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Noise Exposure and Mitigation on High-Speed Craft: Assessing Acoustic Environment and Regulatory Compliance

Luis Alfonso Díaz-Secades [1,*], Rebeca Bouzón Otero [2], Yolanda Amado-Sánchez [3] and Fernando Crestelo Moreno [1]

[1] Department of Marine Science and Technology, University of Oviedo, 33203 Gijón, Spain; fcrestelo@uniovi.es
[2] Department of Nautical Sciences and Marine Engineering, University of Coruña, 15001 A Coruña, Spain; rebeca.bouzon@udc.es
[3] Department of Thermal Engines, University of Cádiz, 11003 Cádiz, Spain; yolanda.amado@gm.uca.es
* Correspondence: secadesalfonso@uniovi.es

Abstract: High-speed craft (HSC) present unique challenges regarding on-board noise levels, affecting crew safety, comfort, and operational efficiency. This study investigates noise exposure and mitigation strategies aboard three Ro-Pax HSC vessels operating in southern Spain, with a focus on noise sources, regulatory compliance, and crew health. Full-scale experimental measurements were conducted in critical on-board locations, and noise maps were developed to identify areas where sound levels exceed International Maritime Organization (IMO) and European Directive 2003/10/EC thresholds. Results highlight that engine rooms and propulsion systems are the primary sources of excessive noise, with significant transmission to passenger and crew accommodation areas. Noise exposure calculations reveal that several crew roles, particularly engineers and deckhands, face exposure to hazardous noise levels during routine operations. Mitigation strategies, including improved insulation, noise mapping, and the implementation of hearing protection, are recommended to enhance on-board acoustic conditions. This research contributes to a deeper understanding of noise pollution on HSC vessels and proposes practical interventions to reduce exposure, improving overall maritime safety and occupational health.

Keywords: on-board noise; high-speed crafts (HSC); acoustic comfort; noise exposure; noise mapping; environmental health; noise mitigation strategies

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1. Introduction

High-speed craft (HSC) are a specialized category of seagoing vessels designed to operate at significantly higher speeds than conventional vessels, often using lightweight construction and advanced propulsion systems. These vessels are divided into two main types: air supported and displacement [1]. Air-supported HSCs include Air Cushion Vehicles (ACVs or hovercraft), Surface Effect Ships (SESs), and foil-supported vessels. Displacement HSCs include monohulls, catamarans (double hull), trimarans (triple hull), Small Waterplane Area Twin Hulls (SWATHs), Wave-Piercing Vessels (WPVs), and Air-Lubricated Hulls (ALHs) [2].

Commonly used for passenger transport, military operations, and high-speed ferry services [3], HSCs such as catamarans, hovercraft and hydrofoils, have gained popularity due to their ability to operate efficiently on high-density, short-haul routes. Over time, the design landscape for HSCs has evolved, with catamaran and monohull designs leading the way and the construction of larger hydrofoil and hovercraft vessels declining. Although primarily passenger ferries, the largest of these vessels can also transport vehicles and cargo [4].

Due to the rapid development of the HSC sector, the International Maritime Organization (IMO) adopted amendments to the Safety of Life at Sea (SOLAS) Chapter X in

December 2000, making the HSC Code 2000 mandatory for new ships [5]. High-speed craft are defined by their speed and Froude Volumetric Number, which distinguishes them from more conventional craft [6]. Specifically, an HSC is capable of reaching or exceeding a maximum speed (V) in m/s (Equation (1)):

$$V = 3.7\nabla^{0.1667} \quad (1)$$

where ∇ is the displacement (m^3) corresponding to the design waterline. This definition excludes wing-in-ground effect crafts but includes crafts partially supported by aerodynamic forces, provided the hull is not entirely clear of the water at operational speed [7].

Despite extensive research on noise exposure in conventional maritime settings, studies specifically focused on HSCs are limited. Existing research primarily addresses noise impacts in traditional vessels, such as passenger ships and merchant vessels, which typically focus on sleeping quarters, cabins, and engine rooms. However, due to their high speeds, lightweight construction, and specialized propulsion systems, HSCs present distinct acoustic challenges, leading to elevated noise levels, particularly in engine rooms and crew accommodations. The short port-to-port distances and high traffic density typical of HSC operations further exacerbate on-board noise, impacting crew health, safety, and performance [8,9].

While previous studies have examined noise pollution in maritime settings, including passenger and merchant ships [10,11], the research specific to HSCs remains limited. Studies by [12] identify unique acoustic challenges across various vessel types but lack detailed recommendations on mitigation strategies specific to HSC operations. Notably, there has been insufficient focus on how noise propagates from machinery spaces to crew accommodation areas, a crucial factor in improving the comfort and safety of HSC crews.

This study aims to fill this gap by examining three HSCs operating within a Traffic Separation Scheme (TSS) on high-density short-haul routes. The study focuses on identifying primary noise sources, assessing the vessels' compliance with international regulations, and proposing effective mitigation strategies [13].

The research is motivated by the significant operational and health-related impacts of noise on crewmembers, as elevated noise levels can impair communication, increase fatigue, and raise the risk of accidents. Furthermore, current regulations by IMO and European directives impose strict noise exposure limits on seafaring vessels. Ensuring compliance on HSCs is critical not only for occupational safety but also for the operational efficiency of these high-speed crafts, which are increasingly essential in intermodal transport systems.

This study uniquely integrates noise mapping, regulatory analysis, and mitigation strategies tailored to HSCs, filling a critical gap in maritime acoustics research. Unlike conventional vessels, HSCs operate with lightweight structures and high-speed propulsion systems that amplify acoustic challenges. By addressing these gaps, this research contributes to enhanced compliance with international maritime noise regulations and promotes healthier working environments for maritime crews.

Noise exposure presents severe health risks, including hearing loss, sleep disturbance, and increased stress levels [14,15]. Noise-induced sleep disturbance, for example, has been linked to fatigue and accidents at sea, posing a significant risk to maritime safety [16–18]. IMO emphasizes that high noise levels can affect communication and concentration, which in turn can affect ship safety and crew performance [19].

Studies on maritime noise in similar environments, such as those conducted in the Royal Norwegian Navy [20] or others performed on merchant [21] and passenger vessels [22], indicate that noise levels in cabins can range from 44 to 78 dB(A), well above the World Health Organization's recommended limit of 40 dB(A) for sleeping areas [23,24]. Identifying and mitigating noise sources on HSCs is critical to improving living and working conditions on board [18,25].

To regulate and control noise levels, various international regulations and guidelines have been established to control noise levels on ships. The IMO Code on Noise Levels on Board Ships, adopted in 1981 and updated in subsequent years, sets maximum allowable noise levels in different areas of the ship, such as work areas, navigation spaces, and living quarters [19,26]. These regulations aim to ensure that the equivalent continuous noise level over 24 h does not exceed 80 dB(A), with stricter limits for certain areas to protect the health of the crew.

The specific noise limits for high-speed craft are set out in paragraph 4.10 of the HSC Code [5], which states that the noise level in public spaces and crew accommodation shall be kept as low as possible to enable the public address system to be heard, and as a general rule, shall not exceed 75 dB(A).

Bibliometric Analysis of Noise on Board Merchant Ships

This study applies bibliometric methods to analyze 84 Scopus-indexed publications (2000–2024) on shipboard noise and its effects on crewmembers, focusing on journal articles and conference papers. Keywords appearing at least five times include "human", "ships", "noise pollution", "occupational exposure", and "acoustic noise". The search used specific Boolean operators and queries, including ("noise") AND ("ship*" OR "vessel*") OR ("high-speed craft") AND ("on AND board") OR ("maritime") AND ("exposure"). The time frame selected coincides with the adoption of the International Code of Safety for High-Speed Craft, 2000, which significantly revised the 1994 HSC Code. This analysis focused exclusively on journal articles and conference papers published in English; notes and book chapters were deliberately excluded from the evaluation. A co-occurrence network (Figure 1) reveals four thematic clusters:

- Cluster 1 (Health Impacts—Red): Keywords highlight health risks such as "adverse effects" and "noise-induced hearing loss".
- Cluster 2 (Risk and Measurement—Green): Focuses on "noise pollution" and "risk assessment", addressing noise levels on fishing and merchant vessels.
- Cluster 3 (Marine Noise Sources—Blue): Explores "shipping" and "under-water noise", emphasizing environmental impacts.
- Cluster 4 (Occupational Settings—Yellow): Links noise impacts to "workplace" and "high-speed" vessel environments.

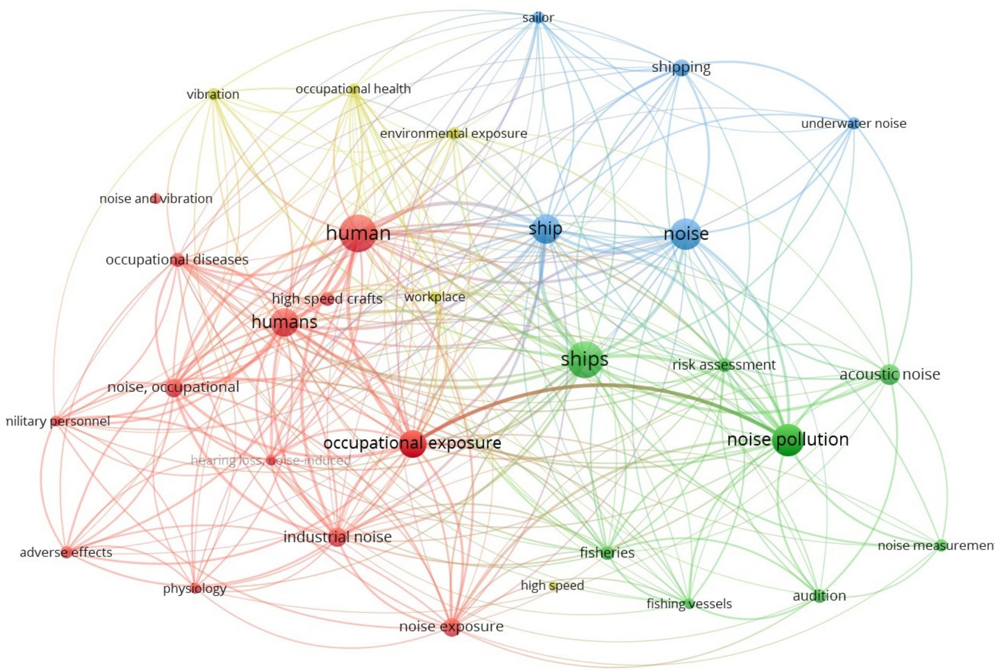

Figure 1. Network visualization of the co-occurrence analysis by keyword in the 84 maritime noise publications from 2000 to 2024, generated by VOSviewer [27].

