	Length (m)	Boat Type	Fishery	Gear	Engine Data		
					Power (HP)	Type	Noise Meas.
FSH001	5.8 (19′)	Undecked, GRP	Lobster	Pots	115	OB, 4s	yes
FSH002	6.7 (22′)	Undecked, GRP	Lobster	Pots	90	OB, 4s	yes
FSH003	10.7 (34′11″)	1 Deck, Wood	Cod	Handline	150	IB, 4s	yes
FSH004	10.7 (34′11″)	1 Deck, GRP	Cod	Gillnet	205	IB, 4s	yes
FSH005	11.9 (39′)	1 Deck, Wood	Whelk	Pots	306	IB, 4s	yes
FSH006	10.7 (34′11″)	1 Deck, Wood	Crab	Pots	217	IB, 4s	yes
FSH007	19.8 (65′)	2 Decks, GRP	Cod	Gillnet	624	IB, 4s	yes
FSH008	10.7 (34′11″)	1 Deck, Wood	Crab	Pots	90	IB, 4s	no
FSH009	10.7 (34′11″)	1 Deck, Wood	Crab	Pots	150	IB, 4s	no
FSH010	11.9 (39′)	1 Deck, Wood	Cod	Gillnet	350	IB, 4s	no
FSH011	13.7 (45′)	1 Deck, GRP	Capelin	Purse Seine	350	IB, 4s	no
FSH012	16.2 (53′)	1 Deck, GRP	Capelin	Purse Seine	440	IB, 4s	no

It is clear from the considered distributions of the characteristics of the fleet that, within the range of vessel lengths $\leq 19.81\,\text{m}$ $(65')$, typical vessel characteristics such as length, installed power, gross tonnage, structure layout, and construction material, for Newfoundland and Labrador fishing vessels, show a large variability within a relatively small vessel length span. This indicates a requirement for a large sample of vessels to have an inclusive description of the acoustic characteristics of the fleet.

Length of the vessel is one of the main factors for the choice of the sample, since it sets the mark between undecked and decked vessels. The distribution might suggest to concentrate most of the surveys on the undecked vessels, which are $< 12\,\mathrm{m}$ ($39'$), where the biggest number of vessels are. It is more convenient to equally distribute the sample amongst the length bins, in order to have equal number of vessels from each of the bins in Figure 2.1. In this way, the sample will have a large variation in length and hence structural layout. Vessel fabrication material variability has to be considered as well in the choice, following Figure 2.3. For undecked vessels, only GRP vessels can be chosen. For decked vessels, both wooden and GRP vessels have to be included in the sample. A positive correlation between gross tonnage and length exists as stated before, so that gross tonnage can be disregarded as a choice parameter. The same statement can be applied to the installed power, due to another existing correlation between power and vessel length. Harvested fish species and type of gear variability certainly are to be taken into account since the kind of fishing operations and gear used on board are relevant in terms of noise sources. The species to be included in the sample are taken from Figure 2.7, where the ten most frequent licenses are identified. The sample has to cover all the types of gear described in the list as well. In summary, the driving criteria for the choice of sample vessels were vessel length, structural layout, the type of fish species, and type of gear used.

A total of 12 vessels that varied equally in the length span to include both decked and undecked vessels was selected and specific vessels in each category were identified and visited. This sample covered both wooden and GRP-constructed vessels. It covered lobster, cod, crab, capelin, and whelk fisheries with some further differences in types of fishing gear and operations. The summary of surveyed vessels is presented in Table 2.1. The vessels in the sample were inspected for the kind of structural layouts, and types of fishing operations and gear used. For seven of the vessels it was possible to perform noise level surveys on board during typical fishing trips. For vessels FSH008 to FSH012 noise measurements collection was not possible, and authors performed only inspections at the wharf, to expand the authors' knowledge in terms of structural layouts, gear and fishing operations. Although the range of structural layouts, vessel construction materials and length span have been reasonably covered in this sample, it was not possible to cover vessels engaged in some fishery species such as mackerel, herring, squid and shrimp; noise levels surveys were not performed for capelin. Work to expand the survey and noise level data for these categories of vessels is continuing.

2.4.2 Structural and equipment characteristics of the visited vessels

The total of 12 vessels inspected can be divided in four categories, for which descriptions of fishing activities, structural layout and machinery are provided:

- **Skiff open boat**

  Two small open boats powered by a 4-stroke outboard gasoline engine were included

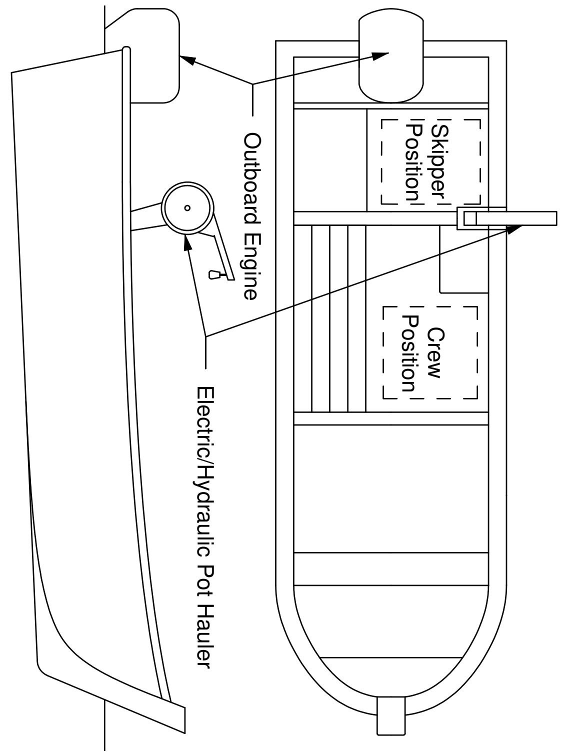

Figure 2.8: Typical skiff outline. Above, planar view, below lateral view. Measurement locations are shown in dashed rectangles.

in the study. These boats were engaged in the lobster fishery at the time of the survey, but were usually employed in the coastal cod and squid fisheries. The mechanical gear on the deck on the boats visited was an electric hauler (horizontal axis electric winch). In some boats of this type, hydraulic equipment to haul nets can be present, where an additional hydraulic pump driven by a thermal engine powers a winch. Most of these boats are made of hand-laminated fiberglass. Stiffeners are also made with the same materials. A typical outline of this kind of boat is presented in Figure 2.8. The crew operate in a confined environment where they spend the whole working day in the same positions.

- **Single decked front wheelhouse**

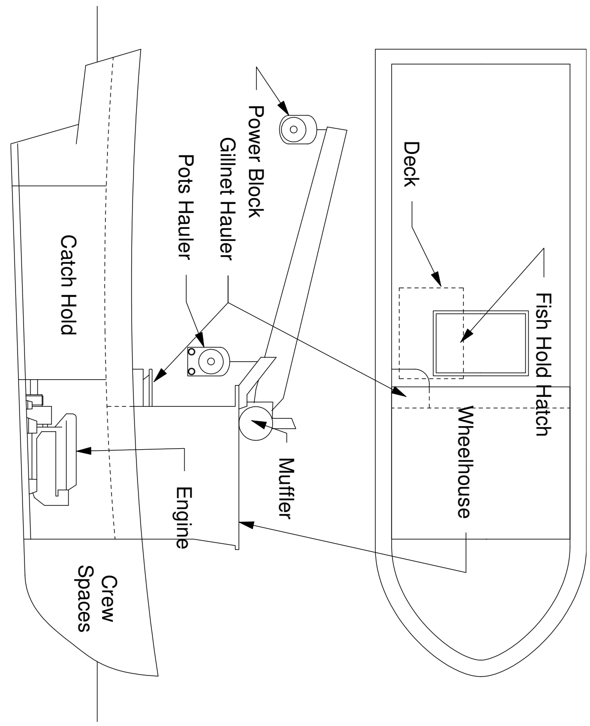

Figure 2.9: Single-decked fishing vessel outline, wheelhouse in the front. Above, planar view, below lateral view. Measurement locations on deck are shown in dashed rectangles.

A single decked vessels with front wheelhouse is shown in Figure 2.9. The length of vessels visited for this category of boat varied from 10.7 m (34′11″) to 16.2 m (53′). The propulsive power ranged from 90 HP to 440 HP. The vessels are propelled by an inboard 4-stroke diesel engine with a reversible gearbox that drives the shaft and a propeller (usually with 3 blades). The vessels visited and surveyed for the noise levels were involved in the cod, crab, and capelin fisheries. The first two fisheries make use of hydraulic winches, to haul the gillnets (cod) and pots (crab). Capelin are trapped in larger seines (either mobile or fixed), and harvested depending on seine size. Smaller seines are hauled on board with the aid of a hydraulic winch called a power block, or for larger seines, a hydraulic fish pump is used to vacuum the catch from the seine while in the water. In all these cases, hydraulic power is either provided by a pump driven by the main engine or by an auxiliary power unit in the engine room, usually for vessels $\geq 12\,\text{m}$ ($40'$). A portable electric generator might be installed on some of the smaller boats on the deck or above the wheelhouse to generate additional electrical power. A muffler for the main engine exhaust is located above the wheelhouse. The inspected vessels were of two types of construction:

- **Fiberglass over wood**: the vessel's entire structure is made of wood, from the stiffeners to the hull plating (plywood planking). In order to provide additional strength and watertightness, the outer surfaces (hull deck and wheelhouse) exposed to the weather are coated with layers of fiberglass.
- **Fiberglass**: the hull, decks and bulkheads plating are made of fiberglass, sometimes with wooden cores. The internal stiffeners are made of fiberglass with a wooden core.

Crew spaces and wheelhouse are located adjacent to the engine space, and most of the time they are connected directly without the presence of a door.

- **Single decked aft wheelhouse**

A single decked vessel with aft wheelhouse is shown in Figure 2.10. The length of vessels visited for this type of boat varied from 10.7 m ($34'11''$) to 11.9 m ($39'$). The propulsive power ranged from 90 HP to 440 HP. The vessels are propelled by an

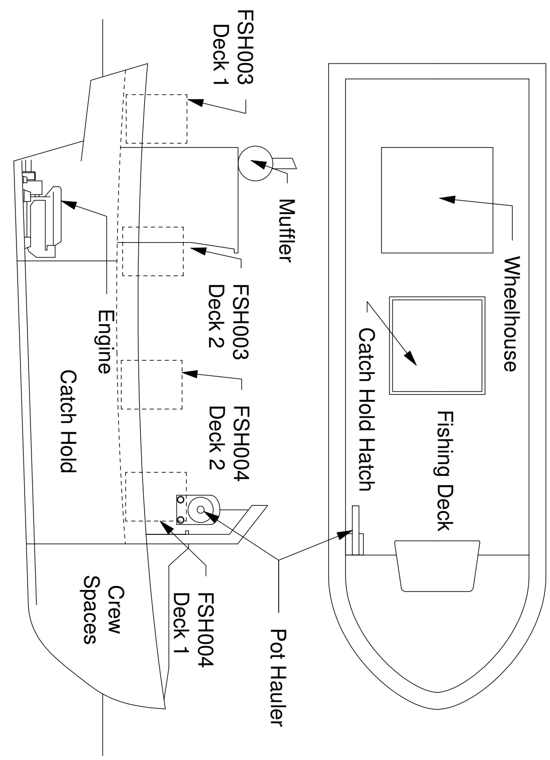

Figure 2.10: Single-decked fishing vessel outline, wheelhouse in the aft. Above, planar view, below lateral view. Measurement locations on deck are shown in dashed rectangles.

inboard 4-stroke diesel engine with a reversible gearbox that drives the shaft and a propeller (usually 3-4 blades). The vessels visited and surveyed for the noise levels were involved in the cod, whelk and crab fisheries. Cod was harvested using handlines, where fish harvesters make no use of hydraulic or electric machinery on the deck. The catch is stored on the fishing deck. Whelk and crab fisheries are similar since they make use of pots that are hauled on board by means of a hydraulic winch called a hauler. Pots are handled on the deck and the catch stored in the hold. The hydraulic machinery on the deck is powered by pumps driven by the propulsive engine. Electric power is generated by an alternator driven by the main engine. No separate power generator set was found in the visited vessels. A muffler was located above the wheelhouse. The only type of construction found in these vessels was fiberglass over wood, as described previously. The engine space is placed directly below the wheelhouse, and is accessed through an access hatch. Crew spaces are located on the front peak of the vessel, and separated from the engine space by the catch hold.

- **Double decked front wheelhouse**

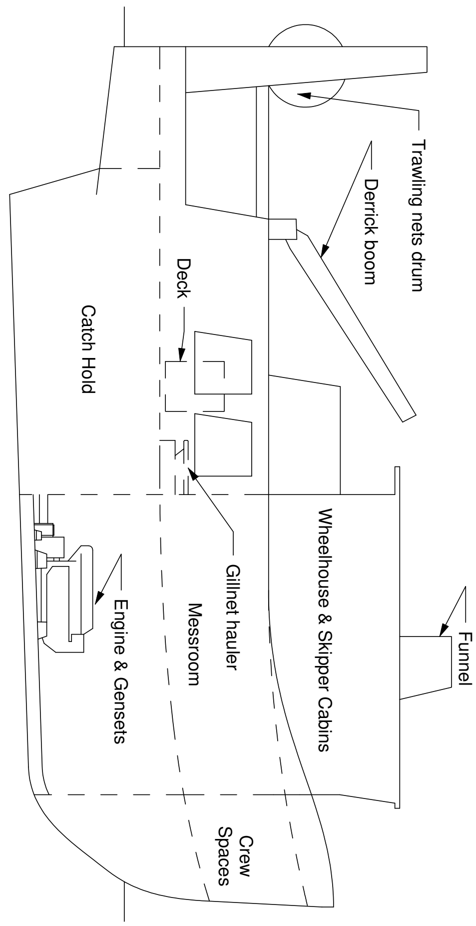

Figure 2.11: Double-decked fishing vessel outline, wheelhouse in the front. Measurement locations on deck are shown in dashed rectangles.

The typical double decked vessel with front wheelhouse is shown in Figure 2.11. Only one vessel of this kind was visited. The length was 19.8 m (65′), with 624 HP of propulsive power. The vessel is propelled by an inboard turbocharged 4-stroke diesel engine with a reversible gearbox that drives the shaft and a nozzle propeller (with 4 blades). The vessel was equipped to be multipurpose, presenting all the typical equipments for the cod, shrimp, and crab fisheries. Cod is in this case harvested by means of gillnets hauled using a net hauler on the fishing deck. Shrimp are harvested using trawling nets, that are hauled by means of an aft hydraulic winch drum. Crab pots are hauled on the deck using a hydraulic winch mounted on the derrick boom. Hydraulics can be powered by one of or both the two hydraulic pumps powered by two auxiliary diesel engines in the engine room. The same two auxiliary diesel engines provide the electric power needed on board. A funnel is located above the wheelhouse, with uptakes for the three engines, and mufflers fitted inside the funnel stack structure. No ventilation systems is installed for this vessel to provide air to the engine room, that is hence fed via natural ventilation.

The vessel's hull, bulkheads and deck plating are made of fiberglass (sometimes with a wooden plywood core), while the stiffening structure is made of fiberglass composite with wooden cores. The engine foundation is made of steel beams.

Due to the presence of a double deck, the structural layout is more complex than those of the single decked vessels or open boats. The engine space is located below the lower deck and accessed through a hatch in the messroom space. Crew spaces share no walls with the engine room. The messroom is located directly above the engine space. The wheelhouse and skipper's cabin are located above the messroom and two decks separate it from the engine room.

It is clear that steady state noise sources that produce sound power can be identified and found in all the visited vessels. Noise sources are the propulsive engine, auxiliary machinery (turbochargers, gearbox, cooling water pumps, etc.), the propulsion machinery (shaft and propeller), the hydraulic pumps, the electric generator sets, the mufflers and uptakes, the hydraulic equipment present on the deck, and the propeller induced pressure field on the hull. All these create either airborne and/or structure-borne sound power that contributes to the overall noise levels on board the vessels. The paths and critical features in the transmission of sound power can only be assessed via a separate analysis, that is not covered in this study.

A distinction can be made between decked and undecked vessels in terms of noise sources characteristics and possible actions to reduce noise levels in crew spaces and hence noise exposure. Undecked open boats and skiffs present the main engine, that generate acoustic power both airborne and structure-borne. Given the size and proximity to the crew of the main noise sources, there is no viable engineering or design solution to reduce noise levels, so that noise exposure is only reduced by adoption of hearing protection device.

For decked vessels, noise sources are also generating airborne and structure-borne sound power. In this case, design and noise control solution can be adopted and applied to the structure since this is subdivided and presents spaces separated by bulkheads and decks. Noise levels can be reduced effectively to the levels suggested by Maritime Safety Committee (MSC) (48), by means of the study of the sound power transmission paths. The

Table 2.2: Spaces description and performed operations.

Space Name	Description	Operations
Wheel house	This space contains rudder and engine controls, and the navigational instrumentation. Space is available for the crew to stand or sit.	The skipper steers the vessels from this position, and supervises all the fishing operations. Crew can be standing by during transfers.
Crew Spaces	Crew space contains usually berths for the crew and skipper to rest.	Crew members and skipper might be using this space to rest during long transfers or during down time.
Mess room	Messroom, is a room equipped with the pantry, kitchen and a table	Crew members and skipper use this space to eat or to rest during downtime.
Deck	The deck is a wide open space exposed to weather where the fishing equipment and gear is located and stored.	On the deck all fishing operations are carried out, including the harvesting, eventual process and storage of the catch. Crew members might be resting on the deck while off or on transfers.
Engine Room	All propulsive, electric and hydraulic power is generated in this space by means of thermal diesel engines.	Crew members might be inspecting the machineries or maintaining them.

noise exposure quota coming from sound power sources in the engine room can then be effectively reduced. Other sources of noise, such as impacts of gear or the usage of hydraulic equipment on the deck are difficult to control by means of engineering control.

2.4.3 Measurement locations and vessels' speeds description

Noise levels were measured in different locations on the vessels at different sailing speeds, that were identified before each fishing trip during the interview with the owner/operator. In Figures 2.8 to 2.11, the measurement locations of sound pressure levels that were performed are presented. Choice of measurement locations was based on the positions of the crew at different vessel speeds. A list of the measurements locations and corresponding operations is presented in Table 2.2.

Two vessel speeds were identified, with different propulsive engine regimes and/or the usage of hydraulic power for fishing operations:

- **Transfer**.

  In the case of decked vessels with inboard engine, this are running at $1800 - 2000$ rpm, the propeller shaft is engaged, the transfer speed is $6 - 7$ kts. The hydraulics are not working on the deck, the crew and skipper either stand in the wheelhouse, messroom, crew spaces or deck. If electric generators are present, they are usually running. In skiffs the throttle is set usually at full speed.

- **Slow Down**.

  In the case of decked vessels with inboard engine, this are running at $600 - 900$ rpm, the propeller is engaged to keep the vessel standing or slowly moving, the vessel's speed is $0 - 2$ kts. The hydraulics are working on the deck, the crew is usually working on the deck, and the skipper stands in the wheelhouse or helps in the fishing operations. On skiffs, the engine is either running idle or shut off. In both cases, if electric/hydraulic generators are present, they are usually running, powering both electricity and hydraulics.

Table 2.3: A-weighted time-integrated equivalent sound pressure levels ($L_{A,eq}$) in dB(A) for the undecked vessels, broadband data range from 20 Hz to 20 kHz, and IMO limits for noise levels.

	Slow Downs		**Transfer**	
Open Boat	**Skipper**	**Crew**	**Skipper**	**Crew**
IMO Criteria	85		85	
FSH001	85.6	68.7	94.9	89.3
FSH002	80.4	77.3	88.8	86.2

2.4.4 Noise levels on surveyed fishing vessels

In Tables 2.3 and 2.4, the A-weighted time-integrated sound pressure level $L_{A,eq}$ are presented for each surveyed vessel and each location. The vessels are subdivided into classes according to the layouts. IMO criteria levels for ships between 1600 to 10000 GT (48), are provided as a comparison in the Tables.

For all the boats, it can be seen that the highest noise levels are always found during the transfer, where the engine is running at a higher rotation rate, and the vessel is sailing at higher speed. The following can be stated for the different ships layouts:

- **Open Boat**

  The noise levels at the skipper's position are higher than at crew's position due to the distance from the outboard engine. Also, FSH001 has higher noise levels than FSH002, that could be due to the difference in engine power (115 HP vs. the 90 HP, see Table 2.1).

- **Front Wheelhouse single decked**

  In this case, the two vessels FSH004 and FSH006 had comparable overall noise

Table 2.4: A-weighted time-integrated equivalent sound pressure levels ($L_{A,eq}$) in dB(A) for the decked vessels, broadband data range from 20 Hz to 20 kHz, and IMO limits for noise levels for various on-board spaces.

	Slow Downs w. Hydraulics				Transfer			
Front Wheelhouse 1 Deck	**Wheel house**	**Crew Space**	**Engine Space**	**Deck**	**Wheel house**	**Crew Space**	**Engine Space**	**Deck**
IMO Criteria	65.0	60.0	110.0	85.0	65.0	60.0	110.0	85.0
FSH004	70.4	70.6	-	64.8	76.4	78.4	104.1	78.2
FSH006	69.8	73.3	98.1	71.0	76.1	82.0	102.9	75.0

	Slow Downs w. Hydraulics				Transfer			
Aft Wheelhouse 1 Deck	**Wheel house**	**Engine Space**	**Deck 1**	**Deck 2**	**Wheel house**	**Crew Space**	**Engine Space**	**Deck 1**
IMO Criteria	65.0	110.0	85.0	85.0	65.0	60.0	110.0	85.0
FSH003 (*)	74.1	95.9	76.2	67.0	77.6	-	107.1	-
FSH005	63.6	91.2	78.3	74.6	67.4	65.4	104.5	68.0

	Slow Downs w. Hydraulics	Transfer				
Front Wheelhouse 2 Decks	**Wheel house**	**Wheel house**	**Messroom**	**Crew Space**	**Engine Space**	**Deck**
IMO Criteria	65.0	65.0	65.0	60.0	110.0	85.0
FSH007	63.8	65.0	74.3	60.7	103.4	73.4

(*) No Hydraulics involved. Data available up to 12.8 kHz.

levels, and comparable engine power (205 HP vs. 217 HP, see Table 2.1). It can be seen that the figure for crew spaces is higher for FHS006 for both vessel speeds. It is clear that in this vessel, a large amount of sound power is transmitted from the engine room to the crew spaces due to the proximity. It is recalled here that FSH004 is a fiberglass vessel, while FSH006 is a fiberglass over wood vessel. The levels indicate that wooden vessels might perform poorly for acoustic power abatement. Referring to the last result for FSH006, the deck seems to be more efficient than a bulkhead in mitigating the transmission of acoustic power between the engine space and the wheelhouse.

- **Aft Wheelhouse single decked**

  In this case, the two vessels FSH003 and FSH005 had different engine power (150 HP vs. 306 HP, see Table 2.1), and both were built with the fiberglass over wood method. The noise level difference between the two vessels in the wheelhouse, and engine space is slight and has an inverse trend from the difference in engine power (FSH005 experiences higher overall levels than FSH003). The vessel FSH005, harvesting whelk with pots and the aid of an hydraulic hauler, experiences higher noise levels on the deck than FSH003, that was harvesting cod with handline jigging and no aid of hydraulics. The measurement locations on the deck differed in the two cases.

  The effect of proximity to the noise sources on deck locations is shown in the noise levels during Slowdown: Deck 1 positions are closer than Deck 2 positions to the relevant noise source (the muffler for FSH003 and the pot hauler for FSH005), and is clear that Deck 1 positions experience higher noise levels than Deck 2 positions. The crew spaces, being separated by the fish hold from the engine space, have rather low noise levels, as seen in the sound pressure levels registered for FSH005 in transfer.

- **Front Wheelhouse double decked**

  No sensible differences in overall noise levels are found in the wheelhouse between transfer and slowdown condition. The effect of the distance of rooms from the engine space can be seen in the measures while the ship was transfer and the engine and an electric generator were running. In this condition, the crew spaces seem acoustically well isolated from the engine room and the main noise sources. The effect of the presence of two decks can be seen in the $L_{A,eq}$ levels difference between the wheelhouse and the messroom, indicating that sound power transmitted from the engine noise sources to the wheelhouse is cut, due to the beneficial presence of an additional deck above the engine space.

2.4.5 Sound power spectra analysis

From the point of view of the frequency spectral content of the sound pressure readings, the study of the operating frequency of periodic noise sources is reported in Table 2.5. This was recorded from the readings of the rotation rate of the main machinery (engine, shaft, blade passage and power generators). All vessels had diesel propulsive engines and generators that were 4-stroke engines. Sound pressure power spectra were assessed for fishing decked fishing vessels where time domain measurements were performed (vessels ID FSH003 to FSH007). These spectra are expected to display peaks in the spectra at the sources operating frequencies and higher harmonics. The sound power is mainly expected to be concentrated in the low frequency range (5 Hz to 500 Hz). In slowdowns, the fre-

Table 2.5: Frequency in Hz of the main spectral components of the sound pressure level power spectra.

		Engine Firing Rate	**Propeller Rate**	**Blade Passage Frequency**	**Generator Firing Rate**
FSH003	**Slowdown w. Hydraulics**	5.4	5.2	21.6	-
	Transfer	15.4	14.7	58.7	-
FSH004	**Slowdown w. Hydraulics**	7.1	7.0	20.9	-
	Transfer	15.7	15.4	61.5	-
FSH005	**Slowdown w. Hydraulics**	6.4	4.3	17.2	-
	Transfer	15.9	10.7	42.9	-
FSH006	**Slowdown w. Hydraulics**	6.6	6.6	24.2	-
	Transfer	15.8	15.7	47.1	-
FSH007	**Slowdown w. Hydraulics**	9.1	3.0	12.0	30.5
	Transfer	13.2	4.4	17.6	30.5
	At Dock	3.1	-	-	30.5

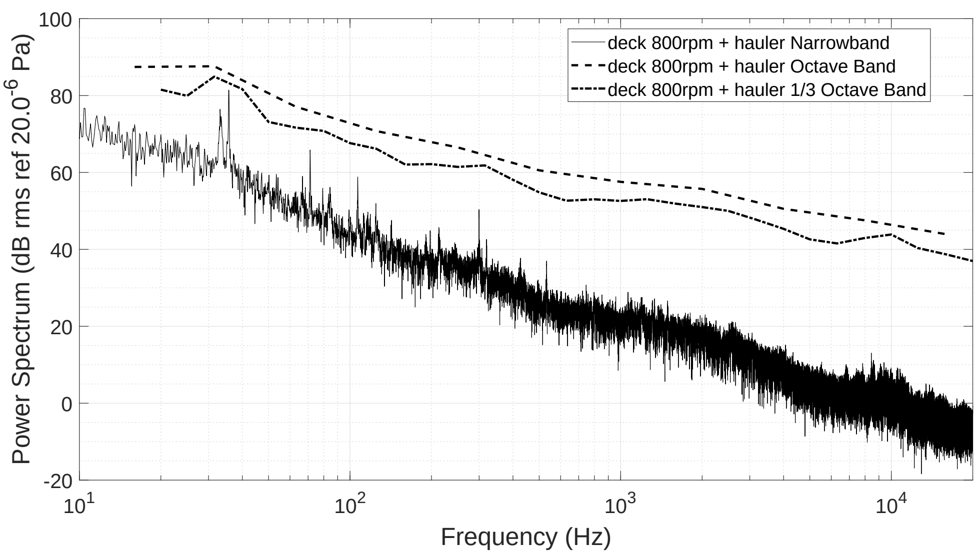

Figure 2.12: Deck sound pressure power spectrum of FSH005 in Slowdown (engine speed 800 rpm), with the presence of the hauler. Comparison between the narrow band, $1/3$ octave band and octave band power spectra is provided.

quency associated with engine rotation and propeller shaft rotation can be lower than 20 Hz, placing them outside the frequency range of acoustics (20 Hz to 20 000 Hz). The use of the narrow band spectrum is necessary to identify the spectral peaks associated with harmonic noise sources. As seen in in Figure 2.12, the spectral peak information is lost in the octave and third octave band spectra, since they display average over frequency bands. It can be seen that at higher frequency the peaks in the narrow band spectrum are becoming more dense and the spectral lines tend to converge to a smooth line, due to the high modal density and the presence of an almost diffuse acoustic field. Thus 1/3 octave band spectra, along with the total band power were calculated and reported, due to the fact that narrow band spectra do not provide any more specific information for higher frequencies.

One characteristic feature of all the power spectrum analyzed in this research is that there might be superposition of spectral peaks corresponding to the harmonics of different noise components as shown for some harmonics due to different sources in Figures 2.13 and 2.14 for FSH004. This is due to the fact that for all the visited vessels, the ratios between engine firing rate, shaft rotation rate and blade passage frequency are close to integer numbers, so that the frequency of harmonics of different components can match.

Regarding the sound power distribution over the frequency bands, it can be seen that the power is mainly concentrated in the lower frequency range, since the majority of the fundamental frequencies associated with the major noise sources are in this range. The difference in sound power levels between different propulsive engine regimes can be seen comparing the spectra from Figures 2.13 and 2.14. The shift of the narrow band peaks to the lower

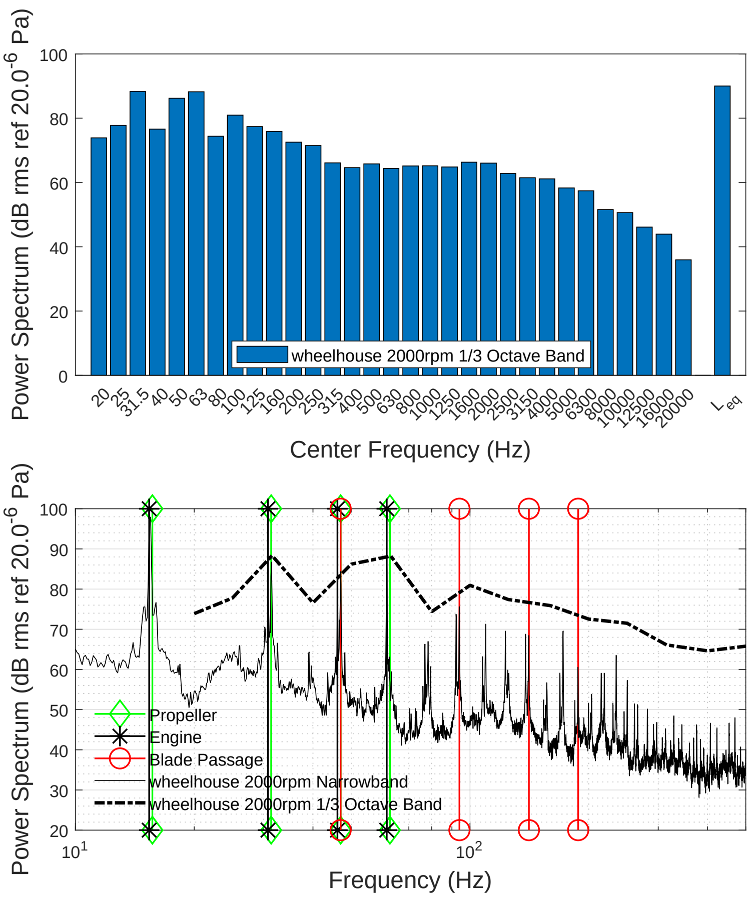

Figure 2.13: FSH004, Wheelhouse in Transfer (engine speed 2000 rpm). Histogram plot of 1/3 octave band sound power spectrum using linear sound weighting curve with associated total equivalent L_{eq} (above). Sound pressure power spectrum (below). The peaks associated with noise sources are identified with the vertical lines up to the fourth harmonic.

frequency when the engine is at low speed influences the sound power distribution in the lower frequency bands, placing some peaks outside the acoustic frequency domain.

