Research Article Open Access

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Holistic control of ship noise emissions

DOI 10.1515/noise-2016-0008
Received Oct 30, 2015; accepted Mar 21, 2016

Abstract: The sustainability of anthropogenic activities at sea is recently gaining more and more attention. As regards shipping, emissions from ships into the environment of various nature (engine exhaust gases, anti-fouling paints leaching, ballast exchange, releases at sea of oil and other noxious liquid or solid cargoes, of sewage and of garbage) have been recognized as sources of pollution and therefore controlled and limited since a long time. The subject of noise emission has been identified only recently. To study the problem, the EU has funded, among others, the FP7 SILENV (Ship Innovative soLutions to rEduce Noise and Vibrations) project that run from 2010 to 2012. In the present work, the holistic approach followed within the project to characterize and control the ship as a source of noise is presented. Three types of noise emissions (in air, in water and inside the ship) are analyzed highlighting peculiarities and different strategies adopted to characterize the source, the impact on the receiver and the possible solutions to set limits to the ship emissions. The project outcome included a socalled “Green Label”: a set of new prenormative requirements defined for the three main areas mentioned above.

Keywords: ship noise pollution; ship airborne noise; ship underwater noise; SILENV Project; Ship Green Label

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1 Introduction: the acoustic impact of ships

In the last decades, various forms of impact by anthropogenic activities on the environment have been identified, studied and later subjected to control by the deputed regulatory bodies. A major attention has been and is being devoted to the releases of solid, liquid and gaseous substances in the ambient. Other forms of pollution, based on releases of energy, have however captured an increasing attention: noise radiation plays an important role within this category, which includes also thermal and electromagnetic emissions.

In the marine field, the noise transmitted on board ships has been considered since more than thirty years. At first, the focus was on the impact on the working and living conditions of the crew: the reference regulatory document was [1], issued by the International Maritime Organisation (a United Nation agency for shipping) and fixing maximum noise levels in various types of technical/living spaces on board. Later, the attention was extended to the comfort of passengers, with the issue of voluntary class notations (generally referred to as Comfort Classes) by the main Classification Societies. The two mentioned sets of requirements were aimed at protecting (with different aims and in different ways) first and second parties of the marine transportation process. More recently, the effect of noise on third parties has come into the focus, with studies and first regulatory actions dedicated to the impact of noise radiation outside the ship on land and in water. In the former case, the object of investigation is still the impact of airborne noise radiation on human being (people living around ports or on the coast near sea routes with dense traffic). In the latter one, the attention is extended to the marine ecosystem and the focus is on the adverse effects of underwater noise radiation from ships on the marine fauna in general and on mammals in particular.

All above-mentioned effects originate from the same source: the ship in her various operating conditions. Based on this, an integrated and holistic approach to the analysis and control of the acoustic emissions from ships has been followed in the SILENV project (Ship Innovative soLutions to rEduce Noise and Vibrations: www.silenv.eu), recently funded within the 7th Framework Programme of the EU. Following the work there developed, the paper examines the ship as a complex source of noise, with the different techniques available or under development for the characterisation of her emissions, the impact of the different types of noise radiation on the different classes of receivers and the options available to enforce or enhance the control of such impacts.

2 The ship as a source of noise

The ship, for her dimensions and characteristics, represents a very complex noise source [2]. The different plants present on board, devoted to propulsion and to the other operational functions of the ship, are all effective contributors to the noise field inside and outside the vessel. In addition to that, in the specific case of cruise or ferry ships, also the passengers on board and their activities can represent sources of noise and of annoyance for other passengers. In the following, the main sources of excitation on board will be briefly reviewed.

2.1 Sources of excitation on board

Machinery

Machinery on board ships are usually subdivided in two categories: main engines and auxiliaries. The main engines are the primary movers of the ship and for most of the sea going ships the propulsion is guaranteed by two or four stroke diesel engines. Auxiliary engines are in almost all cases four stroke diesel engines and are used for the electric power generation and for the cargo processing. Pumps and boilers are also present on board but are usually located in the engine room where their contribution to the overall noise is negligible if compared to the noise emitted by the engines. The engines generate both noise and vibrations as they are fixed to the ship structure. While in the case of four stroke diesel engines resilient mountings are interposed between the engine and the steel structure of the ship in order to isolate the engine, two stroke diesel engines are rigidly mounted to the structure due to their dimensions and weight. The engines noise emissions are characterized by a broadband component and by a series of tonal components and relative harmonics. Tonal components are clearly detectable in both the noise measurements carried out on board and underwater. The frequencies at which tonal components and harmonics are generated depends on the rotational speed of the engine, on the number of strokes and on the number of cylinders. At normal cruise speed the main engines are the most important noise sources while, at lower speeds, induced vibrations generated by the operating machinery are believed to be the predominant noise sources at frequencies below 100 Hz [3]. Furthermore, when the ship is moored at harbor, the main engines are usually turned off, while the auxiliary engines are running to guarantee the cargo processing, ventilation, air conditioning and electric power. In such a condition, auxiliary engines are the main sources of noise.

Due to the high noise emitted by the main engines, on passengers ships, diesel electric propulsion is often adopted. The main advantage of such a configuration is that the engines are decoupled from the shaft and therefore the propeller. This allows to have more degrees of freedom in the location on board of the engines that can be, for example, moved afterward where the ship waterlines are wider and therefore more space is available for isolation by means of enclosures or other devices.