Although all the clusters obtained are related to maritime noise, the publications bounded by the green and blue clusters are most representative of a plausible narrative centered on noise on board, while the red and yellow clusters can be understood as a narrative pattern related to occupational health.

Temporal analysis (Figure 2) shows an evolution in focus, from occupational expo-sure (pre-2010) to crew impacts from noise and vibration (2010–2015), and post-2020, noise exposure on high-speed vessels (HSCs). This study maps noise patterns on three HSCs along busy short-distance routes and analyzes the impact of ship-generated noise on crew safety and comfort.

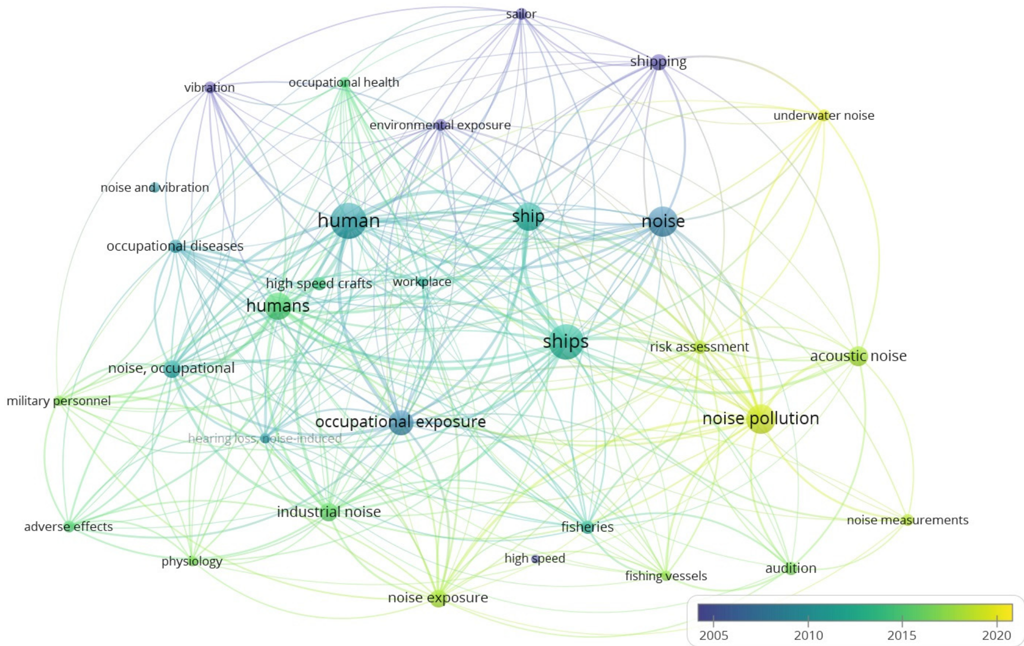

Figure 2. Temporal evolution of keyword co-occurrence analysis in the 84 publications related to maritime noise from 2000 to 2024, created by VOSviewer [27].

Unlike previous research on HSCs, which has focused on hull vibration [28], this study addresses the overlooked issue of ship-generated noise and its impact on the living and working conditions of crewmembers and passengers [10], providing insights for better acoustic conditions and compliance with maritime safety regulations.

2. Materials and Methods

In the present study, an experimental campaign involving full-scale noise level measurements was conducted on board three Ro-Pax high-speed vessels transporting passengers and vehicles in southern Spain. Noise measurements were taken by researchers during each vessel's navigation period.

2.1. Case Study Ships

For comparative analysis, three HSC vessels were utilized in this study. The primary characteristics of these vessels are presented in Table 1.

These three vessels were selected for their similar architecture, aluminum construction, and difference in construction year. The time span between their constructions allows for an examination of advancements in sound insulation technologies, as well as a comparison of the different noise regulations each vessel is required to meet.

Table 1. Main particulars of the three HSC vessels studied.

	HSC-1	HSC-2	HSC-3
Construction year	1997	2003	2021
Length (m)	82	98	123
Breadth (m)	23	26.6	26
Gross tonnage (tons)	5517	6662	12,467
Power of main engines (kW)	24,000	28,320	35,200
Power of auxiliary engines (kW)	1000	1060	1004

2.2. Noise Regulations for Ships

The noise-related regulations applicable to the ships in this case study are analyzed below, beginning with the International Maritime Organization Code on Noise Levels on Board Ships, specifically Resolution A.468(XII) and MSC.337(91) [26,29]. The next key international regulation is the European Directive 2003/10/EC [30], which applies to all three vessels and has been transposed into national regulations: the Spanish Royal Decree 286/2006 and Cyprus Occupational Safety and Health (Noise Protection) C.D.P. 317/2006 [31,32]. The IMO Code on Noise Levels on Board Ships provides global guidelines for the maritime industry, focusing on controlling noise through ship design, construction, and compartment-based noise measurements to enhance crew comfort and operational efficiency. In contrast, the European Directive 2003/10/EC [30], along with its national transpositions, emphasizes the protection of workers' health and safety from noise exposure across various sectors, including the maritime industry within the EU. These EU-based regulations establish exposure limits, mandate risk assessments, and prescribe preventive measures to mitigate noise-related health risks. Together, the regulatory frameworks underscore the importance of coordinated international and regional efforts to protect seafarers from the harmful effects of noise exposure.

2.2.1. Regulatory Framework of the International Maritime Organization

On 19 November 1981, the Code on Noise Levels on Board Ships was approved by Resolution A.468 (XII). The enactment of the Code was intended to guide Administrations on maximum noise levels and exposure limits [26]. Regarding the study of this article, the limits of said resolution will focus on the work, navigation, and accommodation spaces, finding values such as those reflected in Table 2, which are the spaces where the sampling was carried out on all three ships.

Table 2. Noise level limits according to Resolution A. 468(XII).

	Spaces	dB(A)
Workspaces	Machinery spaces (manned)	90
	Machinery spaces (unattended)	110
	Machinery control room	75
	Workshop	85
Navigation	Navigation bridge and chartrooms	65
	Look-out posts including wings	70
	Radio rooms	60
	Radar rooms	65
Accommodation spaces	Cabins and hospital	60
	Messrooms	65
	Recreation rooms	65
	Open recreation areas	75
	Offices	65

These limits were established so that exposure to equivalent continuous noise during a day or a 24 h period did not exceed 80 dB(A). Likewise, the Code requires personnel entering spaces whose noise level is greater than 85 dB(A) to use hearing protectors. The regulations also specify the noise reduction levels provided by different protective devices: earplugs reduce noise by 20 dB(A), earmuffs by 30 dB(A), and the combination of both by 35 dB(A).

Since seafarers' routines on board can vary based on their roles and specific operations at any given time, noise exposure is not consistent throughout. To address this variability, the Resolution recommends using Equivalent Sound Level calculations to determine the maximum noise exposure levels experienced by the crew.

The limits established by Resolution A.468(XII) were reviewed, and new limits were proposed for amending the Code. Whereas Resolution A.468(XII) classified spaces into workspaces, navigation spaces, accommodation spaces, service spaces, and spaces not normally occupied, the proposed amendments revised only two categories: work and recreation spaces (Table 3).

Table 3. Amendments to Resolution A.468 (XII).

	Spaces	dB(A)
Work areas	Machinery spaces, including steering engine	105
	In case of stopped machinery in machinery spaces	85
	Workshops	80
	Separate separator room	85
	Machinery control rooms and maneuvering rooms	70
	Galley	70
	Wheelhouse, including radio room	65
	Listening posts	70
	Offices in the accommodation and deck control rooms	65
	Shops and newsagents	65
	Other work areas	85
Recreation areas	Treatment rooms (infirmary)	60
	Sleeping quarters	55
	Recreational and exercise rooms	65
	Messrooms and other internal accommodation spaces	60
	External recreation areas	70

The most notable change is a reduction of 5 dB in noise limits for spaces such as cabins, machine control rooms, and dining areas [33].

In Force Resolution on the Noise Levels Code, MSC.337(91)

On 30 November 2012, Resolution MSC.337(91) [19] adopted the Code on Noise Levels on Board Ships, which has been in force since 1 July 2014. This Code applies to new ships with a gross tonnage of 1600 GT or more but may also be applied to existing ships where feasible and can be extended to ships of smaller tonnage. While the Code is legally binding, some provisions, such as those in Chapter 5 which set noise exposure limits, have a recommendatory nature. The noise limits established in the Code are presented in Table 4.

The new Code differentiates permitted noise levels based on ship size, categorizing vessels as either exceeding 10,000 GT or falling between 1600 and 10,000 GT. Additionally, for ships with a gross tonnage greater than 10,000 GT, the decibel limits were reduced by 5 dB in work and accommodation spaces, including cabins, hospitals, dining rooms, recreation rooms, and offices.

International Code of Safety for High-Speed Craft

The High-Speed Craft Code was first introduced by IMO in 1994 to provide international standards for the construction and safe operation of high-speed craft, including hydrofoils, hovercraft, and catamarans. The Code was a response to the increasing use of high-speed craft in commercial shipping, which required safety and design standards tailored to their unique operating characteristics, which differ significantly from those of conventional ships.

Table 4. Resolution MSC.337(91).

		dB(A)	
		Ship Size	
	Spaces	**1600 Up to 10,000 GT**	**≥10,000 GT**
Workspaces	Machinery spaces	110	110
	Machinery control rooms	75	75
	Workshops other than those forming part of machinery spaces	85	85
	Non-specified work spaces (other work areas)	85	85
Navigation spaces	Navigating bridge and chartrooms	65	65
	Look-out posts, incl. navigating bridge wings	70	70
	Radio rooms (with radio equipment operating but not producing audio signals)	60	60
	Radar rooms	65	65
Accommodation spaces	Cabin and hospitals	60	55
	Messrooms	65	60
	Recreation rooms	65	60
	Open recreation areas (external recreation areas)	75	75
	Offices	65	60

Due to advances in high-speed craft design, propulsion technology, and construction materials between 1994 and 2000, the HSC Code was revised and replaced by the HSC Code 2000 [5], which entered into force in July 2002. This updated version addressed safety concerns identified through operational feedback and incidents reported under the 1994 Code and introduced more stringent safety measures, including enhanced standards for structural integrity, fire protection, life-saving equipment, and navigational equipment to improve passenger and crew safety.