Another interesting aspect is due to the presence of operating hydraulic machines on the deck during fishing operations at slowdowns. The change of the measured sound pressure power spectrum on the deck space with and without the hauler operating is shown in Figure 2.15 for FSH005. The operation of the hydraulic hauler, used to haul the pots in this

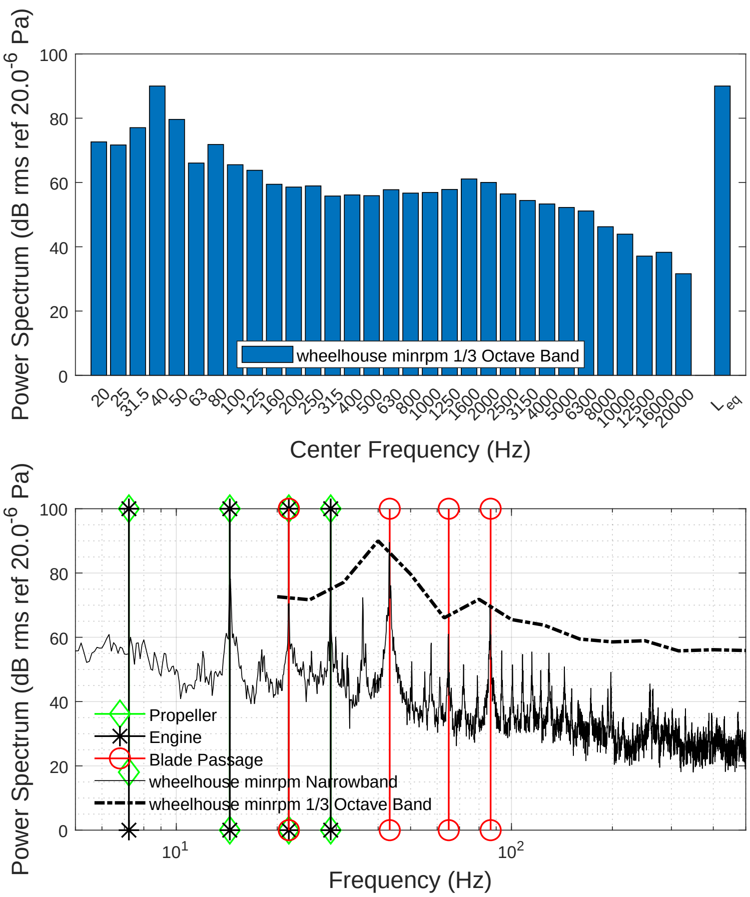

Figure 2.14: FSH004, Wheelhouse in Slowdown (engine speed 850 rpm). Histogram plot of 1/3 octave band sound power spectrum using linear sound weighting curve with associated total equivalent L_{eq} (above). Sound pressure power spectrum (below). The peaks associated with noise sources are identified with the vertical lines up to the fourth harmonic.

case, is causing the presence of additional peaks and higher harmonics in the spectrum. This results in increased octave band power for higher frequency bands, even though it doesn't influence sensibly the sound power for lower frequency bands. A small change between the two cases in rotation rate for the engine can be seen in the shift of the peak for the engine.

Lastly, the influence of the presence of an electric power generator can be seen in Fig-

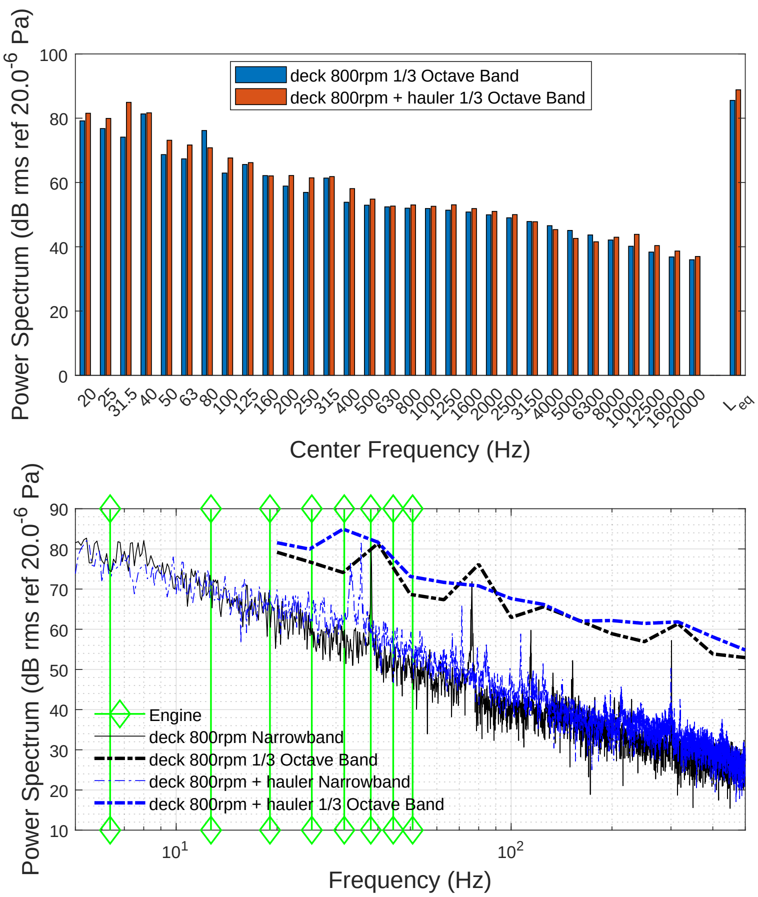

Figure 2.15: FSH005, Deck in Slowdown (engine speed 800 rpm). Histogram plot of 1/3 octave band sound power spectrum using linear sound weighting curve with associated total equivalent L_{eq} (above). Sound pressure power spectrum of with (solid black line) and without (blue dashed line) the presence of the hauler (below). The peaks associated with noise sources are identified with the vertical lines up to the eighth harmonic.

ure 2.16 for the FSH007. The second order firing rate associated with the electric generator (at $\approx$ 60 Hz) produces a peak comparable to those of the engine. This noise component is independent of vessel speed, since generators always run at the same speed, and it is found in all the signals recorded in every location.

In all the inspected spectra other peaks are present. They can be associated with res-

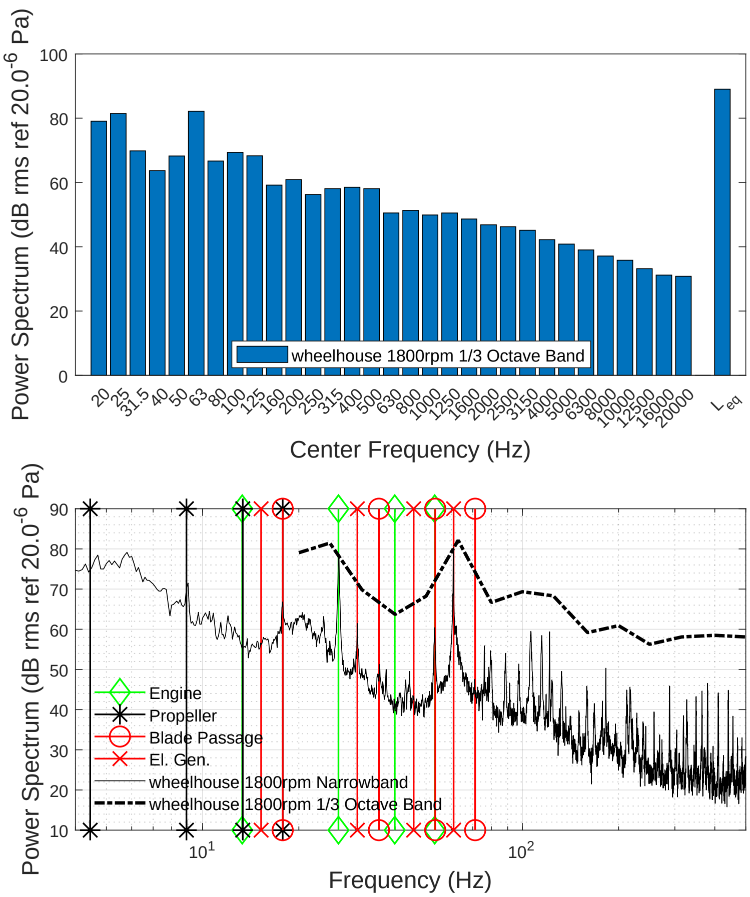

Figure 2.16: FSH007, Wheelhouse in Transfer (engine speed 1800 rpm). Histogram plot of 1/3 octave band sound power spectrum using linear sound weighting curve with associated total equivalent L_{eq} (above). Sound pressure power spectrum of (below). The peaks associated with noise sources are identified with the vertical lines up to the fourth harmonic.

onances in the acoustic spaces or to other unspecified periodic excitation. For the latter cause, they can be linked to any engine driven auxiliary machine, such as cooling water pumps, oil pumps, hydraulic power oil pumps, camshafts, turbochargers, firing sequence of pistons, gear teeth meshing noise, and so on (64). The estimation of these components was impossible due to the lack of data.

2.5 Discussion

2.5.1 Noise levels on board the fishing vessels

The results for noise levels presented in this research are in line with those already found on similar vessels from research available on the literature. Rapisarda et al. (44) (6 fishing vessels with tonnage $\geq$ 10 GT), Peretti et al. (43) (3 vessels between 17 m to 19.8 m), Zytoon (42) (6 gillnetters with mean length 12 m, 11 purse seiners with mean length 15.8 m and 7 trawlers with mean length 18.7 m), and Levin et al. (41) (4 trawlers) all reported noise levels, in both transfer and slow down engine regimes. In these studies, the higher levels were found in engine rooms with 85-111 dB(A), while in other spaces noise levels ranged between 60-83 dB(A) in crew spaces, 70-95 dB(A) in the bridges, 64-94 dB(A) for the messroom, to 71-95 dB(A) on the fishing decks. These studies also reported the variation in sound pressure levels depending on different engine speed regimes, and on the number of engine and generators that were running.

The sound level data presented in the current study fall within the range of values found in the scientific literature. Generally, high noise levels were measured on the inspected vessels and they varied with engines speed regimes and the presence of running hydraulic equipment. In particular, higher speed regimes resulted in higher noise levels, as evinced from Tables 2.3 and 2.4, whereas the presence of hydraulics during slow down condition increased the overall levels as shown in Figure 2.15.

Although the inspected vessels of the inshore fleet of Newfoundland and Labrador are not as loud as vessels from other parts of the world, the measured data reported in Tables 2.3 and 2.4 show that the continuous noise levels in various spaces of the vessels are generally higher than the respective IMO limits. The “IMO Code on Noise Levels On Board Ships” Maritime Safety Committee (MSC) (48) does not apply to fishing vessels, nevertheless the proposed limit values set minimum standards for the habitability of accommodation spaces and for safety in working spaces on board ships, and for this reason they have been used as reference values in this study. From the comparison of the measured levels with these limits, it can be seen that on undecked vessels levels are found to be dangerous, especially for the skipper position that is near the noise source. It is worth pointing out that the authors compared the levels measured on undecked vessels with the IMO limit level of 85 dB(A), corresponding to non-specified work spaces. Nevertheless, it is judged that this level is also too high for such vessels and a more rational limit should be 80 dB(A). As a matter of fact, 85 dB(A) would be a safe noise level if the fishing trips were always 8 hours long or less. As these trips may last more than 8 hours, a 80 dB(A) limit for the maximum 24-hours continuous noise exposure level should be allowed for exposure of seafarers according to the IMO Code. Thus this level would permit harvesters to perform daily fisheries (less than 24 hours), as usually happens on undecked vessels, and not be exposed to hazardous noise levels. This reasoning does not consider contributions to noise exposure such as, for instance, the handling of fishing gear and their impacts on deck, and sources other than the outboard engine or hydraulic generators, that has to be considered in noise exposure assessment, but it provides a reference limit for the design of new vessels.

For decked vessels, the most critical values are found in the spaces adjacent to the engine room, where levels can be 22 dB(A) higher than the IMO criteria (as in the transfer condition of FSH006 in the crew spaces). Efforts should be made to abate these levels to the values recommended by the IMO Code. This is especially true for accommodations, where levels should be even lower and closer to the recommended standard, as to provide a quiet environment to provide some rest to the crew when the trips last more than 8 hours. All of the vessels inspected except FSH007 were used for daily fisheries. As for the case of FSH007, which fish harvesters spend up to several days on during fishing trips, the only living quarter that could be hazardous is the messroom, where levels in transfer are almost 10 dB(A) higher than the recommended IMO criteria.

2.5.2 Analysis of the spectra and identification of noise sources

The usage of the narrowband spectra of noise levels reveals the main contributors to noise sources. In all the cases, engines, generators, auxiliaries and hydraulic equipment were identified as the main noise sources that make up the continuous noise levels on the fishing vessels.

The data from noise levels and the knowledge of the narrowband spectrum characteristics is fundamental to help designers of fishing vessels in the task of finding ways to abate noise levels. The knowledge of how the sound energy is distributed among the frequency bands is the first action to be taken in order to design and implement noise control measures. For instance, as shown in this paper for FSH004, FSH005 and FSH007 in Figures 2.12 to 2.14

and 2.16, most of the sound power is clustered in the lower frequency bands, coming from engine and auxiliaries. This points out that noise control solutions should focus on these sources and they should include the acoustic insulation of the engine room, by applying a proper trim to the walls in this space that stops transmission of sound power in the lower frequency range, or the decoupling of the engine from the ship structure by use of resilient mounts. Of course, a proper design of such solutions should follow a more detailed procedure that can include:

1. Estimation of the airborne sound power of the noise sources using the measures of sound pressure levels and standard values of reverberation times, in fractional octave bands, in order to fully characterize the airborne noise emission of the source in the frequency bands;

2. Knowing the different sound pressure levels in two spaces, and using standard values of reverberation times, the frequency dependent transmission loss of the surfaces of two adjacent spaces can be estimated;

3. Sound power levels and transmission loss data can be used to identify ranges of frequency where the air-borne sound adsorption is deficient. Finally, the insertion loss of commercially available acoustic trims can be adopted to evaluate the expected reduction in sound pressure levels.

4. Structure-borne sound can be measured on board by means of accelerometer on structural members and surfaces enveloping spaces, and transmission losses and transfer

functions can be extrapolated and analyzed.

Such procedure, for the air-borne transmission, could be adopted using the results from this paper. This could provide the basis for a standard for evaluating sound propagation on-board vessels. These procedure to determine an acoustic trim to apply to surfaces to reduce noise is not developed here since it is out of the scope of this paper.

2.5.3 Strengths and limitations of the study

This is the first such study for the fishing fleet of Newfoundland and Labrador for vessels $\leq 65'(19.81\,\mathrm{m})$ and no studies are present on how to rationally control high noise levels on board small fishing vessels, for the province or worldwide. This paper recognizes that the identification of noise levels and sources is the first step of a rational procedure to identify effective noise control measures. From this study, noise levels on board the visited vessels were recognized to be higher than the IMO standards, hence proving that there is potential for poor habitability of such vessels and for exposure to high noise levels of fish harvesters. It is important to present such data, so that knowledge-base on the sound levels and characteristic of noise sources can be made available to designers. This helps also setting a baseline for acoustic performances of fishing vessels, and it can be used to compare the efficiency of the application of acoustic trims against this baseline. Finally, the authors believe that such data can be useful also for other fisheries from other parts of the world that uses similar vessels.

The authors recognize that the vessels' sample size is small and it is not able to effectively represent the variety of vessels, the variation of operations, configuration and equipment of the Newfoundland and Labrador fleet, on which the variability of noise levels depends. The selected vessels visited for the survey were however chosen from a study of the composition of the fleet, and the authors believe that the presented sample covers relevant cases. It is however not possible to draw general, statistics-based, and holistic conclusions about the state of noise levels and sources.In addition some influencing factors, such as the maintenance records for the machinery on board, that might have major influence on the noise levels, as stated by Zytoon (42) have not been considered in this study.

2.6 Conclusions

The overall goal of this research is to introduce a methodology to identify and control hazardous noise levels on small scale fishing vessels, a field for which there is an identified literature gap. This can be achieved if a procedure is implemented that includes the assessment of current noise levels, the characterization and identification of noise sources, the experimental and numerical assessment of acoustic transmission and, finally, the identification of effective design solutions to mitigate the hazardous levels.

This paper covers the initial phases of the outlined procedure, and has given insight on the composition of the fleet and the current state of the noise sources and levels on fishing vessels from the fleet located in the Canadian province of Newfoundland and Labrador. The study surveyed twelve fishing vessels to qualitatively overview their structural layouts, and identify probable noise sources. For seven of them, during normal fishing activity, measurements of the steady state sound pressure levels of spaces during different vessels' speeds and operations were performed. After the fishing trips and acquisition of the time-domain measurements of sound pressure, the A-Weighted time-integrated sound pressure levels $L_{A,eq}$ were calculated and narrow band and one third octave band sound power spectra produced for each measure in order to identify the contributing noise sources.

This study recognizes that there is a distinction between the characterization of steady state noise levels and noise exposure of fish harvesters. Noise levels are linked to the habitability of the fishing platform, and there is no clear international or national standard that sets an acceptable level. For noise exposure, most of the previous studies concentrate on noise characterization and noise level measurements compared with some regulatory requirement on noise exposure, rather than with criteria that take into account habitability and comfort. From the sound pressure surveys on fishing vessels, noise levels characterized by $L_{A,eq}$ were generally found to be beyond the IMO required levels for larger vessels. The analysis of the sound pressure power spectra showed that the bulk of the steady state sound power is found in lower frequency bands, due to the propulsive and auxiliary machinery operating in the engine spaces.

Further development of this research would involve the choice of a case study vessel for an evaluation of the noise transmission and sound energy flow through the structure and air. A model will be developed by means of Statistical Energy Analysis (SEA) to assess the relevant sound power transmission routes and used to find flaws in the acoustic power transmission. Consequently it will be used to evaluate possible noise mitigating solutions.

Parallel to this research activity, further measurements are planned on board other vessels to increase the available data on noise exposure and noise levels for Newfoundland and Labrador fishing vessels. This will increase the sample increasing the covered vessels' lengths; other core harvested fish species such as shrimp, capelin, mackerel, herring and squid; other fishing gears such as trawls, purse seines, dredges and fish traps.

2.7 Acknowledgments

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Chapter 3

Is on-board noise putting fish harvesters' hearing at risk? A study of noise exposures in small-scale fisheries in Newfoundland and Labrador

3.1 Co-authorship statement

The chapter is a preprint version currently under review for publication on the peer-reviewed journal paper *Safety Science* and was authored by Giorgio Burella, Dr. Lorenzo Moro, and Dr. Barbara Neis.

Giorgio Burella led the writing of this paper, and conducted the measurements and acoustic analysis on the case study vessel. Dr. Lorenzo Moro participated in discussions and edited the manuscript to enhance the layout, writing, and the concepts presented in this paper. All authors revised, edited, and made recommendations for improvements to earlier drafts of this paper.

3.2 Introduction

With more than 17 500 km of coastline and access to adjacent fishing grounds inside the 200 nautical mile Canadian Exclusive Economic Zone (EEZ), the Canadian province of Newfoundland and Labrador (NL) has traditionally relied on the harvesting of fish resources as a source of livelihood for its coastal communities (1). The NL fishing industry is composed mostly of small-scale enterprises, owned by a single skipper and conducting operations on one vessel (2). Occupational health & safety (OHS) management in these enterprises has primary importance: if hazards on-board fishing vessels are under-managed, avoidable poor health conditions and injuries are more likely to occur. These in turn can have detrimental effects on the economic viability of fisheries, and the well-being, social integrity, and ultimately the very survival of coastal communities (3). Given the tremendous impact of safety issues, occupational injuries and health issues on the coastal communities, as evidenced by the establishment of the Newfoundland and Labrador Fish Harvesting Safety Association (NL-FHSA) in 2012, OHS has become an important concern for the small-scale NL fishing industry, as well as regulators and for workers compensation.

Internationally, OHS is a recognized issue for fish harvesting: scholars highlighted the high incidence of serious and fatal accidents (4–6), the lack of safety management and procedures (7, 8), and the efforts to enhance safety for specific risks (9, 10). This research includes a) reports on the safety of fishing operations, as reflected in the number of Search and Rescue (SAR) responses (11), b) studies on state-of-the-art national and international safety regulatory frameworks and their effects when enforced (12, 13), c) research on safety on fishing wharves (14), and d) analysis of the relationship between fishing vessel capsizing and operators training (15). In another set of studies, Murray and Dolomount (16), Power (17) and Power et al. (18) addressed the perception of risks among harvesters and the state of the safety culture in the industry. The studies indicate that even though the workforce is more aware of safety issues and hazards than in the past, the presence of factual hazards in the fish harvesting profession is often trivialized (16) and that efforts to change this continue to leave the management of day-to-day risks to fish harvesters' commonsense and experience (17, 18). This particular attitude towards safety is common for fishing vessels operators in fisheries from all over the world (7, 19).

Despite recent initiatives, safety issues continue to be present in the NL and other fisheries, which can benefit from collaborative fishing safety research involving harvester representatives to document safety issues, quantify risk and to design and evaluate interventions to address key OHS management issues. These types of interventions can help improve harvesters awareness and management of risks (20), by using science to enhance awareness based on skippers common sense and day-to-day risk management (21, 22).

This paper presents findings from a study done in collaboration with the NL-FHSA of noise exposures among NL fish harvesters employed in small-scale fisheries and working on small vessels (24.4 m and under in length overall *LOA* (23)). No research has systematically documented the risk of hazardous noise exposure that may lead to occupational noise-induced hearing loss (NIHL) in the NL fishing labor force. Fish harvesting is, however, the occupation with the highest number of compensable claims for occupational hearing loss in the province; 97.3 % of these claims were linked to exposure to hazardous noise levels (24).

Worldwide, few research projects have surveyed occupational noise exposures on fishing vessels (25–27), and only Rapisarda et al. (28), Zytoon (29), Fulmer and Buchholz (30), and Paini et al. (31) focused on small-scale fishing vessels. While all these studies document hazardous noise exposures among the participants, research is still lacking. Most of the existing studies focus only on noise exposures associated with a single fishery, type of fishing gear, and vessel architecture. Furthermore, they do not investigate the activities and noise sources associated with the hazardous noise levels and they do not document the level of awareness of fish harvesters regarding the level and source of noise exposures in their fisheries. The research presented here addresses each of these existing gaps in the literature and provides findings and related recommendations that can be used to design and evaluate strategies to mitigate the risk of NIHL in this sector.

In Canada, health and safety regulation and inspection is the responsibility of provincial governments. In NL, the prevention of NIHL hinges on regulatory standard which uses the limit of 85 dB(A), set by the American Conference of Industrial Hygienists (ACGIH) as the threshold for occupational noise exposure (32, 33). Despite the adoption of this standard, the significant number of occupational disease claims for occupational NIHL in the fishery points to the need to monitor workplace noise in the industry and to identify effective solutions to prevent NIHL.

The objectives of the cross-sectional study presented below were to: a) document occupational noise exposures in diverse fisheries in the small-scale fishing fleet in NL; b) identify job tasks and noise sources associated with any hazardous noise levels; and c) assess skippers awareness of hazardous noise levels on-board their vessels; in order to d) develop recommendations for ways to reduce noise exposures and the risk of NIHL in the future. Unlike previous studies, we present our findings for different types of fisheries and vessel architectures, and we link hazardous noise levels to the sources which are responsible for them.

3.3 Methods

We surveyed and observed operations and work-patterns during regular fishing trips for different types of catch, fishing gear, and vessel architecture. Before each trip, we administered structured questionnaires to skippers to evaluate their knowledge of noise levels on their vessels (see Section 3.3.2). We then assessed noise exposure levels using a job-based measurement strategy in order to evaluate the risk of onset of NIHL and evaluated the contribution of the individual tasks using a combination of microphones and personal noise dosimeter measurements (Section 3.3.3 and Section 3.3.4). Finally we assigned a subjective "noise exposure awareness score" based on the comparison between the responses of the skippers to the pre-trip questionnaires and the outcomes of the noise exposure surveys Section 3.3.5.

Figure 3.1 presents the flowchart of activities performed in the research presented on this paper.

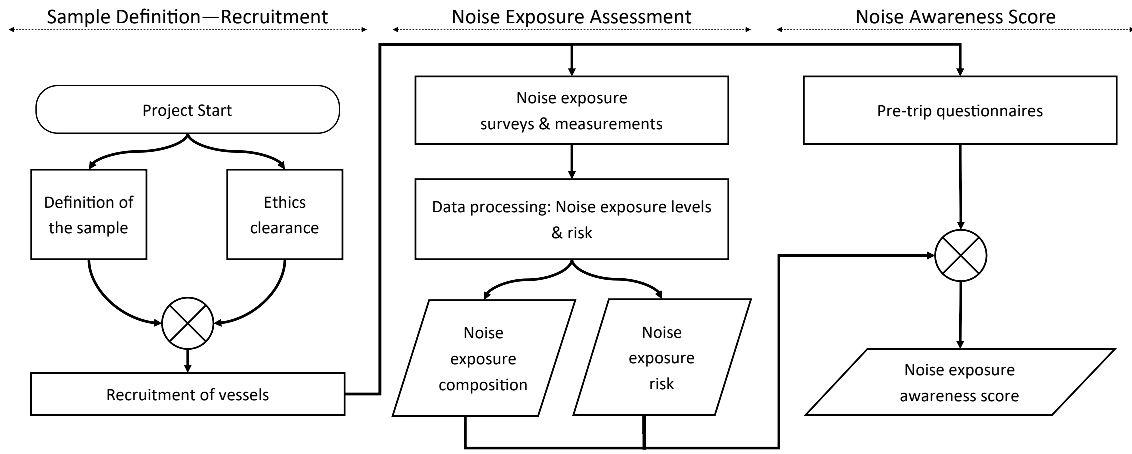


Figure 3.1: Flowchart for the research outlined in this paper.

3.3.1 Recruitment

Prior to starting the research, we received ethics clearance from the Interdisciplinary Committee on Ethics in Human Research (ICEHR) at the Memorial University of Newfoundland. The clearance required participation in the study to be voluntary, with written, informed consent from participants. Individual results were to be kept confidential provided only to the person involved with feedback of aggregated results presented to participating skippers and crew along with an opportunity to discuss ways to address hazardous noise exposure situations. The NL-FHSA co-funded the research, provided input into its design and collaborated in recruitment of participants and dissemination of findings from the study to small-scale fish harvesters. Participants were recruited by mail and phone calls to skippers and crew members working on small fishing vessels in NL. As a result, we recruited 36 fish harvesters working on 12 small fishing vessels of varying lengths, design, and construction, and engaged in 7 types of fishery. Vessel characteristics and type of fishery affect occupational noise exposures as noise sources (i.e. propulsive engine, auxiliary machinery, fishing gear), noise transmission on board, and the work patterns of harvesting operations depend on them.

3.3.2 Administration of pre-trip questionnaires

Before each survey trip, we administered a structured questionnaire to participating skippers of vessels with questions on:

a) vessel characteristics (main dimensions, engine and power generators layout and installation);

b) fisheries (species harvested, length of typical trip, number of trips per year) in which the vessel participated;

c) awareness of noise sources and/or job tasks associated with harmful exposure to noise;

d) hearing protection device (HPD) types and usage on board their vessel; and,

e) general reflections on issues related noise they identified on their vessels and in fisheries in general.

In addition, we performed unstructured interviews with skippers and crew members to document the typical fishing operations, tasks, and gear used in a nominal fishing trip.

3.3.3 Noise exposure surveys

Drawing on the results from the pre-trip questionnaires and unstructured interviews, we developed a plan to monitor occupational noise exposures on the surveyed vessel during a single fishing trip. This plan included: a) the subdivision of the fish harvesters working on a vessel into homogeneous noise exposure groups; b) the use of noise dosimeters worn on the participants shoulders during the entire fishing trip, excluding rest time in the sleeping quarters; and c) an assessment of the 8-hour noise exposure levels $L_{EX,8h}$ and maximum C-weighted peak level $L_{C,peak,max}$ in accordance with the job-based measurement scheme described in the ISO Standard 9612:2009(E) (34).

In addition to collecting the fish harvesters personal noise dosimetry data, we measured noise levels in each space of the vessel, while navigating at different speeds, and recorded time-domain sound pressure signals for each work task. Measurement logs from the dosimeters and narrow-band frequency domain analysis of the time-domain series were used to identify the noise sources responsible for hazardous noise levels in each surveyed fishery.

At the end of the working day, the participants were asked to debrief about their activities by filling in individual log sheets. Information in these logs was supplemented by a log that we compiled during fishing operations to fill possible voids. From these sources, we extracted data on effective working day duration T_e, actual job layouts and deviations from nominal activities, task duration T_m, and information on the presence of crew in specific areas.

Instrumentation

The noise-sampling instrumentation setup was composed of

- personal noise dosimeters Type 4448 by Bruel&Kjær®;
- a Class 1 model 378B02 ICP hand-held microphone by PCB Piezotronic® connected to a National Instrument® model 9234 BNC input card that was connected via USB to a Toshiba® Toughbook laptop computer.

Microphones on both setups were equipped with wind screens to avoid wind flow noise. Before each trip, all microphones and dosimeters were calibrated using a Larson and Davies® calibrator model CAL200. Post-processing of data from the hand-held microphones was performed using National Instruments LabView®.

3.3.4 Evaluation of noise exposure levels

The job-based measurement scheme requires samples of A-weighted equivalent sound pressure levels $L_{A,eq}$ that are representative of the noise exposure of a group of workers performing the same job. In this study, the samples were obtained by randomly extracting 20 noise level measures, each 15 minutes long, from the dosimeter logs. These samples contained all the relevant noise exposure components, discarding samples containing spurious components, such as accidental speech and impacts. Samples acquired in conditions different from the nominal working day, such in the case of accidental vessel shutdowns or issues with the gear, were also excluded. From the $L_{A,eq}$ samples and the information from the logs, we calculated the $L_{EX,8h}$ for each noise exposure group, and the one-sided 95 % confidence interval $U(95\%)$ (34). When the implementation of the job-based method was not feasible due to time constrains, we used a task-based method (34) with samples acquired in a simulated fishing trip to obtain $L_{EX,8h}$ and the $U(95\%)$.

The $L_{C,peak,max}$ were also extracted from the available measurement logs for each trip.

The $L_{EX,8h}$ of each noise exposure group, and $L_{C,peak,max}$ of each trip were then compared against the hygienists' criteria for hazardous noise exposure (32, 33):

- $L_{EX,8h} \leq 85\,\text{dB(A)}$ – continuous noise;
- $L_{C,peak,max} \leq 140\,\text{dB(C)}$ – impulsive noise.

We decided to take into account the impulsive noise criteria even though this is not required by the NL OHS regulations, as we foresaw impulsive noise during fishing operations.

Tasks were identified using the unstructured interviews and on-board observation of work patterns. Samples of $L_{A,eq}$ for each task were also extracted from the dosimeters' noise level logs or from hand-held microphone measures. Mean estimate of $L_{A,eq}$ of specific tasks were obtained following the procedure described in (35). Data on duration of tasks and equivalent levels were used to obtain the $L_{EX,8h}$ and adsorbed noise dose D of specific tasks, in accordance with standard CSA Z107.53-13 (36). Microphone time domain measurements were also processed to obtain a) the time history of the exponential averaging $L_{A,eq}$ with fast time constants during specific tasks, and b) the narrow-band spectra used to identify noise sources responsible for the hazardous noise levels.

3.3.5 Noise exposure awareness score

Cross-referencing the results from the measured noise exposures with the identification of harmful noise sources and job tasks provided by skippers in their pre-trip questionnaires, we identified gaps in their awareness for relevant contributors to the measured noise exposure. The cross-reference study produced a list of harmful noise job tasks and noise sources that were either acknowledged or not as such by the skippers. We considered a job tasks and source harmful when they produced a $L_{A,eq} \geq 80\,\mathrm{dB(A)}$. Drawing from these results, we then assigned a noise exposure awareness score to each visited vessel. Three numerical values were defined in our score:

- **-1: No Awareness**. The skipper did not identify any of the relevant noise sources and activities;
- **0: Limited Awareness**. The skipper identified some of the main noise sources and activities, but neglected others;
- **1: Good Awareness**. The skipper identified all the main noise sources and activities.