Gas or steam turbines are mounted on some specific ship categories such as fast ships or military ships or on gas carriers that take advantage of the cargo boil off.

Propellers

The propeller is definitely the most diffused propulsor in use by sea going vessels. Propellers are probably the most important sources of underwater noise [4], and among the main ones as regards internal noise. The most important contribution for the propeller regards the noise emitted in water. As recalled in [5], there are four main mechanisms which contribute to the noise emission from propellers. Some of them are typical of cavitating propellers, other ones occur also on propellers working in non-cavitating conditions. The fluctuating pressure field generated by the blade profiles moving in water can be seen as the sum of two effects: the displacement of the water by the propeller blade profile (thickness effect) and the pressure difference between the suction and pressure surfaces of the propeller blades (lifting surface effect) [5]. These two effects are influenced by the wake. The wake is, in its turn, influenced by the presence of the hull that is placed upstream in respect to the propeller. Consequently, the velocity field reaching the propeller disc in not uniform both in terms of magnitude and direction. The result is that the angle of attack on the blade profiles fluctuate along the circumferential trajectory inducing fluctuations in the pressure filed around the blades. Such fluctuation generates tonal components at the blade passing frequency both for the cavitating and non-cavitating propeller.

Cavitation occurs when the propeller generates pressures that goes below the vapor pressure, which depends on hydrostatic pressure and water temperature. In such a condition vapour bubbles appears in the fluid region close to the blade suction side. The cavitation volume fluctuates because of variations in the hydrodynamic components of the pressure field and because of the variation in the hydrostatic component, depending on the blade distance from the water free surface. Due to these phenomena, two more noise components are generated respectively due to the periodic fluctuation of the cavity volumes and to the sudden collapse process associated with the implosion of cavitation bubbles when the pressure rises again over the saturated vapour value. The collapse of bubbles creates shock waves and hence essentially 'white noise' covering a frequency band up to 1 MHz [5].

All the above-mentioned phenomena are responsible for noise radiation in water, but the pressures induced by the propeller on the stern counter can excite the ship structure and consequently radiate noise also inside the ship.

2.2 Internal noise radiation

As above mentioned, the main sources of noise on board the ship are the engines (main and auxiliary), the propeller and the air conditioning plant. The engines and the propeller are very strong sources but are usually located at the very aft of the ship (a part from the bow thrusters) while the ventilation and air conditioning is spread all around the ship, in particular in passenger ships. The transmission of sound energy on board involves a continuous energy transformation from mechanical energy (structure borne noise) to acoustic energy (noise). The engines release energy both in air and in the steel structure of the ship, through their foundations. The mechanical energy is transmitted efficiently within the structure, due to its relative flexibility and low damping, reaching zones quite far from the engine room. The same applies to the propeller excitation on the stern counter structure. Vibrations on decks, walls and ceilings in turn generate airborne noise inside the spaces occupied by passengers or crew.

On the other hand, noise generated in air by the engines can easily propagates within the ship through ducts. Another main noise path is represented by the trunk, extended along the entire vertical extension of the ship and containing the exhaust gas ducts running from the engine room to the very top of the ship.

As regards the ventilation system, the main issue is linked to the local effects due to turns and /or outlets generating flow turbulence and, accordingly, noise levels. The problem is enhanced by the relatively high speed of the air in the ducts (due to space constraints) and by the diffused presence of ducts covering the whole extension of the ship.

Powerful compressors, representing, in turn, sources of structure- as well as air-borne noise characterize, on the other hand, the air conditioning system.

The analysis of noise transmission on board is complicated by the presence of several transmission paths connecting sources and potential receivers. These paths may include portions in the structure and in the air, with several possible conversions from structure- to air-borne noise and vice-versa.

A positive aspect is represented, from the point of view of a regulatory action, by the fact that the receiving position as well as the source and the transmission paths are placed on the ship, so that the whole process can be controlled at a design as well as verification stage by the same body.

2.3 Overall external airborne radiation

As mentioned, when the ship sailing, the main sources on board are related to propulsion. While moored, on the other hand, ships still need to run a number of plants related to the functionality of the vessel. In both cases, those locations and devices that establish a direct connection between these plants (propulsion engines, diesel-generator sets, HVAC groups) and the external environment induce the most effective external noise radiation in air. Examples are the funnels as well as intakes and outlets of the ventilation and air condition systems. Other noise sources, which are more dependent on the specific ship type and generally characterized by transient components, are due to cargo handling equipment, both run from the ship or from ashore (*e.g.* grabbers, conveyors, gantry cranes or vehicles ramps).

The impact of the air-borne noise radiated from the ship strongly depends on the shape of the coastline, on the orography and on the topography of the surroundings. A full impact assessment should therefore take into account all the elements of the noise transmission chain, *i.e.* source, propagation and receiver. This is complicated by the reflecting/diffracting surfaces present both on board and on land when the ship is moored at harbor. Despite the number of available numerical predictive models for noise propagation, the specificity of the ship source and of its noise radiation, is not yet fully covered in the existing technical and normative framework [6]. Furthermore, the implications on the evaluation of impact on people living near ports has not been yet completely investigated.

2.4 Overall external underwater noise radiation

The underwater noise radiated by ships has been specifically included, with an increasing emphasis, in the list of emissions into the ambient that need to be assessed and controlled. A general increase of the background noise in the oceans, especially for frequencies below 300 Hz, due to the diffused shipping activity, is an objective datum [7], but how this noise is radiated by ships and how it affects globally and locally the marine wildlife are not yet clear subjects.

