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Evaluation of Acoustic Comfort and Sound Energy Transmission in a Yacht

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Abstract: After being neglected for a long time, in the last years, ships have been recognized and studied as sound emitters. The sound energy they generate impacts the outside, but it can also affect the indoor quality of life if the environments are not properly designed. In fact, acoustic comfort plays a pivotal role, particularly in recreational crafts. In the present work, room acoustics and acoustic camera measurements were performed, inside a 50 m length overall yacht, chosen as a case study in order to evaluate the acoustic comfort. The Italian classification procedure UNI 11367:2010 for buildings was applied, and results have been compared to other international comfort classes. However, all of these are based on prescription for standard buildings, and the present work highlights that they do not account for the effective ship's acoustic issues: sound energy transfer from impacts over ceilings and sound energy leakage. While attention of shipbuilders in acoustic comfort is shown in the measured good reverberation times, the acoustic camera revealed sound energy leakages corresponding to hidden escape ways that have been poorly insulated. This compromises the standardized sound difference between contiguous compartments and also the thermal insulation, as leakage involves air passages. The present work attempts to evolve the classification procedure by also including, for the first time, the reverberation time, but future studies focused on finding correct standardized impact level noise for ship cases are needed. In fact, their values were very high and not comparable with those measured in actual buildings and for which reference values have been designed.

Keywords: sound energy; acoustic comfort; sound energy transmission; room acoustics; acoustic camera; noise; ships; sound energy leakage; reverberation time; acoustic performance indicator

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1. Introduction

Recently, acoustic research on sound energy emissions produced by maritime transportation, both on the inside and on the outside of ships, has growth. In most of the articles, the ships are described as an energy-intense building or, in particular cases as a separate neighborhood. Ships' airborne sound energy emissions have been studied in recent projects of the INTERREG MARITTIMO Italy-France 2014–2020 program, focused on noise mitigation for people exposed to port noise. Different sound emission mechanisms have been studied in [1–6]. It has been shown that environmental issues arise when ships irradiate sound energy outside during their sailing, mooring, and loading/unloading operations in ports.

Comfort and quality of life are issues related to the interior of merchant ships and fishing vessels, or recreational vessels. These issues are mostly generated by the sound energy generated during engines and ventilations operations, which then propagate through both air and structure ways. While the highest levels are produced by the propulsion systems, other sound emitters like the hydraulic system and electric system can be significant contributors to the internal acoustic levels inside the ships. The majority of studies dedicated to internal acoustic in ships have been dedicated to crew's health and long-time exposition to high noise levels hazards [7–12]. However, the last years saw passenger ship acoustics receiving a larger consideration [13–17] and Goujard et al. [18] showed how acoustic comfort is the most critical factor perceived by passengers. As a result, ship-owners and their guests have demanded more attention not only to the functionality of the internal spaces but also to a better quality of life on the ships both in the private and recreational sector.

Given their size and different sectors usage, large ships are usually compared to buildings [19,20]. Room acoustics has been largely studied in the past [21] if compared to ship noise and, therefore, it can be considered as the reference for evaluating acoustic comfort on ships. As the acoustic comfort can be mainly affected by structure-borne noise and by airborne noise [22], different performance indicators are needed. These indicators belong to two main categories: insulation from noise coming from the outside or from the adjacent rooms, and the acoustic field inside the room itself. The inside comfort environment investigated is considered sufficient if specific indicators are higher or lower thresholds. Different ship classification organizations or societies started providing different class notations to vessels to label different ships in terms of the quality of life. However, in a recent study, Rocca et al. [23] showed the difference between the various acoustic classification schemes and the importance of different acoustic indexes. Different classification procedures have different indicators' thresholds or are applicable only to specific kinds of ships and their lifetime. The common reference elements for these classification procedures are specific acoustic indexes of a standard reference wall and floor (ISO 717-1:2020 [24] and ISO 717-2:2020 [25]). Unfortunately, these elements belong to solid buildings, and not ships.

Therefore, a proper universal approach to classify acoustic comfort inside ships is needed before defining a common methodology to improve the life quality onboard vessels and to localize the principal sound energy emitters. This cannot avoid following classification approaches for the acoustic comfort on ships based on buildings procedure methods. The overall issue does not only affect the ships' acoustic comfort but also their thermal energy consumption and insulation. In fact, a recent preliminary study reported on how safe passages inside recreational boat areas are affected by sound energy leakage phenomena and worsen the room acoustics of living areas [26]. Kang et al. [27] quantified this leakage in almost 5 dB(A) of reduction in insulation performances of walls. As this leakage involves air passages, it is expected that these do not only compromise the optimal cabin's acoustic quality but would also deteriorate the overall energy class sustainability by increasing thermal energy dissipation.

The present paper reports an overall determination of ships' comfort acoustic classification on the bases of the existing Italian's prescription of building classification. As a case study, the methodology is applied to measurements performed inside a 50 m length overall (LOA) yacht. The results are then compared with some of the most important comfort classes procedures. Acoustic camera measurements are also shown as support in highlighting the presence of sound energy leakage between partitions.

The analysis investigates all possible difficulties of a ship's acoustic classification, as well as the criticalities arising in room acoustic indicators in the different environments.