In this regard, the updated Code requires that noise levels in public spaces and crew accommodation should be minimized to ensure audibility of the public address system and should generally not exceed 75 dB(A). In the operating compartment, the maximum noise level should generally not exceed 65 dB(A) to facilitate clear internal and external radio communications [5].

2.2.2. European Regulatory Framework

Since the vessels under study are flagged in Spain and Cyprus, it is advisable to review the relevant European regulations and their transposition into national laws. European Directive 2003/10/EC [30] establishes minimum conditions for protecting workers from health risks related to noise exposure, particularly risks to hearing. In contrast to the regulations set by the International Maritime Organization, the European Union prioritizes the monitoring of noise exposure duration and consequently regulates accordingly. The limitation of noise exposure on ships began to be applicable from February 2003. The exposure limit values and exposure values that give rise to an action for an 8-day workday are as follows:

- Exposure limit values: $L_{Aeq,d}$ = 87 dB(A).
- Higher exposure values that give rise to action (hearing protectors, medical controls, etc.): $L_{Aeq,d}$ = 85 dB(A).
- Lower exposure values that give rise to action (hearing protectors, etc.): $L_{Aeq,d}$ = 80 dB(A).

2.2.3. Voluntary Regulation

In addition to the international and regional regulations that vessels must comply with, there exists another set of voluntary standards aimed at improving the on-board quality of life. These standards are typically developed by organizations affiliated with the International Association of Classification Societies (IACS), which was created in 1968 and is a current Advisory Body at IMO, and it is up to the shipowner to decide whether to implement them, based on the potential economic benefits. The objective of Classification Societies is to contribute to the development of technical standards for the protection of the environment, life, and property in the maritime sector. These organizations continuously develop and apply rules for the design, construction, and inspection of marine artifacts, including ships and offshore structures, supported by their research departments and laboratories. Their standards are published as "Classification Rules" [34]. Additionally, each Classification Society has developed a series of "Class Notations" that indicate adherence to specific criteria tailored to various types of ships and their intended purposes.

Regarding on-board noise, both national and international regulations establish maximum permissible levels rather than desirable levels. In this context, Classification Societies have issued a Class Notation known as Comfort Class. This study specifically examines the criteria set by the DNV Classification Society, which categorizes the habitability of ships into three classes, denoted by the V-crn qualifier. This qualifier indicates the rating achieved concerning both noise and vibration throughout the ship, with the ratings as follows: V-1, V-2, and V-3, where V-1 represents the highest standards of comfort and V-3 denotes acceptable comfort. Although meeting the noise level values to achieve Comfort Class is not a mandatory requirement for a ship, it can offer economic benefits in its operation. For passenger ships, it can affect ticket demand and pricing, as clients may prefer quieter vessels and be willing to pay a premium for enhanced comfort.

In Tables 5 and 6, the noise level values established by DNV for achieving Comfort Class, based on vessel type are presented. This Classification Society sets noise level criteria for ships based on their size and type, including those less than 10,000 GT, vessels of 10,000 GT or more, high-speed crafts, military vessels, and yachts. In the case of HSCs, the classification notation varies based on length, with different noise level limits established for vessels shorter or longer than 100 m.

Table 5. Maximum noise levels specified by DNV Comfort Class. Adapted from [35].

Location	V-1		V-2		V-3	
	<10,000 GT	**≥10,000 GT**	**<10,000 GT**	**≥10,000 GT**	**<10,000 GT**	**≥10,000 GT**
Navigation bridge	60	60	60	60	65	65
Radio room	55	55	55	55	60	60
Cabins	50	50	55	53	60	55
Public spaces	55	55	60	58	65	60
Gym	65	60	65	60	65	60
Hospital	55	55	58	55	60	55
Offices	60	55	60	58	65	60
Machinery control	65	65	70	70	75	75
Open recreation decks	70	70	73	73	75	75
Workshops	85	85	85	85	85	85

(1) For working areas, navigation spaces, service spaces, machinery rooms, and unspecified spaces, Resolution MSC.337(91) applies. (2) The levels for open deck recreational areas refer only to ship-generated noise, i.e., excluding noise generated by wind, wave, ice, and propeller effects.

2.3. On-Board Noise Measurement

To determine the sound pressure levels on each of the studied vessels and to ascertain whether they exceed the established limits, followed by the calculation of equivalent noise exposure levels, measurements were taken in various areas of each high-speed craft. The materials and methods used for on-board noise measurement are described below.

Table 6. Maximum noise levels on HSC vessels specified by DNV Comfort Class. Adapted from [35].

Location	V-1		V-2		V-3	
	≤100 m	>100 m	≤100 m	>100 m	≤100 m	>100 m
Passenger Areas	70	60	72	65	75	68
Passenger areas with doors open	75	73	75	75	75	75
Navigation bridge	62	60	65	62	65	65
Shops and kiosks	70	65	73	68	75	70
Cabins during navigation	60	58	63	60	65	63
Cabins in port	50	50	55	55	60	60
Offices, control rooms, and crew spaces	65	65	70	70	75	75

2.3.1. Materials

In the present study, an experimental campaign involving full-scale noise level measurements was conducted on board three Ro-Pax high-speed craft. Initially, measurement points within each vessel were identified and selected based on the presence of noise-generating machinery and the location of people, including both crew and passengers. Following the selection of these measurement points, researchers boarded the vessels to collect noise samples using hand-held devices.

2.3.2. Crew Structure of High-Speed Vessels

This study was conducted on three high-speed vessels representative of typical traffic in this category. Each vessel is operated by a crew of 16, divided into three departments: bridge, engine, and hotel, whose roles are further defined in the Results Section. Due to their operational profile, these vessels make several trips per day and dock in port every day, which eliminates the need for an onboard catering department. Instead, food is provided by an offshore catering service, eliminating the need for a dedicated catering crew.

2.3.3. Measurement Locations

The sampling process was conducted at multiple points to identify the primary sources of noise. The analysis of these sample points considered the standards the ships are required to meet, including the applicability of any new standards and the potential to achieve Comfort Class certification. In Figures 3–5, the points where noise was measured in HSC-1, 2, and 3, respectively, are displayed. Each measured compartment is assigned a number that corresponds to the data presented in Tables 9–11. The letters "P" and "S" denote "Port" and "Starboard", respectively.

2.3.4. Sound Level Meter

According to the regulations established by the IMO through Resolution A.468(XII), the sound level meters used must be manufactured in accordance with IEC standard 651 (1979) and be of type 0, 1, or 2 [36]. The primary distinction between these types lies in the allowable tolerance bands for A-weighting filter networks, with wider tolerances permitted at low and high frequency levels compared to mid frequencies. Measurements were conducted using a PCE Ibérica 999 sound level meter (PCE Ibérica S.L., Albacete, Spain), which is a hand-held device featuring a screen to display real-time measurements. Its technical specifications include the following:

- Frequency range: 31.5 Hz... 8 kHz.
- Measurement range: 30...130 dB.
- Frequency assessment: A and C.
- A 4-position LCD display.
- Resolution: 0.1 dB.
- Data update: every 0.5 s.
- Time rating: FAST 125 ms, SLOW 1 s.
- Accuracy: ±1.5 dB with reference conditions at 94 dB and 1 kHz.

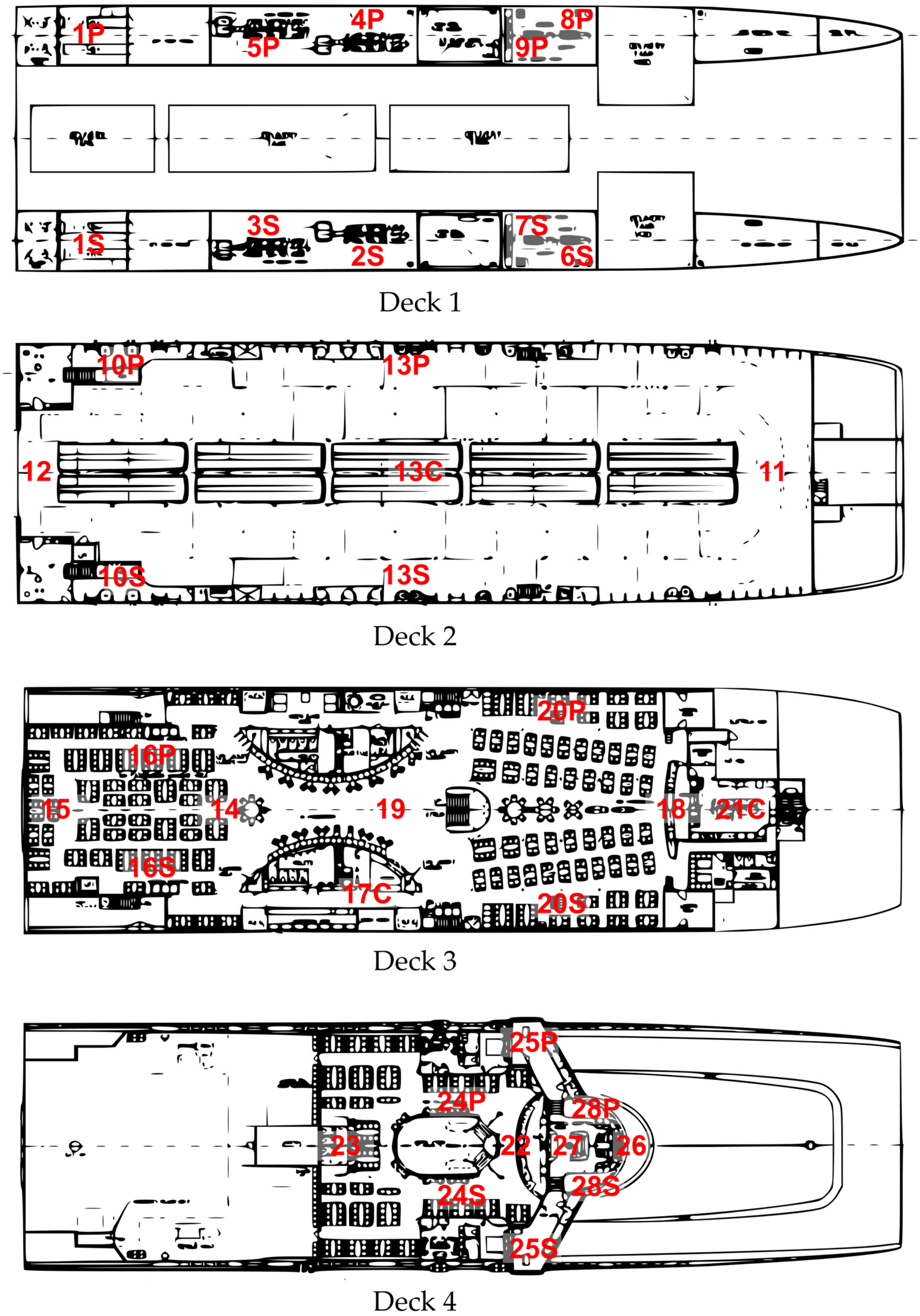

Figure 3. HSC-1 sampling points.