This scoring, although a subjective exercise, helped us understand the awareness of hazardous noise exposures among the skippers, who are responsible for the safety of operations and workers on board (32).

Table 3.1: Outline of surveyed vessels (OB is outboard, IB is inboard, GS is generator set, FRP is Fibre reinforced plastic and WD is wooden).

Fishery type	Number of vessels	Vessel length range (m)	Boat types	Engine power range (Hp)	Engine types
Lobster	2	5.8 -6.7	Undecked, FRP	90 -115	OB
Cod (hand-line) Squid	2	5.8 -10.7	Decked & Undecked, FRP & WD	50 -150	IB & OB
Cod (gillnetters)	2	10.7 -19.8	Decked, FRP	205 -624	IB & IB+GS
Shellfish	4	10.7 -15.5	Decked, WD & FRP	217 -340	IB & IB+GS
Pelagic	1	18.3	Decked, FRP	543	IB+GS
Shrimp	1	19.8	Decked, FRP	624	IB+GS

Table 3.2: Description of fisheries surveyed.

Fishery type	Species caught	Gear		Trip duration	Average crew
		Type	Machinery		
Lobster	Lobster	Pots	Handlaid/Hauler	1 day	2
Cod (hand-line) Squid	Cod Squid	Hand-line Jigger	Manual	1 day	2
Cod (gillnetters)	Cod	Gillnet	Hauler	1 day	2 to 3
Shellfish	Whelk Crab	Pots	Hauler	1 day Multi-day	3 to 5
Pelagic	Capelin	Purse Seiner	Power Block - Fish Pump	Multi-day	5
Shrimp	Shrimp	Trawls	Hydraulic	Multi-day	6

3.4 Results

3.4.1 Surveyed vessels

The surveyed 12 fishing vessels ranged from small open boats (5.8 m *LOA*) with outboard motors and limited hauling equipment engaged in short daily trips to inshore grounds, to larger offshore trawlers (19.8 m *LOA*) engaged in multi-day trips with hydraulic equipment and inboard engines and generators. The vessels were engaged in 7 different fisheries, catching cod, whelk, lobster, crab, capelin, shrimp, and squid using different fishing gear (gill-nets, trawls, jiggers/hand-line, pots, purse-seines).

Table 3.1 presents the sampled vessels and Table 3.2 shows the main characteristics of the surveyed fisheries: gear and machinery used, duration of trips, and number of fish harvesters on the vessels.

3.4.2 Pre-trip questionnaires

Table 3.3: Questionnaires collected from vessels skippers.

Fishery	Number of questionnaires
Lobster	2
Cod (hand-line) and squid (jigging)	2
Cod (gillnetters)	2
Shellfish (crab and whelk)	4
Pelagic	1
Shrimp	1
Total	12

Table 3.3 presents the number of compiled pre-trip questionnaires for each surveyed

fishery. All the skippers of the 12 vessels completed the questionnaire. Table 3.4 shows the results from responses to questions on skipper knowledge of potential harmful noise sources and job tasks that a) were present on-board; and b) might lead to hazardous noise exposures. Table 3.4 also shows if HPDs are present on board. In addition, the survey gave the respondents the possibility to add free-form comments at the end of the questionnaire. These comments are not reported in this paper since not deemed as relevant.

3.4.3 Noise exposure results

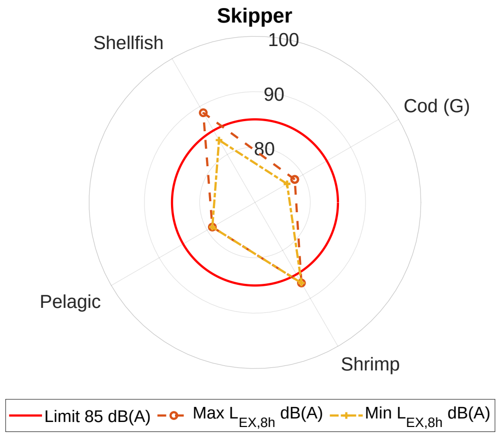
The calculated $L_{EX,8h}$ are shown in Figures 3.2a to 3.2c. The 85 dB(A) limit is plotted as reference. Figures 3.2a and 3.2b present the results for shellfish (crab and whelk), pelagic, shrimp, and cod gillnetter (G) fisheries. For these types of fishery, due to the diversity of the working conditions on board, we analyzed the levels measured the skipper (who mainly performs vessel steering and command operations) and the crew members separately. In the case of cod hand-lining (HL), squid and lobster fisheries, only one exposure group was identified, so the measures from skipper and crew were analyzed together (Figure 3.2c). As shown in the Figures, the cod fishery is plotted in two different graphs as work patterns change depending on the equipment employed, as cod (HL) is carried out without mechanized equipment, while cod (G) uses mechanized winches to haul the gill-nets.

Tables B.1 and B.2 in Appendix B show the detailed noise exposure values for all vessels and noise exposure groups, along with effective work hours.

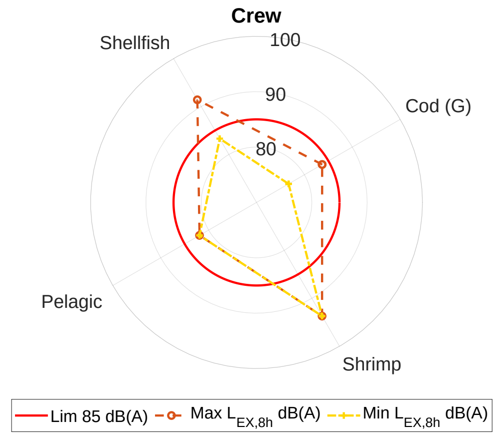
Figure 3.3 presents the range of minimum and maximum peak levels $L_{C,peak,max}$ per fishery

Table 3.4: Skipper responses to the pre-trip questionnaires on the noise sources and job-tasks on the surveyed vessels by vessel skipper and fishery.

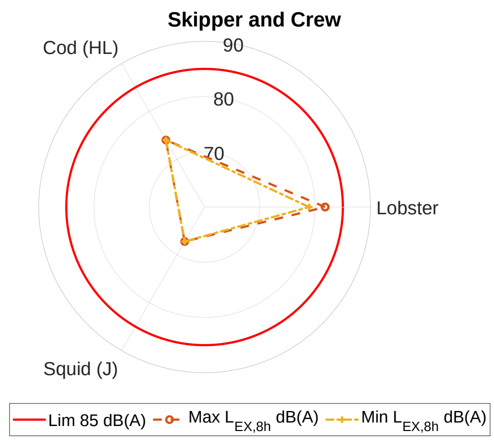
Fishery	Participant	Acknowledged Noise Source	Acknowledged Job-Task	HPD reported
Lobster	1	Engine Environment	-	No
	2	Engine Environment Hauler	Travel to fishing grounds	No
Cod (hand-line)	3	Engine Environment Gear Impacts	-	No
Squid	4	Engine	-	No
Cod (gillnetters)	5	Engine Environment Net Hauler	-	No
	6	Engine & generators Net Hauler	Hauling net on deck Engine check	Ear mufflers, In engine room
Shellfish	7	Engine Environment Pot Hauler	-	No
	8	Engine Pot Hauler Muffler	Gear handling Engine check	Ear mufflers, In engine room
	9	Engine Pot Hauler Muffler	Gear handling Engine check	Ear mufflers, In engine room
	10	-	-	No
Pelagic	11	Engine & generators Hydraulics Fish Pump	Engine check	Ear mufflers, In engine room
Shrimp	12	Engine & generators Trawl Winches Trawl Drums	Gear handling Catch storage Engine check	Ear mufflers, In engine room



(a) Skipper grouping for shellfish, cod, pelagic and shrimp fisheries. (G) refers to gilnetters.



(b) Crew grouping for shellfish, cod, pelagic and shrimp fisheries. (G) refers to gilnetters.



(c) Skipper and crew grouping for lobster, cod, and shrimp fisheries. (HL) refers to hand-lining, (J) refers to jigging.

Figure 3.2: Minimum and maximum values of noise exposure levels $L_{EX,8h}$, subdivided by noise exposure groups and fishery group.

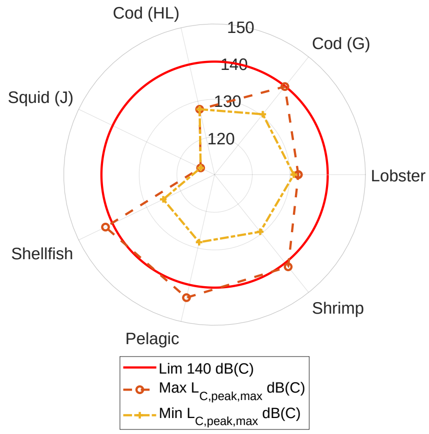


Figure 3.3: Minimum and maximum values of peak levels $L_{C,peak,max}$ per fishery group. (G) refers to gilnetters, (HL) refers to hand-lining, (J) refers to jigging.

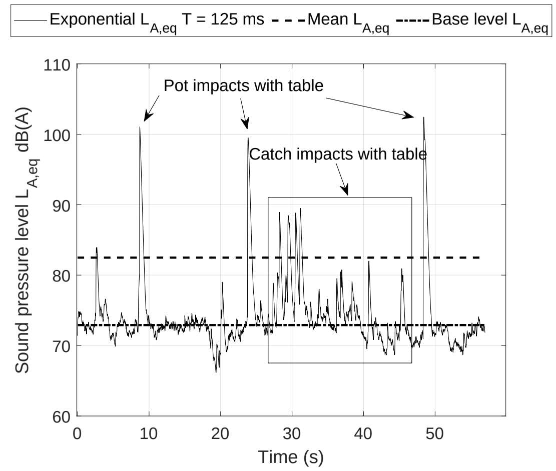


Figure 3.4: Sequence of pot and catch impacts with metal sorting table on a crab trip.

and compares them with the 140 dB(C) limit for impulsive noise.

Impulse noise was identified by analyzing the time history of noise levels with a fast time constant ($\tau = 125$ sec) measured near the ear of a crew member while hauling a single pot on a crab trip, as shown in Figure 3.4. The Figure shows the noise peaks due to gear impact and catch handling on the sorting table, and reports the equivalent mean and base noise level. Base noise level is the sound pressure level due to engine and hauling hydraulic machinery only.

Figures 3.5a to 3.5d present the range of $L_{A,eq}$ measured for each identified task and surveyed fishery. The main tasks we identified are: a) transfer to and from the fishing grounds, b) fishing activities on the deck, c) storage and icing of the catch in the fish hold, and, d) gear preparation for next launch/shoot. The last two of these tasks were only assessed on a limited number of trips, since they were only performed in the case of shellfish, shrimp,

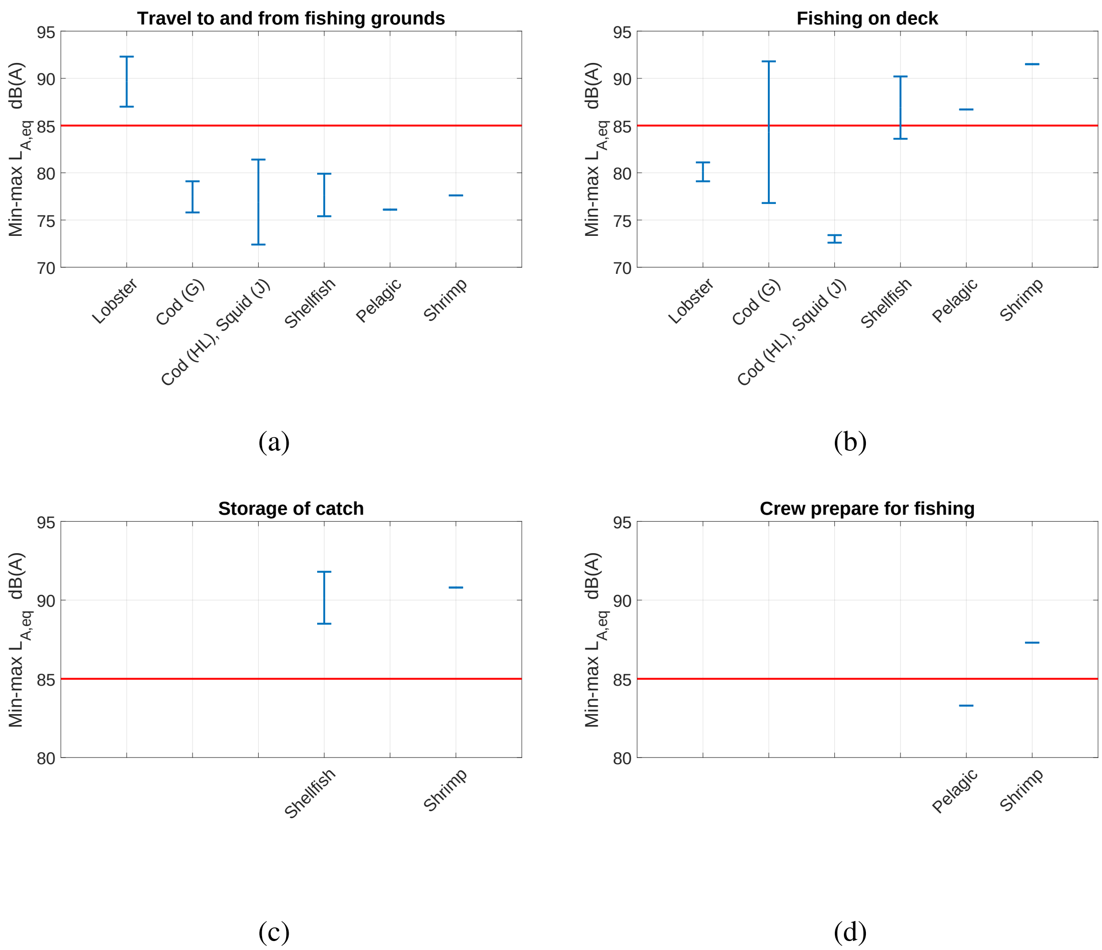
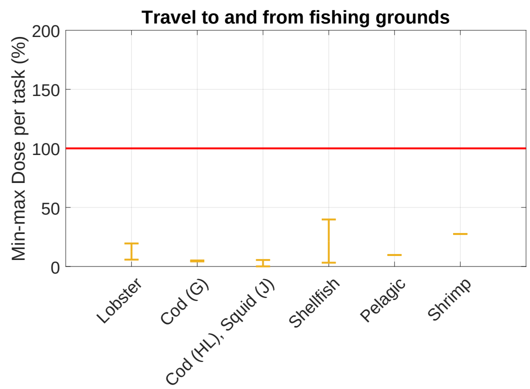
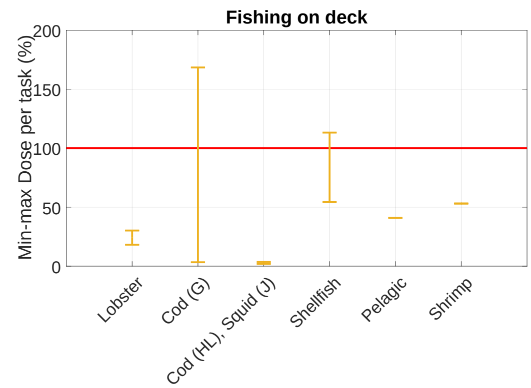


Figure 3.5: Range of min-max $L_{A,eq}$ during specific tasks per fishery. The red line represents the noise exposure criterion of 85 dB(A). (G) refers to gilnetters, (HL) refers to hand-lining, (J) refers to jigging.

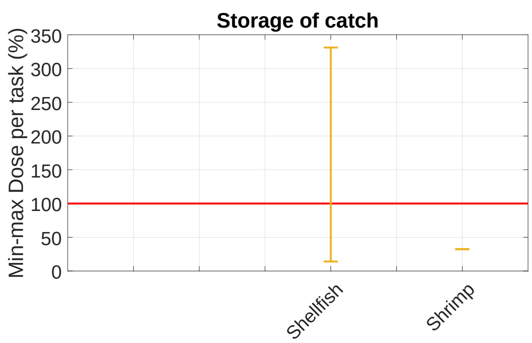
and pelagic fisheries. Figures 3.6a to 3.6d show the adsorbed doses for each task, which allow us to understand the influence of each task on the overall noise exposure.



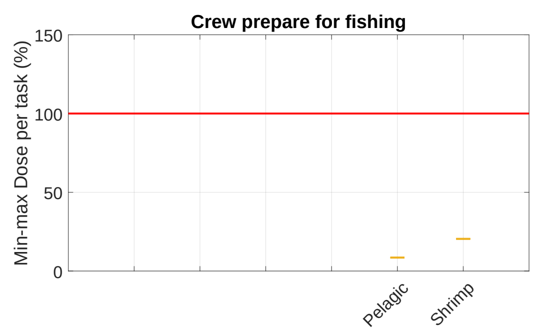
(a)



(b)



(c)



(d)

Figure 3.6: Range of min-max adsorbed doses during specific tasks per fishery. The red line represents the 100 % adsorbed dose, corresponding to a tasks' $L_{EX,8h} = 85\,\mathrm{dB(A)}$. (G) refers to gilnetters, (HL) refers to hand-lining, (J) refers to jigging.

In the case of cod (G), a value of $L_{A,eq}$ over the limit of $85\,\mathrm{dB(A)}$ was detected during the fishing activities (Figure 3.5b). This is likely due to the influence of harsh weather (rain and high wind) on the noise measurement. For this reason, we did not consider this a relevant noise source in the noise awareness score assessment.

3.4.4 Noise awareness scores

Table 3.5 presents the results of the skippers awareness of occupational noise exposures on their vessels. In the Table, we present job tasks with noise levels $L_{A,eq} \geq 80\,\mathrm{dB(A)}$, and the noise sources responsible for hazardous noise levels that were identified on board the vessels during the surveys. From cross-referencing these with the skippers answers to the questionnaires, we devised the following categorization: a) a tick symbol (✓) indicates that a harmful noise sources or job task was correctly acknowledged; b) a cross symbol (✗) indicates that it was not acknowledged, c) a double dash (–) indicates that the a source or a job task was not harmful (i.e. $L_{A,eq}, 80\,\mathrm{dB(A)}$). The last row of each Sub-table reports the noise exposure awareness score that we assigned to each of the skippers of the vessels. Noise awareness was classified as: 1, if all harmful sources and job tasks were identified; 0, if some harmful sources or job tasks were not identified; -1, if no harmful noise source was identified (Section 3.3.5).

Table 3.5: Report of the acknowledgement of harmful Noise Sources from skippers (✓: acknowledged as harmful, ✗: not identified, –: not harmful)

(a) Lobster

Task └ **Noise Source**	**Participants** 1	2
Travel	✗	✓
└ Engine	✓	✓
Fishing	✗	✓
├ Engine	–	✗
└ Hauler	–	✗
Awareness	0	0

(b) Cod (hand-line) & Squid (jigging)

Task └ **Noise Source**	**Participants** 3	4
Travel	✗	–
└ Engine	✗	–
Awareness	0	–

(c) Cod (gillnetters)

Task └ **Noise Source**	**Participants** 5	6
–	–	–
Awareness	–	–

(d) Shellfish

Task └ **Noise Source**	**Participants** 7	8	9	10
Fishing	✗	✗	✗	✗
├ Muffler	✓	✓	✓	✗
└ Gear Impacts	✗	✗	✗	✗
Storage of Catch	✓	✓	✗	✗
└ Gear Impacts	✗	✗	✗	✗
Awareness	0	0	0	-1

(e) Pelagic

Task └ **Noise Source**	**Participants** 11
Fishing	✗
├ Hydraulics	✓
├ Fish Pump	✓
└ Gear Impacts	✗
Gear Preparation	✗
└ Gear Impacts	✗
Awareness	0

(f) Shrimp

Task **Noise Source**	**Participants** 12
Fishing	✓
├ Trawl Winches	✓
├ Trawl Drums	✓
└ Gear Impacts	✗
Storage of Catch	✓
└ Gear Impacts	✗
Gear Preparation	✓
└ Gear Impacts	✗
Awareness	0

3.5 Discussion

3.5.1 The risk of exposure to hazardous noise levels

Fish harvesters were found to be exposed to hazardous noise levels in shellfish (crab and whelk), shrimp, pelagic, and cod (G) fisheries. In particular, $L_{EX,8h}$ are higher than 85 dB(A) in shellfish—crab and whelk—and shrimp fisheries (Figures 3.2a to 3.2c), which represent 8 of the 12 surveyed vessels, and $L_{C,peak,max}$ are above the criterion level in shellfish, shrimp, pelagic fisheries, while they are equal to the criterion level in cod (G) fishery. Crews are also exposed to high noise levels while fishing cod (G), pelagic, and lobster, with $L_{EX,8h}$ just below 85 dB(A) (Figure 3.3). The lowest exposures were measured in squid and cod fisheries, performed using jiggers and hand lines respectively (Figures 3.2a to 3.2c). The analysis of $L_{A,eq}$ for each job task in the surveyed fisheries shows that fish harvesters are especially exposed to hazardous noise levels during fishing operations. In particular, they are exposed to hazardous noise while fishing on decks, with noise levels between 83.6 dB(A) and 91.8 dB(A) in shellfish, pelagic, and shrimp fisheries (Figure 3.5b), and absorbed doses ranging from 40 % in pelagic fishery to 110 % in shellfish fishery (Figure 3.6b). In shellfish and shrimp fisheries, $L_{A,eq}$ were above 85 dB(A) while fish harvesters were storing the catch in the cargo holds (Figure 3.5c), with absorbed doses ranging from 20 % to 340 %. Even though $L_{EX,8h}$ is lower than 85 dB(A) in lobster fishery, our results show that $L_{A,eq}$ is higher than 85 dB(A) during the travel from and to the fishing ground, and this means that fish harvesters are at risk during this task.

Regarding the noise sources, our study found that the fishing gear is the main source that generates hazardous noise levels the most frequently. Examples of this are: impacts of the pots on sorting tables and on the deck (lobster, shellfish, pelagic, and shrimp fisheries), and stationary noise coming from motorized fishing equipment (shellfish, lobster, pelagic, cod gillnetters, and shrimp fisheries).

Main engines, electric generators and auxiliary machinery are prominent noise sources on all the analyzed vessels, but generate hazardous noise levels only in the case of small un-decked fishing boats (lobster fishery) because of the proximity of the crew members to the engine. On decked vessels, main engines are responsible for hazardous noise levels only in the engine rooms (37). It is worth pointing out that in the surveyed vessel engaged in the squid fishery, the main engine did not represent a hazardous noise source due to the lower power of the outboard engine (see Table 3.1 and Figure 3.5a. Another element to be considered is the effect of the weather conditions on the measurements of noise exposure: the survey for the cod (G) is likely to be biased by the additional noise caused by rain, high wind, sea, and ship motions and slamming, which were present while the measurements were performed.

The results of this study are in line with those found in the literature on noise exposures of fish harvesters from other countries. Even though the assessed $L_{EX,8h}$ for each fishery varies as vessel designs and fishing gear are different in different regions of the World, other studies have shown that fish harvesters working on small fishing vessels are exposed to hazardous noise levels.

Unlike previous studies, we identified the job tasks that are responsible for hazardous noise levels. We found that fish harvesters are mainly exposed to hazardous noise levels while fishing and that noise exposure varies depending on the type of catch, vessel design, and sub-tasks performed by skippers and crews. This is shown by the large variation of measured $L_{A,eq}$ while traveling to and from the fishing ground (for shellfish, lobster, and cod (HL) and squid fisheries), fishing on deck (for shellfish fishery), and storing the catch in the cargo hold (shellfish fishery); and by the large variation in absorbed doses for the shellfish fisheries during the tasks fishing on deck (Figure 3.6b) and storage of catch (Figure 3.6c). This is different than the results published by Zytoon (29), who identified the main engines as primary noise sources on board. This may be an indicator of the high variability of noise levels and their sources across different fisheries worldwide.

3.5.2 Considerations on skippers awareness

The results presented in Table 3.5 show that the skippers of the surveyed vessels are not completely aware of the risk caused by on-board noise sources and of the noisy job tasks while fishing. In general, they correctly identified stationary noisy sources, such as the main engines and auxiliary machinery (Table 3.4) as dangerous, but they underestimated the hazard of exposure coming from pot impacts and gear handling during on-board fishing operations. This is also reflected in the fact that HPDs were only provided in 5/12 vessels and were to be used by the crew in the engine room. None of the skippers and crew who participated in this study were wearing HPDs during the surveyed trips and they were not provided with HPDs during fishing operations.

3.5.3 Recommendations on possible short-term solutions to reduce the risk of noise exposure hazards

Based on our findings, we have developed the following recommendations and communicated these to NL small scale fish harvesters through face-to-face findings communication, a noise exposure video under development with the NL-FHSA, and at safety symposia organized by the NL-FHSA. The recommendations are also likely relevant for small-scale fish harvesters outside of NL.

1. The high variation in job tasks, vessel designs, and fishing activities implies that noise assessment on small fishing vessels should be performed in accordance with the job-based method (34), which requires the use of personal noise dosimeters to assess noise exposures.

   Indeed, as it was shown in (38–41), the noise exposure calculated using the job-based method is more accurate than the results obtained with task-based methods or the IMO simplified method ((42)), in the case of job activities characterized by a wide array of tasks and tasks duration. Moreover, our results show that the analysis of the job tasks and noise sources helps identify conditions of exposure to hazardous noise levels.

2. While previous studies (for example (27, 29)) have focused their recommendations on possible ways to mitigate noise coming from the main engines, these solutions

fail to take into account the problem of the noise generated by the fishing gear. With the exception of the lobster fishery, our results show that these solutions would not be effective if applied to the small-scale fishing fleet from NL. Possible solutions to mitigate noise from the impact of the handling of pots and steady-state or intermittent noise from the fishing gear on decked vessels include: a) the use of a thick rubber material coating or mats on pots (crab, whelk and lobster fisheries), sorting tables (crab, whelk, lobster and shrimp fisheries) and on deck floors to decrease the impact noise of the gear; b) soundproofing boxes around electric/hydraulic generators on the deck or above the wheelhouse; and c) modification of pots and net haulers and net drum design to include rubber coating on the drums so that the noise due to rope engaging is reduced.

In the case of the small undecked vessels with outboard engines, noise reduction may be achieved by: a) soundproofing the engine cowling using non-flammable insulation materials; and b) regular maintenance of the engines (29).

The fact that these are easy-to-implement, low-cost, and feasible solutions should contribute to willingness to adopt them (43). On the other hand, pilot studies should assess their effectiveness in noise mitigation as well as their compliance with Transport Canada regulations prior to widespread adoption of these changes (23).

3. HPDs need to be adopted. Our research shows that fish harvesters should wear HPDs while fishing on the deck in cod (G), shellfish, pelagic and shrimp fisheries. They should also be worn while storing the catch in the cargo hold in shellfish and shrimp

fisheries and while preparing for fishing activities in the shrimp fishery. With regards to the lobster fishery, even though our results show the noise dose accumulated during travel from and to the fishing grounds is low (Figure 3.5a and Figure 3.6a), fish harvesters should wear HPDs during this task as the duration of exposure may vary depending on the location of the fishing ground and thus distance and time travelled. Based on the measured noise exposure components, fish harvesters should wear class of reduction B hearing protections, equivalent to a SNR(SF_{84}) (Single Number Rating) between 14 and 17 (44). The selected HPDs should allow communication between crew members and should not interfere with awareness of the surrounding noise as failure to do this might affect other aspects of fishing safety. Use of ear mufflers with active noise reduction is thus advisable. The effectiveness of these HPDs and recommended engineering changes, although based on the evidence of measured noise exposures should be tested in order to quantitatively evaluate their effectiveness to mitigate noise exposures ((25)). Future research should investigate the feasibility and effectiveness of the mitigation solutions we identified based on our study.

4. As skippers are not completely aware of the risks of occupational noise exposures on their vessels, future activities should include programs to enhance their awareness of: a) health issues caused by prolonged exposure to hazardous noise levels; b) fishery and job tasks associated with the risk of hazardous noise exposures; c) on-board noise sources that generate hazardous noise levels; and d) engineering controls solutions and appropriate HPDs that can mitigate hazardous noise exposures.

3.6 Conclusions

The purpose of this study was to assess the risk of exposure to hazardous noise levels among fish harvesters in relevant cases and to propose possible short-term solutions. We travelled on board 12 small fishing vessels, covering the cod, whelk, lobster, crab, capelin, shrimp, and squid fisheries and using gill-nets, trawls, jiggers/hand-line, pots and purse-seine gears. For each of these vessels, we evaluated the 8-hour equivalent $L_{EX,8h}$ using a job-based approach and the C-weighted peak level $L_{C,peak,max}$. The obtained levels were compared to the relevant criteria for NIHL risk used in the province. We found that: a) fish harvesters are often exposed to hazardous noise levels; b) fishing operations which involve the use of hydraulic deck equipment, such as winches and fish pumps, the presence of repetitive gear impacts, as well as the use of outboard engines, are responsible for hazardous noise levels; and c) skippers are not fully aware of the noise exposure hazards on board their vessels. Drawing on these results we have recommendations for engineering solutions and HPDs type and use to mitigate noise exposures whose effectiveness should be tested in future research. Working with our collaborating organization and co-funder of this research, the NL-FHSA, we are communicating our findings and recommendations to small-scale fish harvesters in NL via one-on-one meetings, safety symposia presentations, and a video on noise exposure and effects under development.

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Chapter 4

A comparative study of the methods to assess occupational noise exposures of fish harvesters

4.1 Co-authorship statement

The chapter is a preprint version currently under review for publication on the peer-reviewed journal paper *Safety and Health at Work* and was authored by Giorgio Burella, and Dr. Lorenzo Moro. Giorgio Burella led the writing of this paper, and conducted the noise surveys on board the study vessels. Dr. Lorenzo Moro participated in discussions and edited the manuscript to enhance the layout, writing, and the concepts presented in this paper. All authors revised, edited, and made recommendations for improvements to earlier drafts of this paper.

4.2 Introduction

Noise induced hearing loss (NIHL) is a common occurrence in workplaces characterized by a prolonged exposure to hazard noise levels and frequent impulsive noise (1). In particular, NIHL is a well-documented occupational illness for fish harvesting in literature: studies have been conducted to test fishing workers for hearing threshold shifts (2, 3), and to assess hospital contacts or work health history (4–6) of fish harvesters. This problem might potentially affect a tremendous amount of people worldwide. Indeed, the fishing industry is present in every coastal region worldwide and 40,399,000 people were fish harvesters in 2016, an increase of 25 % over the previous 20 years (7).

While the incidence of NIHL is assessed by means of audiometry, exposure to hazardous noise levels can be assessed through measurements performed during fishing operations. This assessment is the first necessary step to implement risk control measures in the workplace. and its accuracy in the measurement of hazardous noise levels is fundamental to tailor the control interventions. An analysis of the scientific literature on this matter highlights that few studies have been conducted on noise exposure assessment of fish harvesters. The outcomes of these studies do not define a clear and generalized course of action to mitigate noise exposure of fish harvesters, as they were performed in different parts of the world, for multiple fisheries, and using different methods of assessment. Most of the reported research activities on the assessment of noise exposure of fish harvesters used the task-based measurement approach (TBM), where noise levels are measured in each work position and for each work task, and then the overall noise exposure is calculated considering the stationing time in those work positions and the duration of the tasks of a nominal working day. Zytoon (8) conducted extensive measures on 24 vessels; Peretti et al. (9) assessed the exposure on five small to medium sized vessels. Although TBM is well suited for highly standardized works where a worker job can be split into a series of repetitive tasks (10), it has been shown that it can be used to accurately assess noise exposure of workers in several occupations (11–13). Alternatively, full-day personal dosimetry or full-day measurement (FDM) can be performed to assess an average day noise exposure level. According to this method, personal noise dosimeters are worn on the harvesters bodies during normal fishing activities, and monitor noise for the whole working day. Some scholars have used FDM to assess noise exposure on samples of fish harvesters: Paini et al. (2) studied noise exposure on small-size fisheries from Brazil; Levin et al. (3) on shrimp trawlers from the Mexico Gulf; Fulmer and Buchholz (14) on small-scale lobster fisher and gillnetters from Massachusetts; while Zytoon (8) performed FDM for comparison with TBM assessment. Finally, a third method to assess noise exposure is the job-based method (JBM) that identifies jobsintended as the overall occupational activity carried out by a worker during an entire working dayand extrapolate a mean exposure level from a random sample of noise levels associated to that job (10); to our knowledge, no research on fish harvesters exposure has been conducted using this method.