2. Background

2.1. Acoustic Classification of Buildings

Each country has its proper regulation for the acoustic classification of buildings, but they are generally based on the same performance indicators [28]. However, no uniformity in the threshold values among different countries can be found [23]. In Italy, UNI 11367:2010 [29] defines the acoustic classification of buildings referring to single rooms and, whenever possible, to the whole housing unit. The standard can be applied to all kind of buildings, both new and refurbished, except to industrial ones. The indicators considered in the present work are: reverberation time, standardized level difference, and impact sound pressure level, as described in the following chapter.

The prescription followed in the present work is the UNI 11367:2010 [29] one, which produces classification values for internal spaces. These are more restricted and, therefore, more in line with the idea that comfort has stricter requests than only health safety.

The classification can be applied to singular rooms and then extended to the entire study object (e.g., apartment, ship). For each room, the overall weighted apparent sound reduction index (R'_w) and the weighted normalized impact sound pressure level ($L'_{n,w}$) are computed with respect to different partition elements. The overall values are obtained with Equations (1) and (2), in which the index i represents the measured partition's acoustic performance indicator and n is the total number of partitions measured. The number of elements studied must be sufficient to describe the overall acoustic properties.

$$\overline{R'_w} = -10log\left(\sum_{i=1}^{n} 10^{-\frac{R'_{w,i}}{10}}\right) \tag{1}$$

$$\overline{L'_n} = 10log\left(\sum_{i=1}^{n} 10^{\frac{L'_{n,i}}{10}}\right) \tag{2}$$

The acoustic classification of the studied single room is derived with Equation (3), in which Z_i is the class weight and p is the number of acoustic characteristics considered. Then, the overall classification of the studied element can be taken as an arithmetic mean of the singular acoustic classification of the rooms. The acoustic classification classes acceptable for the results go from I to IV (from best to worst), plus another class named Non-Classifiable (NC). In the present work, the NC class is considered and taken as the worst case possible.

$$Z_{UI} = \frac{\sum_i^p z_i}{p} \tag{3}$$

2.2. Acoustic Comfort Classes

Naval agencies of different countries have given an acoustic comfort that does take into account the different life purposes of the ship's compartments. In this paper, the American Bureau of Shipping (ABS) [30], Germanischer Lloyd [31], and the Italian Naval Register (Rina) [32] classes are considered and compared with the results obtained with the Italian buildings classification. Each of the aforementioned classes differ on their ship type application, e.g., recreational boats or cargo vessel, and the different acoustic performance indicator used [24].

2.2.1. ABS Classification

The classification is intended for vessels falling under oil or chemical tankers, bulk or combination carriers, container carriers, multi-purpose cargo vessels, or crew areas on passenger's vessels. Vessels such as offshore support vessels, tugboats, towboats, dredgers, research vessels, drill ships, anchor handling vessels, or any other vessel providing service to offshore oil and gas exploration and production are not included in the scope of the ABS Crew habitability guide. Additionally, ABS considers the overall equivalent level on board moving vessels. In this Guide, comfort means the ability of the crew to use the space with minimal interference or annoyance from noise. The classes presented are three: Habitability (HAB), Habitability plus (HAB+), and Habitability plus plus (HAB++). The HAB class measurement method is based on the International Maritime Organization (IMO) and the measurement is considered close to non-compliance with the HAB notation if its value is in a range of 3 dB within the criteria. Acoustic measurements need to follow ISO 10140-1:2021 [33] and ISO 717-1:2020 [24] for passive acoustic indicators. The airborne sound insulation properties for bulkheads and decks need to satisfy the minimal criteria for $R\prime_W$. No more information about the classification procedure via acoustic performance indicators is reported.

In the present work, the HAB class is equivalent to the IV class in the UNI 11367.

2.2.2. Germanischer Lloyd Classification

This classification, which in 2013 joined the Derk Norske Veritas, has five comfort classes that goes from acceptable to excellent. The values are distinguished between passenger's and crew's spaces. Like in the procedure used in the present paper, the Germanischer Lloyd company follows the ISO 717-1:2020 [24] and ISO 717-2:2020 [25] procedure for the evaluation of the weighted acoustic indexes. The final class name obtained with the weighted sound reduction index is called acoustic privacy and depends on the cabin's scope. The overall quality class is the arithmetic sum of all the "Harmony Classes" (hc).

2.2.3. RINA

RINA formulated two different kinds of acoustic requirements for passenger and crew comfort on yachts, depending on the length between perpendicular (Lpp) of the vessel, namely, if it is greater or lower than 40 m. Airborne noise and structural vibrations levels are evaluated for yacht at berth and in navigation. For a yacht whose Lpp is greater than 40 m, which is interesting for the case study of the present work, the sound indicators considered are:

- the sound reduction index R_w evaluated according to EN ISO 717-1:2020 [24] and EN ISO 10140-2:2021 [33];
- the apparent sound reduction index R'_w evaluated according to ISO 717-1:2020 [24] and ISO 16283-1:2014 [34];
- the normalized impact sound pressure level $L'_{n,w}$ evaluated according to ISO 717-2:2020 [25] and ISO 16283-2:2020 [35].

The results of the measurements are divided into two class, A and B. The assigned comfort class is A if the measured R'_w is equal or greater than the reference values at the A score, and if the measured $L'_{n,w}$ is lower than or equal to the reference value at the A score. The same occurs for B score. Depending on the assignments of these labels to the different environments in the vessel, the yacht under analysis can be labeled with different notations, namely:

- Comfort Large Yachts Passengers (COMF LY PAX) A or B, if, for the guest accommodation, the acoustic indexes belong to the class A or to the class B;
- Comfort Large Yachts Crew (COMF LY CREW) A or B, if, for the crew accommodation, the acoustic indexes belong to the class A or to the class B;
- Comfort Large Yachts Passenger and Crew (COMF LY PACR) AA, AB, BA, or BB. AA, if both passengers and crew accommodations belong to class A; AB, if passengers' spaces belong to class A while crew spaces belong to class B; BA vice versa; while the label BB is used if both passengers and crew accommodation belong to the class B.