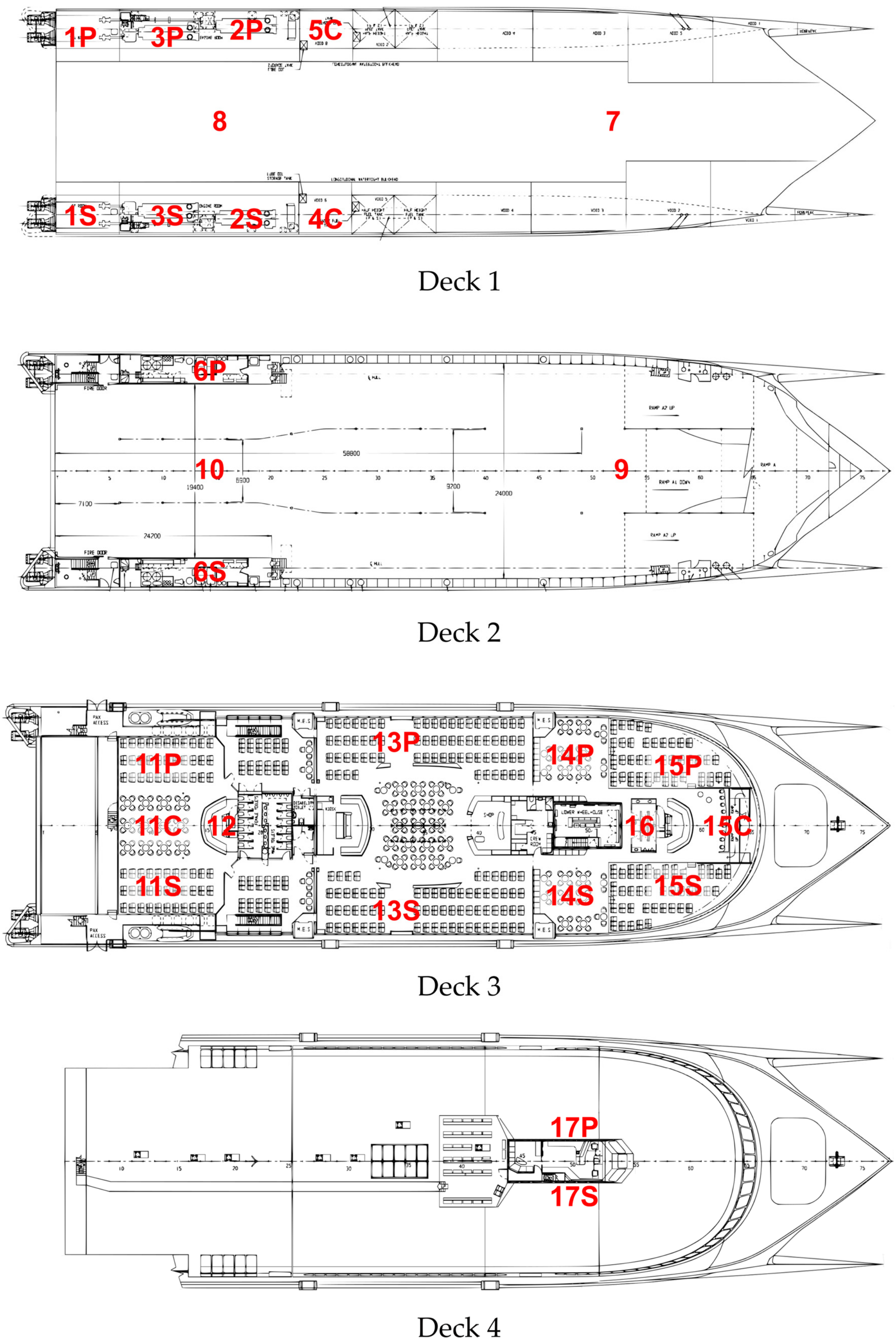

Figure 4. HSC-2 sampling points.

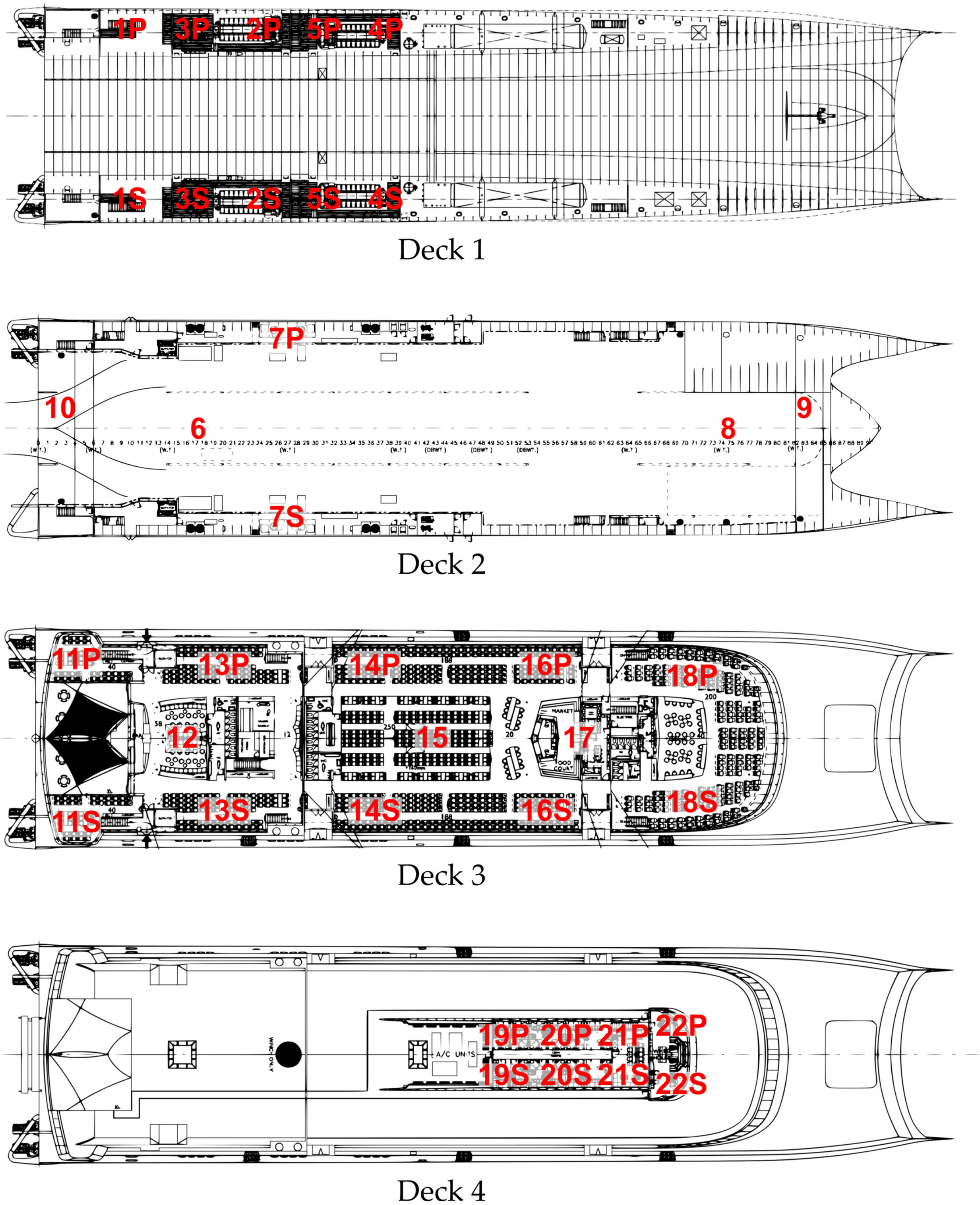

Figure 5. HSC-3 sampling points.

2.4. Methods

2.4.1. On-Board Noise Measurement Protocol

On-board noise measurements were conducted in accordance with Resolution A.468(XII), which specifies that the microphone should be positioned between 1.2 m and 1.6 m above the machinery. Additionally, the procedure stipulates that measurement points must be at least 2 m apart, and in large spaces without machinery, measurements should be taken at intervals not exceeding 7 m throughout the area. In accommodation spaces, measurements should be taken in the center of the space, with the microphone moved slowly both horizontally and/or vertically by 1 m. Additional measurements are required at other points if there are significant differences, specifically greater than 10 dB(A), in the sound level within the cabin, particularly near the head position of a person sitting or lying down.

In this study, a class 2 sound level meter was used, which is slightly less precise than a class 1 device. Given the objective of conducting measurements during navigation, the measurement proved challenging due to the operation conditions of the main engines, usually at high loads. The short duration of the trips constrained the time available to measure each compartment, while the need for accuracy required that the readings stabilize before capturing spot measurements at each designated point.

2.4.2. Noise Exposure Levels

To determine whether the current crewmembers of the studied vessels were affected by on-board noise, their exposure during their work shifts was calculated. Since the high-speed crafts studied only operate during the day, it is common for crewmembers to stay ashore after their work shifts. Initially, the routine of each crewmember was examined by identifying the specific areas where they performed their duties and the number of hours spent in each location. Once these work environments and the corresponding time allocations were determined, the equivalent noise exposure level for an eight-hour work shift was calculated. The equivalent noise exposure level was computed in three ways:

- Assuming that no crewmembers used noise protection devices such as earplugs or earmuffs.
- Assuming that crewmembers used hearing protection devices in the areas specified by Resolution A.468(XII) and considering the noise reduction levels indicated by the regulation.
- Applying a Time-Weighted Average (TWA) of 8 h, taking into account OSHAS noise protection regulations [37], which incorporate noise reduction levels as well as a correction factor for real-world conditions, as opposed to laboratory studies. For this last case, the hearing protectors considered were 3M Peltor II and Peltor III earmuffs, which are widely used on the studied vessels.