With regard to relevant international standards, there is no recommendation on what method should be used to assess noise exposures on fishing vessels. The Maritime Safety Committee of the International Maritime Organization (IMO), which is the main international body regulating safety at sea, does not regulate safety on fishing vessels. This is also reflected in the Code on noise levels on ships (15), which sets noise limits for different vessel spaces and noise exposure for crew members. It recommends to use ISO 9612 methods for exposure assessment, but also outlines a simplified method (sIMO) to determine noise exposure of crew members, using noise levels measured in different vessel spaces and crew standing time. This Code does not apply to fishing vessels, but is used to assess noise exposure on commercial vessels (16). On board a large harvester/processor, ISO and sIMO methods were used together by Neitzel et al. (17), where noise exposure levels of non-work-shifts (obtained via sIMO) and work-shifts (obtained via dosimetry) were combined to get the overall exposure.

This paper presents the results from surveys performed to assess occupational noise exposures of fish harvesters on small fishing vessels in the Canadian province of Newfoundland and Labrador. We travelled on 11 fishing vessels during regular fishing trips, and performed extensive noise exposure surveys, encompassing several types of fishing vessels, diverse in lengthfrom open-deck skiffs to larger decked vesselsfishing gear, and fishing operations. On each vessel, the surveys were performed according to the TBM, JBM, FDM, and sIMO. The noise exposure levels calculated with each method were compared, to understand which method is the most accurate to determine occupational noise exposures on small fishing vessels, and strengths and limitations of each method. The research presented in this paper is part of a larger project that aims to mitigate occupational noise exposures of fish harvesters working on fishing vessels less than 24 m in overall length from the Canadian province of Newfoundland and Labrador (NL), also known as small-scale fishing fleet.

4.3 Materials and Methods

4.3.1 Sample of visited vessels

Table 4.1: Sample of visited vessels.

Vessel ID	Crew #	Length (m)	Boat[1] Type	Fishery	Gear	Engine Power (Hp)	Engine[2] type
FSH001	2	5.8	Undecked,FRP	Lobster	Pots	115	OB
FSH002	2	10.7	Decked,WD	Cod	Handline	150	IB
FSH003	2	10.7	Decked,FRP	Cod	Gill Net	205	IB
FSH004	3	11.9	Decked,WD	Whelk	Pots	306	IB
FSH005	3	10.7	Decked,WD	Crab	Pots	217	IB
FSH006	3	19.8	Decked,FRP	Cod	Gill Net	624	IB+GS
FSH007	3	10.7	Decked,WD	Crab	Pots	217	IB
FSH008	5	15.5	Decked,FRP	Crab	Pots	340	IB+GS
FSH009	5	18.3	Decked,FRP	Capelin	Purse seine	543	IB+GS
FSH010	6	19.8	Decked,FRP	Shrimp	Trawls	624	IB+GS
FSH011	2	5.8	Undecked,FRP	Squid	Handline	50	OB

[1] FRP: fiberglass boat, WD: wooden boat;
[2] OB: outboard motor, IB: inboard engine, GS: electric/hydraulic power generating set

The authors traveled on board 11 vessels from the NL small-scale fleet, surveying noise exposure of 34 fish harvesters engaged in 7 different fisheries. The sample is presented in Table 4.1. In order to define a sampling regime, we studied the composition of the NL small-scale fishing fleet. Thus, the sample was composed of relevant cases that accounts for the variability of noise exposure in the fleet section considered. Parameters such as lengths, vessel layouts and construction materials were considered, since they influence the type of noise sourcesi.e. propulsive engine, auxiliary machinery, fishing gearand noise transmission on board. We also considered the work patterns of harvesting operations, since occupational noise exposures depend on them. A detailed examination of the fleet composition was presented by Burella et al. (18).

4.3.2 Ethics

This research was approved by the Interdisciplinary Committee on Ethics in Human Research (ICEHR) of Memorial University of Newfoundland. Ethics clearance required participation in the study to be voluntary, written, informed consent from participants, confidentiality and feedback of results to participating skippers and crew.

4.3.3 Noise surveys

Noise measurements took place on board consenting vessels during regular fishing trips. Owner-operators provided information on the vessel characteristics via a pre-trip questionnaire. Furthermore, we interviewed the vessels crew about the typical fishing operations and work patterns of the fishing trip. Following these, we developed a noise measurement plan, and we identified homogeneous noise exposure groups among all the fish harvesters working on the same vessel (10).

The noise-sampling instrumentation setup was composed of Bruel&Kjær® Type 4448 personal noise dosimeters. Microphones were equipped with wind screens to avoid wind flow interference. The noise dosimeters were worn on the most exposed shoulder of the harvesters and used to perform personal noise dosimetry for the entire fishing trip. The actual composition of the working day activitiesi.e. tasks and their durationwas extracted from debrief questionnaires that were compiled at the end of each fishing trip. In these questionnaires, harvesters were required to log their tasks during their working day. These logs were supplemented by one compiled by the researchers on board, to fill possible blanks. Class

1 mod. 378B02 ICP hand-held microphone by PCB Piezotronic® connected to a National Instrument® mod. A 9234 BNC input card was used to record sound pressure levels of on-board spaces, and the acquired data were processed using LABView®. The microphones were used to map the noise levels in spaces of vessels, according to the IMO noise code (15). Before each trip, the dosimeters and hand-held microphones were calibrated using a Larson and Davies® calibrator mod. CAL200.

4.3.4 Methods to assess occupational noise exposures

The measured data were processed according to TBM, JBM and FDM, as described in the ISO standard 9612:2009 (E) (10), in order to obtain the 8-hours A-weighted noise exposure level $L_{EX,8h}$ for noise exposure groups. $L_{EX,8h}$ was also calculated according to sIMO as described in the ”Code on noise levels on ships“ (15). According to TBM, noise exposure levels are calculated as follows:

$$L_{p,A,eq,T_m} = 10\log_{10}\left(\frac{1}{I}\sum_{i=1}^{I}10^{0.1L_{p,A,eq,T_m,i}}\right) \tag{4.1}$$

$$L_{EX,8h} = 10\log_{10}\left(\sum_{m=1}^{M}\frac{T_m}{T_0}10^{0.1L_{p,A,eq,T_m}}\right) \tag{4.2}$$

where $L_{p,A,eq,T_m,i}$ is the i-th sample of A-weighted sound pressure level out of I measured samples for the m-th task, $T_0 = 8\,\text{h}$ is the reference duration of the work day, and T_m is the average duration of the m-th task. Duration of each sample $L_{p,A,eq,T_m,i}$ is prescribed by the standard according to the type of noise sources. M is the total number of tasks performed on a working day.

sIMO method is similar to the ISO 9612 TBM, except that $L_{p,A,eq,T_m,i}$ are substituted with the noise levels from the noise mapping of spaces where the crew is standing.

In the JBM, noise exposure levels are calculated for each job and each noise exposure group as follows:

$$L_{p,A,eq,T_e} = 10\log_{10}\left(\frac{1}{N}\sum_{n=1}^{N}10^{0.1L_{p,A,eq,T,n}}\right) \tag{4.3}$$

$$L_{EX,8h} = L_{p,A,eq,T_e} + 10\log_{10}\left(\frac{T_e}{T_0}\right) \tag{4.4}$$

where $L_{p,A,eq,T,n}$ is the n-th sample of A-weighted sound pressure level out of N measured samples associated to the job and T_e is the effective duration of the working day. Thus, for each job, a representative random sample of $L_{p,A,eq,T,n}$ is measured during the day, based on the contribution to the overall noise exposure. The actual size of said sample depends on the number of workers in the homogeneous noise exposure group for that job. Finally, FDM uses full-day measurements from workers of a homogeneous noise exposure group, perform the average using Eq. (4.3), and calculate the noise exposure levels according to Eq. (4.4). This method is conceptually similar to the JBM, except for using a sample of full-day measurements of noise exposure levels of workers instead of random samples of shorter duration.

4.3.5 Analysis of measured data

In JBM and TDM, in order to obtain the samples of time averaged sound pressure levels $L_{p,A,eq,T_m,i}$ for each task and $L_{p,A,eq,T,n}$ for each job, we used of the day activities logs to break down the composition of the dosimeters logs and extract the measured samples and durations. Any spurious noise interference, such as deviation from the nominal working day or presence of impacts on the dosimeters microphones, was removed from the logs.

We also calculated A-weighted sound pressure levels according to FDM using the full working day logs from the dosimeters, when this was possible. Indeed, 4 fish harvesters out of 34 participants removed the dosimeters, as these were impeding their activities. L_{p,A,eq,T_e} were also obtained from sound mapping of on-board spaces measured via hand-held microphones during two typical vessels speedsfull speed and slow-downand used to assess noise exposure according to sIMO. Expanded uncertainties U for TBM and JBM were calculated according to the procedure in (10). No uncertainty evaluation is required for the sIMO method.

We then compared the values obtained according to these four methods to evaluate differences, strengths, and limitations of each method when used to assess occupational noise exposure of fish harvesters in small-scale fisheries.

4.4 Results

The results of the assessment of noise exposures using the ISO 9612 methods are reported in Figures 4.1 to 4.3. The Figures show the mean exposure values $L_{EX,8h}$ with the expanded uncertainty U, which corresponds to the exact one-sided 95 % upper confidence interval (19). The expanded uncertainty of the FDM was not calculated, since not enough full-day measures were available for most of the fishing trips: for instance, the skipper noise exposure group is composed in all vessels by one person only, hence requiring performing measurement over three days, which was not feasible for research time constraints. The standard uncertainty u_1^2 (10) of exposures calculated according to FDM is reported in Table C.1 in Appendix C.

The results in Figures 4.1 to 4.3 are shown for two different groups of vessels, which were identified in a previous study where we performed an analysis of the sound sources on each vessel (18): 1) vessels on board which noise levels are mainly dominated by engine and auxiliaries, such as small open boats, or decked vessels where light gear such as gillnet or handline is used FSH001, FSH002, and FSH011 belong to the first group; 2) vessels on board which noise exposure is mainly dominated by fishing activities noise on the deck (handling and impacts of gear, deck machinery, catch, etc.), as on board decked vessels that uses heavy gear, such as crab pots, or trawls FSH003, FSH004, FSH005, FSH006, FSH007, FSH008, FSH009, and FSH010 belongs to this group. In this group, noise exposures of skippers and crew members is analyzed separately. Detailed exposure levels are presented in tabular form in Appendix C.

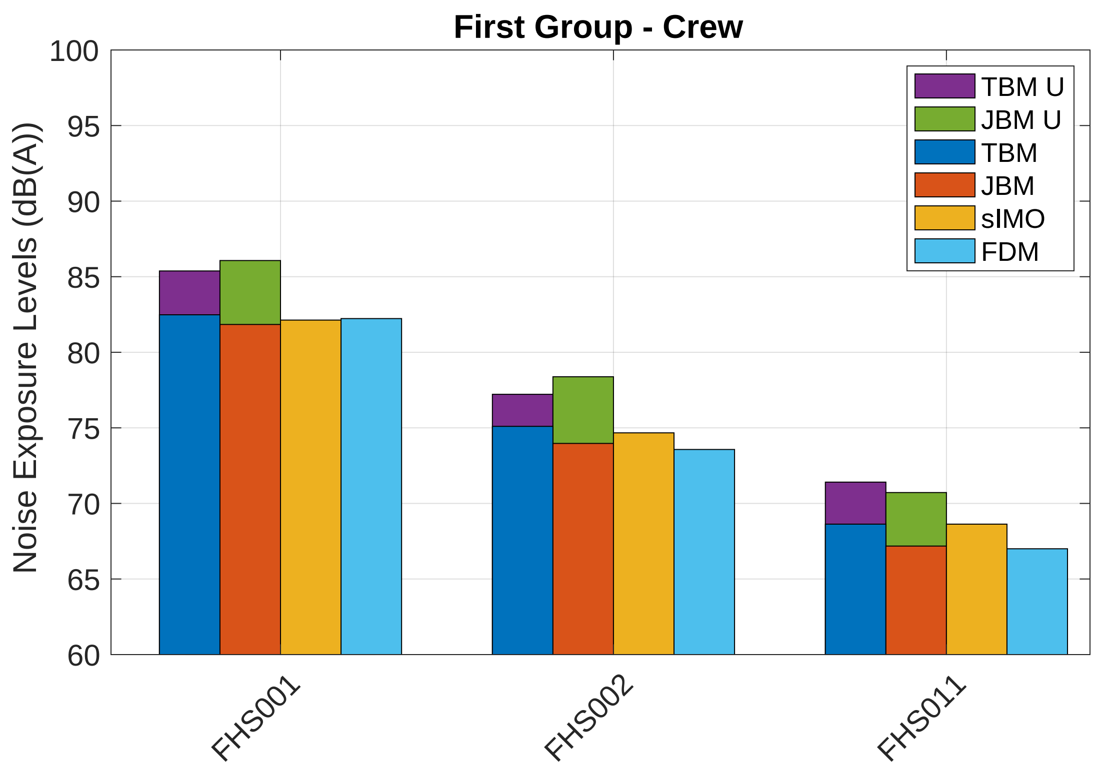

Figure 4.1: 8-hours equivalent noise exposure levels $L_{EX,8h}$ and uncertainties U on the first group of vessels obtained with the four assessment methods.

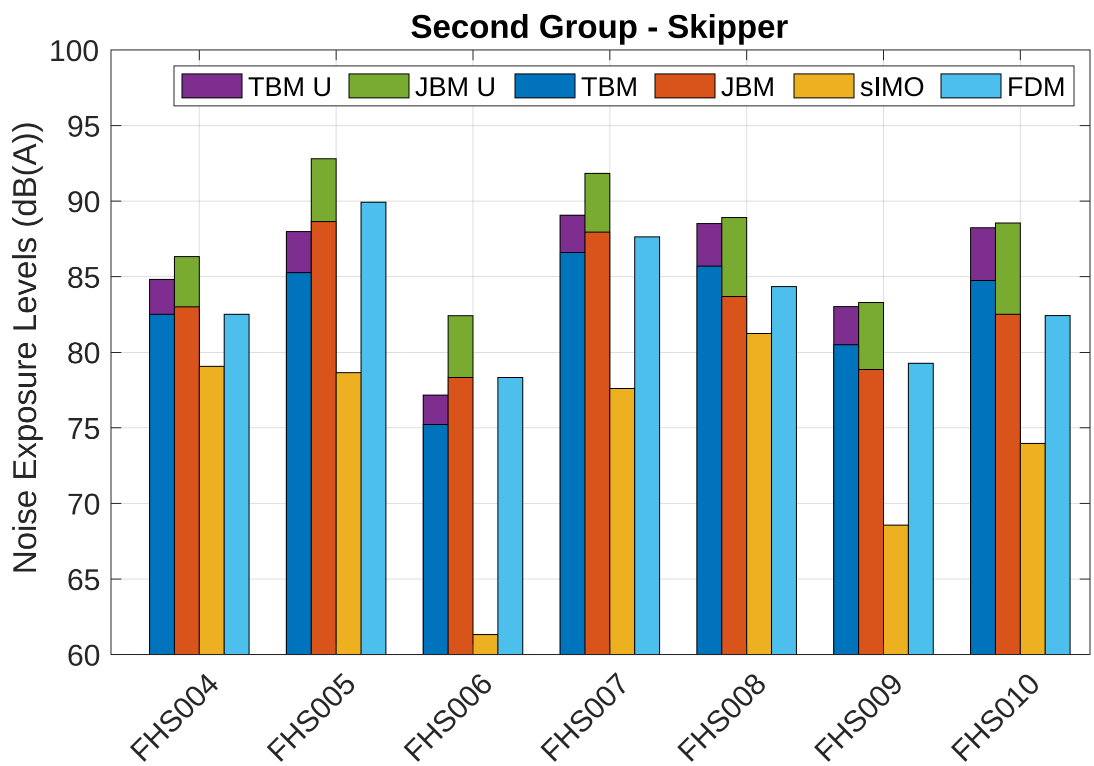

Figure 4.2: 8-hours equivalent noise exposure levels $L_{EX,8h}$ and uncertainties U of skippers on the second group of vessels obtained with the four assessment methods.

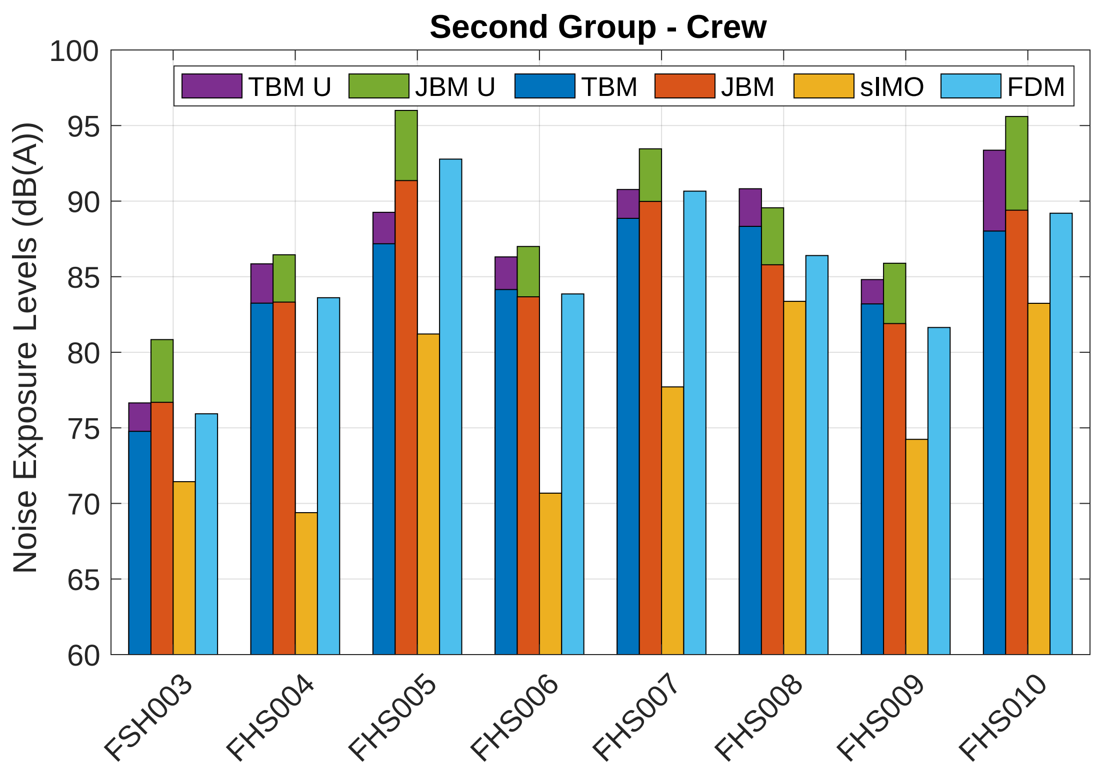

Figure 4.3: 8-hours equivalent noise exposure levels $L_{EX,8h}$ and uncertainties U of crew members on the second group of vessels obtained with the four assessment methods.

4.5 Discussion

The data presented in Figures 4.1 to 4.3 highlight the risk of hazardous noise exposure (noise exposure levels $L_{EX,8h}$ above 85 dB(A) (20)) for personnel of vessels from the second group, especially in the case of crew members (Figure 4.3).

In the following discussion, we consider the exposure levels reported ussing FDM as a benchmark to assess the effectiveness of the other methods to assess noise exposure levels. FDM considers the average daily exposure as measured by the dosimeter of a homogeneous noise exposure group over an entire working day, which is a measure of the true exposure of workers. Table 4.2 shows the difference in dB among the methods JBM, TBM, and sIMO with FDM.

4.5.1 Noise exposure dominated by engine noise

The mean noise exposure values $L_{EX,8h}$ of Figure 4.1 and the $\Delta L_{EX,8h}$ reported in Table 4.2 show that both TBM and JBM are good estimators of the mean noise exposure level when compared to the noise exposure values $L_{EX,8h}$ obtained with FDM. JBM estimates are in general closer to FDMs, with $\Delta L_{EX,8h}$ always less than 1 dB, while $\Delta L_{EX,8h}$ between TBM and FDM is generally greater.

Despite this difference in mean exposure levels, the combined effect of mean exposure level and uncertainty is leveling out the estimates of JBM and FDM. This behavior was already assessed in the study (8).

The prevalence of engine and auxiliaries noise in the exposure is also supported by the

Table 4.2: Difference $\Delta L_{EX,8h}$ [dB] of noise exposure levels obtained via TBM, JBM, sIMO and FDM. A reported negative difference means that the calculated level is lower than the corresponding FDM level.

Vessel ID	**Difference of TBM with FDM** $\Delta L_{EX,8h}$ dB	**Difference of JBM with FDM** $\Delta L_{EX,8h}$ dB	**Difference of sIMO with FDM** $\Delta L_{EX,8h}$ dB
First group: noise dominated by engine noise			
FSH001 Lobster	*All Crew Members* 0.2	*All Crew Members* -0.4	*All Crew Members* -0.1
FSH002 Cod	*All Crew Members* 1.5	*All Crew Members* 0.4	*All Crew Members* 1.1
FSH011 Squid	*All Crew Members* 1.6	*All Crew Members* 0.2	*All Crew Members* 1.6
Second group: noise dominated by noise of fishing activities			
FSH004 Whelk	*Skipper* -0.4; *Crew* 0	*Skipper* -0.3; *Crew* 0.5	*Skipper* -3.4; *Crew* -14.2
FSH003 Cod	*All Crew Members* -1.2	*All Crew Members* 0.8	*All Crew Members* -4.5
FSH006 Crab	*Skipper* -5.6; *Crew* -4.7	*Skipper* -1.4; *Crew* -1.3	*Skipper* -11.3; *Crew* -11.6
FSH006 Cod	*Skipper* 0.3; *Crew* -3.1	*Skipper* -0.2; *Crew* 0	*Skipper* -17; *Crew* -13.2
FSH007 Crab	*Skipper* -1.8; *Crew* -1	*Skipper* -0.7; *Crew* 0.3	*Skipper* -10; *Crew* -13
FSH008 Crab	*Skipper* 1.9; *Crew* 1.4	*Skipper* -0.6; *Crew* -0.6	*Skipper* -3.1; *Crew* -3
FSH009 Capelin	*Skipper* 1.6; *Crew* 1.2; *Skiff Operator* -0.8	*Skipper* 0.3; *Crew* -0.4; *Skiff Operator* -0.3	*Skipper* -10.7; *Crew* -7.4
FSH010 Shrimp	*Skipper* -1.2; *Crew* 2.3	*Skipper* 0.2; *Crew* 0.1	*Skipper* -8.4; *Crew* -6

assessment in Table 4.2: the difference for the selected cases is negligible between the exposure levels calculated with sIMO and FDM.

4.5.2 Noise exposure dominated by fishing gear

In this case, the $\Delta L_{EX,8h}$ between TBM and FDM is greater than the $\Delta L_{EX,8h}$ between JBM and FDM, as reported in Table 4.2.

Although the sample of TBM is obtained from noise levels measured during fishing operations with all the relevant noise components present, it fails to accurately represent the average exposure level, when compared to FDM. This is proven by TBM levels, that differ from FDMs more than 1 dB in all the surveyed vessels, except for vessel FSH004. TBM assessment also gives narrower upper intervals of uncertainty, as shown in Figure 4.2 and Figure 4.3, especially for crew members. This leads to a combined value of uncertainty and mean exposure levels that is lower than JBMs method, in line with what seen in the first group.

The $\Delta L_{EX,8h}$ between JBM and FDM (see column 2 of Table 4.2) are generally smaller than the $\Delta L_{EX,8h}$ between TBM and FDM. These values are lower than 1 dB for all the surveyed vessels, except for vessel FSH006. This is explained by the higher variability of the sample used in JBM. This trend was expected, since the dominating noise component arises from fishing operations, that are highly variable in pattern and composition. Failure of TBM to properly produce reliable exposure estimates in presence of high noise level variability within tasks is confirmed in other works which assessed noise in other occupations (21–24).

With regard to the sIMO, the data reported in Figure 4.2 and in Table 4.2 show that this simplified method largely underestimate occupational noise exposure of fish harvesters, with $\Delta L_{EX,8h}$ always greater than 3 dB. This shows that when noise levels are dominated by non-stationary sources, neglecting the noise contributions from fishing gear cannot be neglected. The $\Delta L_{EX,8h}$ between sIMO and FDM calculated in Table 4.2 in the case of vessel FSH007 are particularly high (17 dB) due to the harsh weather during the survey.

4.5.3 Recommendations

According to the results presented in this paper, we can draw the following considerations:

- Task-based Method (TBM). This method is less time consuming to implement when compared to JBM or FDM. It only requires performing short time duration measures of noise exposure of tasks that compose a specified working activity, as opposed to the other two methods, that require extensive lengthy measurements. Nonetheless, this research shows a shortcoming in the ability to capture a proper estimate of the noise exposure in the case of fishing activities. Differences between TBM and FDM estimates are due to non-representative samples of tasks, that neglect the high degree of variability within the task. In order to be accurate, the job should be decomposed into a higher number of tasks (24), making it extremely difficult to implement. Hence, its application should be limited to the detection of the tasks related to high noise exposure.

- Job-based Method (JBM): This method requires a sample of noise exposure measurements having fixed minimum cumulative duration. Samples must be representative of all noise components, and hence requires a more extensive noise measurement program. Thus, because of the high variability of the noise components in the exposure, this research shows that JBM captures the mean noise exposure levels and expanded uncertainty better than TBM.

- Simplified IMO method (sIMO): This method is similar to TBM, except for the use of noise levels of spaces instead of noise levels measured during specific tasks. The occupational noise exposure assessment performed according to this method is easy to implement and less time consuming than the assessments performed according to the ISO 9612 methods: noise mapping of spaces does not require the collection of a group of sample; the only required activity is the estimation of the time the workers spend performing a certain task. Unfortunately, this research shows that sIMO method is not feasible to assess noise exposure, as it neglects noise components arising from the use of gear during fishing activities; nonetheless these components are dominant sources on several vessels.

- Full-day Measurement (FDM): This method calculates the average of full day measurement of noise exposure from personal noise dosimetry of a selected sample of workers. It is difficult to obtain in a timely fashion all the required samples (minimum 3) on small-scale vessels, where the crew members range from 4 to 6 persons, and where the noise exposure group might be composed by one worker only. Measures are also more difficult to control due to their length in time, and they require the investigator to watch closely the tested workers to avoid the recording of spurious noise components.

We can conclude that JBM is the most effective method to assess noise exposure on small fishing vessels and as it gives accurate results with a small group of samples and takes into account the uncertainties in the measurement procedure and the outliers in the noise exposure sample better than the other methods. JBM assessment, thanks to the random composition and longer duration samples of noise exposure, works better than the other methods for small-scale fishing operations, even when noise exposure is dominated by the engine noise.

A limitation of the study is the sample size, which is not wide enough to be representative of the whole population of small-scale vessels form the province, so that the consideration listed here might not be general. Nonetheless these recommendations can be used for the assessment of noise exposure of similar cases as the one presented on this study.

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The authors would like to thank Ms. Brenda Greenslade and Ms. Sharon Walsh from the Newfoundland and Labrador Fish Harvesting Safety Association (NL-FHSA), Mr. Mark Dolomount from the Professional Fish Harvesters Certification Board (PFHCB), and Dr.

Barbara Neis from the SafetyNet Centre for Occupational Health and Safety of the Memorial University of Newfoundland for their kind help throughout the research activity. Special thanks go to all the vessel owners-operators and fish harvesters who allowed us to travel with them during their fishing trips and visit their vessels at the wharf.

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Chapter 5

A study on the acoustic transmission characteristics of in-shore fishing vessels from Newfoundland and Labrador

5.1 Co-authorship statement

The chapter has been published and presented as a peer-reviewed conference paper in July 2019 at the *26th International Congress on Sound and Vibration (ICSV)* in Montral (1) and was authored by Giorgio Burella, and Dr. Lorenzo Moro.

Giorgio Burella led the writing of this paper, and conducted the noise surveys on board the study vessels. Dr. Lorenzo Moro participated in discussions and edited the manuscript to enhance the layout, writing, and the concepts presented in this paper. All authors revised, edited, and made recommendations for improvements to earlier drafts of this paper.

5.2 Introduction

On-board noise and vibration control can be an important task in the design of marine structures, due to possible detrimental effects on crew and passengers if not properly considered.

The presence of high on-board noise levels affect both comfort and health & safety (HS) of crew and passengers. Prolonged exposure to high noise levels is generally considered to be the main risk factor for the onset of occupational noise-induced hearing loss (NIHL) (2). Furthermore, high noise levels are compounded with other environmental stressors in increasing fatigue of seafarers and hence the risk of injuries or psycho-physical stress (3). Designs that are particularly affected by this are, among others, cruise ships (4, 5), super-yachts (6), and offshore structures (7) due to the high standards required for comfort and HS. Noise control is also becoming important in the management of underwater noise signatures of vessels, and can affect underwater acoustic pollution that impacts marine life (see e.g. (8)).

Noise control and management on vessels from the small-scale, inshore fishing fleet has received little attention from designers and the fishing industry worldwide. Inshore fisheries are known for catching 45 % of the global catch (9), and the inshore fleet (less than 24 m length) accounts for the 98 % of total fishing vessels (10), thus employing a tremendous amount of harvesters. HS and low habitability (i.e. minimum comfort requirements) as a result of elevated noise levels can potentially affect a large amount of people worldwide. Noise control on small fishing vessels is often not considered in the design phase, as reflected by the absence of a consistent regulatory framework. The reference regulation from IMO[1] on noise levels and control does not include fishing vessels (11). The regulations on the matter for small fishing vessels safety are fragmented and often voluntary

[1] International Maritime Organization

(12). For inshore vessels having lengths overall (LOA) less than 24 m the ILO[2], IMO and FAO[3] produced a set of voluntary guidelines for owner/operators which provide guidance for the safety on the vessel design and during fishing operations (13, 14). However, these guidelines do not provide design procedures for noise control for fishing vessel designers.

The literature on the topic is scarce. Noise levels on fishing vessels of different spaces and at various speed are reported in studies where the main goal was the characterization of noise exposures (15–17). Studies that provide a more thorough description of the noise control issue, through the identification of noise sources, levels, transmission and noise mitigation packages, are even scarcer and covers vessels equal to 16.99 m LOA or longer, neglecting smaller vessels (18, 19). The cited studies found rather high noise levels and a potential for hazardous noise exposures for the crew. These research activities show that noise control is an issue for these vessels.