3. Materials and Methods

In order to give an acoustic classification of the ship with the proposed procedures, the ship's acoustic performance indicators should be measured. The present chapter describes the experimental setup and measurement procedure performed by following the most recent prescriptions for building's acoustic indexes and using class I instruments. Before describing in Section 3.3 the measurement procedure and the number of measurements per room, the ship's layout and the measurement conditions of the rooms are described in Section 3.1, while the rooms condition during the measurement are Section 3.2.

All measurements have been performed with a class I sound level meter, calibrated with a class I calibrator, a tapping machine, and an omnidirectional noise source.

3.1. Layout of the Yacht

The yacht structure develops vertically in four levels: the Lower Deck (LD), the Main Deck (MD), the Upper Deck (UD), and the Sun Deck (SD). The LD and the MD are the most concerning compartments of the ship for acoustic comfort issues, as they are those where owner, guests, and crew sleep or mostly spend their indoor time. The Vip and Guest Cabins are all in the LD and have partitions in common; Vip Cabins have a bulkhead with the Engine Room, the other Vip Cabin, and the Guest Cabin on the same side of the ship, port, or starboard (Stbd). Some of these partitions have "escape routes", which will be called "sound energy leakage" routes in this paper due to their properties. Figure 1 shows part of the LD; Figure 2 visualizes a piece of the layout of the MD.

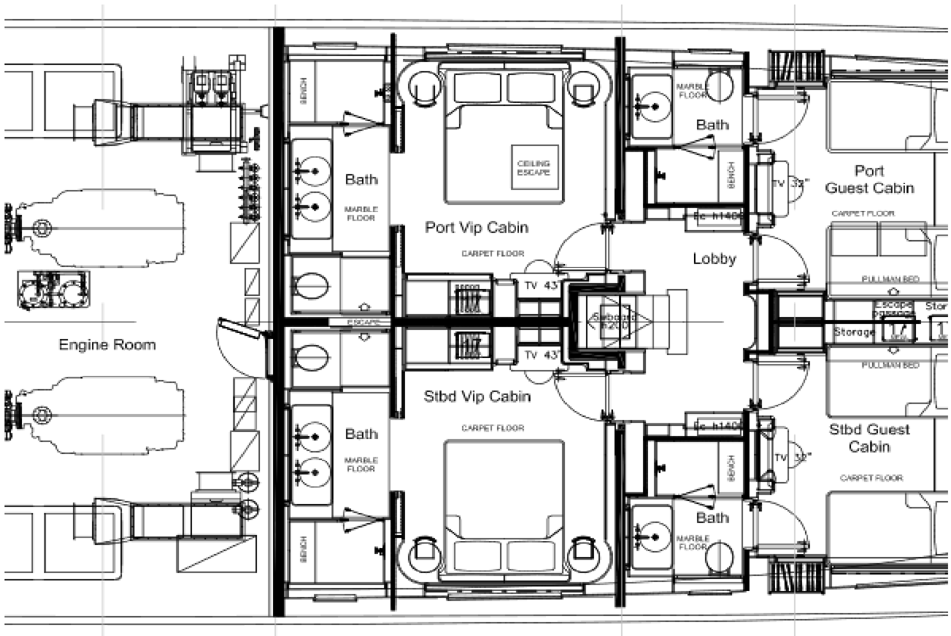

Figure 1. LD layout under analysis.

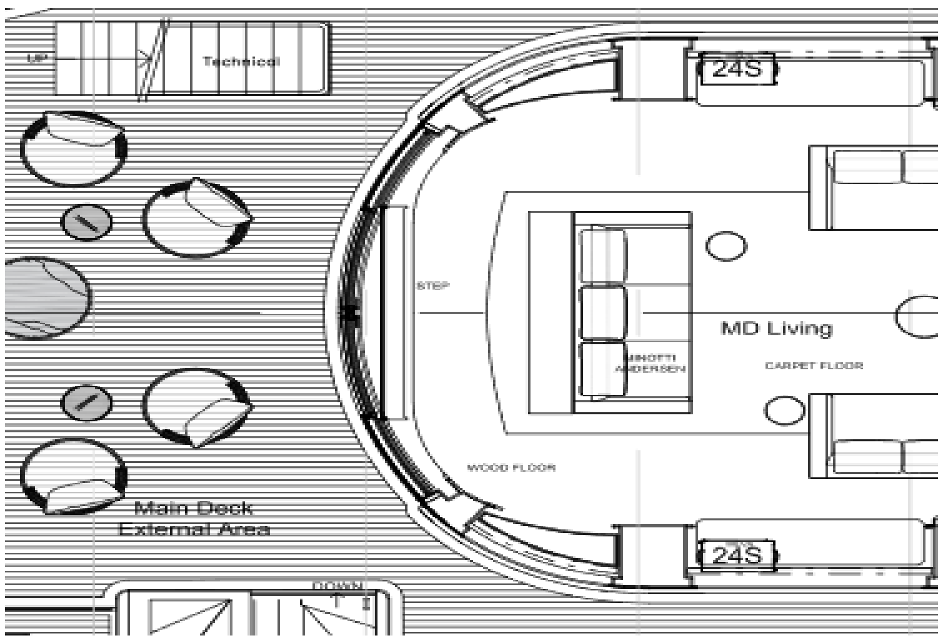

Figure 2. MD Living sliding glass door.