As mentioned above, many different components contribute to the overall underwater noise emission of ships, making it difficult to clearly distinguish the single contributions. Nevertheless the dependence on some ship's macro parameters that characterize the ship can be identified. The size of the ship is in general a rough indicator of the overall noise emitted.

Larger dimensions are usually linked to higher noise levels [8]. This is mainly due to the fact that larger ships necessitate of more power to be moved, and therefore more powerful engines are needed. The ship size has an influence also on the frequency content of the emitted noise as in general smaller ships emits at higher frequencies [9].

Speed has an important role. Noise usually increases with speed. It is however important to underline that ships are designed for a specific speed - called "design speed" - which is always maintained by a ship during navigation. Both the main engine and the propeller are optimized for such a condition that corresponds also to an optimal sound level emission condition. Off design conditions can produce higher noise levels even if the speed is reduced in respect to the design speed as the entire propulsion chain works far from the optimum (see *e.g.* [10]). This phenomenon is particularly important for ships equipped with controllable pitch propellers (CPP).

The propeller type is, as a matter of fact, another important parameter that has a direct impact on the underwater noise. In particular, CPP allows the ship to vary the speed both changing the propeller revolutions and/or rotating the blades along their vertical axis and therefore changing the propeller pitch. With the latter approach the angle of attack is modified for all the profiles along the blade radius, obtaining, in extreme cases, even negative angles of attach. This makes the propeller work in conditions which are very far from the optimal ones, resulting in a dramatic increase of the noise levels.

The loading conditions of the ship (*i.e.* the draft) have an influence on the hydrostatic pressure on the propeller, and therefore on its cavitating behavior. In particular, propeller cavitation is more probable for ships in ballast condition.

As regards the dependence of noise emitted on the aging of the ship, underwater-radiated noise seems not to be heavily dependent on ship maintenance. Damaged or affected by fouling propellers may experience increased cavitation patterns, but are usually cleaned or repaired during dry-docking [4].

3 Receivers

3.1 Humans

The effects of noise on human beings are a well-known topic since decades. Equal loudness contours were first made available by Fletcher and Munson in 1933 [11], then by Churcher and [12] and later by Robinson and Dadson [13] whose experimental determination became the basis for the ISO 226 standard whose last revision is from 2003 [14].

On board ships, noise may cause hearing damage, interfere with communication and/or cause annoyance [15]. The problem of the annoyance on board ships arises for both crew members and passengers, since they spend a long time in a very confined space. On board spaces are sometimes even simultaneously occupied by both passengers and crew. This is difficult to be managed from an acoustical point of view, making it quite hard, if not impossible, to use criteria for assessing noise annoyance coming from other fields. As stated in the literature [16], the specific aspects of large passengers ship structures and their "one of a kind" production prevent to define general quantitative correspondences. Studies on these topics are scarce and quite outdated, and vary from the analysis of noise and vibration effects [17–24] to psychoacoustics, comfort, sleep disturbance and in general well-being aspects [25–28, 30, 31]. Generally speaking, there are indications that passengers' expectations about comfort onboard ships are usually comparable to hotels being the nearest equivalent [29]. Moreover, it was showed from full scale trials [32] that for cruise ship luxury cabins the lower end of the noise band corresponds to the higher end of the accepted noise range for the market of hotel rooms.

For what concerns the noise perceived from inhabitants of the areas surrounding ports, the problem has been raised several times by citizens living in areas close to harbours, usually ending up complaining with municipalities [33, 34]. Moreover, this kind of noise affects also harbor workers [35]. In a recent study [36], Murphy and King underline that port noise has the potential to be a significant health concern, and that the intermittent nature of this kind of low frequency noise can produce great shocks to residents' sleep patterns that can conduce to, for example fatigue, reduced productivity, anger, lack of motivation and focus.

3.2 Marine Fauna

A key aspect in studying the impact of underwater noise pollution is the sensibility of the receiver, *i.e.* how the marine fauna, in particular mammals, perceive sound. Dealing with cetaceans, two sub-orders can be identified: Odontocetes and Mysticetes, differing, among other characteristics, from the acoustic point of view. To determine their hearing capabilities is a very complex task. In the case of species with smaller size (*e.g.* those belonging to the Odontocetes), tests are carried out in laboratory, in order to obtain their hearing threshold. These tests are performed in specific pools, subjecting the animals to tonal noises and recording their reactions by means of electrocardiography (ECG) or "auditory brainstem response" (ABR) methods. This allows to derive a curve of sensibility (audiogram) for the range of frequencies and amplitudes in which the animal can hear. Each species, even if belonging to the same sub-order, is characterized by different hearing characteristics, so a very large number of tests has to be carried out to cover the whole marine fauna of a given area. Such approach cannot anyway be adopted in the case of the big Mysticetes that cannot be confined in a laboratory. More information is, on the other hand, available on the emitted signals, because it is sufficiently easy to record and classify the vocalization of the animals. This can provide an indirect information about the frequencies of maximum sensibility.

As it can be seen from Figure 1, each species is characterized by hearing sensibilities that differ both in the frequency range covered and in the threshold level. In general, the frequency range is quite wide (about 100 Hz to 100 kHz). It is interesting to note that the frequency communication range of the Odontocetes is centered on the minimum of their audiogram (*i.e.* in the maximum of sensitivity). The same apply for many species (also terrestrial).