This study is part of an ongoing research project for the development of a multi-pronged strategy to reduce the risk of hazardous noise exposure of fish harvesters from the Newfoundland and Labrador (NL) inshore fishing fleet (LOA less than 24 m). This can be accomplished by providing: a) short-term solutions, via the adoption of hearing protection devices, best practice, minimal vessel and gear modification, and b) long-term solutions, via the development of vessel design procedures for noise control for designer of small fishing vessels. This paper deals with the development of long-term solutions and is part of an orderly procedure to assess critical noise levels (20), to study the transmission on

[2] International Labour Organization
[3] Food and Agriculture Organization

board, and to propose noise mitigation packages to abate levels to acceptable levels. In this paper, the authors used sound pressure levels measured on board to study the acoustic transmission characteristics of 7 decked fishing vessels ranging from LOA 10.66 m to 19.81 m, based on the relevant standards (21, 22). These data are then used to identify possible critical features in the airborne noise transmission from the main noise sources (the engine and auxiliary machinery in the engine room) to the relevant spaces on board, and to suggest possible intervention on noise control features to reduce noise levels. Such data increase the available literature on the acoustic characterization of small-scale fishing vessels and provide guidance on how to address preliminary noise control in these cases.

5.3 Methods

5.3.1 Survey trips and sound pressure levels measurements

Table 5.1: Characteristics of the surveyed vessels. GRP stands for fiberglass made vessels. OB stands for Outboard, IB stands for Inboard, 4s stands for 4 strokes.

Vessel ID	Vessel type	Length (m)	Vessel material	Engine Data	
				Power (HP)	Type
Vessel 1	1 Deck aft wheelhouse	10.7	Wood	150	IB, 4s
Vessel 2		11.9	Wood	306	IB, 4s
Vessel 3	1 Deck front wheelhouse	10.7	GRP	205	IB, 4s
Vessel 4		10.7	Wood	217	IB, 4s
Vessel 5	1.5 Decks	15.5	GRP	624	IB, 4s
Vessel 6		18.3	GRP	624	IB, 4s
Vessel 7	2 Decks	19.8	GRP	624	IB, 4s

Table 5.1 presents the sample of surveyed vessels. The selection of the vessels sample was conducted in (20), based on a study of the NL inshore fishing fleet composition. Owners of vessels with representative characteristics were contacted through personal contacts

provided by the Newfoundland and Labrador Fish Harvesting Safety Association (NL-FHSA). Once they consented to participate to the research, arrangements were made for the authors to travel on board during regular fishing trips. The measuring trips were scheduled according to the vessel and researcher availability, so that some details like the weather could not be controlled.

During the fishing trips, the authors measured stationary steady-state continuous noise levels on spaces inside the vessels while the engine, auxiliaries and generators were running. The measures were taken at maximum sailing speed when the vessels travelled to, from and in between fishing grounds. Stationary noise was acquired using a setup composed by a Class 1 PCB Piezotronic® mod. 378B02 ICP free field microphone connected to a National Instrument® mod. 9234 BNC input card, that was connected via USB to a Toshiba® Toughbook laptop computer. The sound pressure level was acquired continuously at 52.6 kHz. Care was taken so that the microphones were placed on the center of the space away from surfaces. The software end of the acquisition system was coded using LABView®.

5.3.2 Study of acoustic insulation characteristics

The standardized level differences, D_n, were computed using the procedure from (21, 22) in order to characterize the acoustic insulation from source to receiver spaces. Time-domain sound pressure measures were postprocessed using LABView®. Signals were filtered by third octave bands, and the mean sound pressure levels L for each band obtained:

$$L = 10\log_{10} 1/T \int_0^T \left(p(t)_{1/3\,oct}/p_0\right)^2 dt \tag{5.1}$$

In Eq. (5.1), T is the length of the time domain record of the sound pressure, $p(t)_{1/3\,oct}$ the filtered third octave band sound pressure and $p_0 = 20\,\mu\text{Pa}$ is the reference sound pressure. The standardized level difference used to compute the airborne transmission loss (TL) was assessed according to Eq. (5.2), as reported in (22):

$$D_n = L_1 - L_2 + k + 10\log_{10}\left(\frac{A_0\,T_0}{0.16V}\right) \tag{5.2}$$

where $A_0 = 10\,\text{m}^2$ is a reference absorption area, $T_0 = 0.5\,\text{s}$ is a reference reverberation time, L_1 is the third octave band level in the source space, L_2 is the third octave band level in the receiver space, k is the third octave band reverberation index, and V is the volume of receiver room in m^3. Since no measure of reverberation time was possible, k is obtained from the standard values table presented in (22). No background noise correction was applied. This measure was not possible due to the inability to stop the engines and generators at sea.

5.4 Results and discussion

Figures 5.1 to 5.4 show the airborne transmission paths considered from the measures of sound pressure levels. The spaces considered were enclosed spaces that are manned by

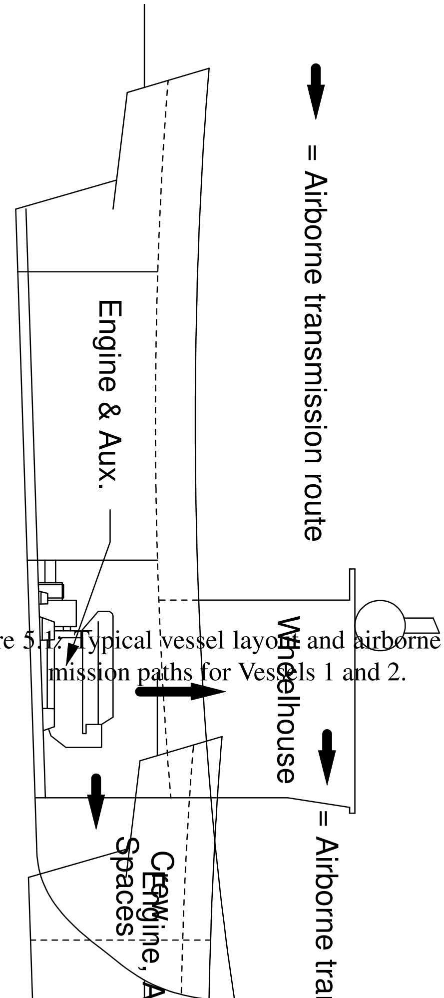

Figure 5.1: Typical vessel layout and airborne transmission paths for Vessels 1 and 2.

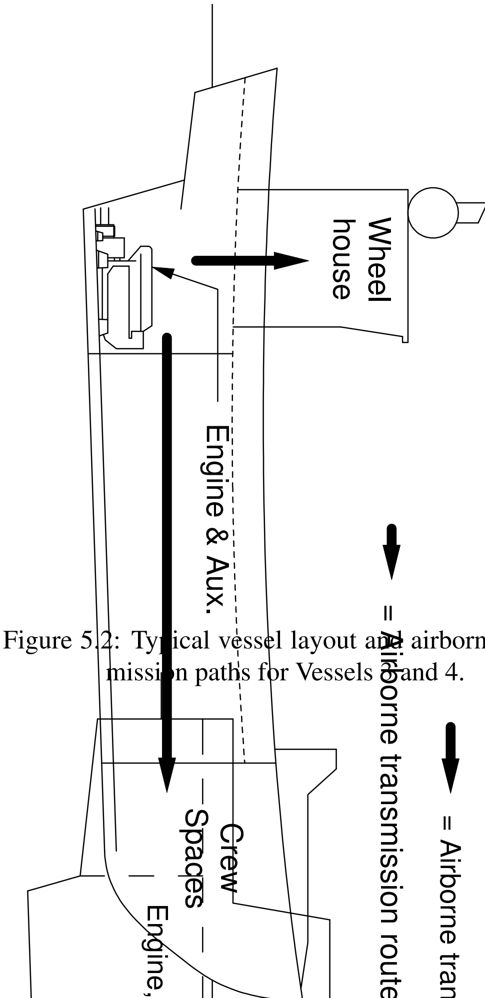

Figure 5.2: Typical vessel layout and airborne transmission paths for Vessels 3 and 4.

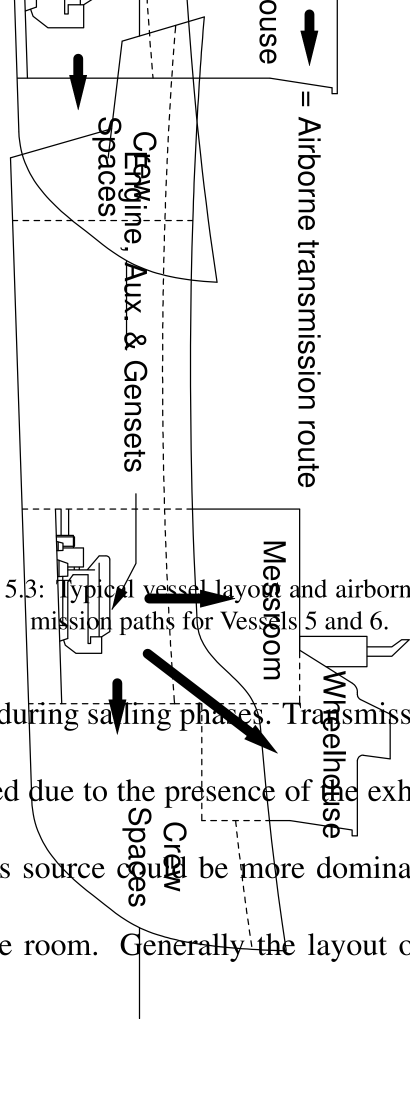

Figure 5.3: Typical vessel layout and airborne transmission paths for Vessels 5 and 6.

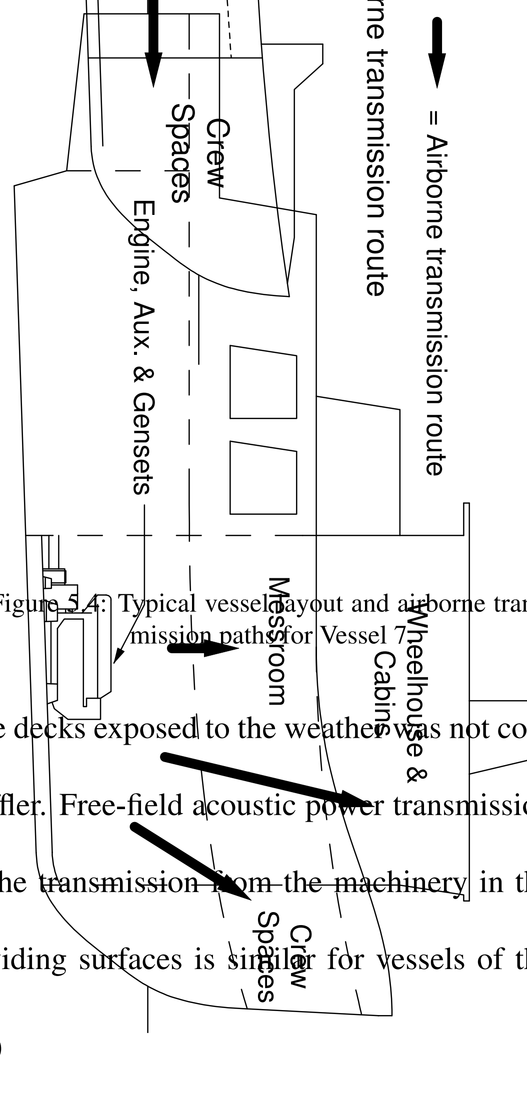

Figure 5.4: Typical vessel layout and airborne transmission paths for Vessel 7.

crew during sailing phases. Transmission to the decks exposed to the weather was not considered due to the presence of the exhaust muffler. Free-field acoustic power transmission of this source could be more dominant than the transmission from the machinery in the engine room. Generally the layout of the dividing surfaces is similar for vessels of the

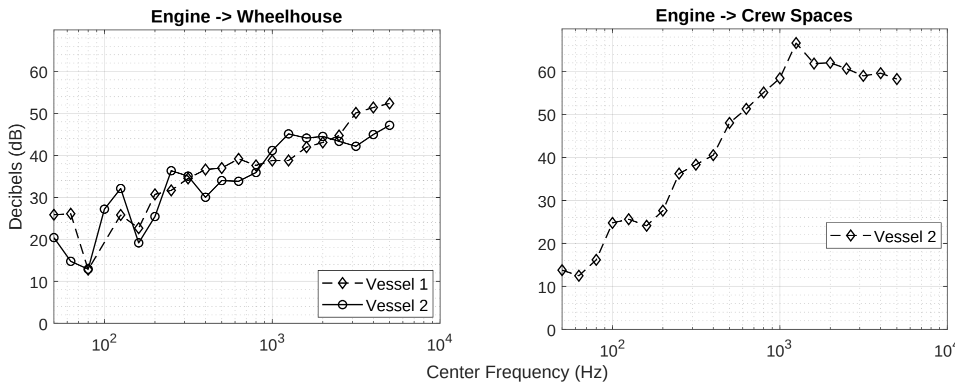

Figure 5.5: Standardized level difference D_n for Vessels 1, 2. Dividing surface from engine to wheelhouse in both vessels made of wood planks coated with layers of GRP, ribbed by wooden beams.

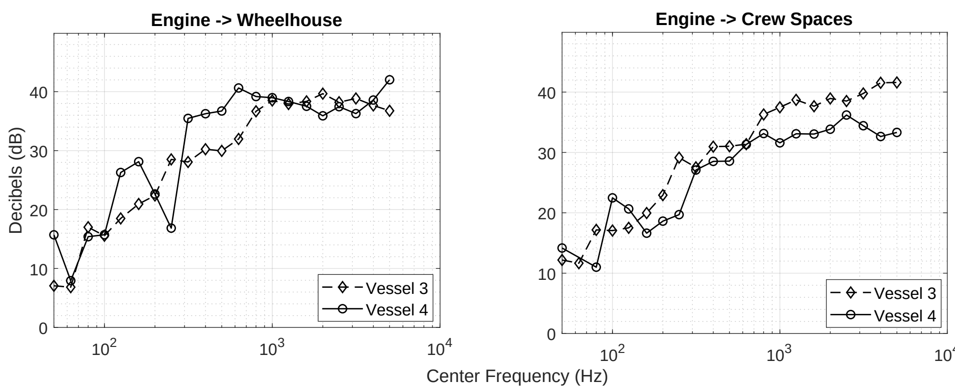

Figure 5.6: Standardized level difference D_n for Vessels 3, 4. Dividing surfaces from engine to wheelhouse were made of plywood coated with layers of GRP, ribbed by wooden beams in both cases. Dividing surfaces from engine to the crew spaces were made of plywood coated with layers of GRP, ribbed by wooden beams in the case of Vessel 3, or made of wood planks ribbed by wooden beams in the case of Vessel 4.

same material construction. On wooden vessels, they will mainly be composed of wooden planks that might be covered with layers of GRP and mounted on a wooden beam frame; on GRP vessels, they are made of plywood covered with layers of GRP and mounted on a wooden beam frame. Generally no acoustic trim is applied to these surfaces. Values for the volume, V, of receiving spaces ranged from $4\,\mathrm{m}^3$ to $29.7\,\mathrm{m}^3$ for wheelhouse, $14.7\,\mathrm{m}^3$ to $46\,\mathrm{m}^3$ for messrooms, $4\,\mathrm{m}^3$ to $11.5\,\mathrm{m}^3$ for crew spaces. Figures 5.5 and 5.8 show D_n for groups of similar vessels. D_n was chosen as the TL measure because it is required in (21) when source and receiver spaces are not adjacent, as in some of the visited vessels (see crew spaces of the vessel in Figure 5.2 or the wheelhouse in Figures 5.3 and 5.4).

The obtained D_n curves follow similar trends for all the vessels. At lower frequencies (up to almost 1000 Hz) the curves slowly rise and at higher frequencies the curves are almost flat. It is important to state that TL is affected by flanking and structure-borne sound transmission because the sources are not purely airborne sources and are mounted in all cases rigidly to the vessel's structures (except for the generators that are mounted on resilient elements).

Among all the presented cases, the acoustic insulation of vessels such as Vessels 1, 2, 3, 4, and 5 was found in line with (19), where at low frequencies the values is as low as 5 dB and increase to 30 dB–40 dB. This is seen in particular in the case of spaces adjacent to the source engine room, as in the transmission to the Wheelhouse (all vessels) and to the Crew Spaces (Vessels 3, 4, and 5). In the latter case, Vessels 3 performs better than 4 in Figure 5.6, probably due to the different layout of the separating bulkhead. The presence of gaps between the planks that compose the bulkhead of Vessel 4 might reduce the airborne acoustic insulation provided by the surface. Higher TLs are identified for Vessels 5 and 6. In this case, the effect of a smaller dividing surface[4] between adjacent spaces is demonstrated by the higher D_n values for Vessel 6 compared to 5 in the case of the Crew Spaces. There seems to be an increase of TL when the receiver space is separated by other spaces from the source space, as in the case of Wheelhouse in Vessels 6 and 7, compared for instance with Vessel 5 (Figures 5.7 and 5.8). The TL to the Messroom in Vessel 7

[4] surface area of 7.66 m^2 for Vessel 5 as opposed to 4.25 m^2 for Vessel 6

(Figure 5.8), is affected by the proximity to the engine room access door. The TL curve associated to the corridor entrance is the one closest to such door, and is sensibly lower than the one of the same space but away from the door, represented by the Messroom TL curve. The same behaviour is seen in the Wheelhouse TL from Figure 5.8, where the starboard side is the closest to the stairway to the lower deck, and the cabin is a divided space within the Wheelhouse.

From the analysis of the TL curves, acoustic insulation could be poor when the space are adjacent and shares a dividing surface. In these cases, the insulation could be so low as to induce high noise levels in the receiver spaces. Often these spaces are living quarters and continuously manned spaces, where levels have to be contained to acceptable levels. For instance, levels can be as high as 83 dB(A) in the crew spaces at max speed (20), which is 23 dB(A) higher than the requested criteria for commercial ships (11). It is then advisable to increase the TL of such separating surfaces in order to cut the airborne transmission of sound directly at the source and hence insulating the sources in the engine room as much and as conveniently as possible. Such solutions should involve: a) the use of resilient mounts for the engine and auxiliaries and a proper design of the engine foundation, that is known to effectively cut off the structure-borne sound (23, 24), b) the adoption of an optimized acoustic trim for the surfaces of the engine room, and c) the acoustic insulation of doorways to the engine room.

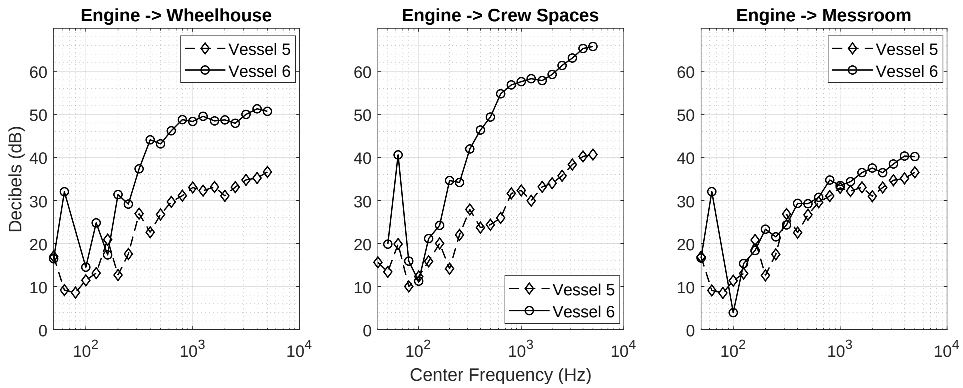

Figure 5.7: Standardized level difference D_n for Vessels 5, 6. Dividing surfaces were made of plywood coated with layers of GRP, ribbed by wooden beams in both cases.

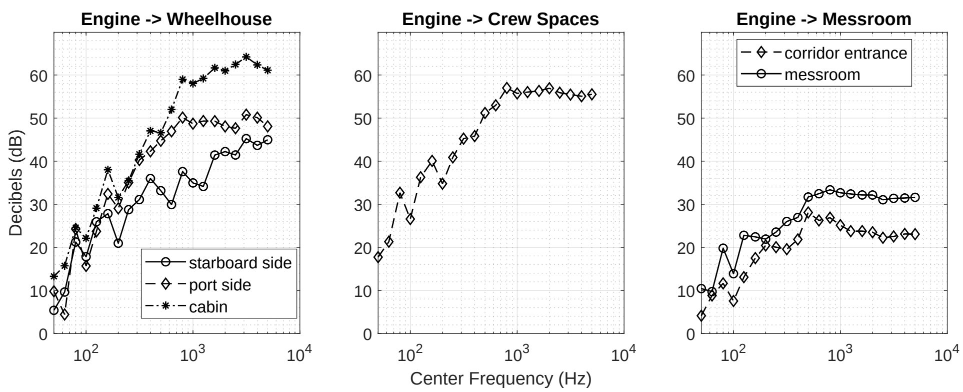

Figure 5.8: Standardized level difference D_n for Vessel 7. Dividing surfaces were made of plywood coated with layers of GRP, ribbed by wooden beams.

5.5 Conclusions

This paper presented a study on the acoustic insulation characteristics of 7 fishing vessels from the Newfoundland and Labrador inshore fleet. The acoustic TL from sources (engine room) to receiver spaces (relevant manned spaces inside the vessels) were calculated in terms of standardized level difference, D_n, using the measurements of sound pressure levels from an in-situ survey program conducted during regular fishing trips. The authors conducted this research as part of an orderly procedure to assess and mitigate noise levels on fishing vessels to acceptable levels. This procedure includes: a) measurement of noise levels and identification of the noise sources, b) characterization of the acoustic insulation on the existing vessels, c) assessment of the acoustic power transmission by means of numerical methods, and d) identification of critical hot-spots in the acoustic design and proposal of noise mitigating solutions. This procedure can be the base for a guideline for designers to include noise control on fishing vessels design.

The acoustic insulation performance of the surfaces of the visited fishing vessels due to airborne and structure-borne transmitted acoustic power was presented in terms of standardized level difference, D_n. Even though the insulation performance of spaces away from the sources is satisfactory, improvements in TL is advised between spaces adjacent to the main source, the engine room. This is important since the adjacent receiver spaces are usually living and continuously manned working quarters. The presented TL data for fishing vessels and interpretation can be useful for fishing vessels designers who need to address noise control on fishing vessels.

Further research will involve the acoustic modelling of a case study vessel using Statistical Energy Analysis (SEA) in order to identify critical sound transmission paths and to propose and evaluate the effect of noise mitigation packages.

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The authors would like to thank Ms. Sharon Walsh and Ms. Brenda Greenslade from the NL-FHSA, Mr. Mark Dolomount from the Professional Fish Harvesters Certification

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Chapter 6

Design solutions to mitigate high noise levels on small fishing vessels

6.1 Co-authorship statement

The chapter is a preprint version that has been proposed for publication on the peer-reviewed journal paper *Applied Acoustics* and was authored by Giorgio Burella, and Dr. Lorenzo Moro.

Giorgio Burella led the writing of this paper, and conducted the measurements and acoustic analysis on the case study vessel. Dr. Lorenzo Moro participated in discussions and edited the manuscript to enhance the layout, writing, and the concepts presented in this paper. All authors revised, edited, and made recommendations for improvements to earlier drafts of this paper.

6.2 Introduction

Fish harvesting is a key source for food security and a major economic activity for coastal communities worldwide. It is a growing activity which employs more than 4M people, mainly working on small fishing vessels (≤ 24 m length overall (LOA)) (1). Fishing is also one of the most dangerous industrial activities, taking its toll on workers health and lives, as highlighted by many studies performed in various parts of the world (2–4). These studies stressed the need to enhance health and safety on fishing vessels, as key elements for a sustainable fishing industry (5).

Noise is an important risk factor for health and safety of workers on board fishing vessels. Studies on noise due to continuous noise sources (such as the engine and auxiliaries) as well as intermittent sources (such as fishing gears) documented hazardous noise levels on a variety of fishing vessels worldwide (6–10).

Internationally, noise hazards on fishing vessels are under-regulated. The latest IMO[1] "Code on noise levels on ships" (11) regulates noise levels for crew and passengers on large commercial vessels, but does not apply to fishing vessels. Over the last two decades, FAO[2], ILO[3], and IMO have collectively developed a set of voluntary guidelines for owner-operators of small fishing vessels, which provide design criteria and operational procedures to improve onboard safety (12, 13). However, these guidelines do not provide fishing vessel designers with any criteria to control onboard noise.

[1] International Maritime Organization
[2] Food and Agriculture Organization
[3] International Labour Organization

The development of cogent criteria to control noise on fishing vessels is therefore mandated to national and local bodies. These regulations vary among countries and usually address the problem of noise exposure exclusively by setting limits related to noise-induced hearing loss, but neglect the risk of crew's noise-induced fatigue caused by high noise in the crew quarter (14).

Noise mitigation is particularly challenging in the case of small fishing vessels. Fish harvesters often work in proximity of noise sources—e.g. gear during fishing operations—and the use of hearing protections is often perceived as a hazard, since these may impede communication while working. Moreover, the small size of these vessels implies that special attention needs to be paid to the transmission of noise generated from the sources in the engine room (6). Other factors play a significant role in the implementation of solutions to mitigate noise, such as their compliance with existing regulations on vessel construction, or their financial impact on fishing enterprises. Indeed, the development of noise control solutions require an accurate acoustic study of the vessel under analysis. The design of larger types of vessels relies on a preliminary acoustic study of the most relevant noise sources, and the prevalent transfer paths. In the case of large commercial vessels, designers use empirical methods based on statistical regressions of data collected on samples of similar vessels (15), or specific ad-hoc numerical simulations and experimental tests (16–19) for navy, research, cruise vessels, and super- and mega-yachts. With regard to small fishing vessels, the application of numerical simulations and experimental tests would significantly affect the overall cost of these vessels, making these studies unfeasible, but no empirical methods are currently available.

International studies on noise exposures of fish harvesters have mainly focused on documenting the risk on noise-induced hearing loss on fishing vessels (7, 9, 10, 20–22) providing in some cases information on adequate Noise Reduction Rating to identify appropriate hearing protections. To our knowledge, only Peretti et al. (23), Veenstra (24) studied the habitability of crew quarters in relation to noise and investigated noise transmissions from main sources to receiver spaces on 6 vessels 16.99 m LOA or longer.

In the Canadian province of Newfoundland and Labrador (NL), noise induced hearing loss is a documented work disability among fish harvesters (25). To investigate the reasons of this issue, a program of research was developed by the Department of Ocean and Naval Architectural Engineering and the SafetyNet Centre for Occupational Health & Safety Research at Memorial University, and the NL-Fish Harvesting Safety Association. The program engaged crew members, owner-operators, and their union representatives, to document noise exposures in fish harvesting and develop feasible solutions to mitigate any hazardous noise level. The latter includes the collection and analysis of data on steady-state noise sources on fishing vessels (6) and on wall and deck insulation indexes (26), which aimed at informing fishing vessel designers on the state-of-practice of the acoustic design of these vessels, and provide them with practical tools for noise assessment in the design of new vessels. The focus of our research was small-scale fishing vessels ($\leq$ 24 m LOA (27)) as they compose the majority of the NL fishing fleet.

In this work, we applied Statistical Energy Analysis (SEA), experimental measurements, Martin-Pascoa-Santo's (MPS) K-shortest paths algorithm (28), and the ranking of dominant transmission paths (29) to a case-study fishing vessel from NL, to extend the works (23, 24) and understand i) main noise transmission paths on board, ii) the contribution of each steady-state source to overall noise levels, iii) any gap in the current state-of-practice of the vessels' insulation plans, and iv) the effectiveness of proposed interventions to mitigate noise levels and improve habitability on board. The results of this activity are useful to researchers, fishing vessels owner-operators, and fishing vessels designers to implement noise control solutions and improve habitability onboard. To our knowledge, this is the first time that this procedure and analysis has been performed on a small fishing vessel.

6.3 Methods

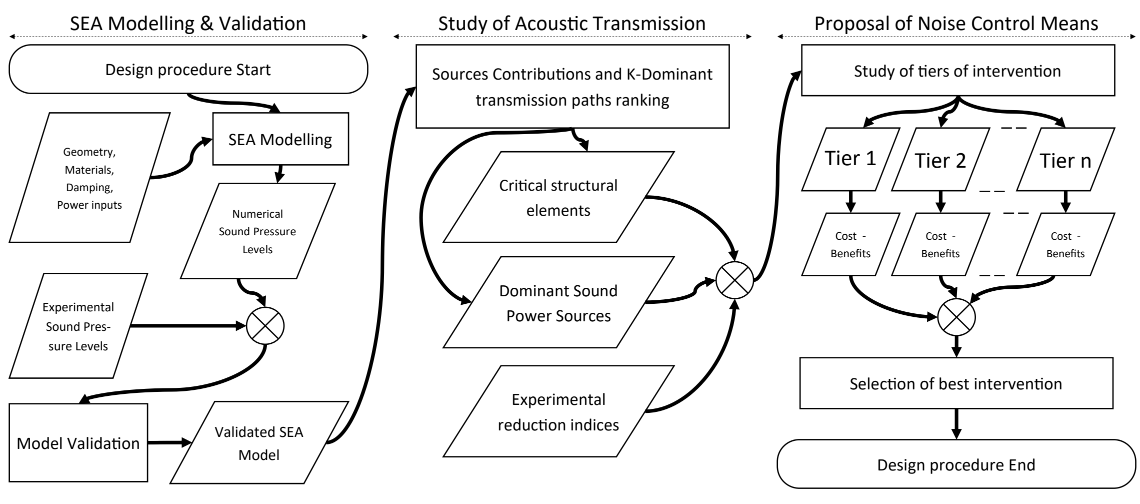


Figure 6.1: Flowchart of the procedure used in this research

Figure 6.1 shows the flow chart of the procedure implemented in this work. The procedure was applied to a fishing vessel from the NL small-scale fisheries presented in Section 6.3.1. Section 6.3.2 reports the measurement survey methods adopted to gather experimental data on noise levels, reduction indexes of walls and decks, and reverberation times of acoustic spaces. Section 6.3.3 briefly recalls the SEA concepts and outlines the modelling procedure. Section 6.3.5 describes the analysis of the noise source dominance, and the procedure to rank the first K-dominant paths and identify critical spots for transmission of acoustic energy. Finally, Section 6.3.6 explains how the information on the noise power transmission was used to assess the effectiveness of selected control solutions.

6.3.1 Overview of the case-study vessel

Table 6.1: Main dimensions, construction materials, and machinery characteristics of the fishing vessel

Length OA (m)	19.81	**Propulsion Engine**	4 Stroke Diesel V12
Bredth (m)	7.01	**Genset engine**	4 Stroke Diesel I4
Depth (m)	3.95	**Propulsive Power kW**	459 @ 1800 rpm
Hull Construction	Glass Reinforced Plastic Wooden Structure	**Genset Power ekW**	40 @ 60 Hz

The selected case-study was a 19.81 m long (LOA) multi-purpose fishing vessel, which main characteristics are reported in Table 6.1. The vessel's layout is shown in Figure 6.2. The vessel is from the NL small-scale fishing fleet, it operates 8 months a year and is employed in cod, shrimp, and crab fishing. On this type of vessel, owner-operators and crew work and live on board up to several weeks over the fishing season. Therefore, the habitability of its living quarters is important to guarantee that they have proper rest and to avoid noise-induced fatigue.

6.3.2 Experimental measurements

We performed two sets of experimental tests on the case-study vessel.

1. Noise measurements during sea-trials, to determine:

   - the 1/3 octave band A-weighted sound pressure levels ($L_{p,A}$), and the A-weighted equivalent continuous sound levels ($L_{Aeq}(T)$) in crew quarters;
   - the 1/3 octave band velocity levels (L_v) and the overall velocity levels ($L_{v,eq}$) in crew quarters;
   - the characteristics of structure-borne noise (SBN) sources.

2. Acoustic measurements when the vessel was docked, to determine:

   - the reverberation times of the vessels' spaces;
   - the apparent sound reduction (R') spectra and weighted sound reduction indexes (R_w) of walls and decks.