Table 1 reports the partition under analysis and the geometrical properties needed to evaluate the acoustic labels of the room. The spatial length accuracy is of the order of mm and therefore plays no role in the total measurement uncertainty.

Table 1. Values of the volume and area of the separating elements under analysis.

Room	$V\ (m^3)$	First near Room	Surface (m^2)
Master Cabin + Dressing Room	79.41	Galley	8.69
Vip Cabin + Bath	30.68	Vip Cabin	9.47
		Guest Cabin	6.78
		Engine Room	9.44
Guest Cabin + Bath	27.01	Guest Cabin	7.00
		Crew Mess	7.05
MD Living	127.44	Engine Room	26.35
MD Living	127.44	MD external area	16.24

3.2. Measurement Condition of the Rooms

In this subsection, the different measurement conditions of the rooms are described. During the measurements, the rooms were partially furnished, and a plastic layer covered the floors.

3.2.1. Master Cabin

The Master Cabin and the Dressing Room located near the Galley are considered as a whole. This arises from considering the Galley as a relevant sound energy emitter for the acoustic comfort of the Master Cabin. Therefore, the only door left open in the measurements was the one connecting the Dressing Room with the Master Cabin. Both doors connecting the Bath and the rest of the ship were closed.

3.2.2. Main Deck Living room

The Middle Deck Living room has the biggest problem arising from the presence of the upper deck rooms: the UD external zone and the Skylounge. The preferential noise transmissions are structural and therefore the impact is characterized by the impact level noise. These measurements are of most interest given the different floors that are present in both the source zones. The UD external zone has a wood floor, while the Skylounge has a wood floor with a carpet. The other two measured indexes in this paper are the standardized level difference measured for the vertical transmission, source positioned in the engine room, which is directly under the room, and the glass door, which divides the MD external zone from the MD Living.

3.2.3. Port Vip Cabin

The entire room taken for the evaluation of the acoustic performance indicators are the Port Vip Cabin with its bath. The shower is not considered in the entire room and the door is closed. In fact, the shower does not have common partition with the other compartments of the ship outside the engine room and the more realistic case is with the closed door. In this case, the airborne noise mitigation plays a bigger role in the overall acoustic comfort level. Nevertheless, impact level noise is measured with the tapping machine placed on the pavement of the MD Living and the Main Pantry.

3.2.4. Stbd Vip Cabin

The compartment considered as one in the analysis is the union of the Stbd Vip cabin and the bath with the shower door closed. The position of the cabin in the layout of the ship is the same as the Port Vip Cabins' and therefore the only acoustic index measured is the $D_{nT,w}$ with the Engine Room. In fact, the fundamental difference between the Vip cabins is the bulkhead between the Engine room and the Port Vip Cabin, which has an escape route that can be opened and, therefore, could worsen the overall sound mitigation.

3.2.5. Port Guest Cabin

No preferential sound energy transmission way is found in this room. Probably, the Crew Mess zone is the one that will have a larger sound emission and, therefore, the Bulkhead needs a bigger sound mitigation.

3.3. Acoustic Performance Indicators

According to what is described in Section 2, the acoustic performance indicators measured in this work are the reverberation time, the standardized sound reduction index, and the impact sound pressure level.

3.3.1. Reverberation Time

The reverberation time (T) of a compartment is the time needed for a sound pressure level to decay 60 dB after the source is stopped. An optimal room's reverberation time needs to consider the room's dimensions and its final use. As an example, the optimal T's limit (T_{ott}) Equation for speech comprehension is given in Equation (4), in which the only structural variable is the volume (V).

$$T_{ott} = 0.32 log(V) + 0.03 \quad (4)$$

The reverberation time measurements of compartments follow the ISO 3382-2:2008 [36] prescriptions. If two compartments have the same configuration and furniture, then the operator can choose one reverberation time measurement as representative of both rooms. Given the small room dimension and the fast decay of the noise saturation level, measurements of the T_{20} have been carried in all cases. This has been done by positioning the omnidirectional noise source generator in one or more places of the room and measuring the sound level pressure in different places. Importance has been given to not following a regular scheme of the sound level meter disposition. Account of the measurement's uncertainty generated by the influence of the operator holding the sound level meter has been considered in the estimation of the uncertainty. The uncertainty is given by Equation (5), in which B is the bandwidth, N is the total number of measurements, and n is the number of noise measurements for noise source location. All measurements have been taken in third-octave band frequencies. Table 2 shows the number of the source position and the respective number of sound level meter positions.

$$\sigma_{T_{20}} = 0.88 \cdot T_{20} \sqrt{\left(1 + \frac{1.9}{n}\right) / (NBT_{20})} \quad (5)$$

Table 2. Number of measurements of the reverberation time.