To calculate the equivalent noise exposure level during an eight-hour work shift, the formula applied by both Resolution A.468(XII) and European regulation was used (Equation (2)):

$$L_{EX,8h} = 10 \cdot \log \frac{1}{T} \sum_{i}^{n} t_i \cdot 10^{L_i/10} \tag{2}$$

where T is the total exposure time, t_i denotes the exposure time in each compartment at a specific point in time, and L refers to the sound pressure level within the specific compartment.

Table 7 presents the sound pressure level mitigation values specified by IMO Resolution A.468(XII).

Table 7. IMO Resolution A.468(XII) ear protection attenuation values.

Ear Protector Type	Attenuation [dB(A)]
Earplugs	20
Earmuffs	30
Combination (earplugs + earmuffs)	35

In the case of calculating noise attenuation using OSHAS and applying the specific Noise Reduction Rating (NRR), Table 8 presents the protectors used on board:

Table 8. Noise Reduction Rating of ear protection devices worn on board case study vessels.

Ear Protector Model	Noise Reduction Rating [dB(A)]
3M Peltor II	27
3M Peltor III	30

2.5. Ships' Noise Mapping

Due to its specific characteristics, the maritime sector experiences high workforce turnover, and it is common for ship crews to change frequently. This, combined with the varying operational practices of the different vessels, means that a general calculation of exposure levels may fall short of meeting safety and well-being expectations. Therefore, in this study, in addition to calculating the exposure levels for the observed crew, noise maps for each vessel are provided. These maps aim to assist shipowners in designing improved work routines for crews and offering on-board behavior recommendations to mitigate noise exposure, thereby enhancing the health and well-being of workers.

Noise mapping has become a crucial tool for understanding and managing the acoustic environment on board vessels. Each vessel was measured for noise at several points. The results of each measurement included the noise level in decibels, along with the deck and the length where the sample was taken. Real noise measurements collected on board were utilized to conduct linear regression analyses for each ship, enabling the prediction of noise conditions in unmeasured areas. The regression models were developed in MS Excel, allowing for the estimation of noise levels in locations where direct measurements were not feasible by incorporating relevant input values into the regression equations. To validate the accuracy of these models, the adjusted coefficient of determination (R^2) was calculated for each regression. Additionally, the graphical validation of each regression model was performed by comparing the real values with the calculated values at the points where actual measurements, as presented in Tables 9–11, were taken. The mean error of each model was subsequently computed to evaluate its reliability. Utilizing the on-board measurements and the results obtained from each regression model, noise maps were subsequently generated in MATLAB R2024a, providing a comprehensive visualization of noise distribution across the ships. These resultant noise maps offer detailed visual representations of sound levels, facilitating the identification of key noise sources and their propagation patterns.

For the first vessel, HSC-1, 59 noise measurements were included into the regression analysis, Equation (3):

$$Noise_{HSC1} = 128.3235 + Deck * (-16.8964) + Length * (-0.1589) \quad (3)$$

In order to analyze the variation explained by only the independent variables, Deck and Length, that actually affect the noise levels, adjusted R^2 was calculated for each regression. In the case of HSC-1, adjusted R^2 = 0.9501.

In HSC-2, 68 measures were utilized. The obtained regression analysis gives Equation (4):

$$Noise_{HSC2} = 123.3632 + Deck * (-11.0008) + Length * (-0.1831) \quad (4)$$

The adjusted R^2 value of 0.7732 indicates that the regression model is highly accurate in representing the noise conditions.

In the last vessel studied, HSC-3, 43 measures were taken. With these, Equation (5) was obtained:

$$Noise_{HSC3} = 110.3976 + Deck * (-11.4476) + Length * (-0.0710) \quad (5)$$

In the case of HSC-3, adjusted R^2 took a higher value, adjusted $R^2 = 0.9272$.

These high adjusted R^2 values suggest that the models explain a significant portion of the variance in the noise levels, thereby providing reliable predictions for unmeasured areas.

3. Results and Discussion

This section presents the results of noise measurements conducted on three high-speed vessels, focusing on noise exposure levels in various compartments and their compliance with applicable regulations.

3.1. Measured Noise

Tables 9–11 present the sound pressure levels recorded at the various measurement locations specified by the IMO standards, alongside the values recommended by these standards.

In regard to the sound pressure limits established by the DNV Classification Society for the attainment of Comfort Class certification, these values are specifically applicable to accommodation areas, where passengers are typically situated, and the wheelhouse, with the exclusion of other work areas. This exclusion is due to the fact that during navigation on this type of vessel, the Engineer Officer and Chief Engineer are typically stationed on the bridge with the Captain and Deck Officer, and the garage area remains unoccupied.

Table 9. HSC-1 noise measurements.

Sampling Point	Compartment	dB(A)	A.468 (XII)	MSC.337 (91)	DNV < 100 m
28p	Navigation Bridge	54.8	65	65	62/65/65
28s	Navigation Bridge	54.1	65	65	62/65/65
27	Aft Navigation Bridge	51.4	65	65	62/65/65
26	Forward Navigation Bridge	60.1	65	65	62/65/65
25p	Port Wing	52.6	70	70	70/73/75
25s	Starboard Wing	51.9	70	70	70/72/75
24p	Club Lounge	62.8	65	65	70/72/75
24s	Club Lounge	60.8	65	65	70/72/75
23	Club Lounge (Aft)	61.1	65	65	70/72/75
22	Club Lounge (Forward)	60.2	65	65	70/72/75
21c	Forward Bar	63.9	65	65	70/72/75
20p	Forward Lounge	66.5 *	65	65	70/72/75
20s	Forward Lounge	69.9 *	65	65	70/72/75
19	Forward Lounge (Aft)	65	65	65	70/72/75
18	Forward Lounge (Bow)	65.4 *	65	65	70/72/75
17c	Shop	70.3 *	65	65	70/73/75
16p	Aft Lounge	70.6 *	65	65	70/72/75
16s	Aft Lounge	72.8 *	65	65	70/72/75
15	Aft Lounge (Aft)	69.2 *	65	65	70/72/75
14	Aft Lounge (Forward)	70.4 *	65	65	70/72/75
13p	Main Garage	84.1	90	85	N/A
13s	Main Garage	85.1	90	85	N/A
13c	Main Garage	79.1	90	85	N/A
12	Main Garage (Aft)	91.3 *	90	85	N/A
11	Main Garage (Forward)	78.4	90	85	N/A

Table 9. *Cont.*

Sampling Point	Compartment	dB(A)	A.468 (XII)	MSC.337 (91)	DNV < 100 m
10p	Anteroom	93.3 *	90	85	N/A
10s	Anteroom	91.9 *	90	85	N/A
9p	Port Auxiliary Engine Room (Aft)	102.5	110	110	N/A
8p	Port Auxiliary Engine Room (Forward)	101.4	110	110	N/A
7s	Starboard Auxiliary Engine Room (Aft)	104.5	110	110	N/A
6s	Starboard Auxiliary Engine Room (Forward)	102.7	110	110	N/A
5p	Port Engine Room Main Engine (Aft)	111.6 *	110	110	N/A
4p	Port Engine Room Main Engine (Forward)	115 *	110	110	N/A
3s	Starboard Engine Room Main Engine (Aft)	111.6 *	110	110	N/A
2s	Starboard Engine Room Main Engine (Forward)	111.6 *	110	110	N/A
1p	Jet Room	110.7 *	90	85	N/A
1s	Jet Room	110.9 *	90	85	N/A

* Noise levels exceed permissible limits. N/A = Not Applicable.

At HSC-1, of the 37 measurements taken, 17 exceeded the regulatory limits, representing almost 46% of the total measurements. The data indicate that noise levels exceed the regulatory limits in several locations, particularly in the engine rooms, jet rooms, and anterooms. In the passenger areas, noise levels also exceeded the regulatory limits up to deck 3, reflecting the transmission of noise from deck 1, where the jet rooms, main engines, and auxiliary engines are located.

Table 10. HSC-2 noise measurements.

Sampling Point	Compartment	dB(A)	A.468 (XII)	MSC.337 (91)	DNV < 100 m
17p	Navigation Bridge	63	65	65	62/65/65
17s	Navigation Bridge	63.5	65	65	62/65/65
16	Forward Lounge–WC	62	65	65	70/72/75
15p	Forward Bar	61.7	65	65	70/72/75
15s	Forward Bar	63.6	65	65	70/72/75
15c	Forward Bar	62.3	65	65	70/72/75
14p	Forward Lounge	60.9	65	65	70/72/75
14s	Forward Lounge	62.8	65	65	70/72/75
13p	Forward Lounge	64.8	65	65	62/65/65
13s	Passenger Lounge	75.1 *	65	65	70/72/75
12	Aft Bar	65.6 *	65	65	70/72/75
11p	Aft Club Lounge	77.2 *	65	65	70/72/75
11s	Aft Club Lounge	68.1 *	65	65	70/72/75
11c	Aft Club Lounge	79.9 *	65	65	70/72/75
10	Aft Upper Garage	81.3	90	85	N/A
9	Forward Upper Garage	76.8	90	85	N/A
8	Aft Main Garage	90.5	90	85	N/A
7	Forward Main Garage	82.5	90	85	N/A
6p	Anteroom	95.7 *	90	85	N/A
6s	Anteroom	103 *	90	85	N/A
5c	Auxiliary Engine Room (P)	97.9	110	110	N/A
4c	Auxiliary Engine Room (S)	98.2	110	110	N/A
3p	Aft Engine Room Main Engine	118.7 *	110	110	N/A
3s	Aft Engine Room Main Engine	118.1 *	110	110	N/A
2p	Forward Engine Room Main Engine	119.5 *	110	110	N/A
2s	Forward Engine Room Main Engine	119.8 *	110	110	N/A
1p	Jet Room	118.0 *	90	85	N/A
1s	Jet Room	117.8 *	90	85	N/A

* Noise levels exceed permissible limits. N/A = Not Applicable.

Of the 28 measurements taken in HSC-2, 13 exceed the IMO standards, i.e., 46.4%. Similarly to the previous case, the highest noise levels are concentrated in the main engine rooms, anterooms, and jet rooms.

In relation to the levels determined by DNV, unlike the previous ship where elevated noise levels were observed in the forward lounge, HSC-2 has higher noise concentrations in the aft section. In particular, the noise levels in the club lounge do not even meet the minimum acceptable standard, V-3, with 2 out of 3 measurements exceeding the limits set by the Classification Society.