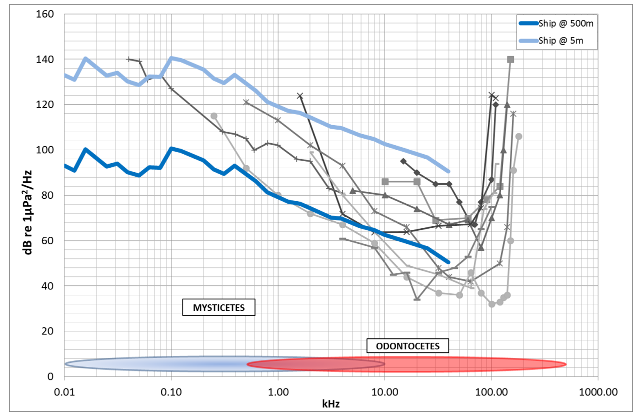

Figure 1: Odontocetes audiograms together with typical ship spectra at different distances and communication ranges of odontocetes and mysticetes

Mysticetes communicate at frequencies significantly lower: this could support the hypothesis that the maximum sensitivity of such mammals is shifted towards low frequencies.

This low frequency range corresponds typically to high levels of the noise emitted by ships (Figure 1).

3.2.1 Effects of noise on the marine fauna

Shipping noise pollution can have two main consequences on the marine mammals:

- behavioral changes in single individuals
- reduction in communication between members of the same species

The responses to noise in terms of behavioral changes are complex and still not fully known [37]. They are conditioned by factors such as auditory sensitivity, behavioral state, habit or desensitization, age, sex, presence of young individuals, etc. Short-term reactions to man-made sounds on cetaceans include sudden dives, fleeing from sound sources, vocal behavioral change, shorter surfacing intervals with increased respiration, attempts to protect the young, increased swim speed and abandonment of the polluted area. Little is known with respect to the long term effects in terms of behavioral changes in individuals or populations. Nevertheless, it is possible to confirm that the disruption induced by noise on feeding activity, reproduction, migration or caring for the young can decrease the possibility of successful reproduction, the chance of survival of the young and the food intake. These detrimental impacts will be more severe in cases where cetaceans

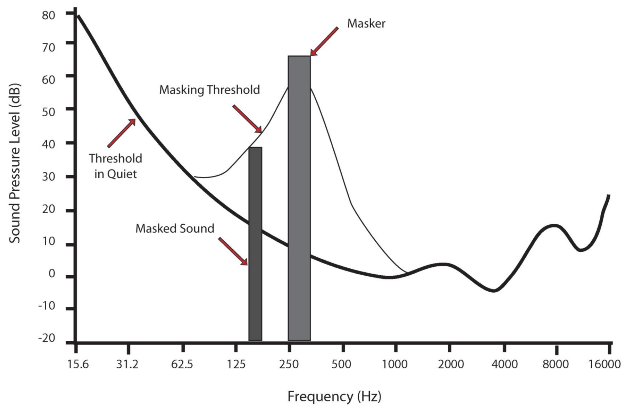

Figure 2: Masking effect of a pure tone

have been displaced (permanently or temporarily) from important breeding and feeding zones.

A different effect is represented by masking, a process that occurs in all auditory systems when a noise reduces, partially or completely, the capacity to hear sound or signals. The situation for the case of two relatively narrow signals is depicted in Figure 2, where the threshold shift due to the masking effect is shown. The effect of the interference depends on the spectrum and the temporal-spatial relationship between the signals and the masking noise [3]. A key parameter in the quantification of the phenomenon is the critical band, which is the range of frequency in which the auditory system of a given species cannot distinguish two tonal components. This quantity can be evaluated experimentally, but a direct quantification of the critical bandwidths is, for large cetaceans, probably even more difficult than the survey of audiograms.

The majority of underwater activities produce low frequency sound. This noise can potentially mask the communication signals of all baleen whales and some Odontocetes, such as sperm whales, that use frequencies below 1 kHz. The direct consequences of this masking of communication and related signals can be diverse: group dispersal, reducing a fundamental part of their interaction with the natural environment (echolocation) [38], impaired feeding ability and separation of mothers from young with usually fatal consequences for the calf. It is believed that a continuous noise is more detrimental than transient signals [39] and that low frequency sounds possess a greater masking effect than higher frequencies [40]. No data or direct measurements are still available, however, on the effect of low frequency masking on baleen whales.

4 Noise control and requirements

4.1 Noise control inside the ship

In the Comfort Classes (CC) issued by the Classification Societies, limit levels in dB(A) are fixed for each space typology on board (for both crew and passengers spaces). The general criteria used to assign a limit value to passenger spaces are:

- The type of use of the space: private (cabins) or public
- The noise level we expect to find: high (discotheque) / medium (restaurant) or low (libraries)
- The time spent by passengers in the space: long stay (cinema, theatre, cabin); medium stay (restaurant); short stay (shop); passage (corridor)

The subdivision of the crew spaces is based on the utilization of the single space. In general, there are four macro categories:

- Machinery and Work Spaces
- Navigation Spaces
- Accommodation Spaces
- Service spaces

The classification of crew spaces is in general quite similar to the one contained in [1].

Another type of requirements regards the noise insulation to be enforced between different spaces on board. Requirements are formulated in terms of the minimum noise insulation index and the maximum impact noise levels in function of the characteristics of the adjacent spaces. For instance, if on one side there is a discotheque and on the other one a cabin, the insulation index must be higher than in the case of cabin to cabin separation.