Cabin	#Pos. Noise Source	#Pos. Sound Level Meter
Master Cabin and Dressing	2	5
MD Living	3	5
Port/Stbd Vip Cabin	1	9
Port/Stbd Guest Cabin	1	6

3.3.2. Standardized Level Difference

The standardized level difference (D_{nT}) is equal to the reduction of sound level pressure characteristic of a separating element. This does account for the airborne sound transmission and does consider the structure-borne noise emission from the interaction with the sound wave. When measuring the characteristics of a bulkhead that cannot be isolated, the different sound transmission ways need to be considered. The overall effect is represented by the apparent sound reduction index (R'), which is used to give a standard value to the partitioning element characteristics. D_{nT} values are computed from R' and corrected considering the reverberation time T_0. As reported in Equation (6) room's receiving volume (V), the common surface dimension of the element between the emitting and receiving room are also considered in the calculation.

$$D_{nT} = R' + 10log\left(\frac{ST_0}{0.16V}\right) \quad (6)$$

The acoustic standardized sound difference best represents the passenger's annoyance. According to the measurement procedure described by ISO 16283-1:2014 [34], the measured value is standardized by the receiving room's reverberation time. Airborne horizontal and vertical propagation ways have been measured. Table 3 reports the number of measurements taken of the source, the receiving, and the background sound pressure level (SPL) measuring positions for different rooms combinations.

Table 3. Number of SPL measurements for D_{nT}.

Emission Room	Receiving Room	#Pos. Emission	#Pos. Receiving	#Pos. Background
Galley	Master Cabin and Dressing	5	5	5
Engine Room	Port Vip Cabin	6	5	5
	Stbd Vip Cabin	-	5	5
	MD Living	-	10	5
Stbd Vip Cabin	Port Vip Cabin	5	5	5
Port Guest Cabin	Port Vip Cabin	4	5	5
	Stbd Guest Cabin	-	5	5
Crew Mess	Stbd Guest Cabin	5	5	5
MD external area	MD Living	5	5	5

The final value assigned to the separation element is the weighted value obtained with the ISO 717-1:2020 [24] prescription and reference wall values.

3.3.3. Impact Sound Pressure Level

The impact sound pressure level is representative for the structure-borne sound pressure and considers all the transmission ways. It can be measured for a principal vertical transmission way, two rooms on different levels, or horizontal way, two rooms on the same level. The equivalent normalized impact sound pressure level (L'_n) does give a general characterization of the structure under analysis. Equation (7) gives its value as a function of the room's receiving volume V, the reference T_0, the reference equivalent absorption surface A_0, and the standardized impact sound pressure level L_{nT}.

$$L'_n = L_{nT} + 10log\left(0.16\frac{V}{T_0 A_0}\right) \quad (7)$$

Only the vertical transmissions have been measured in the present work. All measurements have been made by following the prescriptions given by ISO 16283-2:2020 [35]. As the tapping machine has a white noise spectrum, the resulting impact sound pressure level needs to be corrected with the coefficient C_I. For this reason, in the following, the paper for L'_n is meant the sum of $L'_n + C_I$. Table 4 shows the number of SPL for each noise source position for the different zones' combinations.

The representing standardized impact level is obtained by a weighting procedure described in the ISO 717-2:2020 [25].

Table 4. Number of source positions and SPL measurements for each source position.

Impact Floor	Receiving Room	Source Positions	SPL
UD Fwd external area (wood)	Master Cabin and Dressing	2	4
UD external area (wood)	MD Living	1	3
Skylounge (carpet)	MD Living	1	2
MD Living (wood floor)	Port Vip Cabin	1	5
Main Pantry (vynil floor)	Port Vip Cabin	1	5
Main Foyer (wood floor)	Stbd Guest Cabin	1	5

4. Results

In this section, the acoustic performance indicators measured and the classification procedure results are reported. Their values act as bases for an overall characterization of the rooms.

4.1. Acoustic Performance Indicators

The results are reported in the following Table 5 and Figure 3, ordered according to the room. All acoustic performance indicators are reported with the unilateral uncertainty, with $k = 1.95$ corresponding to a confidence level (CL) equal to 95%.

Table 5. Acoustic performance indicators for the different rooms.

Receiving Room	Source Position	$D_{nT,w}$(dB)	R'_w(dB)	$L'_{n,w}$(dB)
Master cabin	Galley	55.0 ± 0.7	50.3 ± 0.7	\
	UD external area	\	\	72.0 ± 1.0
MD living room	Skyloung	\	\	60 ± 1.2
	UD external area	\	\	71.0 ± 1.2
	Engine Room	56.2 ± 0.7	54.03 ± 0.7	\
Port Vip cabin	Engine Room	61.5 ± 0.7	61.3 ± 0.7	\
	Stbd Vip Cabin	43.7 ± 0.7	43.5 ± 0.7	\
	Port Guest Cabin	49.7 ± 0.7	48.1 ± 0.7	\
	MD Living (wood floor)	\	\	67.9 ± 1.0
	MD Living (vinyl floor)	\	\	70.5 ± 1.0
Stbd Guest cabin	Port Guest Cabin	38.9 ± 0.7	38.0 ± 0.7	\
	Crew Mess	53.8 ± 0.7	52.9 ± 0.7	\
	Main Foyer (covered marble floor)	\	\	70.1 ± 1.0

The Stbd Vip cabin's acoustic performance indicator $D_{nT,w}$ for the partition with the Engine Room is equal to 56.7 ± 0.7 dB. All the other acoustic performance indicators are taken as equal to the Stbd Vip cabin, given the same disposition of the cabin in the ship.

4.2. Comfort Acoustic Classification

In this section, the yacht's cabin acoustic classifications are computed with respect to the different classification threshold values. The ship's acoustic classification arises from an arithmetic mean of the different classification results obtained.