Table 11. HSC-3 noise measurements.

Sampling Point	Compartment	dB(A)	A.468 (XII)	MSC.337 (91)	DNV > 100 m
22p	Navigation Bridge	52.7	65	65	60/62/65
22s	Navigation Bridge	53.4	65	65	60/62/65
21p	Chief Engine and Captain Cabin	52.7	60	60	58/60/63
21s	Chief Engine and Captain Cabin	52.4	60	60	58/60/63
20p	Crew Cabin	48.4	60	60	58/60/63
20s	Crew Cabin	47.5	60	60	58/60/63
19p	Crew Cabin and Changing Room	45.5	60	60	58/60/63
19s	Crew Cabin and Changing Room	50.1	60	60	58/60/63
18p	Forward Club Lounge	54	65	65	60/65/68
18s	Forward Club Lounge	56.5	65	65	60/65/68
17	Forward Bar	58.1	65	65	60/65/68
16p	Middle Passenger Lounge to Forward	54.7	65	65	60/65/68
16s	Middle Passenger Lounge to Forward	54.6	65	65	60/65/68
15	Middle Passenger Lounge to Forward	54.6	65	65	60/65/68
14p	Middle Passenger Lounge to Aft	55.2	65	65	60/65/68
14s	Middle Passenger Lounge to Aft	55.2	65	65	60/65/68
13p	Passenger Lounge to Aft	61.8 *	65	65	60/65/68
13s	Passenger Lounge to Aft	62.9 *	65	65	60/65/68
12	Aft Bar	61.1 *	65	65	60/65/68
11p	Aft Club Lounge	65.9 *	65	65	60/65/68
11s	Aft Club Lounge	65.5 *	65	65	60/65/68
10	Upper Garage (Aft)	87.6	90	85	N/A
9	Upper Garage (Forward)	75.9	90	85	N/A
8	Main Garage (Forward)	79.3	90	85	N/A
7p	Anteroom	73.7	90	85	N/A
7s	Anteroom	80	90	85	N/A
6	Main Garage (Aft)	88.2 *	90	85	N/A
5p	Aft Auxiliary Engine Room	92.6	110	110	N/A
5s	Aft Auxiliary Engine Room	102.3	110	110	N/A
4p	Forward Auxiliary Engine Room	97.2	110	110	N/A
4s	Forward Auxiliary Engine Room	104.4	110	110	N/A
3p	Aft Main Engine Room	99.3	110	110	N/A
3s	Aft Main Engine Room	102.2	110	110	N/A
2p	Forward Main Engine Room	94.9	110	110	N/A
2s	Forward Main Engine Room	99.1	110	110	N/A
1p	Jet Room	92.8 *	90	85	N/A
1s	Jet Room	98 *	90	85	N/A

* Noise levels exceed permissible limits. N/A = Not Applicable.

In this final case study, there are significant differences between the two previous cases. Of the 37 measurements taken in HSC-2, 8 exceed the IMO standards, i.e., 21.6%. The HSC-3 has a greater length than the other two vessels, at 123 m. As a result, the DNV standards for granting Comfort Class certification are different, with the criteria for ships over 100 m in length being applied in this case.

Of the points measured, only four exceed the limits set by Resolution A.468(XII): points 1p and 1s, corresponding to the jet lounges, and points 11p and 11s, corresponding to the stern club lounge. In addition, item 6 in the main garage would exceed the standard if the ship were required to comply with Resolution MSC.337(91).

There is a reduction in noise levels in the engine rooms, anterooms, and jet rooms compared to the previous vessels, which contributed to lower noise levels on the upper decks. This highlights the significant influence of noise transmission from these areas to the passenger areas.

3.2. Noise Exposure Levels

This subsection presents the calculated noise exposure levels for each crewmember of the three high-speed crafts studied. In addition to the levels determined for their respective routes, attenuated noise levels were calculated for those using hearing protection. The on-board surveys revealed that during normal operations, only the Second Engineer and the Donkeyman regularly used hearing protection devices while working. Tables 12–14 show the exposure levels of the different workers on board each HSC vessel studied.

Table 12. Calculated noise exposure levels of workers on board the HSC-1.

Role	L_{EX},8h [dB(A)] No. Attenuation	L_{EX},8h [dB(A)] IMO	L_{EX},8h [dB(A)] NRR I	L_{EX},8h [dB(A)] NRR II
Bridge Department				
Captain	56.62	-	-	-
First Officer	82.95	-	-	-
Boatswain	87.13	-	-	-
Deckhand 1	88.07	-	-	-
Deckhand 2	87.82	-	-	-
Deckhand 3	85.08	-	-	-
Deckhand 4	84.57	-	-	-
Engine Department				
Chief Engineer	51.40	-	-	-
Second Engineer	107.71	100.00	97.71	96.21
Donkeyman	107.83	100.12	97.83	96.33
Hotel Department				
Hotel Chief	70.52	-	-	-
Stewardess 1	71.52	-	-	-
Stewardess 2	69.98	-	-	-
Stewardess 3	64.10	-	-	-
Cleaner 1	71.39	-	-	-
Cleaner 2	65.58	-	-	-

Table 13. Calculated noise exposure levels of workers on board the HSC-2.

Role	L_{EX},8h [dB(A)] No. Attenuation	L_{EX},8h [dB(A)] IMO	L_{EX},8h [dB(A)] NRR I	L_{EX},8h [dB(A)] NRR II
Bridge Department				
Captain	71.46	-	-	-
First Officer	78.04	-	-	-
Boatswain	83.17	-	-	-
Deckhand 1	83.34	-	-	-
Deckhand 2	83.70	-	-	-
Deckhand 3	78.33	-	-	-
Deckhand 4	77.82	-	-	-
Engine Department				
Chief Engineer	68.30	-	-	-
Second Engineer	110.14	102.43	100.14	98.64
Donkeyman	109.74	102.03	99.74	98.24
Hotel Department				
Hotel Chief	66.09	-	-	-
Stewardess 1	70.12	-	-	-
Stewardess 2	64.87	-	-	-
Stewardess 3	61.36	-	-	-
Cleaner 1	73.30	-	-	-
Cleaner 2	63.10	-	-	-

Table 14. Calculated noise exposure levels of workers on board the HSC-3.

Role	L_{EX},8h [dB(A)] No. Attenuation	L_{EX},8h [dB(A)] IMO	L_{EX},8h [dB(A)] NRR I	L_{EX},8h [dB(A)] NRR II
Bridge Department				
Captain	54.76	-	-	-
First Officer	77.67	-	-	-
Boatswain	82.83	-	-	-
Deckhand 1	83.48	-	-	-
Deckhand 2	83.35	-	-	-
Deckhand 3	78.62	-	-	-
Deckhand 4	78.23	-	-	-
Engine Department				
Chief Engineer	52.7	-	-	-
Second Engineer	95.88	88.17	85.88	84.38
Donkeyman	95.16	87.45	85.16	83.66
Hotel Department				
Hotel Chief	59.94	-	-	-
Stewardess 1	59.95	-	-	-
Stewardess 2	54.60	-	-	-
Stewardess 3	60.79	-	-	-
Cleaner 1	63.97	-	-	-
Cleaner 2	62.00	-	-	-

The bridge of HSC-1 features enclosed wings, serving as an extension of the bridge and located on the same plane. There is a maneuver console on each wing, and during the measurements, the one located on the starboard side was used. As shown in Table 12, all members of the Bridge and Engine Departments, except for the Captain and Chief Engineer, experience high levels of noise exposure. Among them, the Boatswain, Deckhand 1 and 2, Second Engineer, and Donkeyman are exposed to noise levels exceeding 87 dB(A) LEX, 8h. In the case of the Engine Department, both the Second Engineer and Donkeyman use hearing protection, but noise mitigation remains insufficient. In the case of the Bridge Department, no hearing protection is used, although it would help reduce their exposure levels below the limits set by EU Directive 2033/10/EC.

HSC-2 does not have bridge wings. The Captain performs docking and undocking maneuvers using a console integrated into the bridge, located just behind the main steering console. For this purpose, the bridge is equipped with a centralized camera system that provides visibility of the maneuvers' forward and aft as well as the ship's sides. In this case, workers in the Bridge Department do not exceed the noise exposure limits, though they are close. As for the Engine Department, the situation is similar to that on the HSC-1, as noise levels in the engine and propulsion areas are very high, and much of the Second Engineer and Donkeyman's workday takes place in these areas. On this vessel, HSC-2, the noise levels experienced by the Captain and Chief Engineer are higher than those on the HSC-1 due to the greater sound pressure level in the wheelhouse of the HSC-2. However, the noise levels experienced by the heads of both departments remain below legal limits.

The structural design of this vessel is very similar to that of the HSC-2; therefore, HSC-3 also does not have bridge wings. In the case of this more recently constructed vessel, modern sound insulation is more effective, reducing the overall noise levels and de-creasing the LEX,8h exposure levels for the Captain, Chief Engineer, and the entire Hotel Department compared to the HSC-2. Although the noise exposure levels for the rest of the crew in the Bridge and Engine Departments remain high, a slight reduction is observed, particularly for the Second Engineer and Donkeyman. On this vessel, the use of hearing protectors combined with the new noise mitigation technologies implemented on board could indeed result in Engine Department crewmembers being exposed to noise levels below the limits set by EU Directive 2003/10/EC. As with the HSC-2, if crewmembers with noise exposure levels above 75 dB(A) were to adjust their work routines to avoid spending excessive time in the noisier areas, a significant reduction in noise exposure could be achieved, which would positively impact their quality of life on board.

3.3. Noise Mapping

This subsection presents the noise mapping analysis of the three high-speed ships studied in this article. With the results obtained from real measurements and the three regression analyses, noise mapping of the three high-speed craft ships was performed. Figures 6 and 7 present the validation of the HSC-1 regression model (Equation (3)) and the corresponding elaborated noise map. In Figure 6, the y-axis represents the noise levels, while the x-axis corresponds to the measurement points listed in Table 9. At each of these points, both the measured and calculated noise levels in dB(A) are presented for comparison. For Equation (3), when applied to the measured points, the mean error between the measured and calculated values is 2.13%. This error is within the allowable range, proving the reliability of the model.