Generally speaking, the CC, which are voluntary class notations, focus on the same aspects of [1], issued back in 1981, but they contain lower limits as a result of the availability of more modern techniques to reduce noise impact and of higher standards of comfort requested by passengers.

For what concerns measuring procedures, the rules of the Classification Societies, with some exceptions, suggest to carry out measures in standard conditions, *i.e.* on straight course at design speed or 85% of maximum continuous rating. Low speed or maneuvering conditions during which high noise levels can be generated for example when bow thrusters are in function [40], are taken into account only in the CC issued by Germanischer Lloyd.

Table 1: Pre-normative SILENV N&V limits (Green Label).

#	Type Name	Location Example	Noise dB(A)	Vibrations (mm/s - rms)
1	Cabins	Passenger, crew cabin	50	1
2	Offices	Hospital	53	1.5
3	Calm public spaces (A)	Libraries, Calm Public Spaces	55	1.5
4	Medium noise public space (B)	Restaurant, lounge, Mess room, Shops	60	1.5
5	Noisy public space (C)	Disco, Ballroom, Corridor, Staircase	65	2
6	Outdoor Areas	Open recreational area, Bridge wings/Open deck working areas	70	2
7	Wheelhouse	Wheelhouse, Radio room	60	1.5
8	Workspace A	Engine control room, Galleys	65	2
9	Workspace B	Pantry, Store Laundry ,Workshop, Garage	75	2.5
10	Workspace C	Continuously Manned Machinery Space	90	2.5
11	Workspace D	Not Continuously Manned Machinery Space	105	3

In comparison with the previous regulatory framework, within the SILENV project the maximum acceptable values for noise and vibrations are reduced, being in general more restrictive than the CC and in some cases much more restrictive than the compulsory IMO Noise Code. These values, reported in Table 1, are linked to the award of a “Green Label” notation [54].

4.2 Noise radiated outside the ship in air

As reported in [42] and [43], at an international level, the control and the assessment of the impact of airborne emissions from ships has not been deeply investigated. Such impact may anyway affect the residents of areas near ports or channels and is usually faced at a local level by administrations, driven by citizens’ complaints.

The fact that the ship noise impact depends not only on the ship characteristics, but also on local aspects (topography, orography, local regulations and noise limits, etc.) partially justifies the lack of coverage of this aspect by International Normative Bodies. Aspects of the problem involve potentially quite different institutions such as the International Maritime Organization (IMO), Classification Societies, Coast Guards (for ships), Port Authorities (for harbours), Municipalities, health care institutions and other local authorities (for urban areas). Such a large number of entities involved makes very difficult the assessment of noise impact due to ships and prevents a unified normative approach for noise control of harbours.

In general, the airborne sound emitted by inland waterway vessels (exception made for recreational crafts) is covered by ISO 2922:2000 standard, whose last amendment dates from 2013 [45]. In this standard, which is valid for both sailing and moored vessels, the descriptors adopted are the A-weighted sound exposure level and the maximum AS-weighted sound pressure level for moving vessels, whereas for stationary ones the time-averaged AS-weighted sound pressure level is adopted. As previously said, recreational crafts (with length up to 24 meters) are covered, in sailing condition only, from ISO 14509-1:2008 [46] standard, whose procedure prescribes to report the maximum AS-weighted sound pressure level during the passage of the vessel and the same quantity corrected for background noise and distance. Part 2 of the same standard [47] describes a comparative procedure to assess the maximum sound emission of powered mono-hull recreational crafts using the concept of reference craft. For inland vessels, the maximum source levels (75 dB(A) under way and 65 dB(A) in moored conditions) are covered in the European directive 2006/87/EC, and are to be verified at ground level, at a distance from the side of 25 m.

Need for an effective characterization of the ship source

Both the above mentioned ISO standards refer to measurements carried out at ground level and are mainly focused at carrying out monitoring tests and/or acceptance. On the other hand, the Environmental Noise Directive (hereafter END) of the European Commission introduced the tool of Noise Strategic Mapping (NSM) in order to analyze and control the environmental noise pollution, which calls for a proper acoustic characterization of the sources. This tool uses Day-Evening-Night Level (L_{den}) and Night Level (L_{night}) as noise indicators recommended for the mapping,

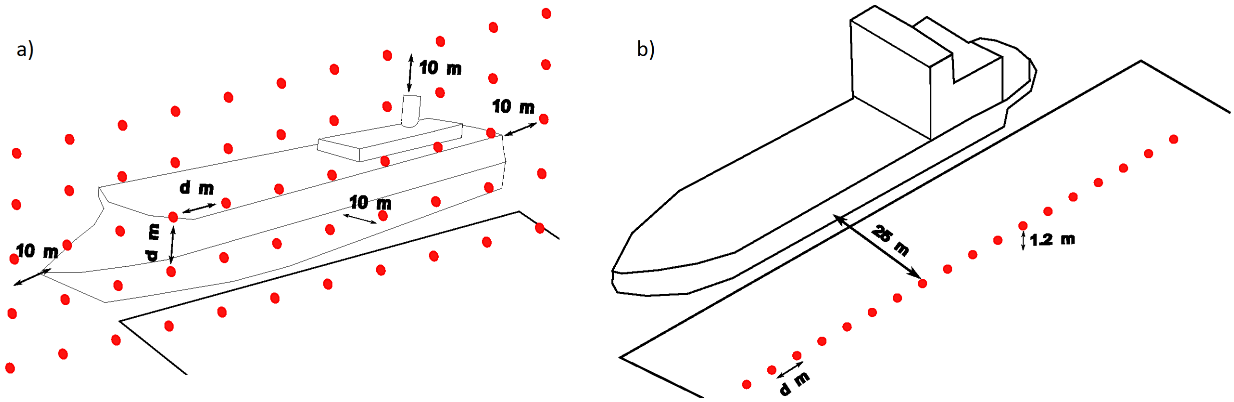

Figure 3: Grid of points for the characterization of airborne radiated noise [54].

and in its Annex IV the END explicitly cites harbours as locations where a NSM should be developed. Since ships are the most relevant sources (even though not the only ones) of noise in ports, the problem of their accurate characterization in terms of sound power definitely arises [48].