Tables 6 and 7 report the different classification values obtained by following UNI 11367:2010 [29]. The values $D_{nT,v}$ and $L'_{n,v}$ are the validation values and are equal to the rounded weighted value with the unilateral uncertainty up to the nearest integer number to the worst case. This means that $D_{nT,v\cdot}$ are rounded up to the lowest value in the 95% CL and $L'_{n,v}$ to the highest value. The MD living standardized difference level ($D_{ls,2m,nT,v}$) of the glass door in common with the MD external area is also reported and does not account to the mean standardized level difference of the room.

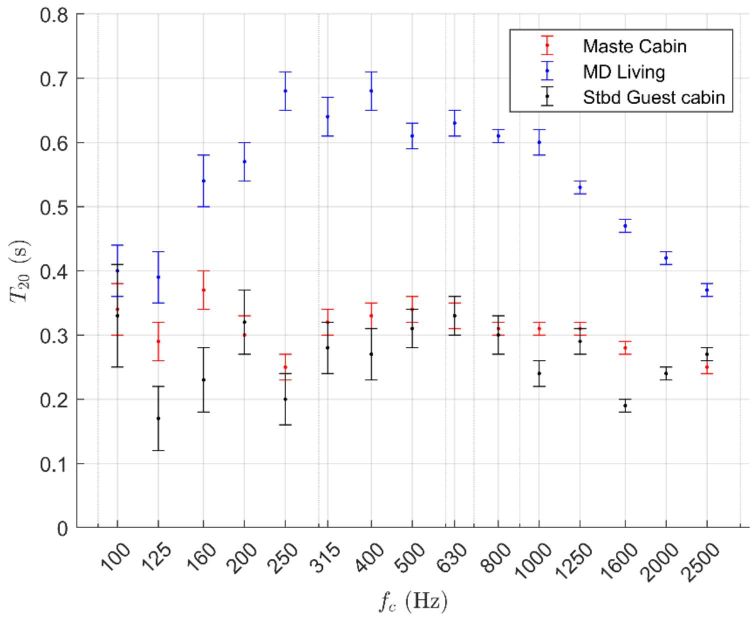

Figure 3. Reverberation time of the different rooms.

Table 6. Ship's compartment acoustic evaluation indicators.

Receiving Room	Source Room	Indicator (dB)	Acoustic Class
Port Vip Cabin	Engine Room Stbd Vip Cabin Port Guest Cabin MD Living Main Pantry	$D_{nT,v} = 61$ $D_{nT,v} = 43$ $D_{nT,v} = 49$ $L'_{n,v} = 70$ $L'_{n,v} = 72$	I ($\geq$ 56 (dB)) NC ($<$ 45 (dB)) IV ($\geq$ 45 (dB)) NC ($>$ 68 (dB)) NC ($>$ 68 (dB))
Stbd Vip Cabin	Engine Room	$D_{nT,v} = 56$	I ($\geq$ 56 (dB))
Stbd Guest Cabin	Port Guest Cabin Crew Mess Main Foyer	$D_{nT,v} = 38$ $D_{nT,v} = 53$ $L'_{nT,v} = 71$	NC ($<$ 45 (dB)) III ($\geq$ 50 (dB)) NC ($>$ 68 (dB))
MD Living	Engine Room MD external Area UD external area Skylounge	$D_{nT,v} = 56$ $D_{Is,2m,nT,v} = 26$ $L'_{n,v} = 72$ $L'_{n,v} = 61$	I ($\geq$ 56 (dB)) NC ($<$ 32 (dB)) NC ($>$ 68 (dB)) II ($\leq$ 58 (dB))
Master Cabin	Galley UD external area	$D_{nT,v} = 54$ $L'_{n,v} = 73$	II ($\geq$ 53 (dB)) NC ($>$ 68 (dB))

Table 7. Acoustic classification of the ship's compartments.

Compartment	Mean Evaluation Index and Classification (dB)	
Master Cabin	L'_n D_{nT}	73 NC 54 II
MD Living	L'_n D_{nT} $D_{IS,2m,nT}$	70 NC 56 I 26 NC
Port Vip Cabin/Stbd Vip Cabin	L'_n D_{nT}	71 NC 48 IV
Stbd Vip Cabin	L'_n D_{nT}	71 NC 47 IV
Stbd Guest Cabin	L'_n D_{nT}	71 NC 42 NC
Port Guest Cabin	L'_n D_{nT}	72 NC 41 NC

5. Discussions

In a usual classification procedure, the final acoustic performance indicator is taken as a weighted value in function of a reference curve. UNI 11367:2010 [29] takes the ISO 717-2:2020 [25] heavyweight floors reference curve for the normalized impact sound pressure level and the unique ISO 717-1:2020 [24] curve of reference values for airborne sound. As an example, Figure 4 reports the one-third octave spectrum of the measured D_{nT} between the Port Vip Cabin and the Engine Room, with the reference curve reported in order to mark the difference with it in terms of spectral components.