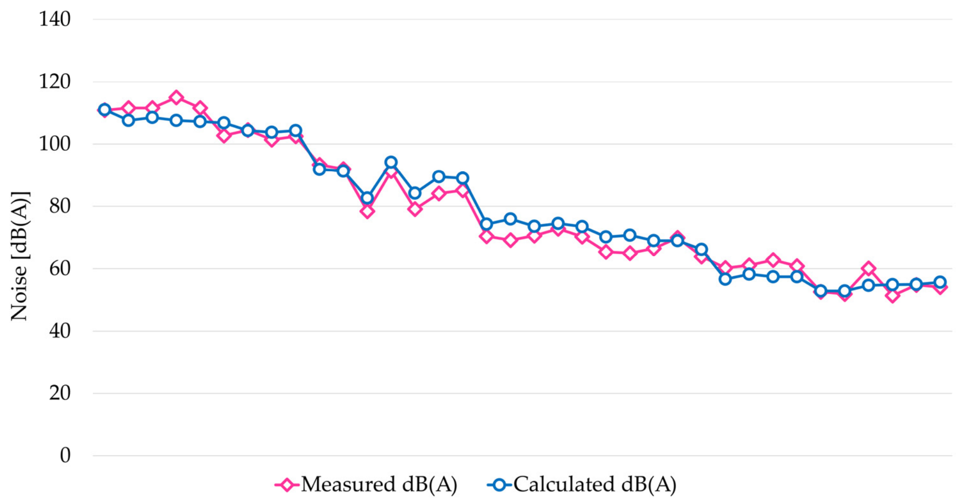

Figure 6. Validation of HSC-1 regression model.

For the first high-speed craft, serving as an example for the others, noise levels were determined by inputting the length values for deck 1 into Equation (3). These length values, derived from the vessel's general arrangement, were measured from the aft to the fore. The process was repeated for all available length values on deck 2 and deck 3. In the specific case of deck 4, only the lengths between 22 m and 46 m were considered, as the fourth deck is constructed solely within this range. The values calculated using Equation (3) were compiled into a database, which was subsequently used to generate noise maps in MATLAB R2024a. The same method was applied to generate noise maps for HSC-2 and HSC-3.

In this first HSC, the engine room deck has high noise levels similar to those found in HSC-2. Conversely, noise propagation around the vessel seems to be lower, as the second deck, the garage, is already in the 80 to 90 dB(A) range. The accommodation area of the vessel, situated on deck 3, experiences noise levels over 75 dB(A) in the aft section but drops to the 65 dB(A) range in the forward section. As usual, the wheelhouse noise is below 60 dB(A).

Subsequently, the second regression model, presented in Equation (4), was applied to the HSC-2 vessel. For validation purposes, a comparison between the on-board measured and calculated values was conducted, as illustrated in Figure 8. The mean error of this validation was 3.32%. In the validation in Figure 8, the x-axis corresponds to the measurement points listed in Table 10. At each of these points, both the measured and calculated noise levels in dB(A) are shown for comparison. Following the validation, Figure 9 presents the noise map developed for the HSC-2.

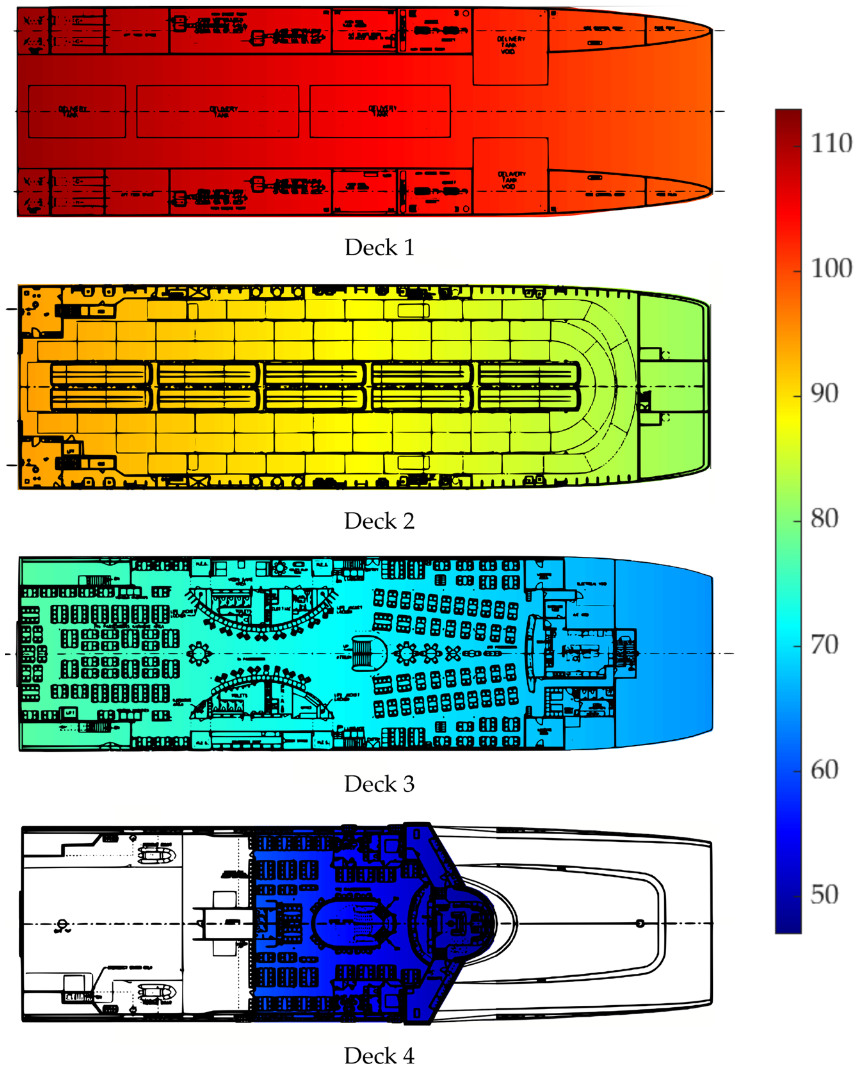

Figure 7. Noise map of HSC-1.

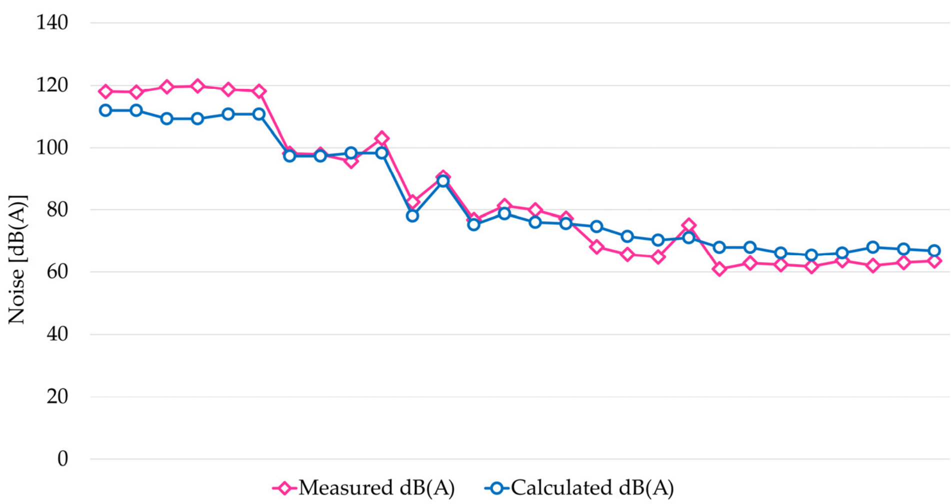

Figure 8. Validation of HSC-2 regression model.

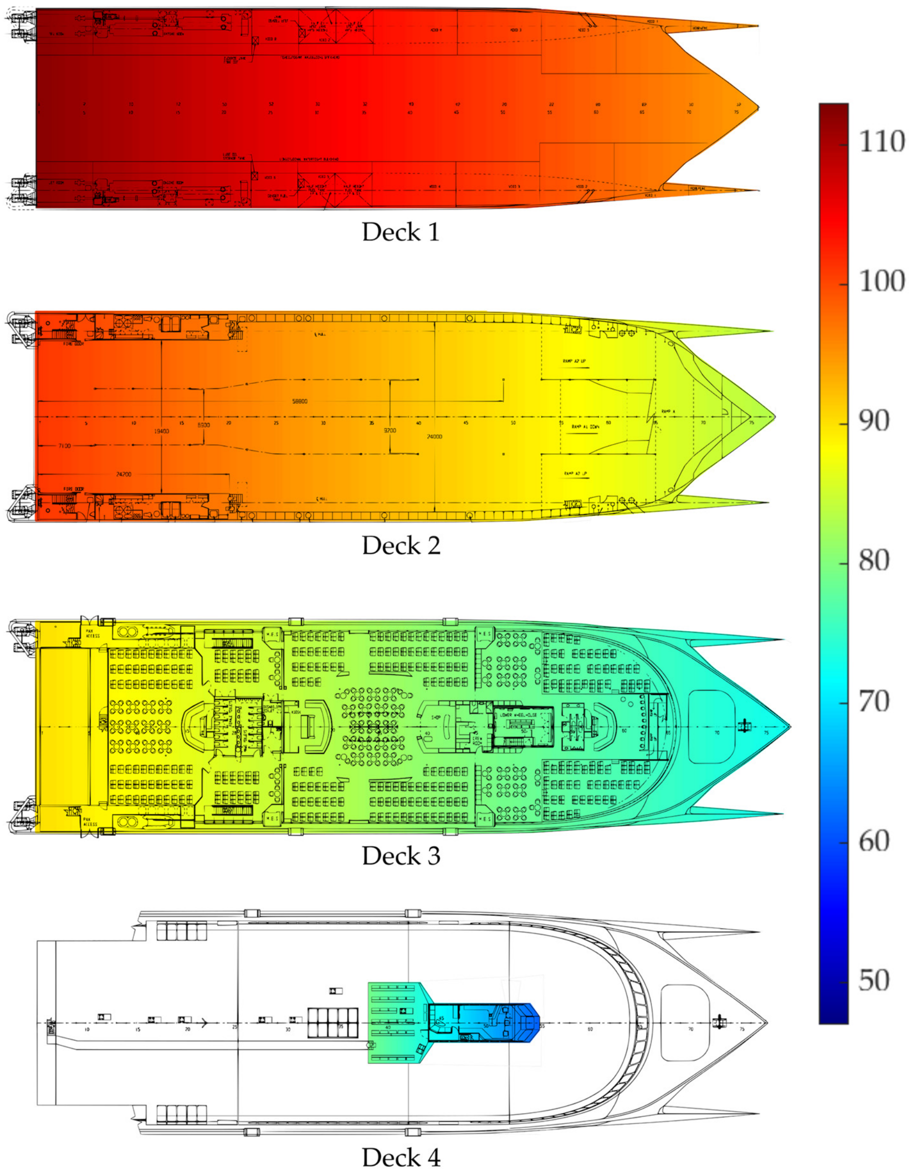

Figure 9. Noise map of HSC-2.