It must be underlined again that ships have specific features that make difficult a proper characterization. Ships are very large sources of noise (in particular when compared with the local geography of the sites to be evaluated) and feature a strong directivity and shadowing effects, as pointed out by experimental as well as numerical investigations carried out within the SILENV Project [49, 50]. These characteristics are particularly relevant for studying the impact of moored ships, for which the interest may be focused on areas comparatively close to the ship (as in small ports very close to inhabited areas). In this context, measurements carried out at ground level and without accounting for directivity may not be enough to characterize completely the source [50].

Sailing ships usually move in a relatively free field, at large distances from potential receivers, so that for the prediction of propagation patterns the near field effects (such as the interaction of the emitted sound with obstacles) are less important. Moreover, the characterization of sailing ships is unavoidably carried out at a large distance which will be even higher for large ocean going vessels.

In the light of what above, the objective of a more complete acoustic characterization of the ship source was pursued in the SILENV Project. In addition to measurements recommended by the existing Standards, other ones have been identified to be carried out on a grid of points (on each side of the ship) in order to capture the noise generation from local sources (*e.g.* ventilation systems, vents, funnels) which are located at a certain height in the side or above the deck and even at the top of superstructures (Fig. 3a). The grid of point should be placed at a fixed distance from the side, with small tolerances, in order to make possible a direct comparison among source levels, avoiding the application of a propagation model to refer the measured to a common reference distance. A limit value of 70 dB(A) was set for the levels surveyed on the grid, derived from existing requirements [54].

The distance between the measurement points is influenced by the dimension of the source and by the position of the measurement surface: the farer the surface is placed from the source, the coarser may be the grid of points on the surface (see ISO 3746:2010). In the light of these considerations, the spacing for the points was set as:

$$d = 6\,\text{m for } L < 100\,\text{m}$$

$$d = 10\,\text{m for } L > 100\,\text{m}$$

The first row from below is to be set at 1.2 m from the ground. These values seem to be a good compromise between accuracy of the measurements and their duration.

What above described represents the suggested procedure for a proper characterization and limitation of the noise radiation from a moored ship, that aims to be possibly used later for an accurate prediction of the external sound propagation.

Additionally, within the SILENV, it was decided to set an alternative simpler criterion that can be accepted when it is impossible to carry out measurements on a parallelepiped surface around the ship. According to this simplified procedure, measurements can be carried out along a horizontal line of points at ground level, again at least 1.2 m over the quay, at 25 m from the ship side (see Figure 3b).

The longitudinal spacing follows the general rule described above, and, of course, no obstacles must be present between the ship and the measurement rows.

The limit set in this case is 60 dB(A), stricter than the limit set on the complete grid for two reasons: it is to be verified at a larger distance from the ship and it takes into account that at ground level important contributions due to sources at higher levels may be underestimated.

As in the case of the complete grid measurements, the procedure is to be repeated for both ship sides.

Finally, taking inspiration from the European directive 2006/87/EC (but with an increased reference distance), the SILENV text provides also a measurement procedure for sailing ships.

In order to avoid extreme or exceptional weather conditions that could affect the measured sound pressure level, the measurements are to be carried out in weather conditions fulfilling the following requirements: wind velocity less than 5 m/s; absence of rain or any other type of precipitation; sea state lower than 3.

The ship must sail in straight line at a speed of 10 knots, and a pass-by test must be carried out using the same layout reported in ISO 14509-1:2009. The limit set by SILENV state that noise measures at 25 meters from the ship side during the pass-by test must not exceed 75 dB(A) [54].

4.3 Radiation in water

In the last decade, there has been a rising concern about the impact on marine wildlife of the noise radiated into water by shipping activities. In particular, at IMO, the Marine Environmental Pollution Committee (MEPC) has established, since the 58th session in 2008, an agenda item on 'Noise from Commercial Shipping and its Adverse Impact on Marine Life'. A particular matter of concern is represented by marine mammals. These animals depend heavily on sound transmission in water for survival and are therefore particularly exposed to alterations in the ocean background noise levels.

Despite the novelty of the subject of underwater noise radiation (at least for nonmilitary vessels), a few standards and requirements have been already issued for commercial ships on this topic.

It is important to note that many aspects of ship-borne noise emission and propagation in water have been studied in a military context and the techniques for the control of source levels in the case of commercial ships can certainly benefit from the experience gained in naval vessels. The purpose of the control of noise is however quite different and may reflect in a different way of characterizing the source levels and of formulating limits for the emissions.