Sea-trial measurements were taken while all the continuous sources were running. While measuring, the propulsive engine was operating at its maximum continuous rating, while the generator was operating at its nominal speed. The measured data were acquired at a sampling frequency of 52.6 kHz. The software end of the acquisition system was coded using LABView® and the data were post-processed in LABView® and MATLAB® to obtain the $L_{p,A}$ and L_v spectra and the overall levels $L_{Aeq}(T)$ and $L_{v,eq}$. The sound pressure levels measurements were performed according to the IMO "Code on Noise Levels on

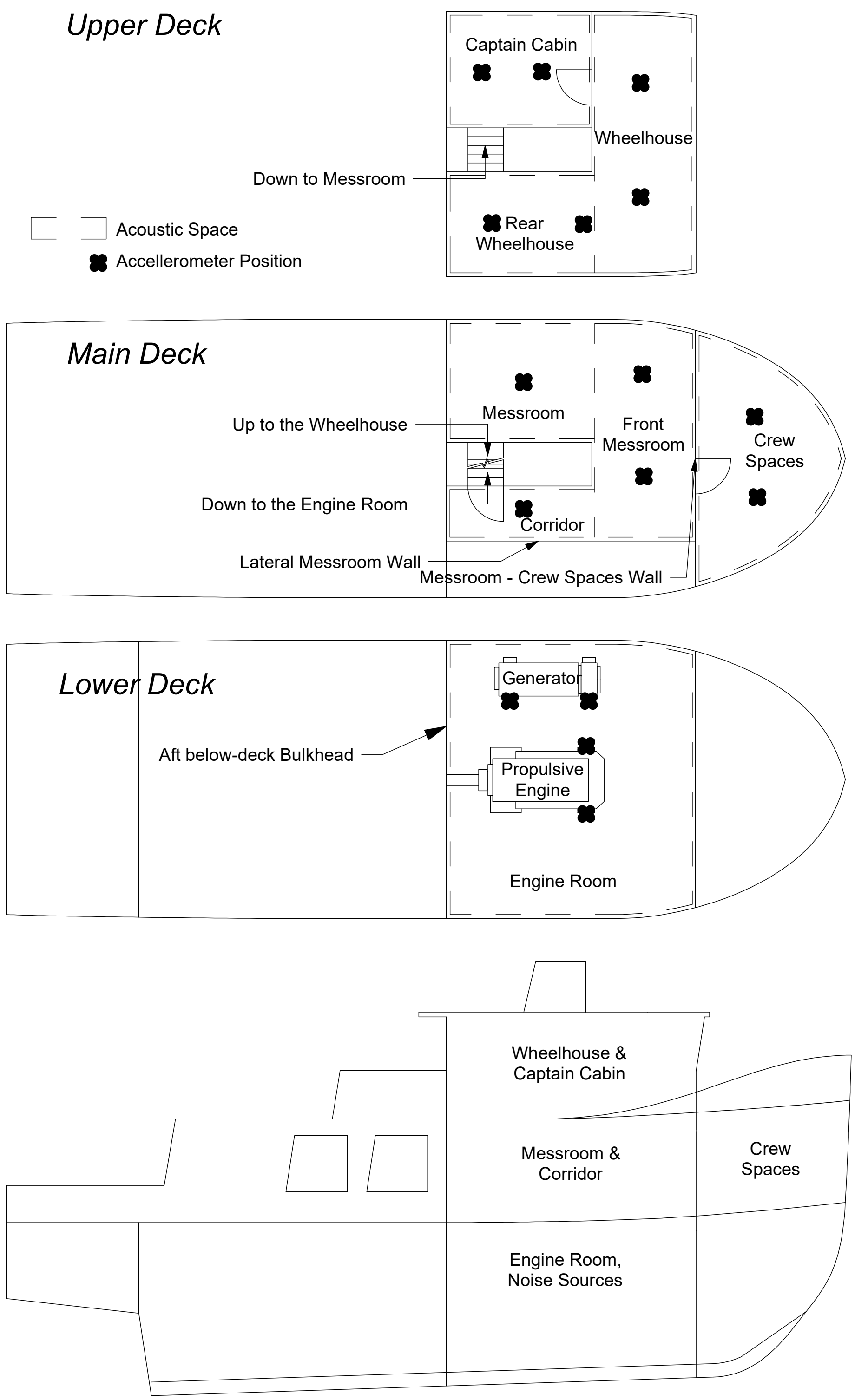


Figure 6.2: Layout of the fishing vessel and measurement points

board Ships" (11), using a Class 1 PCB Piezotronic® mod. 378B02 ICP free field microphone connected to a National Instrument® mod. 9234 BNC input card. The microphone equipment setups is shown in Figure 6.3a.

L_v were recorded at several locations on the vessel's decks (See Figure 6.2) using PCB Piezotronic® ICP mod. 352C33 accelerometers, whose bases were glued to the surface of interest. The sensors were connected to the same National Instrument® input card. The accelerometer setup is shown in the bottom-left corner of Figure 6.3a.

(a) Instrumentation setup to assess sound pressure levels $L_{p,A}$ and velocity levels L_v during the sea-trials

(b) Dodecahedron omnidirectional source and microphone during the measurement of the reverberation times

Figure 6.3: Experimental setups

As per the second set of acoustic measurements, the reverberation times of the vessel's spaces were obtained in accordance with (30), using the microphone setup of the sea-trial measurements and a dodecahedron omnidirectional noise source (Larson-Davies® BAS001), that generated pink noise in the frequency range of interest. The same experimental setup was used to obtain R' spectra and R_w of the vessel's structures, in accordance with (31) and (32), respectively. The measurement setup for reverberation times and reduction indexes is shown in Figure 6.3b.

6.3.3 SEA modelling

SEA overview

SEA was used to predict the diffuse field L_p in the acoustic volumes and L_v of the structural elements of the vessel.

In SEA, the steady-state acoustic energy of the n subsystems and the continuous steady-state noise sources powers are related by the energy balance equation (33):

$$\omega \begin{bmatrix} \eta_{11} & -\eta_{12} & \dots & -\eta_{n1} \\ -\eta_{12} & \eta_{22} & \dots & -\eta_{n2} \\ \vdots & \vdots & \vdots & \vdots \\ -\eta_{1n} & -\eta_{2n} & \dots & \eta_{nn} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_n \end{bmatrix} = \begin{bmatrix} \Pi_{1,in} \\ \Pi_{2,in} \\ \vdots \\ \Pi_{1,in} \end{bmatrix} \tag{6.1}$$

where $\omega = 2\pi f$ with f the central frequency of the considered band in Hz, E_i, $\Pi_{i,in}$ are the total energy and power input of the subsystem i respectively. η_{ij} are the coupling loss factor, which are related among each other as follows:

$$\eta_{ji} = \frac{N_i}{N_j}\eta_{ij} \tag{6.2}$$

where N_i is the number of modes of subsystem i in the band centered at frequency f.

The diagonal elements of the loss factors matrix η are calculated as follows:

$$\eta_{ii} = \eta_{i,diss} + \sum_{i \neq j}^{n} \eta_{ij} \tag{6.3}$$

where $\eta_{i,diss}$ is the damping loss factor of the i-th subsystem.

From Eq. (6.1), we can calculate the total energy E_i of the i-th model subsystems, and from E_i we can calculate the velocity levels $L_{v,i}$ and sound pressure levels $L_{p,i}$ as follows:

$$L_{v,i} = 20 \log_{10} \left(\sqrt{\frac{E_i}{M_i}} \Big/ 10^{-9} \right) \quad , \quad L_{p,i} = 20 \log_{10} \left(\sqrt{\frac{\rho_i c_i^2 E_i}{V_i}} \Big/ 2 \times 10^{-5} \right) \tag{6.4}$$

where M_i is the mass associated to a i-th structural subsystem, ρ_i, c_i, and V_i are the density, phase velocity and volume of the acoustic medium in the $i-th$ acoustic subsystem, respectively. These levels are calculated in 1/3 octave bands, and can be validated against the experimental results: the $L_{v,i}$ can be directly compared, while $L_{p,i}$ should be first weighted applying an A-weighting filter to obtain $L_{p,i,A}$.

SEA model of the fishing vessel

The SEA model of the fishing vessel was developed using SEAM® [4]. We identified the SEA subsystems by discretizing the vessel's structures into interconnected structural elements and acoustic volumes (spaces or layers). The fishing vessel's structures are made of

[4]Developed by Cambridge Collaborative, version 2011 for Windows, revision 7a

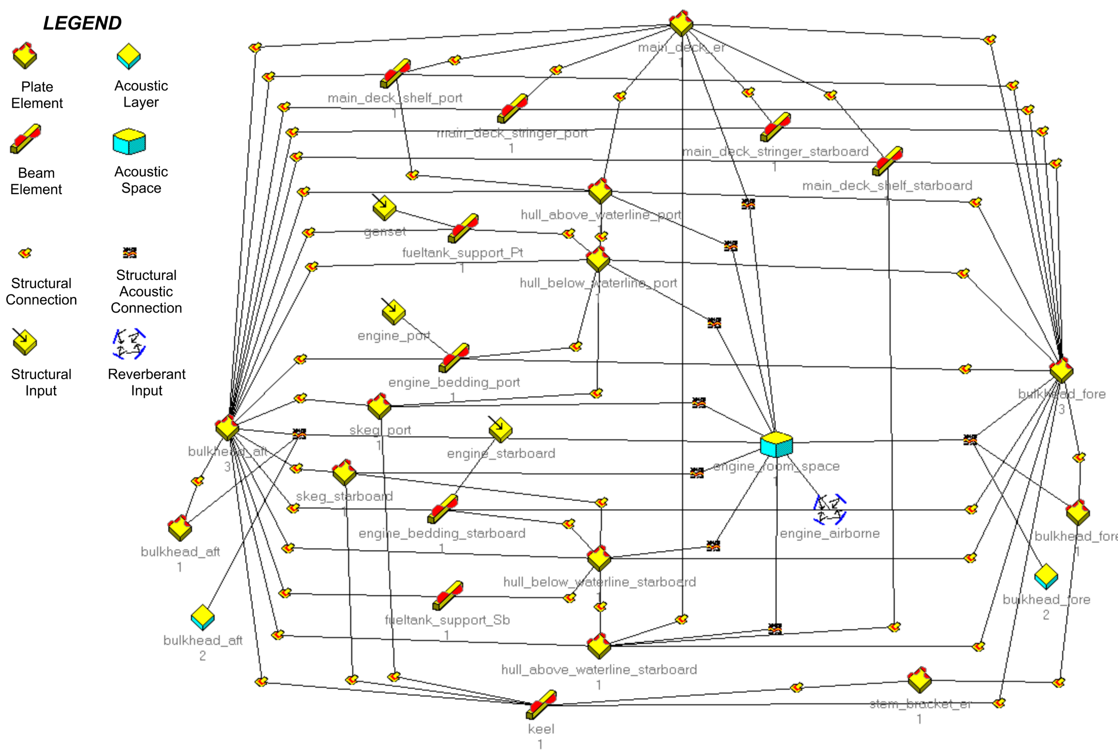


Figure 6.4: SEA model of the engine room

composites: laminates of glass reinforced plastic (GRP) or GRP over plywood, and they behave as orthotropic materials. The plates of the hull, bulkheads, and decks were modeled as well, as equivalent isotropic plates with bending stiffness equal to the geometric mean of the bending stiffness in the two orthogonal directions (33). Longitudinal ribbing members that run continuously from aft to fore, such as the keel, deck shelf, and deck stingers were also included in the model. The transverse bulkheads below the deck were modeled as three subsystems: two plate elements and an acoustic layer filled with glass wool, which is used as fire retardant material. Table 6.2 presents the type and properties of structural elements and SEA subsystems that were identified.

Table 6.2: Structural and acoustic subsystem characteristics of the SEA model

Structural Element		**Subsystem Type**		**Material**	**Loss factor** η **(-)**
Type	Number of elements	**Type**	**Number of subsystems**		
Acoustic	20	acoustic layer	3	glass wool & air	calculated from material properties: Density: $80\,\mathrm{kg\,m^{-3}}$ airflow res.: $60\,\mathrm{kN\,s\,m^{-4}}$
		acoustic space	17	air	measured reverberation times
Beams	38	beam bending	76	wood	$1.172\,f^{-1.2}$
Plates	68	plate bending	68	glass reinforced plastic with smeared wooden ribs	0.15
		plate inplane	68	glass reinforced plastic with smeared wooden ribs	$1/3 \times 0.15$
Total	126		232		

The damping of the structural elements was obtained from relevant literature or via the experimental tests. The damping of the acoustic volumes was calculated from the measured reverberation times (Section 6.3.2). The structural damping of wooden beam elements was found in (34), the structural damping of ribbed GRP plates was found in (35), and the bulkhead acoustic layer damping was defined by the fire retardant material characteristics.

Two energy sources were considered: the propulsive engine and the genset, both located in the engine room. The SBN sources were characterized using the L_v spectra at the sources foundations. As per the airborne sound, the input power was modelled by imposing the diffuse field sound pressure level to the acoustic volume of the engine space. We used this simplified method as there was not enough clearance between the onboard sources and the boundaries of the acoustic volume to ensure a correct estimation of the power input using the standard (36).

In the model, the subsystems were connected by structural-to-structural, structural-to-acoustic, or acoustic-to-acoustic links. Each of these defined i) point (for example beam to beam), ii) line (plate to plate or beam to plate), or iii) area (plate to acoustic volume or volume to volume) couplings. All structural-acoustic connections simulated non-resonant (mass-law) and resonant transmission mechanisms. The coupling loss factors of the model were calculated according to the coupling type, and used to obtain the SEA coupling matrix (Eq. (6.1)). Acoustic leaks, such as door gaps, were also modelled. The final model was composed of 232 subsystems. Figure 6.4 shows the SEA model in SEAM® of the fishing vessel's engine room.

Before performing the simulations, we checked that number of natural modes and overlap factor were consistent with the SEA hypothesis (37) to identify the frequency range for the SEA calculation. These were found to be all above unity in the frequency range 160 Hz to 8000 Hz.

6.3.4 SEA model validation

$L_{p,A}$ and L_v obtained from SEA were validated against the levels measured in sea-trial (Section 6.3.2). The following procedure was applied for the validation depending on the response quantity:

- average SEA $L_{p,A}$ and 95 % confidence intervals were compared to available experimental $L_{p,A}$ in the broad- and third-octave bands for relevant subsystems. Since the experimental measure of sound pressure levels is already space-averaged for each subsystem, just one experimental value was compared to SEA predictions.
- average SEA L_v and 95 % confidence intervals were compared to available experimental L_v in the broadband and third-octave bands for relevant subsystems. Since several experimental measures were performed for each subsystem, all of these datapoints were compared to SEA predictions

Validation could be achieved when the experimental results both in broad- and third-octave bands lied within the provided SEA confidence interval, as shown in other similar studies from the literature (16, 38, 39).

6.3.5 Source contributions and K-dominant transmission path ranking

Once the model was validated, we analysed the contribution of the sources to the response of selected target subsystems. Given the linearity of SEA, this was assessed by performing a series of simulations with one source at the time, while keeping the others off. To confirm the results, we performed a second series of simulations varying the input power of the airborne sources, keeping constant the power of the structure-borne sources, and vice-versa, and calculating for each case, the difference in the calculated responses ($\Delta L_{Aeq}(T)$ and $\Delta L_{v,eq}$).

To identify the paths from source to target subsystems that mostly contribute to vibration and sound pressure levels on the fishing vessel, we used the K-dominant transmission path ranking with MPS algorithm, following the procedure described by Guasch and Aragonès (29). The MPS algorithm considers an SEA model as a digraph, where subsystems are nodes of the digraph and connections between them are edges. Each edge is associated with a weight value, which is derived from the SEA coupling matrix. A path is identified by a sequence of nodes connecting the source to the target node, and is characterized by a path weight w_{ij}, which is proportional to the power fraction transmitted through that path, from the source node i to the target node j.

Given the total energy E_i at a source node i, the total energy $E_{j,Pij}$ at the target node j is calculated as follows (29):

$$E_{j,Pij} = w_{ij} E_i \tag{6.5}$$

The output of the MPS algorithm is a list of K paths in a given frequency band, sorted from the one that transmits the most energy to the one that transmits the least (40).

In this study, we developed a MATLAB® code to implement the MPS algorithm, and verified it using the example presented by Guasch and Aragonès (29). Once the code was verified, we used the coupling loss factor matrix from the SEA outputs to apply the MPS algorithm to our case study.

6.3.6 Analysis of the effectiveness of practical solutions to mitigate high noise levels

The outcomes of the experimental measurements, the SEA simulations, and the K-dominant transmission path ranking were used to detect high noise levels in the crew quarters, nodes of the SEA digraph that are clusters for the set of the sorted dominant paths, and flaws in the insulation plan of the vessel.

Drawing on these results, we hypothesised several tiers of intervention using materials and solutions that are commercially available, commonly used in marine applications, and that can be applied to new vessels as well as to existing vessels through retrofitting. These encompassed the use of viscoelastic materials in constrained layer damping configurations (VEM-CLD) (41, 42), mineral wool materials, floating floors (43, 44), and resilient mounts for diesel engines and gensets (45). For each tier of intervention, we updated the SEA model and calculated the new response of the target subsystems, assessing the impact of the design update. The target was reducing the noise levels below the IMO levels (11) while monitoring any variation to the deadweight ΔDW and the initial stability ΔGM of the vessel not to impact its cargo capacity and comprise its stability. ΔDW and ΔGM were assessed according to the Canadian flag requirements to re-evaluate the vessel's stability after a structural modification (27).

6.4 Results and discussion

6.4.1 Experimental results

$L_{Aeq}(T)$ and $L_{v,eq}$ measured in sea trials are reported in Figure 6.5. Table 6.3 compares the measured $L_{Aeq}(T)$ with the IMO noise level limits (11). It can be seen that $L_{Aeq}(T)$ in the Corridor, Messroom, and Rear Wheelhouse are above the IMO limits, while in the Crew Spaces, Wheelhouse, and Captain Cabin the noise levels approximately equal the IMO limits.

Table 6.3: A-weighted equivalent continuous sound levels ($L_{Aeq}(T)$) (frequency range: 20 Hz to 20 000 Hz) and corresponding IMO noise limits

Acoustic Space	Experimental $L_{Aeq}(T)$ dB(A) re 20 μPa	IMO limits dB(A) re 20 μPa
Engine Room	104.2	110.0
Crew Spaces	60.8	60.0
Messroom	74.5	65.0
Corridor	81.3	65.0
Wheelhouse	65.2	65.0
Rear Wheelhouse	69.5	65.0
Captain Cabin	60.7	60.0

Figure 6.6 shows the reverberation times of the crew quarters, while Figure 6.7 shows the R' spectra of the internal surfaces (decks and walls). Table 6.4 presents the resulting R_w and the corresponding minimum values required by IMO. The indexes show that insulation of the main deck plating (Engine Room to Messroom) is higher than the vertical surfaces

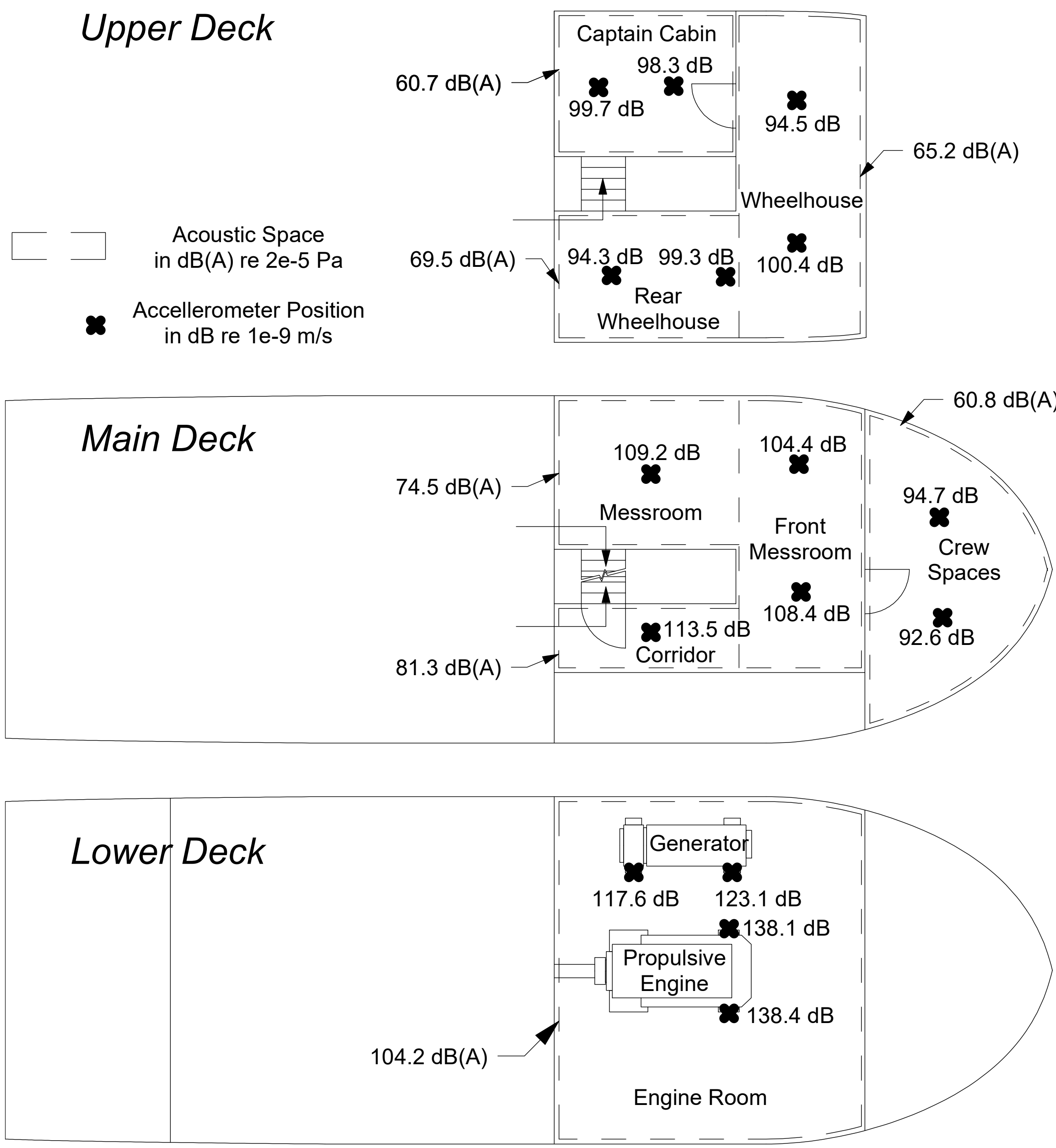


Figure 6.5: Experimental $L_{Aeq}(T)$ (frequencies from 20 Hz to 20 000 Hz) and $L_{v,eq}$ (frequencies from 160 Hz to 8000 Hz) measured during the sea trials

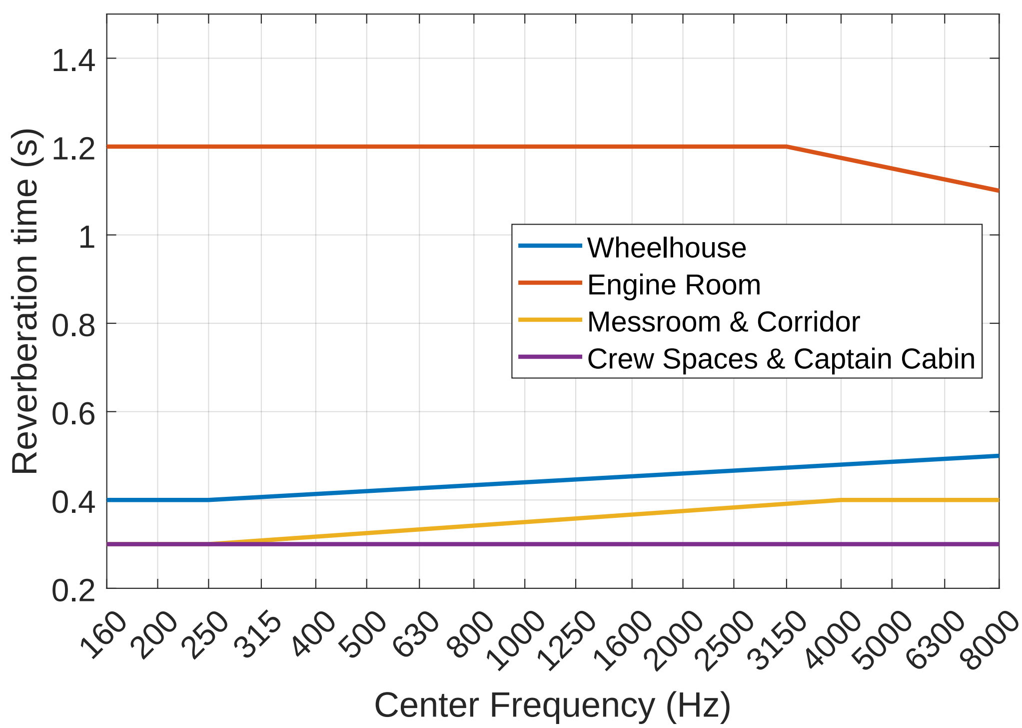


Figure 6.6: Experimental reverberation times of the vessel's spaces

considered in the plot, which are more lightweight constructions than the main deck plating. Despite this, $L_{Aeq}(T)$ in the Corridor (81.3 dB(A)) and in the Messroom (74.5 dB(A)) are above the IMO maximum acceptable level of 65 dB(A).

The results of Table 6.4 confirm that the vessel's spaces are poorly insulated, as the measured R_w values are all lower than the IMO R_w requirements. In order to reduce the noise levels and improve the insulation of these spaces, we need to understand if the acoustic power is mainly airborne or structure-borne, and if the transmission of acoustic power is airborne, structure-borne, or a composition of the two.

Table 6.4: Weighted sound reduction indices R_w calculated in accordance with (32) and corresponding minimum values required by IMO (11)

Airborne transmission route	R_w dB	IMO requirements dB
Engine Room $->$ Messroom	39	-
Messroom $->$ Crew Spaces	25	45
Messroom $->$ Wheelhouse	19	45
Wheelhouse $->$ Captain Cabin	25	45

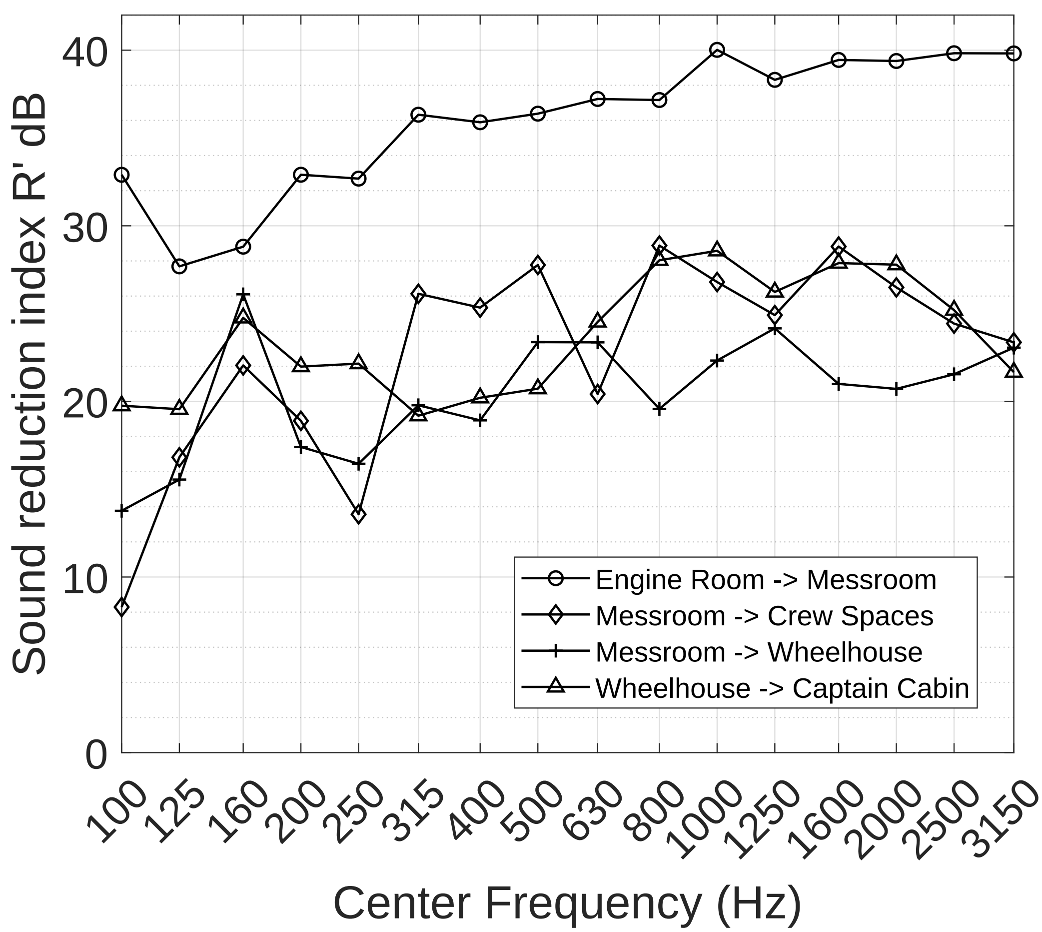


Figure 6.7: Sound reduction indexes R' 1/3 octave band spectra (100 Hz to 3150 Hz) of walls and decks obtained in accordance with the standard (31))

6.4.2 SEA results and model validation

Table 6.5: Experimental $L_{Aeq}(T)$ calculated in the SEA frequency range (160 Hz to 8000 Hz), and in the audio-frequency range (20 Hz to 20 000 Hz). Negative difference corresponds to higher levels in the audio-frequency range

Acoustic Space	Experimental $L_{Aeq}(T)$ dB(A) re 20 µPa		$\Delta L_{Aeq}(T)$ dB re 20 µPa
	160 Hz to 8000 Hz	20 Hz to 20 000 Hz	
Crew Spaces	60.8	60.8	0.0
Messroom	74.0	74.5	-0.5
Corridor	80.7	81.3	-0.5
Wheelhouse	62.4	65.2	-2.7
Captain Cabin	59.0	60.7	-1.7

Table 6.6: Target subsystems considered for the model validation and the analysis of noise levels

Target Subsystems	Type
Crew Spaces	Acoustic Space
Messroom	Acoustic Space
Corridor	Acoustic Space
Wheelhouse	Acoustic Space
Captain Cabin	Acoustic Space
Upper Deck	Plate Bending
Main Deck (Messroom)	Plate Bending
Main Deck (Crew Spaces)	Plate Bending

Since the SEA frequency range differs from the experimental frequency range, we first assessed how neglecting low (20 Hz to 160 Hz) and high frequencies in the SEA (8000 Hz to 20 000 Hz) affects the measured overall noise levels. This was done by applying a pass-band filter to the experimental levels and calculating the resulting $L_{Aeq}(T)$ in the SEA frequency range. Table 6.5 shows that the $\Delta L_{Aeq}(T)$ values, defined as the difference between the experimental data before and after the application of the pass-band filter, is lower than 3 dB(A). To validate the SEA model, we used the experimental levels calculated in the SEA frequency range.

Table 6.7: $L_{Aeq}(T)$ and velocity levels L_v calculated and measured (160 Hz to 8000 Hz). Positive difference values $\Delta L_{Aeq}(T)$ and ΔL_v means that SEA overestimates $L_{Aeq}(T)$ and L_v

Acoustic Space	$L_{Aeq}(T)$ dB(A) re 20 µPa		$\Delta L_{Aeq}(T)$ dB(A) re 20 µPa
	SEA response	Mean Experimental	
Crew Spaces	61.3	60.8	0.5
Messroom	75.5	74.0	1.5
Corridor	80.6	80.7	-0.2
Wheelhouse	65.9	62.4	3.5
Captain Cabin	59.8	59.0	0.8

Structural Part	$L_{v,eq}$ dB re 1 nm/s		$\Delta L_{v,eq}$ dB re 1 nm/s
	SEA response	Mean Experimental	
Upper Deck	94.5	98.1	-3.6
Main Deck (Messroom)	104.6	110.5	-5.9
Main Deck (Crew Spaces)	96.4	95.8	0.6

While the SEA model considered the entire fishing vessel, we focused our analysis on the response of the target subsystems reported in Table 6.6. These are the main accommodation quarters of crew and skipper. The target structural components we considered were the decks of these spaces. The rear wheelhouse was not included as owner-operator and crew do not station in this area during fishing operations. Table 6.7 reports the $L_{Aeq}(T)$ and $L_{v,eq}$ calculated in SEA and the corresponding experimental levels. The experimental $L_{v,eq}$ of each subsystem was defined as the average of the L_v at the measurement points of that subsystem (shown Figure 6.5).