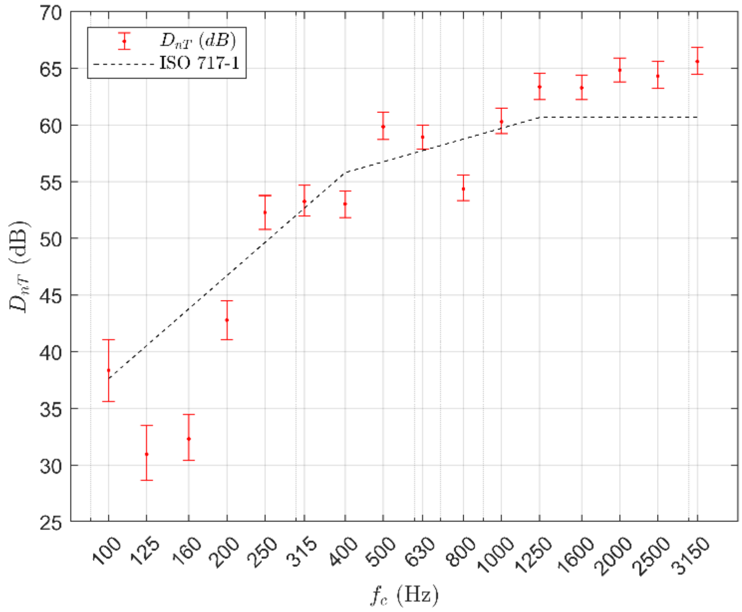

Figure 4. Standardized level difference of the Stbd Vip Cabin—Engine Room partition and reference values according to ISO 717-1:2020 [24].

All the different spectral components of the measured D_{nT} for all the partitions and the ISO 717-1:2020 [24] reference curve are reported in Figure 5.

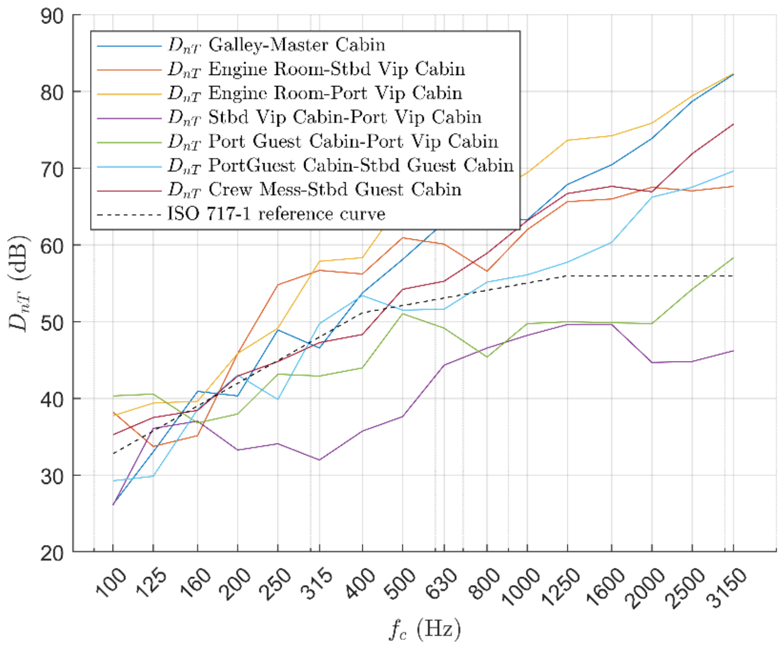

Figure 5. Spectrum behavior of the different D_{nT} of the analyzed partitions and reference values according to ISO 717-1:2020 [24].

Although most of the measured acoustic performance indicators exceed the UNI 11367:2010 [29] threshold values, they effectively represent the specific and overall acoustic performance of the different rooms under analysis. In fact, an overall ship's classification class NC is probably a non-realistic final class notation if considering that the classification is set for buildings and not for ships.

The reported result highlights that the standardized impact level noise results are the main cause of noise inside the investigated rooms, and they will worsen the overall acoustic comfort inside the vessel. However, while the present study has been only conducted on a singular vessel, it is expected that all others would show similar behavior. Thus, the results should warn ships' shipbuilders to seriously take this indicator into consideration for future designs. A correct acoustic classification procedure would help pinpoint the ship's zones needing more care, but the reference standardized impact level noise values used for buildings are actually too different with respect to what is needed for ships' comfort acoustic classification. For this reason, the authors encourage future studies aimed at defining proper threshold levels. In order to support this thesis, Tables 8 and 9 report the class assigned to the different rooms according to the Germanischer Lloyd classification procedure, which classifies the acoustic comfort in five different classes as in the Italian one. As the Germanischer Lloyd threshold values are dependent on the room use, Pax cabins to public spaces are the most similar ones to the threshold used in UNI 11367:2010 [29]. Following a one-to-one correspondence between the two regulations, the paper's NC class corresponds to the IV Germanischer Lloyd class, and so on.

Table 8. Standardized level difference with the Germanischer Lloyd classification.

	Passenger's Space	
Receiving Space	**Emission Space**	**hc**
Port Vip Cabin	Engine Room Stbd Vip Cabin Port Guest Cabin	II E E
Stbd Vip Cabin	Engine Room	IV
Stbd Guest Cabin	Port Guest Cabin	I
	Crew's Space	
MD Living	Engine Room MD External Area	III /
Master Cabin	Galley	II
Stbd Guest Cabin	Crew Mess	III

Table 9. Impact level classification with the Germanischer Lloyd classification.

	Crew's Space	
Receiving Space	Emission Space	hc
Port Vip Cabin	MD Living Main Pantry	IV IV
	Passenger's Space	
UD external area	Master Cabin	/
Main Foyer	Stbd Guest Cabin	IV

The results show that in most cases, both classification procedures do assign the worse class to the different rooms, although they have different values for compartments utilization.

Only the Geramnischer Lloyd classification is used to confront the different results because of the similarity of the classification procedure between the UNI 11367:2010 and Germanischer Lloyd classification, while the other two classification procedures are different.