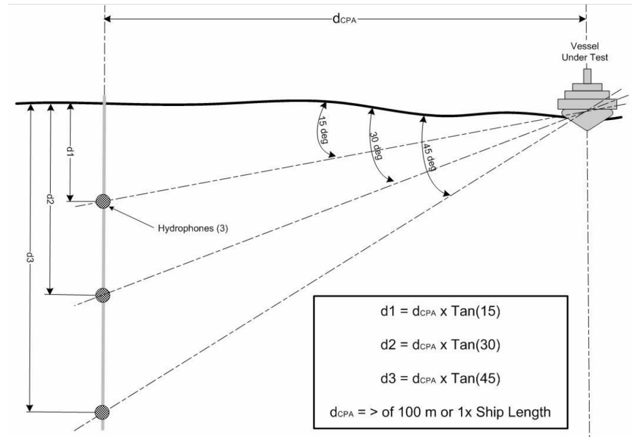

Figure 4: Sketch for underwater noise measurements (from [51]).

Analysis of existing documents (underwater noise)

As regards the measurement of the underwater noise radiated by commercial ships, four standards are presently available:

- ANSI/ASAS12.64-2009/Part1 [51]
- ISO/PAS 17208-1:2012
- DNV Silent Class Notation [52]
- BV Rule Note NR 614 [53]

The ANSI/ASA and the ISO/PAS standards are very similar. Both documents cover measurements of underwater sound pressure levels from ships in prescribed operating conditions. They apply to all kind of surface vessels (with no limitations in size) transiting at a speed up to 50 knots. The general arrangement for measurements foresees a line of hydrophones deployed in the water column (see Figure 4) and a passage of the tested vessel aside the hydrophones at a fixed distance. Three grades are described in the standard, corresponding to higher accuracies achieved increasing the number of hydrophones, the number of runs and the frequency bands for measurements. The final results are reported in source levels in dB referred to 1 μPa and 1 m. The measurement procedure is in principle applicable to any location (in deep water) and it is not foreseen in the standard to compare results to specific sets of limit values.

In [52] both a measurement procedure for the radiated sound pressure and limits to be fulfilled (in order to get the class notation) are included. The test arrangement is quite different from the previously described ones and foresees a single hydrophone placed on a sloping seabed. (see Figure 5). The peculiar test arrangement suggests that measurements are meant to be used in a comparative way with other surveys carried out in the same specific test location,

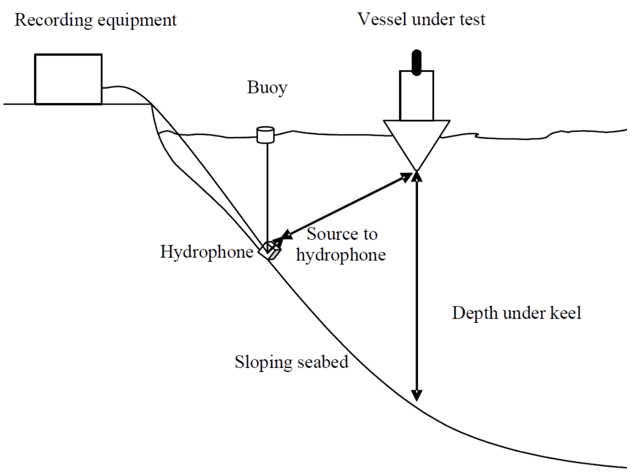

Figure 5: Sketch for underwater noise measurements (from [52]).

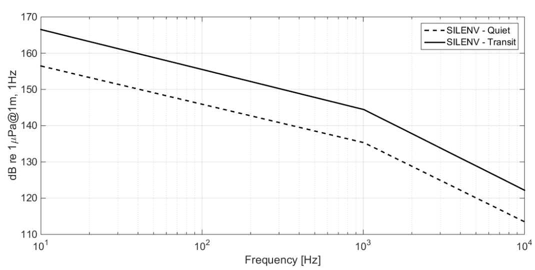

Figure 6: SILENV limits for the underwater noise radiated from commercial ships [54].

more than used as absolute evaluations or compared with results obtained in other sites.

Limit values are provided for different classes of ships, but no information are given about the background of the limit curves, probably originating from a database derived on similar vessels.

On the other hand, a different background is behind the formulation of the limit curve expressed in pressure levels vs frequency provided for fishing research vessels by the International Council for the Exploration of the Sea [8]. The curve is derived (in a rather simplified way) from a single point of the cod sensitivity audiogram. Fulfillment of the limit is meant to ensure that the vessel can get close to fishes without frightening them.

As regards the BV rule note, limits for the underwater noise emissions of three different vessel categories are given. The problem of transmission losses is treated more deeply than in the above mentioned standards.

Criteria for definition of limits (underwater noise)

In defining a limit for the underwater noise of ships, the attention should be focused on the effects of noise on the receivers, (limits based on the receivers' sensitivity) following the same line adopted for the ICES limits. In this case, the receivers are the marine mammals and in particular the cetaceans. The main problem in following such an approach is represented by the uncertainties about the hearing sensitivity of the animals. As a matter of fact, the hearing threshold is known only for a limited number of species, all belonging to the Odontocetes, while for the largest marine mammals (Mysticetes) the information is not available. Furthermore, all species have a different sensitivity. In the light of this, at the moment, it seems not possible to tune limits for ship emissions on the actual perception of noise by marine mammals. Nevertheless, limits aimed at reducing the impact of shipping can be based on the present state of the art, represented by the most silent existing commercial vessels (technology based limits, same approach apparently followed in [52]).