Figures 6.8a to 6.8e show the $L_{p,A}$ spectra calculated in the target acoustic spaces and the corresponding experimental spectra. Likewise, Figures 6.9a to 6.9c report the L_v spectra—calculated and measured—of the target structural subsystems.

The comparison between calculated SEA and experimental sound pressure levels $L_{Aeq}(T)$

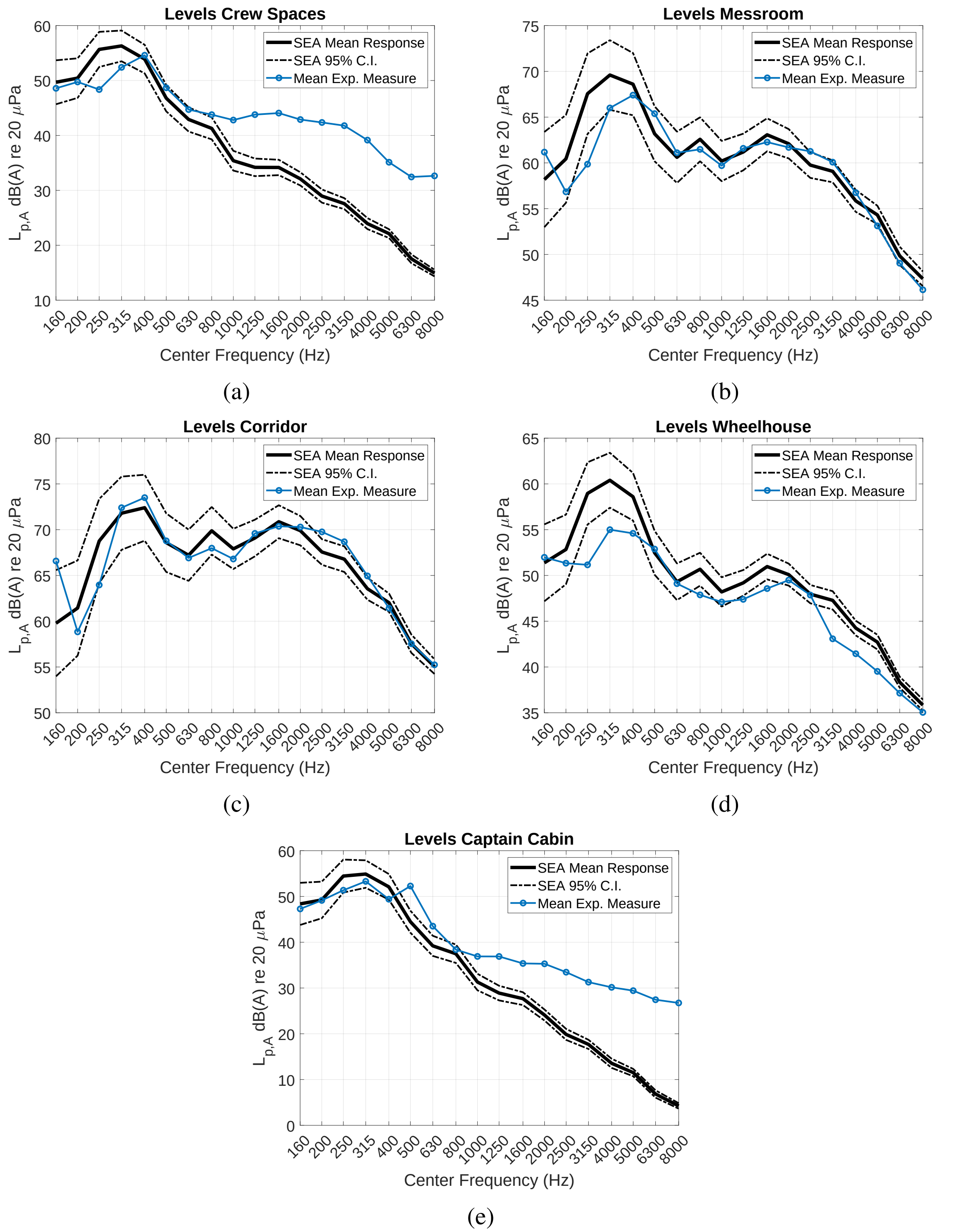
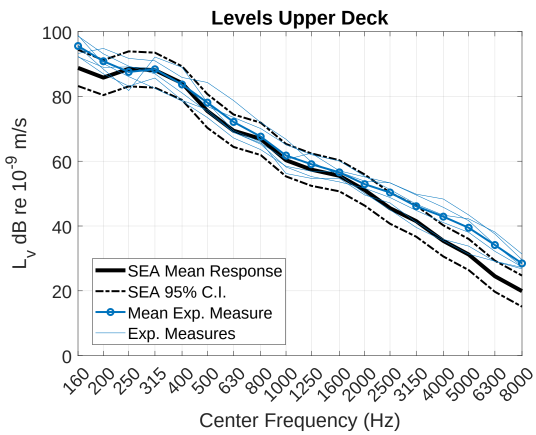


Figure 6.8: Calculated and measured 1/3 octave band $L_{p,A}$ spectra (160 Hz to 8000 Hz) of target subsystems



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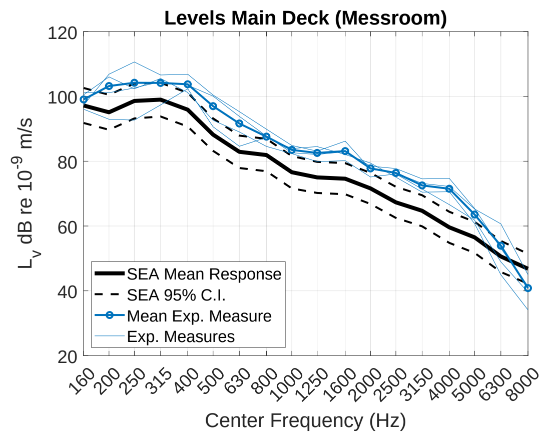

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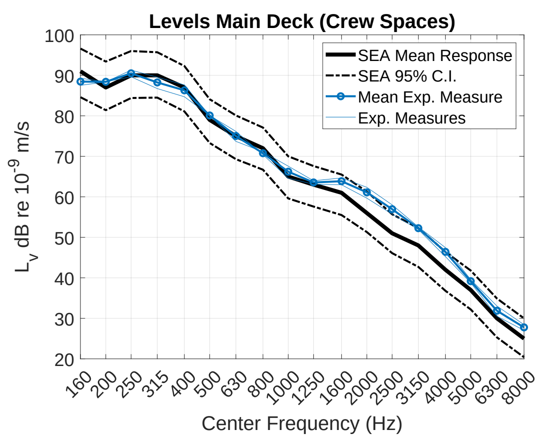


(c)

Figure 6.9: Calculated and measured 1/3 octave band L_v spectra (frequency range 160 Hz to 8000 Hz) of the target subsystems

presented in Table 6.7 is within the accuracy of the results presented in similar studies. Weryk et al. (16) assessed an acceptable maximum error $\Delta L_{Aeq}(T)$ between experimental and calculated levels in $4\,\text{dB(A)}$. In the study of Rockwood et al. (38) SEA velocity levels were in the range of $\pm 5\,\text{dB(A)}$ of the experimental data. In our study, the maximum $\Delta L_{Aeq}(T)$ was equal to $3.5\,\text{dB(A)}$, and the maximum $\Delta L_{v,eq}$ was equal to 5.9 dB. Even though this $\Delta L_{v,eq}$ is larger than the ± 5 dB reported in (38), this does not affect the accuracy of the calculated $L_{Aeq}(T)$, which is the ultimate quantity that we wanted to control and mitigate.

Figures 6.8a to 6.8e show the $L_{p,A}$ spectra in the target acoustic spaces. The experimental spectra are usually within the calculated 95 % confidence interval, which confirms the accuracy of the numerical simulations. Exceptions are the $L_{p,A}$ spectra calculated in the crew spaces and in the captain cabin (Figures 6.8a and 6.8e). In these cases, SEA underestimated the sound pressure levels at frequencies higher than 800 Hz, as the simulations did not include the environmental noise. Nonetheless, this discrepancy did not affect the accuracy of the $L_{Aeq}(T)$ calculated in these spaces (Table 6.7). With regard to the wheelhouse, we notice that the experimental levels are within the 95 % confidence interval with the exception of the levels at 250 Hz, 315 Hz, 3150 Hz, and 4000 Hz where SEA overestimated the sound pressure levels. This resulted in a calculated $L_{Aeq}(T)$ $3.5\,\text{dB(A)}$ higher than the experimental level, which can still be considered accurate, as discussed above.

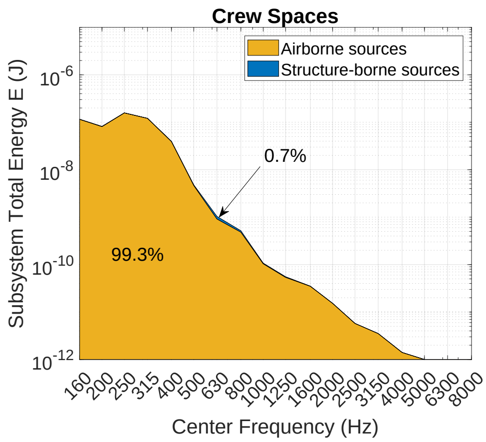
The comparison of experimental and SEA L_v spectra in Figures 6.9a to 6.9c shows good agreement between sea-trial and numerical quantities. The structure-borne spectra of the messroom floor Figure 6.9b shows the largest discrepancy, which resulted in a $\Delta L_{v,eq}$ equal to 5.9 dB(A) (Table 6.7). This behaviour is due to the proximity of the airborne sources, which are directly below the messroom floor, and this means that the deck plating is within the airborne direct field of these sources rather than the diffuse field.

Comparing the SEA levels against the experimental levels we validated the numerical model. Although we deemed this analysis sufficient within a reasonable confidence interval for validation purposes, further improvements to this should require an extensive study of spatially-averaged third-octave band transfer functions and transmission losses to experimentally characterize the airborne and SBN transmission. These quantities could then be used to provide additional strength to the validation here presented.

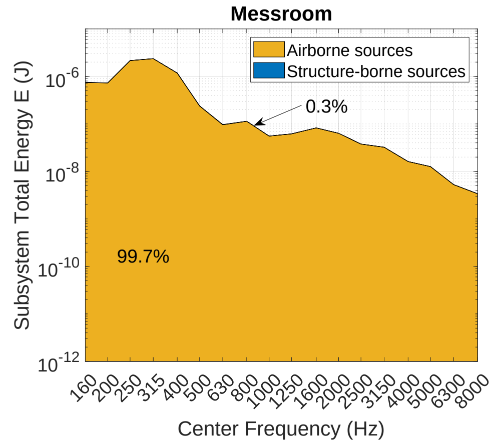
Further improvement of the model would be obtained using hybrid SEA-FEA methods (46), which would extend the frequency range of this analysis to include 10 Hz to 160 Hz, and providing a better characterization of the structure-borne sources (47), which would improve the accuracy in the calculated L_v.

6.4.3 Analysis of source contributions and K-dominant transmission paths

Once the SEA model was validated, we studied the dominance of the type of source (airborne or structure-borne) to the overall response of the target subsystems. Figures 6.10a to 6.10e report the contribution of each source type to the total SEA response energy E_i of the target subsystems. In all the analyzed cases, the airborne sources were the greater contributor to the total energy, constituting more than 99 % of the overall response. The results



(a)



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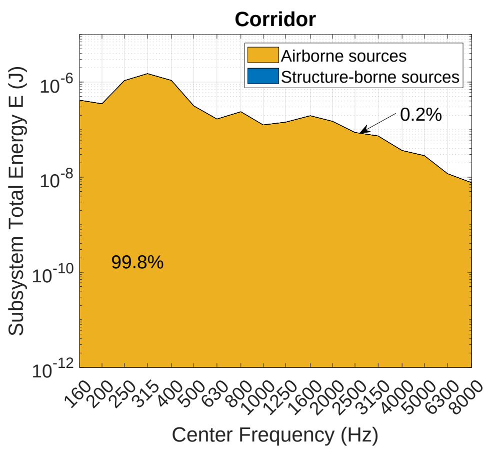

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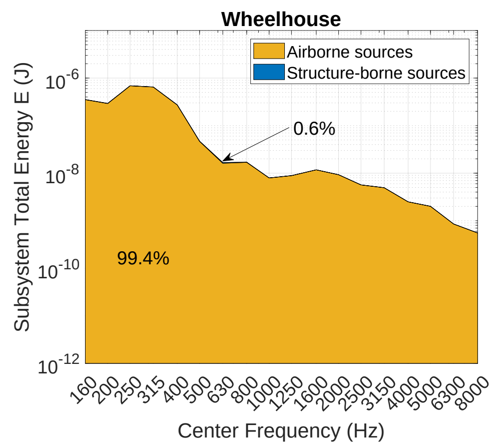

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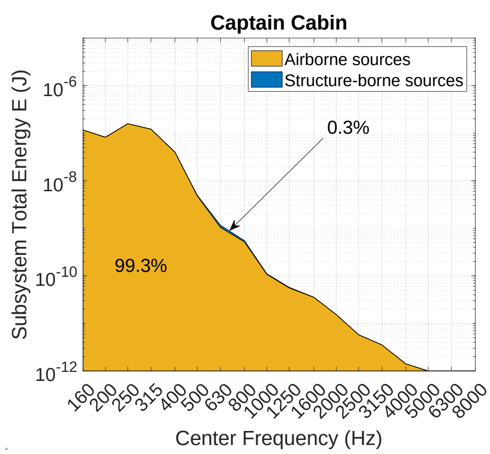


(e)

Figure 6.10: Contribution of the airborne and SBN sources to the overall total energy level E_i (160 Hz to 8000 Hz) of the target subsystems

of Table 6.8 show the difference in the calculated $L_{Aeq}(T)$ and $L_{v,eq}$ by varying the input power levels L_w of the airborne sources, while keeping constant the structure-borne input power, and vice-versa. The results confirm the prevalence of the airborne noise sources as it was shown in Section 6.4.2.

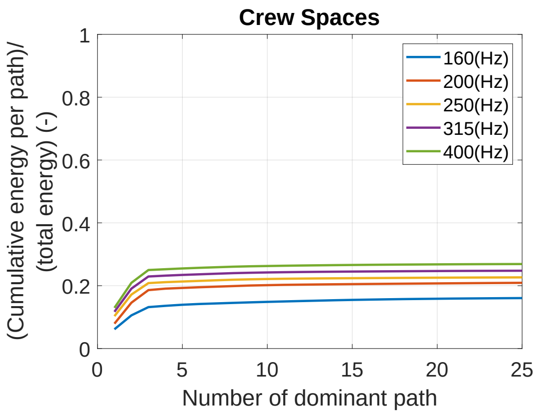
The search for the K-dominant transmission paths was performed considered the engine

Table 6.8: Variations of responses of target subsystems due to variations of airborne and structure-borne input power levels of sources in the SEA frequency range (160 Hz to 8000 Hz). ΔL_w represents the variation in source power levels in decibels. Negative difference represents lower response than the zero case $\Delta L_w = 0$

ΔL_w	Crew Spaces	Messroom	Corridor	Wheelhouse	Captain Cabin	Upper Deck	Main Deck (Messroom)	Main Deck (Crew Spaces)
	$\Delta L_{Aeq}(T)$ dB(A) re 20 µPa					$\Delta L_{v,eq}$ dB re 1 nm/s		
Variation of response due to change in airborne sources power (engine)								
-6	-5.7	-6.0	-6.0	-5.9	-5.9	-5.9	-6.0	-5.6
-3	-2.9	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-2.9
0	0	0	0	0	0	0	0	0
+3	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9
+6	5.9	6.0	6.0	6.0	6.0	6.0	6.0	5.9
Variation of response due to change in structure-borne sources power (engine and generator)								
-6	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
-3	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
0	0	0	0	0	0	0	0	0
+3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
+6	0.3	0.0	0.0	0.1	0.1	0.1	0.0	0.4

room as a source of airborne noise from the propulsive engine and genset, and the subsystems of Table 6.6 as targets.

For these nodes, we extracted and sorted the dominant paths only for the first four 1/3 octave bands (160 Hz to 400 Hz), since higher frequencies are responsible for a small fraction of the overall energy, as shown in Table 6.9.



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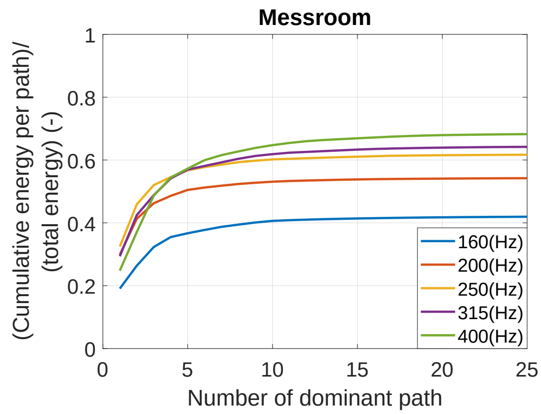

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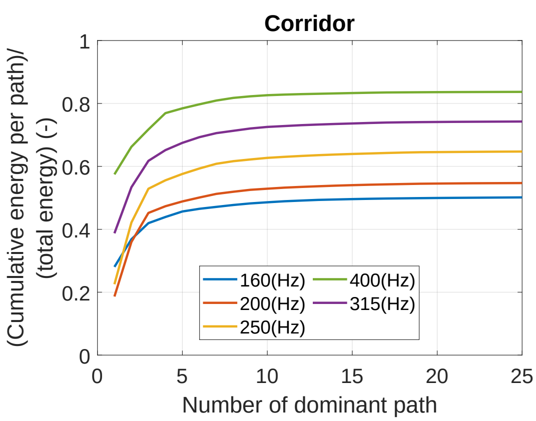

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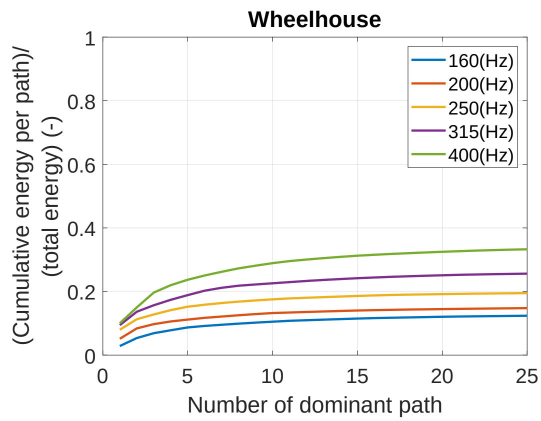

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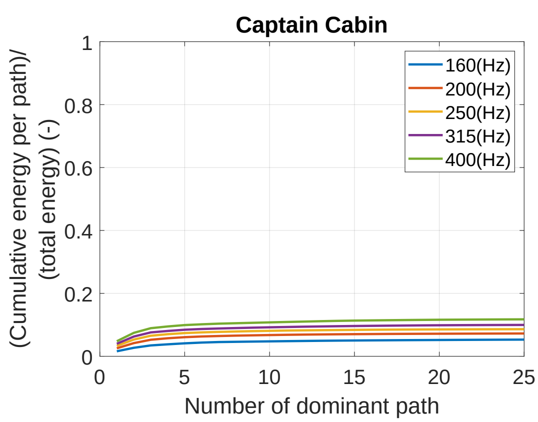

(e)

Figure 6.11: Cumulative contribution of each dominant path from airborne sources (Engine Room) to the total energy response E_i of the subsystems, for each considered 1/3 octave band

Table 6.9: Fraction of the overall total energy transmitted to the acoustic subsystems by airborne sources in the third octave bands 160 Hz to 400 Hz

Target Subsystem	Fraction
Crew Spaces	98.8%
Messroom	90.0%
Corridor	73.7%
Wheelhouse	94.4%
Captain Cabin	98.7%

Figures 6.11a to 6.11e show the fraction of the total energy of each subsystem that is transmitted by the airborne sources through the first 25 dominant paths per each considered 1/3 octave band. A common feature of these Figures is their asymptotic behaviour as the ranking number of dominant paths—represented in the graph abscissas—increases, reaching a quasi-constant ratio of transmitted cumulative energy. In the case of the subsystems adjacent to the engine room, which are the messroom and the corridor (Figures 6.11b and 6.11c), the first few paths transmit a significant amount of energy. For the other subsystems (Figures 6.11a, 6.11d and 6.11e) the dominance of the first few paths is not evident.

Table 6.10 present the first K-dominant path for each target acoustic subsystem in the frequency range 160 Hz to 400 Hz. With the only exception of the Corridor, all of the first paths follow secondary structure-borne transmission routes, which means that the airborne power emitted in the Engine Room is converted into SBN, due to resonant coupling between the engine room acoustic space and the messroom floor. The structure-borne power is then either i) directly re-radiated in the adjacent spaces—Corridor and Messroom—and transmitted airborne via the stairway to the Wheelhouse; or ii) transmitted to other structural members and re-radiated into other acoustic volumes—Captain Cabin and Crew Spaces. The first K-dominant path transmits a consistent fraction of the overall energy in the case of the Messroom (29 % of the total response energy), and the Corridor (37 % of the total energy). In the latter, the path transmits airborne sound from the engine room to these spaces through the acoustic leaking of the engine room doorway. Such transmission mechanism is different from what is usually seen in more complex structures. For instance, in multi-decked vessels, airborne and structure-borne sources and their relative transmission paths are equally important (17).

Table 6.11 shows the occurrence for the 3 most frequent second nodes in the 25 K-dominant paths for the analyzed 5 frequency bands (160 Hz to 400 Hz). The second node on a path is located right after the source node. Table 6.11 points out the critical hotspots in the noise transmission, where most of the airborne and structure-borne sound power is transmitted through.

Table 6.10: First K-dominant transmission path in the frequency range 160 Hz to 400 Hz. Each path is reported as a sequence of connected SEA graph nodes. $E_{i,1st\ dom}/E_i$ is the fraction of the total response energy transmitted through the first dominant paths to the overall total response energy of the subsystem. Acoustic subsystems are **Bold**. Structural subsystems are Underlined

Source node: Acoustic Engine Room Target node: Crew Spaces	Overall 160 Hz to 400 Hz $E_{i,1st\ dom}/E_i$
Engine Room $-->$ Main Deck (Messroom) $-->$ Messroom - Crew Spaces Wall $-->$ **Crew Spaces**	10 %
Source node: Acoustic Engine Room Target node: Messroom	
Engine Room $-->$ Main Deck (Messroom) $-->$ **Messroom**	29 %
Source node: Acoustic Engine Room Target node: Corridor	
Engine Room $-->$ **Corridor**	37 %
Source node: Acoustic Engine Room Target node: Wheelhouse	
Engine Room $-->$ Main Deck (Messroom) $-->$ **Messroom** $-->$ **Rear Wheelhouse** $-->$ **Wheelhouse**	8 %
Source node: Acoustic Engine Room Target node: Captain Cabin	
Engine Room $-->$ Main Deck (Messroom) $-->$ Lateral Messroom Wall $-->$ Upper Deck $-->$ **Captain Cabin**	3 %

Table 6.11: Frequency of occurrence of 2nd nodes from the whole set of extracted K-dominant paths (125 paths), per pair of source/target considered in Table 6.8, for all third octave bands 160 Hz to 400 Hz. **Bold** node name represent an acoustic subsystems, underlined text represent a structural bending subsystems.

Acoustic Engine Room → Crew Spaces	
Node Name	Frequency
Main Deck (Messroom)	62
Side Hull Plating Engine Room Port	31
Side Hull Plating Engine Room Starboard	29

Acoustic Engine Room → Messroom	
Node Name	Frequency
Main Deck (Messroom)	78
Corridor	21
Messroom	13

Acoustic Engine Room → Corridor	
Node Name	Frequency
Main Deck (Messroom)	89
Corridor	16
Front Messroom	14

Acoustic Engine Room → Wheelhouse	
Node Name	Frequency
Main Deck (Messroom)	99
Corridor	15
Messroom	9

Acoustic Engine Room → Captain Cabin	
Node Name	Frequency
Main Deck (Messroom)	105
Corridor	12
Side Hull Plating Messroom Port	4

6.4.4 Identification of practical solutions to mitigate onboard high noise levels

Noise control should first aim to control the noise at the source. In our case, this means either enclosing the engine and genset in insulating cabins, or decoupling them via resilient mounting systems. While the first solution is not feasible for small fishing vessels, and is not a common solution on commercial ships, the second solution would not be effective to reduce noise levels, as we proved that SBN sources are not the primary sources on board. From the analysis of Section 6.4.3, noise control solutions on this vessel should target i) the secondary structure-borne transmission routes, and ii) the acoustic gaps through the door used to access the engine room from the corridor.

In addition, the K-dominant path analysis showed that the floor of the messroom and the corridor is a cluster of noise transmission paths (Table 6.11), which means that our solutions should mitigate the energy transmitted through these subsystems.

We identified 7 tiers of intervention:

- **Tier 1**: remove the doorway gap in the access to the engine room;
- **Tier 2**: Tier 1 + application of VEM-CLD to the messroom floor subsystem above the engine room;
- **Tier 3**: Tier 1 + application of VEM-CLD to all the enclosing surfaces of the engine room;
- **Tier 4**: Tier 1 + application of double-leaf panel filled with mineral wool to the engine room ceiling;

- **Tier 5**: Tier 1 + application of mineral wool to all the surfaces enclosing the engine room;
- **Tier 6**: Tier 5 + application of a floating floor to the messroom floor;
- **Tier 7**: Tier 2 + Tier 6.

We updated the SEA model by including these solutions to evaluate their impact on the $L_{Aeq}(T)$ in the target acoustic volumes. Figure 6.12 shows the solutions tested in this analysis. The application of VEM-CLD configuration was modelled increasing the structural damping of the subsystems where this material was applied to. The data on the damping characteristics of the VEM-CLD were obtained in the experimental work (41). The double-leaf treatment was modelled as a sandwich structure in SEA. Finally, the floating floor is made of a layer of mineral wool laid on the deck plating and covered with a panel of plywood and was modelled as a distributed surface stiffness in the area between the deck and the upper surface of the floating floor. The characteristics of the mineral wool was found in the experimental work (44).

Tables 6.12 and 6.13 report respectively the calculated $L_{Aeq}(T)$ and $L_{v,eq}$, and the penalties on DW and metacentric height GM due to each intervention. The results show that Tier 1 reduces of 6.4 dB(A) the $L_{Aeq}(T)$ in the Corridor, but noise levels in other spaces are not affected. Tier 2 decreases the $L_{v,eq}$ in all the subsystems, with a maximum reduction of 7.3 dB on the floor of the messroom, and $L_{Aeq}(T)$ in all the target spaces, with a maximum reduction of 12.8 dB(A) in the corridor. Nevertheless, the noise levels are still beyond the limits in the messroom and in the corridor.

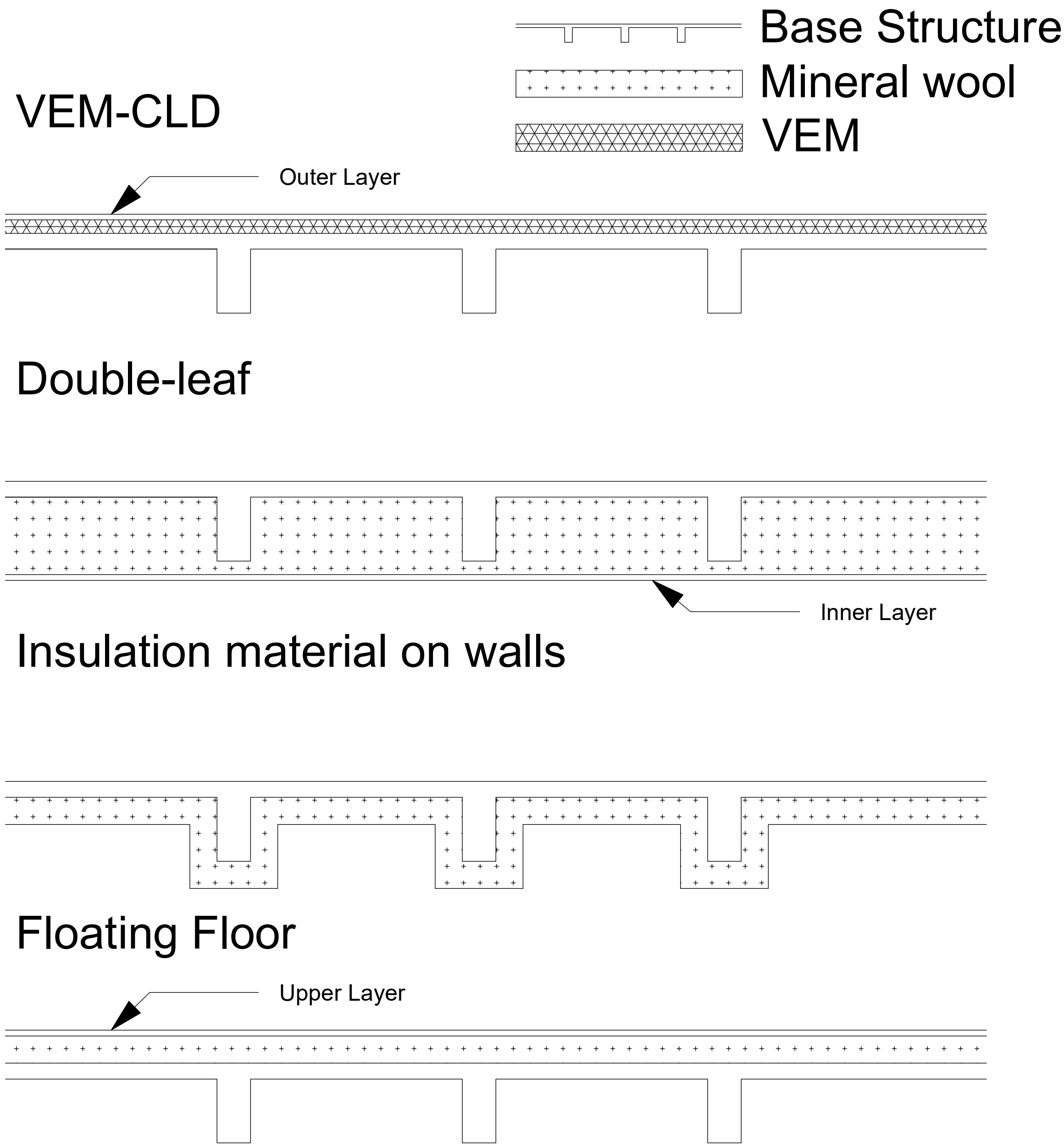

Figure 6.12: Outline of CLD-VEM, double-leaf, and floating floor trims for the Messroom Main Deck above the engine room

Table 6.12: $L_{Aeq}(T)$ and L_v (160 Hz to 8000 Hz) from the 6 tiers of noise control intervention. **Red**: $L_{Aeq}(T) >$ IMO limits. **Yellow**: IMO limits$-5\,\mathrm{dB(A)} <$ $L_{Aeq}(T) \leq$ IMO limits. **Green**: $L_{Aeq}(T) \leq$ IMO criteria $-5\,\mathrm{dB(A)}$

.