In fact, the ABS classification and the RINA classification do not classify single partitions in different classes or consider different vessels and operations. Figure 6 highlights the different occurrences by class for the standardized level difference for the Germanishcer and UNI 11367:2010 classification procedure.

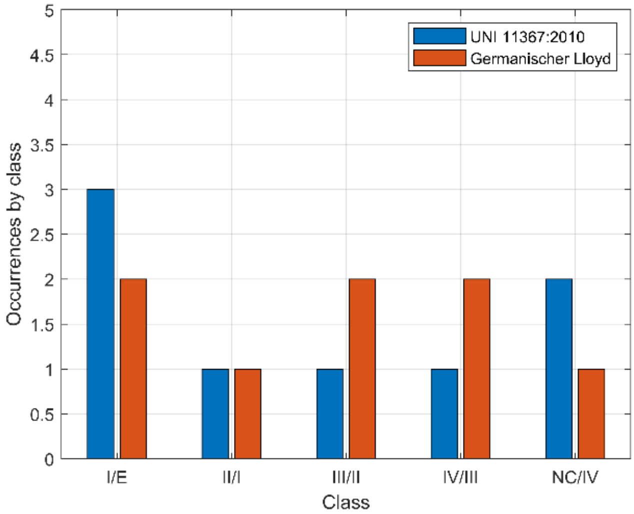

Figure 6. Occurrences by class for the standardized level difference.

The difference between the translated reference curve and the measure third-octave band spectrum of D_{nT}, reported in Figure 5, is a possible sentinel of the presence of sound energy leakage, responsible for the worsening of the overall standardized sound difference index of up to almost 5 dB according to Kang et al. [27]. However, in [27], the measurements performed to verify such behavior were taken under controlled situation, thus only accounting for the direct propagation ways of air-borne noise. According to the previously presented work [26], sound energy leakage of different kinds can be found with the acoustic camera. Figure 7 reports the localized sound energy leakage in the Stbd Vip Cabin—Engine Room partition. This, as well as all the others, correspond to the escape ways and the acoustic camera measurements helped on revealing them, which are voluntarily hidden for recreational reasons. However, the combined acoustic camera and room acoustic analysis shows that their design has not been carried out to take into account the attenuation of the sound energy, and they are responsible for the scarce apparent sound reduction index. Moreover, poor sound energy insulation surely corresponds to poor thermal insulation, thus, also in this case, more attention must be paid by the designers.

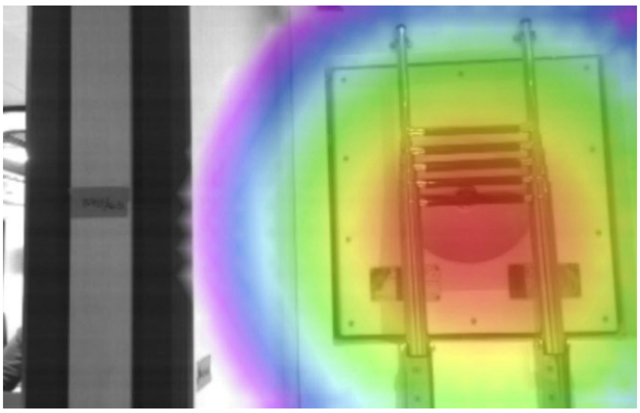

Figure 7. Sound energy leakage of the Stbd Vip Cabin—Engine Room partition. Frequency: 250–500 Hz.

6. Conclusions

An attempt to determine ships' comfort acoustic classification has been done in the present studies on the bases of the existing Italian's legislative framework on building classification. Room acoustics and acoustic camera measurements have been performed, as a case study, inside a 50 m LOA yacht, also in order to evaluate sound energy transmission.

The results of this work have shown that the acoustic classification of ships based on the existing prescription for the normal buildings does not account for the effective ship's acoustic issues: sound energy transfer from impacts over ceilings and sound energy leakage. While the other parameters are well performed, showing attention of shipbuilders to some aspects, all the evaluated standardized impact levels do result as non-classifiable (NC) or equivalent. This confirm that impact sounds are a concrete issue for acoustic comfort inside recreational boats and, at the same time, that the actual classification prescription has been projected to give an acoustic classification to ground buildings, with values that should be considered only as lower boundary values. In fact, they are also not referred to acoustic comfort. The present work proposes also to use the reverberation time as an acoustic performance indicator itself, and not only as a parameter to standardize the different acoustic performance indicators. Until now, it has found a small place in the acoustic classification of rooms that do not require a specific utilization. Nevertheless, it plays a fundamental role in the acoustic comfort of any kind of room. In small rooms, a high reverberation time could generate high sound level pressures that can drastically deteriorate the overall comfort in a room.

The standardized sound difference between contiguous compartments did not show any critical behavior in the classification, with their values ranging from class I to NC. Nevertheless, with the aid of an acoustic camera, sound energy leakages were revealed, coinciding with hidden escape ways that were poorly insulated, from both sounds and thermal ways. A specific localization of sound-leakage routes could not only improve the acoustic properties of the separating elements but with further studies, it could show energy transmission loss ways, which do worsen the energy consumption of a ship. The work is expected to raise awareness in shipbuilders to place attention on the design of all aspects that can influence acoustic comfort of interior spaces. Finally, for proper classification, future studies should focus on finding correct standardized impact level noise for ship cases, whose values are not comparable with those measured in actual buildings and for which reference values have been designed.

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