In the second vessel, it can be observed that the first two decks, where the engine room and the garage are located, respectively, have noise levels well over 85 dB(A). Consequently, these areas should be avoided during operation, or noise exposure should be limited by using personal protective equipment (PPE). On deck 3, where the passengers travel, noise levels range between 70 and 80 dB(A). These levels are not adequate for proper rest periods and are only acceptable for short-term exposure. On deck 4, which houses the wheelhouse, noise levels rarely exceed 70 dB(A), and therefore, should not affect the crew's performance.

Following the same procedure, the HSC-3 regression model (Equation (5)) was validated by comparing the measured values with the calculated values. The mean error was determined to be 1.85%, demonstrating the model's reliability, consistent with the other two models, as all three mean errors are below 5%. Figures 10 and 11 present the graphical validation, where measured and calculated noise values are displayed, as is the noise map developed for HSC-3, respectively.

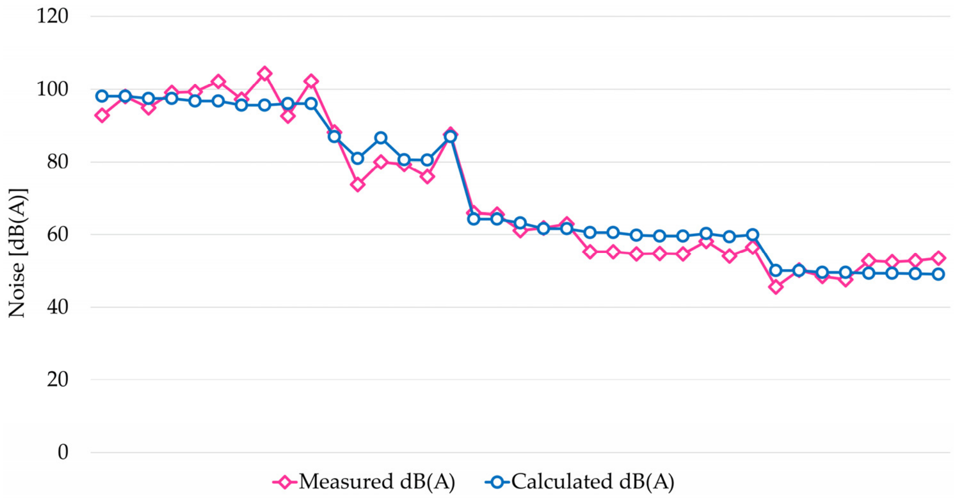

Figure 10. Validation of HSC-3 regression model.

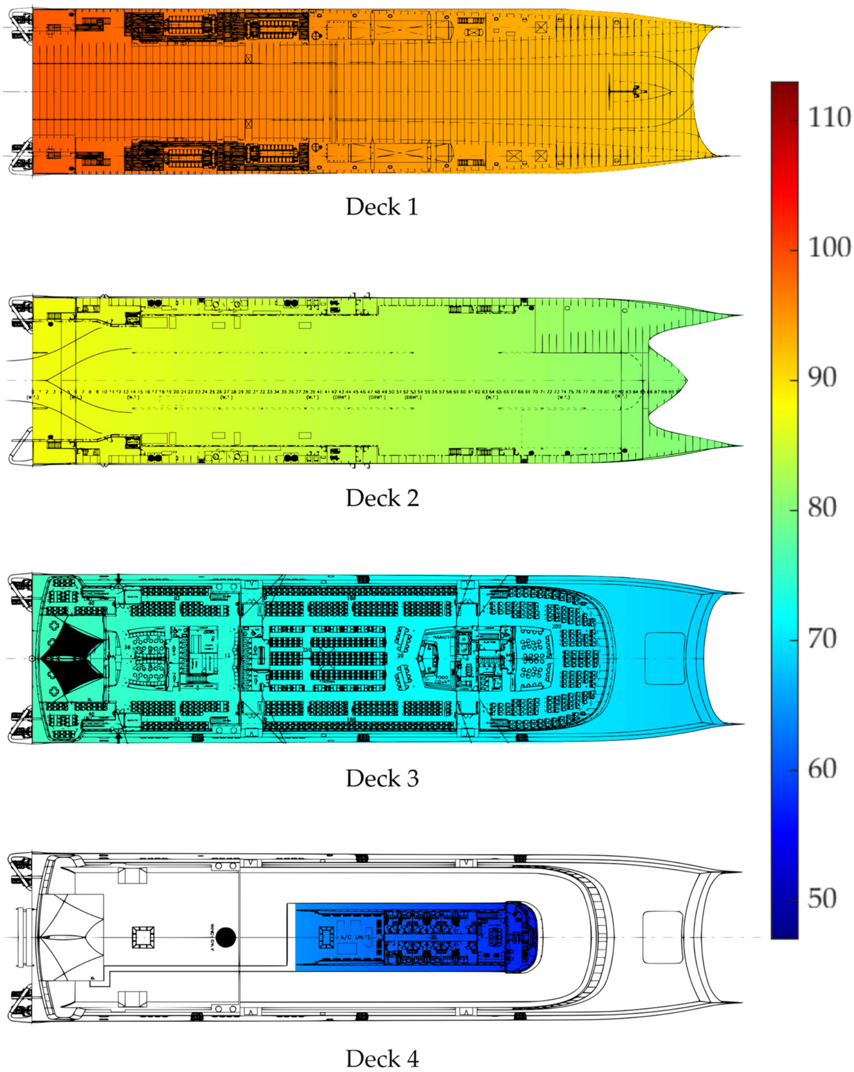

Figure 11. Noise map of HSC-3.

As in the previous validation Figures 6 and 8, Figure 10 presents the measured and calculated noise levels, in this case derived using Equation (5), in dB(A). The x-axis represents the different measurement points listed in Table 11.

In the third HSC, it can be observed that noise levels on deck 1 are comparatively much lower than in the other two vessels, with levels ranging from 90 to 100 dB(A). The propagation of noise to the upper decks is also mitigated, as noise levels on deck 2, the garage, do not exceed 87 dB(A). This significantly reduces the crew's exposure. On deck 3, noise levels are below 75 dB(A), which, while not appropriate for rest, are lower than those on HSC-1. As with the other two studied ships, the bridge deck has a noise level of 50 to 70 dB(A), which is moderately loud but acceptable.

By understanding the current noise exposure levels of on-board workers based on their routines, these maps can assist in designing new routes or recommending behavioral adjustments to reduce noise exposure. This behavioral adaptation, combined with traditional attenuation methods such as encouraging the use of hearing protection, can effectively reduce seafarers' noise exposure, even when noise levels in certain compartments exceed expectations.

4. Conclusions

This study highlights the significant noise challenges aboard high-speed crafts, with particular focus on three vessels operating under different noise regulations.

While the noise measurement effort of this study is substantial, the methodology reflects an innovative approach by integrating systematic noise mapping with the targeted analysis of propulsion systems and crew exposure patterns. This study employs advanced co-occurrence network analysis, a novel tool in maritime noise research, to contextualize findings within broader industry trends. This approach provides a framework not only for identifying noise sources but also for assessing their operational and health-related impacts in a comprehensive manner.

The findings show that engine rooms and jet propulsion systems are the primary sources of excessive noise, contributing to elevated levels in nearby passenger areas, particularly in the stern sections. The noise transmission to upper decks, as observed in HSC-1 and HSC-2, further illustrates the impact of propulsion systems on on-board acoustic comfort. Comparatively, HSC-3 exhibited lower noise levels in critical areas, a result likely attributable to advances in design and insulation technologies. These comparative results highlight the potential for innovative design modifications to reduce noise and provide actionable recommendations for future ship construction and retrofitting.

This study acknowledges the limitations of its sample size, which is limited to three ships. This limitation may affect the generalizability of the findings to the wider HSC industry. However, the innovative methods and frameworks developed in this study provide a robust basis for future research. Expanding the dataset to include a larger and more diverse sample will enhance the understanding of industry-wide noise challenges and solutions.

This research integrates regulatory analysis with practical noise management strategies. The measured noise levels, which often exceed IMO and European Directive 2003/10/EC limits, underscore the urgency of implementing effective mitigation measures.

To rectify these excessive noise levels, modifications at the construction level of the vessel must be undertaken, which pose significant operational and financial challenges, primarily due to downtime and potential loss of revenue.

For existing vessels, a strategic noise management plan tailored to crew exposure is essential. Exposure can be mitigated by adopting behavioral approaches, modifying routines, and minimizing the time each crewmember spends in the loudest areas of the vessel. This plan should include clear guidelines on permissible exposure times, protective equipment requirements, and real-time monitoring to ensure both safety and comfort. To this end, the noise mapping developed in this study serves as a practical tool for occupational health professionals to design better work routes and reduce noise exposure.

In conclusion, voluntary notation classes are an effective tool for reducing noise exposure for crew and passengers on HSC vessels. However, these frameworks remain incomplete. To make the voluntary notation classes more effective, efforts should focus on aligning cabin noise regulations with the World Health Organization (WHO) recommendations for adequate rest (40 dB(A)). In addition, more stringent workplace noise limits should be set to improve health outcomes and ensure compliance with evolving safety standards. These recommendations not only address current gaps but also provide a pathway for future regulatory improvements in the high-speed craft sector.

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Abbreviations

ACV	Air Cushion Vehicles
ALH	Air Lubricated Hulls
dB	Decibels
DNV	Det Norske Veritas
EU	European Union
GT	Gross Tonnage
HSC	High Speed Craft
IACS	International Association of Classification Societies
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
LCD	Liquid Crystal Display
MSC	Maritime Safety Committee
NRR	Noise Reduction Rating
OSHAS	Occupational Health and Safety Assessment Series
SES	Surface Effect Ships
SOLAS	Safety of Life at Sea Convention
SWATH	Small Waterplane Area Twin Hulls
TSS	Traffic Separation Schemes
TWA	Time-Weighted Average
WHO	World Health Organization
WPV	Wave-Piercing Vessels

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