	Crew Spaces	Messroom	Corridor	Wheelhouse	Captain Cabin	Upper Deck	Main Deck (Messroom)	Main Deck (Crew Spaces)
	$L_{Aeq}(T)$ dB(A) re 20 µPa					$L_{v,eq}$ dB re 1 nm/s		
IMO limits	60	65	65	65	60	-	-	-
Original SEA Model	61.3	75.5	80.6	65.9	59.8	94.5	104.6	96.4
Tier 1	61.5	74.0	74.2	65.1	60.0	94.7	104.7	96.7
Tier 2	58.7	67.5	67.8	60.7	56.4	91.5	97.3	94.9
Tier 3	58.1	67.5	67.8	60.4	56.1	91.1	97.6	93.7
Tier 4	56.1	67.5	72.7	59.0	54.0	88.6	97.0	92.3
Tier 5	54.9	66.6	66.7	57.9	53.2	88.7	98.2	91.1
Tier 6	53.6	60.3	63.1	55.3	51.6	87.7	90.5	90.4
Tier 7	50.6	56.9	56.2	50.1	46.1	82.2	90.8	88.9

Table 6.13: Deadweight decrease (ΔDW) and initial stability decrease (ΔGM) due to each tier of intervention

Original vessel at worst loading condition		
Displacement Δ 221.350 tons	Deadweight (DW) 96.940 tons	Metacentric height (GM) 13.167 m

Intervention Tiers	ΔDW $\frac{\text{DW}_{new}-\text{DW}_{original}}{\text{DW}_{original}}$	ΔGM $\frac{\text{GM}_{new}-\text{GM}_{original}}{\text{GM}_{original}}$
Tier 1	-	-
Tier 2	-0.7%	-0.3%
Tier 3	-2.6%	-1.1%
Tier 4	-0.9%	-0.4%
Tier 5	-0.5%	-0.2%
Tier 6	-1.1%	-0.5%
Tier 7	-1.8%	-0.8%

The application of the VEM-CLD to all the surfaces enclosing the engine room (Tier 3) increases the DW of the vessel of 2.6 %, and decreases the GM of 1.1 % without improving the $L_{Aeq}(T)$ and $L_{v,eq}$ of Tier 2 (Table 6.13). The application of a double-leaf to the ceiling of the engine room (Tier 4) reduces the noise to comparable levels of Tier 2, with approximately the same effect on DW and GM. The application of mineral wool to the surface of the engine room walls (Tier 5) improves the results of Tier 4 especially in the corridor where the noise is reduced of 6 dB, but levels in corridor and messroom are still beyond the IMO limits. The penalties introduced by Tier 5 are the lowest found in this analysis with ΔDW equals to 0.5 % and ΔGM equals to 0.2 %. If we install a floating floor on the messroom floor in addition to the mineral wool applied in Tier 5, $L_{v,eq}$ decreases of 7.7 dB on the messroom floor, and $L_{Aeq}(T)$ decrease in all the target spaces below the IMO limits

(Tier 6). Finally, combining Tier 2 and Tier 6 we obtained further mitigation of $L_{Aeq}(T)$ and $L_{v,eq}$ (Tier 7), at the expense of a reduction of DW and GM with $\Delta DW = -1.1\,\%$ and $\Delta GM = -0.5\,\%$ for Tier 6, to $\Delta DW = -1.8\,\%$ and $\Delta GM = -0.8\,\%$ for Tier 7.

6.5 Recommendations

The results of Section 6.4.4 show that to mitigate noise levels on the case-study vessel we should tailor the interventions to the hotspots identified in Section 6.4.3. This is particularly evident when we compare the results of Tier 2 and Tier 3: the application of the VEM-CLD to all the surfaces enclosing the engine room does not effect the overall $L_{Aeq}(T)$ values. Our results show that Tier 6 and Tier 7 are the most effective interventions to mitigate noise on board this vessel as the resulting noise levels are lower than the IMO limits and the variations on DW and GM are little. These solutions can be applied to new and existing fishing vessels without major structural renovations.

The results of Section 6.4.3 show that airborne noise sources are responsible for most of the noise levels in the spaces, and that secondary structure-borne noise is the main transmission path of acoustic energy to the upper deck. From this, we can conclude that:

1. decoupling the main engines via resilient mounts is not effective in reducing noise on the vessel;
2. all the walls and the ceiling of the engine room should be insulated using mineral wool;

3. the doorway to the engine room should be properly insulated and any gap should be filled;
4. a floating floor should be installed in the space immediately above the engine room;
5. to further decrease the noise levels, VEM-CLD should be applied on the surfaces that separate the engine room from the crew quarters.

We believe that these recommendations are valid for the decked small-scale fishing fleet in NL at large. In (6), we presented an analysis of this fleet and we highlighted that i) these vessels are mainly built in GRP or GRP on wood, ii) engines and gensets are the main sources of stationary noise, and iii) the vessel we analysed in this paper has the most complex structure. For these reasons, we expect that airborne sources will be prominent sources also on other vessels, and that airborne and secondary SBN are the main transmission paths. In (26), we measured the sound reduction indexes of walls and decks on a sample of vessels from this fleet, and the results confirmed that onboard spaces, and in particular the engine room, are poorly insulated. Though, our recommendations can not be generalized to fishing vessels from other regions, as the characteristics of the vessels vary with region, fishing species, and areas of operation.

Future work should include the implementation of the identified recommendations on case-study vessels either through retrofitting or implementation on new designs. The effectiveness of the noise control measures can then be experimentally tested to further identify their strengths and limitations.

Future activities will also include the presentation of these results to fishing vessel designers, owner-operators, and crew. Using the community-based approach that we applied to our research on noise exposures of fish harvesters, we will engage these key stakeholders to discuss the proposed solutions in order to understand any implementation challenges we haven't identified so far.

6.6 Conclusions

In this paper, we presented the results of an extensive experimental and numerical analysis to identify gaps in the acoustic design of a small fishing vessel from NL. We developed i) SEA model to predict the vibro-acoustic response of the structures, and ii) an analysis of the K-dominant paths using the MPS algorithm to to identify hotspots in structural and acoustic elements of the vessel. The results from these analysis allowed us to tailor effective interventions to reduce noise on this vessel and provide recommendations for designers and ship owners to reduce noise on other small scale fishing vessels in NL. The results showed that i) SEA is a powerful tool to predict noise on small vessels, ii) the use of the MPS algorithm can be used to identify critical spots on the vessel and tailor the solutions, and iii) noise mitigation can be achieved with simple and economical interventions.

6.7 Acknowledgements

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A special thanks goes to the vessel owner-operator who allowed us to perform the sea trials onboard their vessel.

We acknowledge the support of SIKA AG in providing us with the viscoelastic materials, Cambridge Collaborative in providing us with SEAM®, and TRINAV in sharing the construction plans of the case-study vessel.

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Chapter 7

Summary

7.1 Conclusions

Fish harvesting is a dangerous profession. Among many health and safety issues found in fisheries all over the world, noise-related hazards are, compared to others, more subtle, understudied, and often neglected in the design of fishing vessels and during fishing operations. The focus of this doctoral research is on documenting these hazards, and to propose short- and long-term solutions to reduce the associated risk to high noise levels on fishing vessels. Two main risk areas associated with elevated on-board noise levels have been identified: a) hazardous noise exposure of fish harvesters that might onset noise-induced hearing loss, and b) habitability of fishing vessels that might increase the risk of noise-induced fatigue.

In order to document occupational noise exposures, measurements were made on board a representative sample of fishing vessels from the NL small-scale fishing fleet. This showed that harvesters are often exposed to hazardous noise levels, and that their awareness of this risk is low. Specific fisheries that exhibited high numbers of gear impacts and extensive use of hydraulic machinery are the ones where harvesters are exposed to noise the most. Furthermore, the best methodology to assess noise exposure on small-scale fishing vessels was found to be a combination of personal dosimetry and the job-based method, due to the high variability of noise components during fishing operations. Short-term solutions have been proposed requiring minimal gear and equipment modification and selection of appropriate hearing protection devices to be used during fishing operations.

On the noise survey trips, continuous noise levels, sources, and the apparent sound reduction indices of bulkhead and deck assemblies were all assesed. Noise levels during sailing phases in living quarters, even though below the noise exposure criteria, were too high with reference to minimum habitability criteria. The main continuous sources of noise were identified to be the engine and electric generators. The study of sound reduction indices also showed poor acoustic insulation between the engine room and adjacent spaces. The study then focused on the study of the vibroacoustic behaviour of a case-study fishing vessel via SEA. The model enabled the assessment of the dominant noise transmission paths and noise sources to identify hot-spots in the noise insulation capabilities of fishing vessel. Airborne noise sources and second structure-borne paths were found to be the most dominant. Drawing on this result, several tiers of intervention to reduce noise to acceptable levels were proposed. Given the similarity of the case-study to other vessels of the fleet, the mitigation solutions presented have a high probability of working for similar fishing vessels.

7.2 Recommendations and future works

Based on the findings of the research, recommendations are given for future developments and research:

1. The research presented in this thesis shows that hazardous noise is present on-board NL small-scale fishing vessels, and provides an objective measure of the noise-related risk to fishing operations and the health of the harvesters. The research found that owner/operators and harvesters are often unaware of such risks and the consequences for their health. Thus it is recommended to disseminate the findings widely among fish harvesters to raise awareness on the issue, and inform them viable solutions to mitigate noise-related hazards. Furthermore, engagement with fish harvesters from the province is important to get their feedback on the proposed solutions. Future engagement and partnership with the NL-FHSA, which is a primary stakeholders in OHS matters for NL fisheries, to further develop dissemination and education programs of harvesters is also a key aspect for improve awareness of the industry on noise-related hazards.

2. Although a representative sample of the NL fishing fleet was sampled as part of this study, it is necessary to expand the noise surveys to document noise exposures and noise levels on a larger group of vessels, to cover even more variability of fishing operations. If feasible, the sample should be expanded so that a statistical study of noise exposure and dominating components can be done. Indeed, a statistical framework

would help better understand differences between fisheries, between samples, and ultimately it would help the development of a statistical model for noise exposure of fish harvesting in the province.

3. Among the proposed solutions, one option is the adoption of appropriate HPDs. It is well known that the effectiveness of these devices is drastically reduced by incorrect usage. Future works should investigate appropriate HPD designs and test them on fish harvesters. A study of appropriate training programs for correct use of HPD should also be developed.

4. The SEA model, although validated, is restricted to the high frequency range. Noise in the mid-frequency range gives a relatively small contribution to the overall noise levels on the case-study vessel. On different vessels this might be different. The use of hybrid FEA-SEA models could enable a full frequency study and is advised for future applications of the procedure applied in this doctoral research. The modelling using this method is still a matter of research and could add to the current knowledge of numerical modelling for vibroacoustic behaviour of ship structures in the mid-frequency range.

5. Experimental studies could be conducted on the case-study vessel presented in Chapter 6 to provide additional validation to the SEA model. This experimental analysis should provide thorough identification of airborne transmission losses and structure-borne transfer functions, to experimentally characterize the noise transmission mech-

anism. These quantities can then be compared to the SEA results to provide further validation to the model.

6. The design solutions identified in this study should be tested on real case studies. Their effectiveness has been verified using numerical simulations, but an implementation of these solutions may identify other strengths and limitations that are beyond the analysis here presented.

7. Noise-related hazards are likely present outside the section of the fleet studied on this thesis. Indeed, fishing vessels of all sizes are under-regulated, and there is potential for hazardous noise exposure and elevated noise levels on board all fishing vessels. The studies performed on this doctoral research could be undertaken on a sample of vessels 24 m LOA and longer operating in the province and elsewhere.

Appendix A

Ethics clearance application

ICEHR - Application for Ethics Review (Sub-Project)

Project Info.

File No: 20180434
Project Title: Short-term and Long-term Methods and Procedures for the Reduction of Hazardous Noise Exposures on Newfoundland and Labrador Small Fishing Vessels
Principal Investigator: Mr. Giorgio Burella (Faculty of Engineering and Applied Science\Department of Ocean and Naval Architectural Engineering)
Start Date: 2017/06/20
End Date:
Keywords: Marine,A8 - Oceans, Fisheries and Aquaculture,Health

Related Awards:

Award File No	Principal Investigator	Project Title	Funding Snapshot	Notes
20161650	Barbara Neis	Improving fishing safety in Newfoundland and Labrador	**Cape Ashley Fish Ltd.** Program: Operating Fund Type: Grant Requested: CAD 0.00 Awarded: CAD 0.00 **Mitacs** Program: Accelerate Type: Contract-Agreement Account#: 211477 44310 2001 Requested: CAD 66,000.00 Awarded: CAD 66,000.00 **NL-FHSA** Program: Operating Fund Type: Grant	N/A

			Requested:CAD 54,000.00 Awarded: CAD 54,000.00 **PROJECT TOTALS:** Requested:CAD 120,000.00 Awarded :CAD 120,000.00	
20180684	Barbara Neis	Fishing safety project	**MUN** Program: John Lewis Paton Distinguish University Professorship Type: Grant Account#: 212327 40123 2000 Requested:CAD 20,000.00 Awarded: CAD 20,000.00 **PROJECT TOTALS:** Requested:CAD 20,000.00 Awarded :CAD 20,000.00	N/A

Project Team Info.

Principal Investigator

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Common Questions

1. Sub-Project Details

#	Question	Answer
1.1	ICEHR Approval Number of Larger Project:	4718
1.2	Title of Larger Project:	Short-term and Long-term Methods and Procedures for the Reduction of Hazardous Noise Exposures on Newfoundland and Labrador Small Fishing Vessels
1.3	Principal Investigator(s) of Larger Project:	Dr. Lorenzo Moro
1.4	Estimated START date for recruitment:	2017/05/01
1.5	Estimated END date for data collection:	2017/10/30
1.6	Project Program:	Doctoral Dissertation
1.7	If you answered "Other" in question 1.6, please specify.	

2. Project Funding

#	Question	Answer
2.1	Please select the appropriate funding status for this project. If this project is NOT funded and no funding is being sought, skip questions 2.2 - 2.5 and proceed to the "Summary of Sub-Project Research" tab (Section 3).	Funded. Same as larger project.
2.2	If funded, or funding is being sought, please indicate the funding agency / sponsor.	N/A
2.3	Will funds be administered through Memorial's Research Grant and Contract Services (RGCS) office?	Yes
2.4	If you answered "No" to question 2.3, explain why not.	
2.5	If YES to 2.3, specify the principal investigator for the associated funding AND provide the RGCS Awards file number (see information button) or award title.	ROMEO 20161650

3. Sub-Project Purpose and Objectives

#	Question	Answer
3.1	Briefly summarize the purpose, objectives, and hypotheses of the LARGER project. (Approximately 250-500 words)	The fishing industry has always been one of the most important activities of the province, registering more than 9,200 registered fishing harvesters. This profession is also reported as one of the most dangerous professions. Amongst other hazards, noise related diseases such as hearing impairment and noise-induced hearing impairments are increasingly reported in the fishing sector all over the world. Moreover, high noise levels can induce fatigue caused by poor comfort, and hence major risks for injuries. The larger project this proposal is a part of is an interdisciplinary research activity intended to assess the entity, possible solutions and outreach for the noise exposure of fishing harvesters from Newfoundland and Labrador (NL). This research activity will help filling the gap in the available literature on noise exposure for the fishing harvester profession and in methods for reducing noise onboard in both existing and to-be-built vessels Concerns for the noise exposure of fishing harvesters have been showed by several Newfoundland and

		Labrador provincial agencies and associations, amongst which the provincial Department of Occupational Health, the Workplace Health, Safety & compensation Commission, and the NL Fish Harvesting Safety Association (NL-FHSA). The NL-FHSA approached the SafetyNet Centre for Occupational Health & Safety Research (SafetyNet) and the Department of Ocean and Naval Architectural Engineering, Faculty of Engineering and Applied Science, Memorial University (MUN) to co-fund a study to design and carry out a research intended to: a) Document noise levels and noise sources on a sample of fishing vessels in the < 65 foot fleets engaged in diverse fisheries. b) Study the vessel designs and identify ways to mitigate noise exposures within the existing fleet in the short-term. c) Identify appropriate hearing protection equipment for current conditions d) Design an education and training program to help the NL-FHSA communicate research results to members of the fleet e) Design solutions to mitigate hazardous noise levels on fishing vessels. After this phase of the research is completed we will develop, in consultation with the NL-FHSA, f) A communications strategy related to the findings for the members of the larger fishing fleet. An application for ethics approval for the so far described project has already been submitted. This project is here referred as the larger project and is funded via MITACS/NL-FHSA. Expected deliverables from this project include: - Set of recommendations in terms of best practice to design quiet fishing vessels and hearing protection to reduce noise exposures where exposure is critical - Series of workshops. - The development of a Self-assessment tool for noise hazard exposure assessment. - A vessel noise level data sheet including results on noise exposure and noise levels on different areas of the vessel - Final Report(s) to owner-operators and crew on participating vessels - Final Report to MITACS.
3.2	Based on your response in 3.1, explain IF or HOW the purpose, objectives, and/or	No differences are present between the purpose, objectives, and/or hypotheses of the

	hypotheses differ for this SUB-PROJECT.	sub-project and the larger project

4. Sub-Project Study Design / Method

#	Question	Answer
4.1	Briefly summarize the study design / methodology used in the LARGER PROJECT, including the type(s) and/or method(s) of data collection used. (Approximately 200-250 words)	The following methodologies will be used to achieve the objectives of the larger project: 1) Personal noise monitoring: The doctoral student Giorgio Burella will participate to the fishing trips of each participant fishing vessels. During these trips, he will perform personal noise monitoring on fishing harvesters onboard. The measurements will be done using personal noise dosimeters, according to the standard ISO 9612:2009. Exposure levels will be commensurate with the NL Regulation on the matter. 2) Activity logs: Activity log will be completed during the trips by the owner, crewmembers or the doctoral student Giorgio Burella. The data collected will be used to interpret the results from the personal noise monitoring, and to identify potential best practice for reducing personal noise exposure. 3) Vessels Survey forms: Owner-operators will be asked to complete a survey form prior to each trip to characterize the type of vessel, including information on design, fishing activity and information on existing noise mitigation measures. 4) Noise level testing and inspection: Some owner-operators will be asked to consent to vessel's noise-level testing and to access to the vessel design. This activity will involve measuring the level of vibration and noise using class 1 microphones and accelerometers to characterize the noise sources and transmission through the vessel's structure and air. Comfort assessments will be carried out using ISO 6954:1984. 5) Selection of appropriate hearing protection equipment: This activity will be carried out as follow-up. Currently a methodology is still being developed by the investigators.
4.2	Based on your response in 4.1, explain IF or HOW the study design / methodology is different for the SUB-PROJECT.	No differences are present between the study design / methodology of the sub-project and the larger project

4.3	Is the data for the sub-project a subset of the larger project data? If YES, explain.	NO
4.4	Is the data to be collected for the sub-project different than that of the larger project? If YES, describe the nature of the data and how it will be collected.	NO

5. Participants and Recruitment

#	Question	Answer
5.1	Indicate the anticipated number of participants to be recruited, or whose data will be analyzed, for this SUB-PROJECT.	50
5.2	Will participants be recruited using the already approved method(s) of the larger project?	Yes
5.3	If you answered "No" to question 5.2, or if additional methods will be used, describe:	
5.4	Will the type of participants recruited, or exclusion criteria used be the same as those approved for larger project?	Yes
5.5	If you answered "No" to question 5.4, describe:	

6. Free and Informed Consent

#	Question	Answer
6.1	Is a consent addendum required for this sub-project?	Addendum NOT Required

7. Experience

#	Question	Answer
7.1	Please provide a brief description of your experience with this type of research. Include all people who will have contact with the participants. This is particularly important if your study involves a vulnerable population, the collection of sensitive data, or methods that pose greater than minimal risk to participants.	Mr. Giorgio Burella is a PhD student in the Department of Ocean and Naval Architectural Engineering, Faculty of Engineering and Applied Science at Memorial University. He graduated in Naval architecture and marine Engineering at the University of Trieste. His master thesis was related to the propeller-induced vibrations on yachting vessels. He is currently developing research on noise simulation on fishing vessels and will collect information on noise exposure of fishing

		harvesters. He will also collect data from the participating vessels to pursue his research. Mr. Burella will be boarding small fishing vessels and accompanying some vessels on fishing trips in order to undertake this research. In preparation for this the following required fishing safety training and requirements have been met: • Medical clearance according to the Marine Institute Medical Policy. • Basic Safety training for Fish Harvesters course including MED A3 and basic first aid (completed September 2016) • MED A1 (Basic Safety Course Training) providing seafarers with the minimum knowledge of emergency response required to safely work aboard a vessel according to the Transport Canada course syllabus in Marine Publication TP 4957. Dr. Lorenzo Moro is an Assistant Professor in the Department of Ocean and Naval Architectural Engineering at Memorial University. He graduated in Naval Architecture and Marine Engineering at University of Trieste, Italy. His main work has been in ship structural dynamics and ship noise and vibration. He first focused on measuring methods, both inside and outside the laboratory, for example on yachts and cruise ships. He tuned a new test-rig for the dynamic characterization of large resilient mounts for marine diesel engines. He then continued his activity focusing on development of new devices to control noise and vibration on ships. During his post-graduate activities, he worked on experimental tests and numerical simulations both in Italy and in Nantes, France. His research activities have been developed in strict collaboration with several industries such as Wärtsilä, Fincantieri, Azimut|Benetti and Vulkan. Dr. Moro is a member of the Design Methods Committee of ISSC 2018. Dr. Moro has carried out a number of projects where he has conducted personal and area noise monitoring. Dr. Moro will supervise the principal investigator during the development of the research activity. Dr. Barb Neis , has extensive experience doing fishing safety research. She is a University Research

		Professor in the Department of Sociology at Memorial University and co-Director of the SafetyNet Centre for Occupational Health and Safety Research. She has helped design recruitment and other research tools and will participate in the development of tools for communicating research results to participants.

8. Is your research HEALTH research?

#	Question	Answer
8.1	I completed the "Ethics Application Screening Tool" from the Researcher Portal login page, and was directed to complete ICEHR's Application for Ethics Review (Sub-Project) including the Health Research tab.	Yes
8.2	Check all relevant primary data sources:	Residents in the community
8.3	Does your study involve secondary use of data, such as a pre-existing dataset?	No
8.4	Please give name(s) and location of data custodian(s).	
8.5	Please specify.	

9. Declaration

#	Question	Answer
9.1	I have read, and understand that I must comply with, Memorial University's Policy on Ethics of Research Involving Human Participants and the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (TCPS2 - 2014).	Agree
9.2	I will ensure that all procedures performed under the project will be conducted in accordance with the TCPS2 (2014) and all relevant university, provincial, national, and international policies and regulations that govern the collection and use of personally identifiable information and/or any other data in research involving human participants.	Agree
9.3	I agree to conduct the research subject to Section 3 (Guiding Ethical Principles) and	Agree

	accept the responsibilities as outlined in Section 18 (Responsibilities of Researchers) of Memorial University's Policy on Ethics of Research Involving Human Participants.	
9.4	I understand that if I misrepresent and/or fail to accurately and fully disclose any aspects of the research, my ethics clearance may be suspended.	Agree
9.5	I understand that Article 6.16 of the TCPS2 (2014) requires that I submit an amendment request to ICEHR before making any changes to my approved protocol that may affect participants including, but not limited to, changes in recruitment, informed consent, test instruments, and/or tasks or interventions involved in the research. I understand that changes implemented without approval constitute a violation of the TCPS2 (2014) and Memorial University policy.	Agree
9.6	I understand that Article 6.14 (Continuing Research Ethics Review) of the TCPS2 (2014) requires that I submit an annual update for each year my project is active, and a final report after my project is completed.	Agree
9.7	If there is any occurrence of an adverse event(s), I will report it to ICEHR immediately by submitting an Adverse Event Report.	Agree

Attachments

Doc / Agreement	Version Date	File Name	Description
		Agreement_NLFHSA_Signed_2.pdf	Agreement MUN-NLFHSA
Annual Update	2018/06/27	Agreement_NLFHSA_Signed.pdf	Agreement MUN-NLFHSA

Information Sheet/Letter	2017/04/29	008_Information sheet April_4_2017.docx	Information sheet flyer
Information Sheet/Letter	2017/04/29	007_Project Information Sheet_04_April_2017.docx	Project Information Sheet
Informed Consent Form	2017/04/29	010_Owner-operator_Consent Form_April_4_2017.docx	Informed Consent Form - Owner/Operato r
Informed Consent Form	2017/04/29	009_Crew Consent Form_April_4 2017.docx	Informed Consent Form - Crew
Informed Consent Form	2017/06/20	009_Crew_Consent_Form_20_June_2017.doc x	Revised - Larger project consent form
Informed Consent Form	2017/06/20	010_Owner-operator_Consent_Form_20_June_2017.docx	Revised - Larger project consent form
Letter (Approval)	2017/06/20	4 - 0434 Approval Letter (Sub-Project).pdf	N/A
Other	2017/04/29	005_Vessel Survey Form_April_4_2017.docx	Vessel Survey Form
Other	2017/04/29	004_Vessel Report_April_4_2017.docx	Vessels Report Template
Other	2017/04/29	003_Crew Report (indiv)_April_4_2017.docx	Crew Report Template
Other	2017/04/29	002_Activity Log_April_4_2017.docx	Activity Log
Recruitment Document	2017/04/29	006_Sample Recruitment Letter_04_April_2017bn.docx	Sample Recruitment

			Letter
Signature Form	2017/06/12	Supervisor_signature_page.pdf	Supervisor signature Page - Dr. Lorenzo Moro
TCPS2 Certificate	2017/04/29	tcps2_core_certificate_giorgio_burella.pdf	TCPS 2:Core Certificate - Giorgio Burella
TCPS2 Certificate		tcps2_core_certificate_B_Neis.pdf	TCPS 2:CORE Certificate Barabara Neis
TCPS2 Certificate		tcps2_core_certificate_L_Moro.pdf	TCPS 2:CORE Certificate Lorenzo Moro

Appendix B

Appendix to Chapter 3 "*Is on-board noise putting fish harvesters' hearing at risk? A study of noise exposures in small-scale fisheries in Newfoundland and Labrador*"

See next page.

Table B.1: Noise exposure levels per and exposure groups - part 1.

Vessel ID	Effective Work hours T_e	$L_{A,eq}$ dB(A)	$L_{EX,8h}+U_{(95\%)}$ dB(A)	$L_{C,peak}$ dB(C)
Lobster: skipper and crew members				
1	5h30m	83.5	81.8 + 4.2	131.0
2[1]	6h00m	78.7	78.9 + 5.1	132.2
Groundfish (gilnetters): skipper and crew members				
1[2]	8h00m	76.7	76.7 + 4.2	131.0
2[3]	4h45m	80.6	78.3 + 4.1	130.5
Groundfish (hand-line) and squid (jigging): skipper and crew members				
1	5h00m	76.0	74.0 + 4.4	127.8
2	2h48m	71.7	67.2 + 3.5	114.1
Shellfish: skipper				
1	13h00m	80.9	83.0 + 3.3	125.1
2	16h30m	85.5	88.7 + 4.1	139.0
3	14h50m	85.3	88.0 + 3.9	136.9
4	11h23m	82.2	83.7 + 5.2	131.5
Pelagic: skipper				
1	11h30m	77.3	78.9 + 4.4	129.4
Shrimp: skipper				
1	17h00m	79.2	82.5 + 6.0	129.4

[1] task-based method used to assess noise exposure
[2] skipper only
[3] sea conditions: sea state 5

Table B.2: Noise exposure levels per and exposure groups - part 2.

Vessel ID	**Effective Work hours** T_e	$L_{A,eq}$ **dB(A)**	$L_{EX,8h} + U_{(95\%)}$ **dB(A)**	$L_{C,peak}$ **dB(C)**
Groundfish (gilnetters): crew members				
1	-	-	-	-
2[1]	4h45m	85.9	83.7 + 3.3	139.9
Shellfish: crew members				
1	13h00m	81.9	83.3 + 3.1	130.0
2	16h30m	88.2	91.4 + 4.6	132.7
3	14h50m	87.3	90.0 + 3.5	135.1
4	11h23m	84.3	85.8 + 3.8	142.1
Pelagic: crew members				
1	11h30m	80.3	81.9 + 4.0	143.5
Pelagic: skiff operator				
1	11h30m	80.4	82.0 + 3.6	128.4
Shrimp: crew members				
1	17h00m	86.1	89.4 + 6.2	141.3

[1] sea conditions: sea state 5

Appendix C

Appendix to Chapter 4 "*A comparative study of the methods to assess occupational noise exposures of fish harvesters*"

See next page.

Table C.1: 8-hours equivalent noise exposure levels $L_{EX,8h}$ obtained with the four different methods and uncertainties.

Vessel ID	**TBM** $L_{EX,8h}+U$ dB(A)			**JBM** $L_{EX,8h}+U$ dB(A)			**sIMO** $L_{EX,8h}$ dB(A)		**FDM** $L_{EX,8h}(u^2)$ dB(A)		
First group: noise dominated by engine noise											
FSH001	*All Crew Members*			*All Crew Members*			*All Crew Members*		*All Crew Members*		
Lobster	82.48 + 2.90			81.84 + 4.23			*82.1*		82.23(2.00)		
FSH002	*All Crew Members*			*All Crew Members*			*All Crew Members*		*All Crew Members*		
Cod	75.10 + 2.12			73.97 + 4.41			74.67		73.57(2.13)		
FSH011	*All Crew Members*			*All Crew Members*			*All Crew Members*		*All Crew Members*		
Squid	68.63 + 2.78			67.18 + 3.54			68.6		67.00(0.67)		
Second group: noise dominated by noise of fishing activities											
FSH004	*Skipper*	*Crew*		*Skipper*	*Crew*		*Skipper*	*Crew*	*Skipper*	*Crew*	
Whelk	82.52 + 2.31	83.25 + 2.60		83.00 + 3.32	83.32 + 3.12		79.08	69.4	82.52	83.61(2.50)	
FSH003	*All Crew Members*			*All Crew Members*			*All Crew Members*		*All Crew Members*		
Cod	74.77 + 1.88			76.69 + 4.16			71.44		75.93(3.57)		
FSH005	*Skipper*	*Crew*		*Skipper*	*Crew*		*Skipper*	*Crew*	*Skipper*	*Crew*	
Crab	85.26 + 2.73	87.18 + 2.08		88.65 + 4.15	91.36 + 4.65		78.64	81.2	89.93	92.78	
FSH006	*Skipper*	*Crew*		*Skipper*	*Crew*		*Skipper*	*Crew*	*Skipper*	*Crew*	
Cod	75.21 + 1.96	84.15 + 2.16		78.33 + 4.09	83.67 + 3.33		73.98	83.2	78.33	83.86(1.09)	
FSH007	*Skipper*	*Crew*		*Skipper*	*Crew*		*Skipper*	*Crew*	*Skipper*	*Crew*	
Crab	86.61 + 2.46	88.86 + 1.92		87.95 + 3.89	89.98 + 3.48		78.64	81.2	87.63	90.66	
FSH008	*Skipper*	*Crew*		*Skipper*	*Crew*		*Skipper*	*Crew*	*Skipper*	*Crew*	
Crab	85.70 + 2.82	88.33 + 2.50		83.70 + 5.22	85.79 + 3.77		81.25	83.4	84.34	86.40(2.99)	
FSH009	*Skipper*	*Crew*	*Skiff Operator*	*Skipper*	*Crew*	*Skiff Operator*	*Skipper*	*Crew*	*Skipper*	*Crew*	*Skiff Operator*
Capelin	80.49 + 2.51	83.20 + 1.61	81.51 + 1.93	78.86 + 4.44	81.90 + 3.98	81.97 + 3.55	68.57	74.2	79.28	81.64(2.29)	82.3
FSH010	*Skipper*	*Crew*		*Skipper*	*Crew*		*Skipper*	*Crew*	*Skipper*	*Crew*	
Shrimp	84.76 + 3.47	88.02 + 5.35		82.52 + 6.03	89.40 + 6.20		73.98	83.2	82.42	89.20(3.08)	