Definition of SILENV limits (underwater noise)

A number of full scale measurements carried out in the SILENV project have been utilized to set the limit curves of Figure 6 [54]. The requirement is fulfilled if the ship spectrum in dB referred to 1 μPa, 1 Hz at the distance of 1m keeps below the associated limit curve. For converting levels from the actual measurement distance to the nominal one, a spherical propagation law is adopted.

Two curves are provided (see Figure 6) for commercial ships, corresponding to different operating conditions: 'transit' and 'quiet'. The transit condition refers to the design speed, while the quiet condition is related to a reduced speed, particularly studied in order to minimize the acoustic impact of the ship. For example, in the case of cruise ships, this operating condition may be adopted to enter protected areas, specially defined for the safeguard of the local marine fauna. For fishing vessels, only the SILENV 'quiet' limit is applied, while for the category of fishing research vessels the same limit proposed by the ICES [8] is adopted.

5 Comments and future developments

In the SILENV project, a holistic approach to the analysis and control of ship noise was adopted. A global assessment of the acoustic impact of the noise generated on board was carried out for the various fields involved. Cabins, living and working spaces onboard and external areas on shore have been analyzed with reference to the effects on human beings, while waterborne emissions from ships have been studied with reference to the marine fauna. This assessment has implied the synthesis of inter-disciplinary expertise, ranging from naval architecture and mechanical engineering to architectural acoustics to human response evaluation to bioacoustics: this is believed to be a rational approach for dealing with this complex theme.

The general aim of the investigation was the identification, quantification and control of the impact of ship noise on the three different fields on which such noise is acting. The level to which this process has been actually completed is considerably different for the various aspects.

Human response to noise and vibration has been studied for a few decades: a set of relevant indicators have been identified since a long time, even though investigations are undergoing and have been developed within the SILENV project, too, to improve the choice of indicators for a better description of the noise annoyance.

The situation is less defined as regards the sensibility of the marine fauna, in particular mammals, to underwater noise. A particular issue is represented by the problem of interference by ship noise with cetacean communication, *i.e.* the masking of signals. This effect is difficult to be quantified because of the difficulty in identifying the critical bandwidths of the animals.

From a regulatory point of view, a coherent set of requirements is already available for the control of noise and vibration on board, issued by the deputed international regulatory bodies for shipping (the International Maritime Organization and Classification Societies). As regards the crew, the focus is both on the health safeguard and on comfort, while for passengers, due to their shorter stays on board, the attention is on comfort only. New limits for N&V in ships were introduced in the project, substantiated through a direct evaluation of the human response by means of questionnaires. To assess the feasibility of the limits, they were compared with the performances of the vessels in service, by using collected data regarding acoustic and vibration performance of different kinds of vessels, see *e.g.* [55].

A more uncertain situation is found as regards the requirements for limiting the impact of ship noise radiation on shore: the existing regulations are generally not specific for ships, but cover noise from stationary sources, like industrial plants, or from more standardized vehicles (cars, airplanes). Ships feature acoustic characteristics that are typical of the single unit and an effective characterization of the radiation is not available (not for single ships, but neither for class of vessels). The situation is further complicated by the fact that the impact on population is dependent on the local geography of the site and on the relative positions of the ships to the receiver, which is more variable than for other vehicles. In the SILENV project, both the aspects of the characterization of the ship source and of the propagation of noise ashore have been covered. A new procedure for an effective quantification of the ship radiation at wharf has been proposed, together with limits to such radiation that were set on the basis of practical considerations. When a large enough database of ship emissions will be available, it will be possible to tune the limits to the impact of noise on people (given the geography and the population distribution of a site).

Finally, as regards the formulation of requirements for the underwater noise radiation from ships, it is noted that, at the moment, only technology-based limits based on good practices can be formulated, because of the lack of knowledge about the sensitivity of the receiver (marine fauna, characterized in addition by a large variety of responses), and about the animal population distribution. This subject has been tackled within SILENV with a reanalysis of existing recommendations and a check with existing data about ship underwater radiation. The aspect of source characterization has been covered, too.

A Green Label for ships was proposed in the project, including targets levels and associated guidelines, for the purpose to qualify the environmental sustainability of the vessel in terms of acoustic emissions in the three fields above mentioned [54].

The work began with SILENV is far from being concluded, as further investigations are needed on all the aspects covered. A follow up is being provided by three more EU projects, namely AQUO, SONIC and MESP, covering specific aspects among those addressed in SILENV.

The AQUO project (Achieve QUieter Oceans by shipping noise footprint reduction [56] as well SONIC (Suppression Of underwater Noise Induced by Cavitation [57]) are both aimed at the mitigation of underwater noise due to maritime transport. In particular, AQUO follows the same holistic approach of SILENV, including also the bioacoustic viewpoint. The target is to achieve a good environmental status (GES) consistent with the objectives of the European Marine Strategy Framework Directive [58]. To this aim, the development of a tool for monitoring the noise field of the shipping activities going on in a given area is foreseen in AQUO.

The environmental noise impact of ports and its management are under study in MESP (Managing the Environmental Sustainability of Ports for a durable development [35]), which addresses the sustainable environmental management of port areas. The target is to reduce harmful consequences for local population through the implementation of a multidisciplinary approach, which encompasses technological, regulatory and administrative solutions, including noise mapping.

Acknowledgement: This work was developed in the frame of the collaborative project SILENV-Ships oriented Innovative soLutions to rEduce Noise & Vibrations, funded by the E.U. within the Call FP7-SST-2008-RTD-1 Grant Agreement SCP8-GA-2009-234182.

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